

Video Streaming in Vehicular Ad Hoc Networks: Challenges, Protocols and The Use of Redundancy

by

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Abstract

Vehicular Ad Hoc Networks (VANETs) are no longer a futuristic promise but rather an attainable technology. Vehicles are already equipped with a variety of computational devices that control or assist drivers in many tasks such as localization, safely breaking, parking and passengers entertainment. The majority of services envisioned for VANETs either require the provision of multimedia support or have it as an extremely beneficial additional feature. In particular, video streaming capabilities over VANETs are crucial to the development of interesting and valuable services. However, VANETs' highly dynamic topology poses as a demanding challenge to the fulfillment of video streaming's stringent requirements.

The main goal on this thesis is the development of feasible solutions that support the streaming of video content over VANETs. Initially, the main issues of VANETs are explained through both a discussion of its characteristics and the results of some preliminary conclusions. Based on this understanding of VANETs' peculiarities, three distinguishing solutions are designed REACT-DIS, REDEC and VIRTUS; the two first for video dissemination and the later for video unicast. These solutions offer a great advancement towards the provision of video streaming capabilities but packet loss is still an issue at high data rates.

In order to improve the delivery ratios reached by the previous solutions, redundancy is used as an error correction mechanism. The use of redundancy is ideal for VANETs in handling packet loss as they do not require any interaction between source and receivers nodes. Sophisticated coding techniques were used for an efficient use of the increase on entropy of the information sent by the source node. It was also evaluated the selective use of redundancy solely on packets carrying the crucial information of I-frames. Although this selective approach obtained lower overall delivery ratios than when redundancy is used for all packets, the video quality obtained similar improvements under a much lower cost. The evaluation on the use of redundancy has considered the impact on the rate by which unique video content is received at end-users which is fundamental to understand the resolution of videos that can be displayed.

This thesis provides several contributions as it advances the knowledge in the peculiarities of VANETs, solutions for video streaming over VANETs and the use of redundancy as an error correction mechanism for video streaming over VANETs.

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Chapter 1

Introduction

Vehicular Ad Hoc Networks (VANETs) are no longer a futuristic promise but rather an attainable technology. Vehicles are already equipped with a variety of computational devices that control or assist drivers in many tasks such as localization, safely breaking, parking, passengers entertainment and etc [127]. It is intuitive then that the next step is to provide on-board communication capabilities to merge sensed information (e.g. speed, objects proximity, vehicle malfunction), automated mechanisms (e.g. breaking, parking, cruise control) and infotainment equipment (e.g. on-board screens, video and audio systems, video game stations) available at several vehicles with many valuable services (e.g. collision avoidance, accident alerts, notification to first responders, services in the cloud, multiplayer games). The fusion of these devices, information and services should be maintained by the cooperation of all the entities involved.

There are yet many new technologies in development for vehicles that are going to enrich even more the options of services to be deployed over VANETs. There has been many suggestions on ways of detecting eventual driver's sleepiness [76] (e.g. seat belts with heart beat monitor, face recognition in search of drowsiness, hands pressure on steering wheel) that could be used to prevent accidents. Technology that uses windshields as monitors have been proposed and they would allow augmented reality solutions to be provided [123] (e.g. display of roads/streets limits in poorly lighted regions, indication of wildlife animals crossing, early notification of traffic lights turning red). Cloud computing has emphasized the need on the provision of on-board communication capabilities in order to achieve a fully ubiquitous access to a variety of online services and to enrich the distributed stored information with data obtained from vehicles [38].

The majority of services envisioned for VANETs either require the provision of mul-

timedia support or have it as an extremely beneficial additional feature. In particular, video streaming capabilities over VANETs are crucial to the development of interesting and valuable services. A camera installed in an intersection could capture crucial information of an accident to be streamed towards an incoming ambulance and even further to doctors in a hospital which could decrease significantly the response time in the provision of life saving healthcare. The same camera would also be able to capture the current status of streets and if this content is transmitted to drivers they could better assess the traffic conditions and take informed decisions on their route selection. Police could use cameras installed in vehicles for the purpose of assembling a local view of spots to be surveilled or to be used on the pursue of fleeing suspects. Video streaming could also be used by on-board game consoles to be used either as gameplay variations (based on local characteristics) or local business advertisement within the game.

However, VANETs are a challenging environment for the transmission of video content due to the network's dispersion, vehicles' movement and video streaming requirements [129]. The design of a feasible solution for the successful and timely deliver of video frames over VANETs has to be in accordance with all features of this network model. This thesis focus on this issue and it describes all the decisive contributions towards this goal.

The following Section lists the main contributions of this thesis. Section 1.1 describes the peculiarities of Vehicular Ad Hoc Networks while the details of the provision of video streaming capabilities over this network model are discussed in Section 1.2. The structure of this thesis is specified in Section 1.4.

1.1 Vehicular Ad Hoc Networks

Pervasive computing is no longer a promising futuristic idea but rather a current reality. Laptops, tablets, netbooks, smartphones are widely available and every new model is compulsorily equipped with at least one wireless interface, often with more than one. These interfaces can be of a variety of technologies with different applicabilities based on their specific characteristics, where radio range is the most influential aspect. Radio ranges vary from a few meters of Bluetooth [41], to a couple hundred meters of WiFi [4] or even a few kilometers of WiMAX [122]. Wireless communication is the backbone behind ubiquity access to computational resources and networks.

Furthermore, wireless communication allows that computational devices carried by users maintain their connectivity while moving. Mobility changes the paradigm on net-

work research since links among nodes are not as stable nor robust as in static networks. Mobility is not only a source of new challenges but it provides itself as an opportunity to improve protocols and to offer new services.

Networks formed of moving devices must consider the scenario in which such devices move to regions where no infrastructure is previously deployed. Mobile Ad Hoc Networks (MANETs) are these networks and the communication relies mostly on the exchange of messages between mutually reachable nodes. In this case, links intermittency is even more severe as they are usually between nodes that are both moving.

We have witnessed in these last years an accelerating evolution in vehicular technology. A lot has been done in terms of equipments for improving security (breaks, sensors, airbags), and there are increasing investments in the development of solutions that increase comfort (heating/cooling, automatic parking) and provide entertainment options (sound systems, screens). Year after year, vehicles are more equipped with computational devices and it is clear that the next step is to provide an inter-vehicle communication system. Therefore, wireless communication has been considered to be used by vehicles in order to enhance further the on-board computational facilities.

Vehicular Ad Hoc Networks (VANETs) are networks formed by the connection of these modern vehicles. Although this process may be assisted by roadside infrastructure, it is assumed that a vehicle-to-vehicle exchange of information is frequently necessary. In this sense, VANETs form a collaborative network of on-board computational devices that are moving at high speeds.

It has still been discussed what will be the technology used as wireless interfaces for the vehicles. The Dedicated Short Range Communication (DSRC) [9] standard is a guidance for the wireless communication between vehicles. The initial and direct approach is to use the current most common wireless interface in the market: IEEE 802.11 b/g/i/n (Wi-Fi) [15]. However, Wi-Fi was designed for communication among static devices and offers a limited radio range. IEEE 802.16 (WiMAX) [5] has been considered as an alternative due to its substantially longer communication range but it is still not clear how WiMAX would perform with devices moving at high speeds as vehicles do. A promising technology is the new IEEE 802.11p [52] together with the Wireless Access in Vehicular Environments (WAVE) [24] which are being proposed taking into consideration the specific details of vehicular networks and offers a reasonable range of up to 1 km.

VANETs are a specific kind of MANETs with fundamental peculiarities that make unfeasible the straightforward use of the majority of solutions for general MANETs.

Instead of people carrying portable devices, VANETs are composed by vehicles equipped with on-board computers that are capable of wireless exchange of messages. Users are mainly drivers and passengers with each having their specific interests and restrictions that have to be considered as scopes for the envisioned services.

Vehicles' on-board devices are much more powerful than the common portable devices of MANETs, thus, having significantly less restrictions. The most important advantage over MANETs is that, in VANETs, power source is practically unlimited so energy consumption is not an issue. Furthermore, we can consider that the computational power (both CPU and memory) are as good as the best options available on the market. For this reason, protocols developed for MANETs must be reevaluated in order to provide better performance since these restrictions can be ignored.

In VANETs, there are several entities interacting with each other with distinct roles. Some examples of this entities and their roles are:

- **Vehicles:** These are clearly the most predominant in VANETs and they act both as users and collaborators. Vehicles are the main users as drivers and passengers are the target "clients" for the majority of envisioned applications. Drivers can take advantage of applications that improve safety on roads and streets, alert messages or augmented reality with extra information displayed on the windshield itself (information such as routes, traffic, nearby stores and restaurants or other vehicles speed and distance). Passengers in the other hand can take advantage of entertainment applications (such as games, film streaming or Internet access with browsing capabilities) or enhanced communication (i.e. videoconferencing). Besides the role as users, the collaboration that vehicles offer to VANETs is on the ad-hoc relay of messages in order to provide support to the communication between nodes distant from each other. Vehicles' collaboration is fundamental to the applicability of VANETs since they are responsible to maintain the communication within areas not covered by any other infrastructure.
- **Roadside nodes:** VANETs may be composed solely by vehicles ad hoc-ly communicating with each other or they can also rely on the support of other computational devices placed by the vicinity of streets or roads. This auxiliary set of nodes are called in the literature as roadside infrastructure. There are several types of roadside nodes that vary in functionality such as connectivity and source of content. Multi-interface access points are roadside nodes that enhance the connectivity among vehicles as they form a backbone (wired or with more powerful radios

capabilities) and, by this manner, they offer shortcuts for the exchange of messages between distant vehicles. Sensors may be deployed by the border of streets or roads and broadcast the captured information to other entities. Examples of captured information are: vehicles speed, which can be used to infer traffic conditions; roads condition such as dry/wet or icy/snow covered in order to enhance safety by properly informing or alerting drivers; live video stream, where a camera is considered a sensor and it broadcasts the sampled video of specific locations.

- **Government Agents:** The government does not only play an important role in VANETs by regulating it but they are also interested parties in using this technology to improve existing services. Transit Departments may use VANETs to collect data throughout the network, gather and analyze it together in order to infer valuable information that may also be disseminate back to vehicles to improve drivers and passengers safety. One example of this would be of identifying accidents through reports of nearby vehicles and use this information to alert other vehicles that are heading towards this area. VANETs are an important tool for law enforcement agents as they support mechanisms for both surveillance and criminals pursuit. Emergency response (either provided by government or private organizations) can provide a more effective service using VANETs where either video streams are sent to doctors/paramedics, or ambulances may follow a faster, shorter and safer route by proper analysis of traffic or alerts sent to drivers.
- **Private Companies:** It is straightforward for companies that already operate dealing with vehicles in roads or streets to take advantage of the availability of VANETs to improve the quality of their offered service. For example, companies that manager private roads may offer services such as Internet access, traffic conditions information, automate toll charging or accident alerts. Besides that, other companies might decide to approach this new niche since it offers many opportunities for the deployment of interesting and profitable services. Companies might choose from different methods of exploiting these opportunities through either charging users or relying in a model based on having a large number of users and, thus, a channel for advertising.

Although VANETs do not suffer from CPU, memory or power limitation as in general MANETs, the high speeds by which vehicles move does incur into defying challenges. A vehicle can easily reach 100km/h which means that vehicles moving at this speed on

opposite directions using IEEE 802.11p (up to 1,000m radio range) would certainly be out of range of each other in less than 20 seconds. Therefore, links are highly intermittent having a very short duration. Fast moving vehicles create new links at the same rate as they are broken, with short duration though. For all these reasons, we observe that a VANET's topology is extremely dynamic and this is the main challenge of VANETs.

The ad hoc communication between vehicles is performed through a wireless medium. Therefore, all vehicles within the same vicinity share the same communication channels. This impacts significantly how protocols should consider single transmissions of packets as it consumes resources from all nearby nodes but also simultaneously reach them. It means that every transmitted packet, independently of being directed at one specific neighbor or a broadcast, is observed by all neighbors and prevents them from successfully transmitting a different packet for a time window. It is necessary to take precautions in order to avoid the concurrent transmission of packets by vehicles within range as this incurs into the likely failure on the reception of these packets. The collision of transmitted packets is common and many times frequent in dense regions of any wireless network. Therefore, the shared wireless medium has dual role as both a challenge regarding shared bandwidth consumption and an opportunity since many nodes are reached by the same single transmission.

One issue in VANETs that is often neglected by many protocol designers is the severe non uniformity of density throughout the network. The distribution of vehicles throughout a city or a highway varies significantly [78, 31]. In highways, we observe that vehicles with similar mobility patterns (i.e. speed and direction) form connected clusters that may be disconnected from other clusters though. Besides that, constructions, traffic or other particular events create spots of high density while other regions become sparsely populated. Non uniform density is even more evident in urban environments. In a macro perspective, traffic seasonality, popular neighborhoods (either for commercial, entertainment or residential reasons) or common routes tend to attract concentration of nodes from some other areas. Furthermore, lights, intersections or stop signs cause density fluctuation to be even more dynamic.

The main problem with density non-uniformity is that solutions usually try to be optimized for the trade-off of overhead and effectiveness and this become complicate with such wide density variety. For example, routing protocols focus on achieving high delivery ratios with the least amount of transmissions. In order to be able to successfully delivery packets from sources to destinations, a routing protocol has to be able to relay packets through low density regions but solutions for these lead probably to a unnecessary

highly overhead over denser regions.

It is crucial that any protocol proposed to work on VANETs has to consider that many services and applications are potentially offered to a constantly increasing number of nodes. Solutions that require the use of a large percentage of available bandwidth or monopolize the use of the wireless channel are impractical to an envisioned environment with many available services to a large amount of users. Scalability is an imperative requirement for any solution designed to VANETs.

Another problem faced by Vehicular Ad Hoc Networks is that vehicles may easily move to regions where all vehicles in it are out of reach of any other node in the network [136]. Long lasting disconnected periods are common and its occurrence deteriorates substantially the quality of the services provided over VANETs. Disconnection can be caused by the aforementioned issues of topology dynamism or non uniform density but also by physical characteristics that create communication holes in the network such as block of buildings, parks, lakes or rivers. The most widely used solution for disconnection is the paradigm of carry-and-forward (also known as store-and-forward). In this approach, nodes use their mobility to assist in reaching other nodes in a different region than the one they primarily received a packet from. In the next Section, carry-and-forward and its relation to video streaming are discussed.

VANETs pose themselves as extremely challenging environment for the deployment of any valuable service. VANET's topology dynamism, shared wireless medium, non uniform density, scalability necessity and frequent nodes disconnection shape fundamentally the design of any protocol envisioned to thrive in such scenario. In the following Section, we discuss the specific application of video streaming and the issues in its provision over VANETs.

1.2 Video Streaming

Video streaming capabilities are either crucially necessary or greatly valuable for a high level of users satisfaction for the majority of envisioned applications and services over VANETs. Computational devices and display screens available inside vehicles do not suffer from the same restraints imposed to MANETs' usual devices. Therefore, they are capable of reproducing high quality videos.

Video streaming support over VANETs can be used to improve the effectiveness on emergency response in case of car accidents by streaming a live video from the accident location. This stream would be available for paramedics in incoming ambulances that

could prepare for the proper care even before they arrive at the site. Besides that, the same stream can be forwarded to hospitals so the waiting doctors may also start their analysis. The initial treatment given by paramedics could also be broadcast to hospitals, thus, further assisting doctors into taking informed decisions.

When accidents and collisions happen a live stream video of the road/street can be broadcast so drivers can check the traffic conditions and decide regarding routes to their destination. Drivers could use live video streams of roads or streets ahead in order to use such information to estimate traffic conditions. With such information, they are able to decide about which are the faster routes to their destination. Assuming a scenario where vehicles are equipped with cameras that capture images from their vicinity, it would be possible for law-enforcement authorities to use such images to identify other vehicles or pedestrians they are searching for.

Video transmission capabilities may also be used to entertain passengers while they are in a vehicle. A valuable application would be of providing videoconferencing capabilities so a passenger in a vehicle can communicate with another person with a live video/audio stream of both sides. Online multi-player gaming could also be offered improving the overall experience of passengers during trips or simply commuting.

In this thesis, video streaming refers to the transmission of live video content that is either instantly sampled from a local camera or stored. The live aspect of the video means that its content is of interest to users only for a small window after it is transmitted. For example, a video that is used to show traffic conditions is only useful to help drivers in deciding which route to take if its in respect to the street/road conditions only up to a couple minutes earlier.

The provision of video streaming support over VANETs stress to the maximum the requirements and challenges in these networks. The transmission of video content differs notably from general data due to the usual larger amount of information in a video and the need of a timely delivery of packets, thus, imposing stringent requirements of delay and delivery ratio [75]. Furthermore, jitter and buffer control have to be considered as they have a strong impact on the quality of service experienced by end users.

The most challenging point in video streaming over VANETs is how to achieve high rates of delivery ratio. Delivery ratio is the percentage of unique packets and/or frames that are successively received by nodes interested in their content in relation to the total number of unique packets/frames sent by the source. Higher rates of delivery ratio are not easily achieved due to VANET's topology dynamism, the wireless nature of communications and the frequent occurrence of disconnected platoons. As it has

been pointed out, delivery ratio can be either of packets or frames in the case of videos. The loss of a packet may lead to three different situations when video transmission is considered: 1) a packet lost relates directly to the loss of the full content of one single video frame; 2) a packet can contain information of more than one frame, thus, its lost prevents receivers from assembling multiple frames; and 3) a packet can contain partial information of one frame and the receivers could be able to assemble a lossy frame based on other received packets. Packets loss is strongly related to frame loss and often directly proportional to the quality of video received. The proportionality is broken only if the transmission process treats differently packets containing information that have distinguish importance on the quality of the video. If this is the case, a metric that compares frames fidelity to the original video (e.g. PSNR, MOS, MIV) is more suitable.

Besides delivery ratio, delay is also a challenging issue in the provision of video streaming dissemination support in VANETs. Delay is the time difference between the reproduction of a video at the end users and its transmission by the sender. It is caused by the time spent for the successful transmission of data through the network from the source to destinations. Delay requirements vary among different applications, they can be less demanding in services like stored video playback (however an excessive delay would cause severe degradation on the quality of service experienced by users). However, the majority of applications for VANETs that require video transmission capabilities are for services where video should be reproduced at the receivers in real-time. In these scenarios, end-to-end delay must not exceed a few seconds [118]. An even more demanding set of applications is the one when video transmissions are interactive between users in both endpoints of the communication (e.g. videoconferencing). These services do not tolerate delays of seconds but rather of a few hundreds milliseconds [118].

Although some solutions might provide a low delay average, its variation could negatively impact the ability of receivers to reproduce incoming videos. Jitter is the metric that represents this delay variation. As it is shown in [118], jitter is not a limiting requirement for video streaming because if the delay requirements are fulfilled, simple solutions such as buffering should be able to solve it.

Video transmission is known to be a demanding application in terms of bandwidth consumption. Due to the large amount of data and the necessity of a high frequency in its exchange (i.e. high data rates), solutions to video streaming are expected to use a substantial amount of available resources. However, these solutions have to be able to scale to a large number of nodes in the network and of concurrent video transmissions.

In [118], a study is conducted to determine the network requirements in video trans-

Table 1.1: Quality-of-Service Requirements of Video

Parameter	Video-streaming	Interactive video
Delivery Ratio	< 5%	< 1%
Delay	< 5 seconds	< 150 ms
Jitter	N/A	< 30 ms

mission. Although these values may vary depending on the video coding technique used, they are a reliable guideline to define minimum requirements. The authors have categorized video transmission into two classes: video-streaming and interactive-video. Video-streaming is defined as the transmission of video content from one source to one or multiple receivers where the content sent does not depend on any video content produced by its reception at the receiver(s). Interactive-video is composed by two or more streams of video where one influences the other, the best example is the one of videoconferencing where different users are communicating through a live feed captured by their cameras. Video-streaming is not only of stored video (e.g. movie, TV shows) but it can also be of live content (e.g. traffic conditions, accidents alert).

Table 1.1 summarizes the requirements of video transmission over VANETs based in the two categories aforementioned [118]. As mentioned before, the focus in this thesis is on the first set of applications –Video-streaming.

At this point, it is clear that video streaming over VANETs is a extremely challenging task and it is fundamental to a successful deployment of valuable services. The challenges can be summarized in the design of solutions that overcome VANETs’ topology dynamism, shared wireless medium, non uniform density and disconnection to successfully deliver packets that carry video information in a timely fashion without consuming the majority of available bandwidth. In this thesis, we describe in detail my contributions towards this goal.

1.3 Contributions

The contributions on this work start with this gathered knowledge on the topic of video streaming over VANETs. This thesis offers a thorough discussion of underlying characteristics of Vehicular Ad Hoc Networks. Several defining aspects of this network model are described and their impact on the design of possible solutions are highlighted. The specific requirements of video streaming are also delineated and the composition of these

requirements with VANETs challenges and opportunities are discussed.

Vehicular Ad Hoc Networks are defined mainly by the increasingly availability of on-board technology and the nature of the movement of vehicles. This later aspect dictates the majority of VANETs' challenges. One of the contributions in this thesis is a detailed analysis of the role of mobility in VANETs connectivity [104] (Chapter 3 Section 3.1). VANETs are studied as complex networks and the impact of mobility in changing a static lattice to a Small-World scenario is measured.

Besides the contributions towards a video streaming framework for VANETs, there are other initial contributions that are shown in this thesis. These preliminary works are necessary for a deep understand of VANETs features, challenges and opportunities. Three background works are shown in this thesis (Chapter 3): neighbor localization [17] (Section 3.2, neighbor prediction [107] (Section 3.2.4) and link reliability [18, 101] (Section 3.3). The first consists in understanding the issues and the design of a solution to the problem of having a neighbor table with accurate information of neighbors' current location without incurring into excessive overhead due to frequent exchange of beacons. The solution for this problem was extended to multiple hops (instead of a single one) and the information could be used to predict future neighborhood. This prediction is valuable to plan ahead possible routes to replace eventual broken ones. The last one was a model that estimates link reliability based on link duration with the observation that older links indicate the similarity between movement patterns and an increased likelihood of successful exchange of packets. This link reliability estimation was used to provide mechanisms for differentiated levels of service.

The main contributions of this thesis are in regard to solutions for the support of transmissions of video content over VANETs. The initial efforts on this issue are twofold into two separate problems based on the number of destination nodes: dissemination and unicast. Two solutions for video dissemination (Chapter 4), namely REACT-DIS [106] (Section 4.1) and REDEC [105] (Section 4.2), were designed aimed at being reactive to topology changes, delivering packets in time and handling the non-uniform density of VANETs. For video unicast (Chapter 5), VIRTUS [102, 99] was developed and it is also a receiver-based solution that has the selection of relay nodes balanced between geographic advancement and link stability.

The issues regarding packet loss observed by REACT-DIS, REDEC and VIRTUS at higher data rates requires the implementation of an error correction mechanism. Redundancy is studied as a solution to packet loss in this thesis [106, 98] (Chapter 6) and it could be seen how it successfully increases delivery ratios to levels that fulfill video

streaming requirements. The advantages on the use of redundancy are its asynchronous nature as it does not require any interaction between source and destination. Different coding techniques were evaluated and interesting results on their suitability depending on the scenario were observed. Furthermore, the selective use of redundancy on the crucial data of I-frames was evaluated and this perspective was valuable to provide improvements in the quality of videos received while limiting overhead.

This is a summary of the contributions in this thesis. Many of the results shown here were reviewed by the scientific community and published in well-known venues. The next Section lists the structure of this thesis.

1.4 Thesis Structure

The main goal in this thesis is to study, understand and design feasible solutions to transmission of real-time video content over Vehicular Ad Hoc Networks (VANETs). In order to achieve this goal, it is necessary to investigate thoroughly the details and peculiarities of vehicular networks and video streaming. Based on this knowledge, solutions have to be designed to handle VANETs' challenges and fulfill video streaming requirements.

This first chapter introduces the concept of ubiquitous connectivity and how vehicular networks pose as the new frontier on mobile networks. VANETs are contextualized into other wireless networks and their details and specific challenges are comprehensively discussed. The most important aspects of video streaming and how its requirements emphasize or attenuate VANETs' challenges were discussed. We have also listed applications and services envisioned to be offered over VANETs that demonstrate the benefits they can provide to drivers, passengers, pedestrians and authorities.

The following chapter contains the discussion and study of the current state of the art regarding both vehicular networks and video streaming solutions. We describe the main approaches and techniques that have been suggested for VANETs and video streaming. This study ranges from the identification of interesting solutions to localization and other services for VANETs to the few existing works related to video-streaming over VANETs. We analyze the suitability of most of these solutions to the transmission of video content over VANETs.

Chapter 3 is a compilation of some of my initial works in Vehicular Ad Hoc Networks. These works are listed in this thesis as they exemplify some of my contributions to the scientific community. Besides that, these studies were fundamental to a deep understanding of VANETs and this knowledge is the base to the design of proper solutions.

In this chapter it is also included an abstract study of the role of mobility in Vehicular Networks. This study provides an insightful analysis on how mobility fundamentally shapes the performance of any protocol on VANETs and it also already describes the mobility models used to emulate vehicles' movement used for the simulations throughout this thesis.

We have divided the study of video streaming over VANETs in two distinguish classes based on the relation of numbers of receivers. We have studied separately the design of solutions for unicast and broadcast. In this thesis, Video Unicast is defined as the transmission of video content from a single source to a single destination while Video Broadcast (or Video Dissemination) as from a single source to all nodes within a distance to it. We have not tackled the model of Video Multicast (from one source to many destinations and not necessarily all nodes) but our discussions regarding Video Dissemination can be used to the development of a multicast solution that uses video dissemination and filters the content to be forwarded to application layers of only the appropriate receivers. Although we have not explicitly handle the Geocast model (from one source to all nodes in a defined region), such solution could be easily created as an approach that combines the unicast solution to deliver packets from the source to one node in the target area with the broadcast solution that disseminates them when the region is reached.

In Chapter 4, we examine the process of disseminating video content over VANETs. We go over the specific challenges and issues that any solution with the same goal has to deal with in order to fulfill video streaming requirements. In this chapter, we describe the Reactive, Density-Aware and Timely Dissemination Protocol (REACT-DIS) which is my first solution to video dissemination over VANETs. REACT-DIS is described in detail and thorough evaluated. After, we have designed a new solution called REDEC. It is based on a similar reactive perspective of REACT-DIS but among other strategies, it decouples the process of relay node selection from that of video transmission. It is also thoroughly evaluated and the performance of both REACT-DIS and REDEC are compared between them and other state-of-the-art solutions.

Chapter 5 discuss my solution for video unicast over VANETs, namely the Video Reactive Tracking-based UnicaSt (VIRTUS) protocol. This solution is also extensively evaluated and its perform is compared to other solutions. It is shown how VIRTUS is a significant step towards high rates of successfully and timely delivered of video content from one source to one destination over VANETs.

Although REACT-DIS, REDEC and VIRTUS greatly outperform other solutions, packet loss is still an issue. For this reason, we decided to investigate error correction

mechanisms that can overcome the observed rates of packet loss. We have concluded that additional redundancy is the most suitable approach due to its asynchronous quality in terms of interaction between source and destination(s). The use of redundancy and its impact on video streaming over VANETs is analyzed and evaluated in Chapter 6.

Finally, in Chapter 7, We summarize my contributions with this thesis, highlight the advancements towards video streaming over VANETs and suggest future directions.

Chapter 2

Related Work

The study of Vehicular Networks is a relatively recent topic but there has been a lot of research on this topic already. And in a more generic view, Mobile Networks have been studied thoroughly. In this chapter, we list and discuss some of the existing work in the literature. We try to evaluate these solutions suitability to video streaming and to compare them to the solutions we propose in this thesis.

Initially, in Section 2.1, we analyze the existing solutions in Mobile Ad Hoc Networks. This is a more consolidated field however its direct applicability to Vehicular Ad Hoc Networks is not straightforward.

After that, we describe the most well known techniques applied to routing in Vehicular Networks in Section 2.2. Routing is certainly the most popular topic tackled as it is the fundamentally more challenging aspect of VANETs due to its highly dynamic topology. However, the vast majority of protocols designed to VANETs do not deal with the peculiarities of video streaming.

In Section 2.3, we discuss about Localization in VANETs. The availability of nodes physical position information is assumed extensively by solutions proposed for VANETs, however, different applications and protocols require different levels of accuracy. Some of these issues are discussed in Section 2.3 and my contribution to this topic is described in the next chapter in Section 3.2.

Finally, in Section 2.4, we study the state of the art in regard to solutions towards the provision of video streaming capabilities over Vehicular Ad Hoc Networks. The main techniques and solutions are described and their contributions and limitations are also discussed. Furthermore, we compare these solutions to the ones proposed in this thesis.

2.1 MANET Solutions

Vehicular Ad Hoc Networks are a specific network model of a Mobile Ad Hoc Network (MANET). MANETs are defined by nodes that are mobile and rely, at least partially, to hop-to-hop communication between wireless nodes that do not belong to a previously deployed infrastructure. This model has been studied since the early 1990s as mobile computational devices with wireless communication capabilities began to become available. Later, with further minimization of personal computational devices to PDAs and smartphones, the pertinence of this network model has increased followed by an increase on research interest.

The provision of a routing protocol for MANETs has been widely studied and the topic is mostly consolidated in four solutions or variations of them: DSDV [93], AODV [92], DSR [55] and LAR [60].

The Destination-Sequenced Distance Vector (DSDV) [93] routing protocol is a proactive solution that works by the exchange of a node's routing table with its neighbors. DSDV is based on the Bellman-Ford routing algorithm [30] and it assumes that after some time of exchange of next hop neighboring tables entries between nodes, this information converges to description of routes to every other node by any node in the network. Although it provides a timely route to destinations when necessary by a source node, it consumes many resources to maintain all these paths known with many of them being unnecessary.

The most well known routing protocol for MANETs is the Ad Hoc On-Demand Distance Vector Routing (AODV) [92]. It is an on-demand routing protocol as routing routes are only built upon the necessity of a source node to transmit packets to a destination that it has no previous route to. When this happens, the source node assembles a route request that is disseminated to the whole network and once the destination is reached, it replies with a route reply following the reverse path that it has reached. This works by intermediary nodes storing the information of from which node they first received the route request in question. Upon the reception of the route reply by the source node, it starts sending packets to the proper neighbor. It is necessary to keep track of the continuity of communication between adjacent nodes and when a link break is detected, a new route request is created. There are different ways of observing the status of a link, some with no additional cost to the network such as using MAC layer acknowledgments or overhearing transmissions in a symmetric link, and others with additional cost like with the use of beacons exchange (the later is the one suggested by the designers of AODV).

AODV does not require the use of network resources to the maintenance of routes that are not used and it provides a simple way of creating new routes when they are needed.

The Dynamic Source Routing (DSR) [55] uses the same concept of AODV in the use of on-demand route requests and route replies to find a path from source to destination. However, the route is kept in packets headers and it is defined by the source node once it receives a route reply sent from the destination. DSR also requires that intermediary nodes monitor if path breaks occur and the authors focus on the aforementioned mechanisms that require no additional cost to the network. Furthermore, DSR defines a route maintenance mechanism where cached routes are used if any path break on the previous route is detected. These cached routes are gathered through the reception of different route replies or the observation of intermediary nodes of alternative routes towards the destination. Although this is a reactive solution that does not need the exchange of frequent beacons to maintain an updated neighboring table, this solution is limited to a scenario where communication paths do not extend through many hops since the whole route is stored in every single packet's header.

Location-Aided Routing (LAR) [60] uses nodes' geographical positions to estimate a request zone based on the previous known position of the destination and the age of this information. Once the request zone is defined, a source node that requires a route to this destination limits the broadcast of a route request to a geographical zone between the source node and the request zone. By this manner, the dissemination of the route request is not flooded to the entire network wasting resources in regions that do not lead to a route to the destination. LAR tackles the crucial issue of broadcast storms of route requests however it requires that nodes know their physical location and that the destination position is known in priori by the source (otherwise LAR behaves as AODV and DSR).

In summary, DSDV introduces some useful concepts but its proactive approach is not the most suitable to MANETs. The reactive solutions AODV, DSR and LAR have been proved to outperform proactive solutions due to MANETs intermittent topology. DSR defines that routes are fully informed by the source while AODV and LAR distributes through the intermediary nodes this responsibility. LAR uses location information to limit the broadcast storm of route request by AODV and DSR.

We have evaluated the performance of DSDV, AODV and DSR over Vehicular Ad Hoc Networks through preliminary experiments in the Network Simulator 2 (ns2)¹. All

¹The 2.34 version of the simulator comes with effective and efficient implementations of these protocols.

of them achieved insignificant delivery ratios and the majority of route requests did not incur into route replies received by source nodes (independently if source and destination nodes are moving or static). This happened because the dynamism of links in VANETs is so great, that even for the time between route requests and replies, some of the nodes in the route have moved out of range. In the next Section, we discuss the routing solutions that are specifically developed to VANETs.

Calafate et al. [23] study and describe the issue of streaming video over MANETs. They analyze the performance of solutions at the link-level and later investigate the behavior of routing solutions when video content is transmitted. The authors have observed that although path breaks are properly detected, the process of reconstruction of new routes is not compatible with a reasonable service of video streaming. They suggest that the main issue is the excessive number of collisions that incur into long periods of disconnection. Furthermore, they point out that mobility that create communication holes affect significantly the observed end-to-end delay and jitter.

In [112, 113], the authors proposed a comprehensive protocol named Distributed Rate-Distortion method (DRD) where Raptor code [114] is used as a forward error correction (FEC) mechanism on the top of Scalable Video Coding streams. This solution builds an overlay network on the top of MANETs aimed at organizing the cooperation between peers and clients. They have shown promising results however their network model is of slow moving nodes (up to 3m/s) when compared to VANETs and video data rates are limited to 200 kbit/s. Yi et al. [132] also use a FEC mechanism to improve delivery ratio but they suggest that a multipath approach is able to decrease the frequency of collisions.

2.2 Routing in VANETs

Routing over Vehicular Ad Hoc Networks is significantly different than the same process for MANETs. The topology is extremely more dynamic due to the unique movement pattern of vehicular networks. Furthermore, the non uniformity of density poses as an arduous challenge because it requires contradicting solutions for different regions. Therefore, it is fundamental to re-evaluate MANET solutions and to come up with new paradigm of solutions suitable to VANETs' properties.

There are some works on data dissemination in VANETs in the literature but they have a substantially different perspective. In [80], the authors discuss dissemination techniques for the exchange of messages containing either traffic conditions or vehicles

current status information (e.g. speed, direction), thus, focusing in a scenario where information shared is not as large (in terms of bytes) as videos. Besides that, every node in the network is not only an interested party but also a potential source of data.

Benslimane et al. [13] discuss the dissemination of alert messages (e.g. collisions or accidents) throughout a VANET using special relay nodes to improve the performance of the protocol. In [34], the authors also focus on the application of informing vehicles about traffic conditions in their surroundings. Dornbush et al. propose a mechanism for vehicles to estimate traffic conditions and, through a clustering approach, disseminate the obtained information to vehicles in the network.

In [137], the authors propose a data pouring scheme based on available roadside infrastructure that take in consideration vehicles movement to avoid an excessive number of transmissions. Furthermore, the authors suggest placing this roadside infrastructure strategically on intersections in order to optimize coverage of each transmission. However, this solution assumes that applications are reasonably delay tolerant which it is not suitable to describe video-streaming services.

In [128], the authors have studied the period of disconnection in highways. They have observed that this period can range from a few seconds to minutes. One of the most often used approach to handle long periods of disconnection is the carry-and-forward, also known as store(-carry)-forward, that requires nodes to store received packets and forward them after they have moved within reach of new nodes. The main problem with this mechanism is that it increases strikingly the end-to-end delay and it is only suitable to delay tolerant applications, however its concept of how to use mobility for connectivity is valuable. This technique is used for unicast in [87] and for dissemination in [62].

Most of the known routing solutions (in wired and wireless networks) demand the intermediary nodes relay packets to neighbors that are specified in packets headers by the relay transmitting node. A different paradigm is the one where receiving nodes are the entities that decide the participation in the communication path between source and destination. By this manner, a node forwarding a packet simply broadcasts it and its neighbors decide

Receiver-based solutions have been proposed for data dissemination [82, 10]. These works take into consideration overheard retransmissions of packets for each node's decision to broadcast further or drop received messages. The time a node waits to decide to retransmit is biased towards favoring farther nodes. In [82], the waiting time is chosen randomly from 0 to a maximum waiting time that decreases exponentially with the distance from the previous node. Additionally, both solutions requires nodes to keep track

of overheard retransmissions of the same received packets, while in [82] this is done by comparing relay nodes that are closer to or farther from the previous node, in [10], the comparison is done based on inter-arrival time of duplicate packets. Although these two mechanisms depend on the number of overheard transmissions, they do not directly reflect the non-uniformity of VANETs' density. My approach in this thesis (see Chapter 4) implements better the greedy heuristic of choosing farther nodes to rebroadcast received packets and it is better suitable to VANETs' density distribution.

The Adaptive approach for Information Dissemination (AID) [11] is another receiver-based solution that conducts relay node selection during the transmission of the disseminated content itself. AID does not consider the availability of location information and nodes' waiting time is uniformly and randomly chosen. When this time expires, the decision of a node to become a relay node depends on an comparison between the average rate of duplicates' reception and the actual time intervals between these receptions.

Tonguz et al. [119] define an unicast (despite having broadcast on the protocol's name) solution called Distributed Vehicular Broadcast (DV-CAST) that uses a receiver-based approach when the network is dense enough. The interesting concept in this work, it is that the authors have observed the importance on considering the variability of density in VANETs to take distinguished steps. It follows a geographic advancement based heuristic for a receiver-based mechanism when the network is dense. In a scenario with average density, nodes assume a dissemination state where they continue to broadcast the packet until they perceive it has been forwarded towards the destination. If it is a sparse network and the node does not have any other neighbor, it shifts its operation mode to a carry-and-forward approach and it waits until it moves within reach of a new node. DV-CAST relies on the exchange of beacons for the knowledge of the local topology by each node which leads to excessive overhead and often inaccurate assumptions.

Contention-based Forwarding (CBF) [36, 37] is a receiver-based solution where relay node selection is based solely on geographic advancement. Every transmission through CBF triggers the relay node selection process; and, when a node decides it is suitable to forward further a received packet, this decision is valid only for this respective transmission. The area-based suppression scheme of CBF makes use of the Reuleaux triangle to define its forwarding zone.

Routing solutions aimed at urban environments frequently use the observation that streets segments intersections are crucial locations for the relay of packets between distant end points. The main idea is that buildings within blocks prevent the communication between nodes in different streets even if the distance between them is shorter than that

of the communication range.

The Road-based using Vehicular Traffic (RBVT) routing protocol [86] follows the paradigm of using roads intersections as routing points. In this work, the authors suggest two versions of the protocol depending on how nodes build their knowledge of the network topology: one reactive (RBVT-R) and another proactive (RBVT-P). Both of these solutions aim to provide transmitting nodes with updated information in terms of the intersection points towards the destination that currently have vehicles to relay packets. RBVT-R builds a route to a new destination on-demand by having the source node disseminate a route request through the network but, differently than AODV and DSR, the dissemination of the route request follows a receiver-based approach limiting the issue of a broadcast storm. Once the destination receives the route request, it analyzes the path transversed by the request packet and replies with the intersection points that should be followed by the source node. The proactive approach of RBVT-P requires that nodes at random times disseminate "Connectivity Packets" (CPs) that travel road segments and store intersection points. The node responsible for a CP disseminates the obtained information to the whole network. By this manner, when a node needs to transmit a packet, it has a reasonably updated route to the destination node (it is assumed that its location is previously known). Independently of how the topology information is gathered by nodes, once a packet is sent, it uses a receiver-based approach that follows the straight lines between the intersection points towards the destination. This is an interesting solution that merges both receiver-based and intersection-based approaches and it considers many of VANETs characteristics but it does not consider the requirements of video streaming. The results shown in the work do not fulfill these requirements and the data rate used is much smaller than the one necessary for video transmission.

Other works have studied the impact of density in the performance of protocols for VANETs [42, 46, 79]. In [42], the authors describe stochastic traffic models to estimate and predict vehicles density. They discuss the use of density information to improve routing and channel access strategies in order to optimize throughput. Hsu et al. [46] make use of local knowledge of density to dynamically adapt Contention Window's parameters in order to avoid excessive collisions. In their work, they use the periodical exchange of beacon messages to estimate local density. Monteiro et al. [79] suggest the use of density knowledge to shift paradigms of message exchange where in sparse regions carry-and-forward strategies are used to overcome communication holes and in denser regions suppression techniques are used. VIRTUS adapts to variations in density through the observations on the reception of duplicated messages. In a receiver-based approach,

duplicates are an indication of higher than expected density that lead to nodes with similar waiting times. In this way, VIRTUS is a density-aware solution that does not require the exchange of additional messages for the estimation of density.

The applicability of Network Coding in VANETs has already been studied [64, 65, 3]. In [64, 3], Network Coding is used for content distribution over VANETs, Lee et al. [64] present an efficiency analysis of Network Coding in VANETs based on computational costs and both works show the impact of network coding on delivery ratio by measuring the time necessary to distribute stored content within a VANET. However, QoS requirements on content distribution are much less rigorous than those on video-streaming.

The use of redundancy through XORed packets (like in Erasure Coding) is used in VANETs by Wang et al. [125] to improve the delivery ratio of beacons carrying information regarding safety conditions of roads and streets. They have enhanced the concept that retransmissions of copies of packets are effective mechanisms to deal with packet loss. They have observed that using Erasure Coding, they could reduce in 60% the amount of packets lost.

Zhang et al. proposed a solution that combines both Erasure and Network Coding using Random Linear Coding [135] for lossy network. In their work, the source node and the intermediary nodes send a number of encoded packets that is greater than the size of a block. They suggest that the redundant information should be used to handle packet loss while Network Coding to improve throughput efficiency. However, their work does not take into consideration peculiarities of wireless networks and shared bandwidth. On the other hand, our Hybrid solution observes that dissemination over VANETs is already redundant and exploits erasure coding only for the first hop of communication. It is through this manner that we could achieve higher receiving data rates at the application layer.

2.3 Localization

The most common and most widely deployed localization mechanism is the triangulation signals received from orbiting satellites. Although there are other proposed systems (e.g. Galileo, GLONASS), the one which is currently most used is the Global Positioning System (GPS) [44]. Many vehicles already come with the necessary equipment for GPS, and several others have been equipped as well. Therefore, this technology is widely available in existing trunks, buses and cars. It provides a reasonable accuracy, with errors from 10 to 30 meters; however, this can be unsuitable for applications that require high

precision. Nevertheless, the errors of GPS receivers close to each other are correlated, and this property is used by Differential GPS (DGPS) [48] in order to provide sub-meter accuracy. DGPS takes advantage of correlated errors by broadcasting the measures of a GPS placed on a location whose real position is previously known.

Another well studied approach to nodes localization in a wireless environment is through analysis of the communication between nodes and base stations. This is called "trilateration" or "multilateration" and it requires that the node's radio is within reach of at least three base stations (for a 2D position). This approach is based on the concept that it is possible to calculate a node's position if the distance or angle between this node and three non-colinear fixed points whose positions are known. The distance between a node and a base station can be inferred by the strength of the received signal (this technique is called Received Signal Strength - RSSI) or by the time a packet takes to travel from the node to the base station (technique called Time of Arrival - ToA). Besides that, the angle by which the signal arrived can be used as well in a technique called Angle of Arrival - AoA. However, trilateration is not accurate enough for most applications designed for VANETs, with errors up to 250m [27, 20].

There are two techniques that can be used to improve accuracy on localization mechanisms: Map Matching [50] and Dead Reckoning [57]. The first consists of using an already extensive amount of geographic information, such as city and roads maps, to determine the areas where a vehicle can actually be. For instance, in an urban area, if a GPS indicates a position where a car would be inside a museum, lake or any other unfeasible place, the system could automatically adjust the position to the closest street or avenue. Dead Reckoning estimates a node's current position based on a previously known position and information regarding node's movement (e.g. direction, speed, time) or current surroundings. This technique is suitable for scenarios such as tunnels, where GPS does not work for a period of time.

A recently proposed approach to developing a more accurate localization scheme is based on the concept of Data Fusion [21]. In this scheme, the idea is to aggregate all available information related to the localization of vehicles, thus leading to more precise information. It is possible to design models that provide the most accurate position based on the availability of different information, so that the more localization systems are available, the more accurate the informed position will be.

Although there are many studies on how to provide accurate localization for VANETs, there were no studies regarding how to handle the problem of the position of nodes becoming quickly outdated when stored by neighbors. A naïve solution to this problem

would be to increase the frequency by which the periodic messages (beacons) containing nodes' positions is broadcast. However, this would likely lead to an overhead of messages, specially in a dense scenario, causing many packets collisions and substantially decreasing the overall bandwidth. In [121], the authors suggest that, under a congested scenario, these periodic messages should be sent with a lower power in order to provide a fair sharing of bandwidth in the network. This solution only decreases the density of the network and partially handles the impact of excessive beacons but does not deal with outdated information at the nodes.

2.3.1 Location Prediction

In [70], the authors suggest the advantages of using motion prediction algorithms to assure service continuity in a mobile network. This work focus on enhancing the handoff procedure in Cellular Networks. Their prediction mechanism (Mobile Motion Prediction - MMP) is divided into two models based on two levels of movement length, one for long term and another for routine movement among cells, the Movement Circle (MC) and the Movement Track(MT), respectively. The authors utilize long term movement history to predict future position of nodes. The predicted movement is for a long period of time as well, different from our approach that is based on short time movement pattern for the prediction of the location of near future positions. Thus, the NPP is much more suitable to VANETs than the MMP.

A different work [89] also proposes a hierarchical mobility prediction model (Hierarchical Location-Prediction - HLP) with two different levels of precision. HLP is designed for wireless ATM networks, thus, the network is divided into cells. The high level is based on regular daily user movement among cells while the low level is based on previous speed, direction and cell geometry. The low level does introduce a better precision, however, the authors goal is to predicted what it is going to be the next cell the node will move to. Therefore, the precision requirements for this scenario are much lower than the requirements for VANETs that we have assumed.

A survey on mobility prediction [25] shows a comparison between some of the first solutions for wireless networks. Besides the two previously mentioned works, it compares also three other ideas [14, 66, 51]. These early works have defined most of the challenges and have proposed initial solutions. However, all this solutions are still based on a scenario with a previous deployed infrastructure and of long term movement patterns

In [109], the authors consider a different approach for mobility prediction based on

context aware instead of movement history. This work describes how user context information should be gathered, stored and used by the prediction model. Personal information, interests, tasks details and environment characteristics are examples of the type of information used in order to predict future location of nodes. Although it is an interesting idea, the granularity of the localization is still based in cells and therefore not suitable for an infrastructureless VANET.

Previous works in the literature regarding mobility prediction in mobile networks is mostly developed for scenarios where a previously deployed infrastructure exists. Vehicular Ad Hoc Networks have distinct peculiarities when compared to other mobile networks which demand different solutions. Besides that, these existing solutions usually consider a long term movement pattern rather than the prediction of location of vehicles in a near future which have a better potential to improve the overall performance of the network.

The concept of using location prediction to improve the performance of routing solutions has been previously studied [124, 1]. Wang et al. show the advantages of using mobility prediction in the selection of more stable paths for communication streams that have higher priority. In [1], the authors modify AODV so that intermediary nodes select next hops prioritizing nodes with similar mobility patterns. A dissemination solution is proposed in [63] that uses speed and direction to select relay nodes.

An interesting study on the suitability of mobility prediction to reduce excessive beaconing to sensitive safety applications for VANETs is shown in [45]. The authors first discuss the challenges location estimations and issues that inaccurate predictions can incur into when safety applications are considered. They extend a Particle Filter to take in consideration VANETs peculiarities and to improve the reactivity to sudden changes in direction. They show their solution is feasible to sustain effective and efficient safety applications.

2.4 Video Streaming over VANETs

An elaborated attempt on providing a feasible video dissemination solution is presented in [116]. Soldo et al. describe a mac layer protocol, namely Streaming Urban Video (SUV), that aims at selecting and scheduling relay nodes based on their positions regarding the previous hop sender. Their idea is to select four different relay nodes for each transmitter, one in each of the 90° sector of the circle around the node and ideally within the ring formed by a distance far enough to facilitate the dissemination towards the whole network with few hops but also close enough to prevent connectivity oscilla-

tions. SUV requires that neighboring nodes exchange beacons containing their positions, time (for synchronization) and list of one-hop neighbors with their respective location and the signal power perceived by the reception of their own beacons. All these information is used in the selection of relay nodes and on scheduling their time of transmission. This solution requires the exchange of a vast amount of data and the synchronization (both in time and information) of many nodes. This limits the contribution of this solution due to both costs and non feasibility of gathering such information with high accuracy.

Xie et al. [130] conduct an overview study of the suitability of some techniques to video streaming unicast over VANETs and evaluate their performance. Their first conclusion is that receiver-based approaches outperform sender-based solutions as they handle better the constant changes in VANETs' topology. They have also analyzed the impact of intermediary nodes' buffers size in the delivery ratio as they are required to store packets until a valid route to the destination is found (in the case of receiver-based solutions, this is related to the waiting time before the broadcast of packets). They have concluded that it is necessary to buffer a large amount of packets in order to achieve high delivery ratios but it does not need to be unlimited as after a point, improvements in delivery ratio are minimum with further increase in the size of the buffer. Furthermore, they have also studied two different dropping policies in the case of overflow of buffers and they could observe that if the packet's information playback time is taken in consideration, better quality videos can be assembled at receivers. This means that it is better to discard packets containing information of frames that are played earlier in the video than simply discarding the oldest received packets. The authors evaluate these aspects through scenarios with different densities and their observations indicate that the protocols perform better in high density scenarios. In this thesis (see Chapters 5 and 6), it has been observed that this is not always accurate as scenarios with excessive density are prone to increases in collisions that deteriorate overall performance.

The authors in [6] focus on a VANET scenario where roadside units (RSU) are widely available with most of video transmission conduct directly from RSU to vehicles and multihop communication does not exceed three hops. In this scenario, their main concern is in providing seamless handover between adjacent RSUs and to prevent playback freezes. They adapt the Proxy Mobile IPv6 (PMIPv6) [40] accordingly to the specific characteristics of VANETs. In a previous work [7], the same authors come up with a analytical model to use video applications requirements at lower layer protocols to offer a QoS solution for the transmission of video. The main constrain in these works is the assumption of a wide availability of roadside units, thus, the issues of ad hoc communication are

mostly neglected.

There are some works [91, 131] that use network coding for video dissemination over VANETs. Park et al. [91] suggest the use of network coding in video dissemination by forcing relay nodes to wait the reception of whole decodable blocks so they can forward newly encoded packets (with a new set of random coefficients) and by this manner improving bandwidth consumption as unique packets are sent by different nodes. However, this approach incurs into prohibitively delays after a few hops of communication. Yang et al. [131] use neighboring cooperation in a way that relay nodes can detect nodes that have not received enough packets to decode blocks. When this is detected, relay nodes encode new packets from the same blocks and broadcast them. Encoding by intermediary nodes is one of the advantages of network coding, however, its use in video-streaming leads to an excessive delay as new encoded packets can only be created after relay nodes receive enough packets to already decode a whole block. In this work, we refrain from encoding new packets at intermediary nodes but rather limit these nodes to forward packets encoded at the source node.

Network Coding is also used in [39] to handle packet loss in video streaming over VANETs. The authors have used Network Coding over a video divided in different layers through MDC in a way that packets containing frames from the same layer are in the same block, thus, the reception of an insufficient number of packets for the decoding of a block does not affect different layers. Furthermore, they have used fuzzy logic to dynamically decided the amount of redundancy sent depending on nodes local density and channel interference.

Sardari et al. [110] use rateless erasure coding for the dissemination of video content over VANETs. In their model, RSUs transmit packets encoded with rateless erasure coding and the information is carried by vehicles (in a carry-and-forward fashion) when they are not within reach of any RSU. The clear disadvantage with this approach is that the use of vehicles mobility increases excessively the end-to-end delay experienced by users.

2.5 Summary

Although many solutions have been designed to MANETs, they are not straightforward suitable to VANETs. VANETs do not suffer from computational power and energy restrictions observed in MANETs. Furthermore, the topology of VANETs are significantly more dynamic than those of MANETs. Therefore, it is necessary to design new solutions

that take into consideration the peculiarities of VANETs.

Localization solutions have been proposed for VANETs, however, they are focused solely on the perspective of a node's own position. This is problematic because nodes positions are many times used by neighboring nodes. It is fundamental to study this issue through the perspective of how a node keeps track of the positions of their neighbors.

The general solutions for VANETs are mostly focused on the issues of intermittent connectivity due to topology changes. Interesting solutions such as AID [11] and CBF [36, 37] utilize the receiver-based approach due to its ability to react to topology changes. However, these solutions do not take into consideration the stringent requirements of video streaming.

The efficient use of redundancy has been advocated by many works [91, 39, 110] however they do not provide a through investigation on its benefits. Although in the majority of times it leads to improvements in delivery ratio, it is fundamental to understand the real impact on video quality and end-to-end delay. The quality of video that can be displayed at end-users is not only subject to low packet loss but also to the rate by which unique video content is received.

In the next chapter, the preliminary contributions of this thesis in regard to improvements in VANETs are discussed. They are not necessarily related to video streaming but they are important to provide an insightful understanding of VANETs.

Chapter 3

Mobility, Neighbor Localization and Link Stability in VANETs

Vehicular Ad Hoc Networks offer many areas of study in Computer Science as its unique model makes unfeasible the straightforward use of previous solutions to general Mobile Ad Hoc Networks. Among these areas, it can be included Localization, Movement Pattern Recognition, Movement Prediction, Quality of Service, Connection Stability, Security, Complex Networks, Context Aware, Transmission Power Control and many others. In this chapter, we discuss about some of my contributions to a few of these areas.

These are not only specific scientific contributions but they also form the background necessary for a deep understanding of VANETs and their main challenges and opportunities. The work described in Section 3.1 provided insightful knowledge in the role of mobility in VANETs. Furthermore, the mobility models developed for this study were used for all the other simulations in this thesis. The concepts used in the work in Section 3.2 of avoiding frequent beacons exchange and to use mobility prediction towards a more sustainable and efficient performance have proved to be of great value to the solutions designed for video dissemination (Chapter 4) and unicast (Chapter 5). Additionally, the correlation between link duration and stability analyzed in the work in Section 3.3 is also used in the solution for video streaming.

3.1 The Impact of Mobility

In VANETs, nodes' mobility presents itself as a complex challenge since it causes frequently topology modifications and, consequently, paths disruptions. Mobility does not

only pose as a challenge to keep an ongoing communication but it also makes difficult the initial establish of communication since the location of a specific destinations is not easily obtained as in static networks.

Vehicular Ad Hoc Networks behave distinctly from other networks and an useful way to study them and determine their intrinsic attributes is through the perspective of Complex Networks. In assuming VANETs as Complex Networks we can make use of techniques to identify non-trivial recurrent characteristics. Therefore we are able to understand clearer how these networks behave and propose more suitable solutions.

Mobility plays an utmost important role in the analysis of VANETs as Complex Networks. Nodes movement dictates how links among them are created. Whenever a node in the network moves to a different region, it provides a shortcut connection between the original region and the new one.

In this work, we study broadly the role of mobility in VANETs to the formation of different Complex Networks. Our goal is, through this analysis, to understand the behavior of varied forms of VANETs and to determine important characteristics that may guide the development of more efficient and better suitable protocols.

VANETs are subdivided into two scenarios: urban and highway. An urban VANET is formed by vehicles moving along streets in a city. They are subject to streets boundaries, thus their movement is not so erratic as in general MANETs. The movement behavior in an urban scenario has peculiarities that would be describe later in this work. The highway VANET is also composed by vehicles but not moving in a road instead of streets. This scenario differs from the previously described urban scenario in terms of even higher speeds and more restricted movement in the sense that vehicles follow the same direction for longer periods.

Therefore, we analyze these different VANETs scenarios in terms of how mobility affect their topology. With such analysis, we was able to identify characteristics that can certainly be used to improve the performance of protocols and mechanism in a variety of VANETs' aspects (e.g. routing, QoS, localization).

A study of the evolution of VANETs' topology is presented by [88]. Although they show the variance of some parameters over time, they have lacked to analyze the impact of mobility on these parameters. Another approach to the study of VANETs' topology is using a non-ad hoc communication, instead of mobility, for random links connecting distant nodes [35]. Similar work is presented by [33], where they investigate cellular wireless networks and how mobility or communication through mechanisms different than the one between the mobile and a Base Station (e.g. ad hoc, secondary infrastructure)

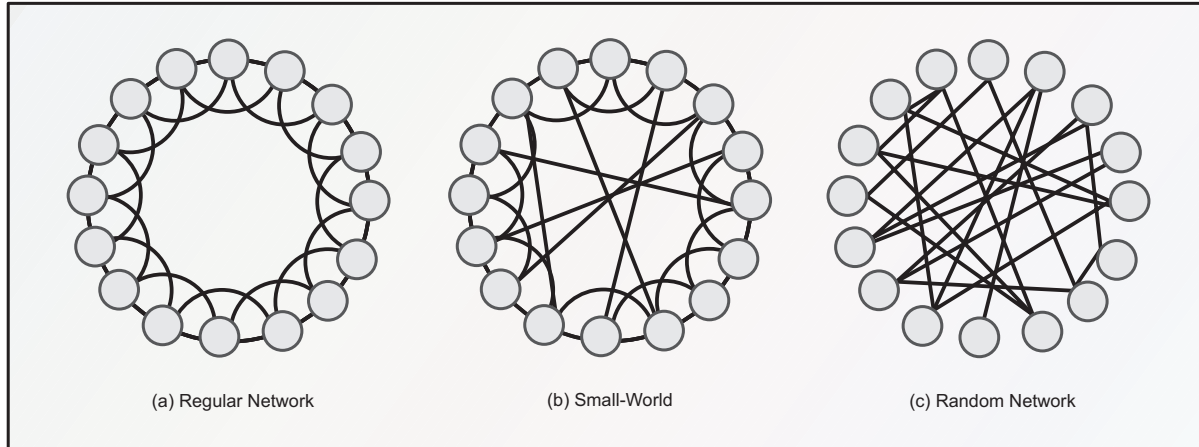


Figure 3.1: Evolution from a Lattice, through a Small-World to a Random Network

can impact the network's topology changing it into a small-world or scale-free network.

In this work, it was considered the mobility aspect and the communication mechanism in these VANETs and the conclusion was that such scenario would be represented with more fidelity by a Small-World. The short-range wireless communication based on broadcast transmissions creates a strong locality in package exchange in the sense that a group of nearby users are able to communicate with each other. This leads to a consistently high clustering coefficient. Although the mobility creates random links between distant groups of users which decreases significantly the path length among nodes.

3.1.1 Experiments Setup

In this section, it is described in details both highway and urban scenarios and thoroughly evaluate the impact of mobility in the networks topologies. The methodology used consists of assembling a graph that represents the connectivity of the network through time. A vertex in this graph represents a vehicle and an edge between any two vertices indicates a communication capability between the respective vehicles. Consequently, the considered graph represents all the communication among vehicles during the defined period of time.

We have used the Network Simulator 2.31 for these evaluations. Table 3.1 shows the value for the most important parameters used in this evaluation. The performance evaluation the network lasts for 30 minutes. However, in order to avoid the influence of cold start issues in the results, it was included 10 minutes of simulation where the only event is node movement and in the following 10 minutes messages are exchanged

Parameter	Value
Radio Propagation Model	TwoRayGround
Mac Layer	IEEE 802.11
RXThresh _l	1.92278e-08(100m)
Antenna	OmniAntenna
Total Simulation Time	50 minutes
Simulation Time Analyzed	30 minutes

Table 3.1: Impact of Mobility - Simulation Parameters

but not considered in our results ¹. By this manner, a steady scenario is reached before evaluation starts.

In order to determine if two vehicles are capable of communicating, each vehicle broadcasts a beacon package periodically. The interval between consecutive beacons is randomly chosen between 0.8 and 1.2 seconds (thus, an average of 1s between beacons). When a beacon is received, the triple consisting of timestamp, source vehicle and receiving vehicle is stored in a separate file.

Every plotted result is an average of the evaluation of 32 graphs, each taken from distinct execution instances. Therefore, each graph is assembled from the information gathered from unique instances with different seeds for random number generation, different vehicles' movements and different beacon broadcasts. Besides the average, confidence intervals were also plotted. Table 3.2 summarizes the statistical analysis in the following experiments.

An important concept in the graph definition is the length of the time window T during which connections are considered. A graph G_T is formed by links between vehicles through a time window of T seconds. Different values of T are evaluated so that the impact of mobility in the topology of VANETs is discussed. The majority of values considered for T are smaller than the duration of the simulation t . For this reason, the starting time t_s of the window considered is randomly chosen between 0 and $t - T$.

Sections 3.1.2 and 3.1.3 describe in details the simulation mobility models and specifics of the experiments setups of urban and highway scenarios, respectively. In each of these sections, the results and conclusions are discussed.

¹The use of 10 minutes of simulation is sufficient to evaluate the role of mobility as connections that require more than that to be available are not useful for the majority of applications.

Parameter	Value
Number of Samples	32
Confidence Level	95%
Distribution	Gaussian

Table 3.2: Impact of Mobility - Statistics Analysis

3.1.2 Urban Scenario

The urban scenario presents itself as an environment for the deployment of interesting services on the top of VANETs. It is possible to use this architecture to provide on board Internet access. Emergency response can be improved in several fronts such as alerting vehicles of incoming emergency vehicles or provide the infrastructure for live streaming directly from the accident scene to hospitals and paramedics in ambulances.

An efficient architecture in this scenario would provide the technology for the development of a wide variety of additional facilities and marketing opportunities for companies in diverse niches. A service discovery mechanism could provide a search engine based on the vehicle's current location offering a much valuable information to the users. Shopping centres and malls may use such infrastructure to offer their customers directions for the closest available parking space or even the capability of previously reserving a spot. Another appealing example is that fast food restaurants with a drive-through facility could provide an ordering mechanism so customers would have an even more convenient experience.

In order to provide the necessary infrastructure for the deployment of these applications, it is of utmost importance to first understand the underlying characteristics of the network topology. In the following subsections, it is provided a detailed explanation of our experiments and the analysis of the results it have been observed.

3.1.2.1 Mobility Model - Urban Mobility Model

Vehicles' movement within a city environment are not as free of constrains as the movement of pedestrians in an university campus. Vehicles move along streets and avenues which restrict the direction of the movement. Although vehicles are not able to change direction anywhere in a city, abrupt changes of directions are possible at intersections. Therefore, there is still some erratic behavior in their movement. Furthermore, vehicles movement in this scenario differ from pedestrians in a general MANET in terms of their speeds. Vehicles in a city move much faster than walking users in the previous scenario.

Parameter	Value
# Density	25 vehicles/km (550 vehicles in total)
Area	1 km x 1 km
Segment Length	100 m
Number of Blocks	10 x 10
Speed Range	5 to 30 m/s
Segment Maximum Capacity	20 vehicles
Reducing Factor	$5^{-[(\#vehicles/5)-1]}$

Table 3.3: Urban Mobility Model Parameters

In [8], the authors describe a mobility model for the city environment named Manhattan Model based on streets placed as in a grid (as the New York borough of Manhattan). In this model, each street has two lanes (one for each direction) and vehicles move at a random speed within a predefined range. When a vehicle reaches an intersection it randomly chooses which direction to pursue. Vehicles have a 50% chance of continuing straight and 25% chance of turning left and the remaining 25% probability of turning right.

For this thesis, it has been designed the Urban Mobility Model (UMM) which extends Bai's Manhattan Model taking into consideration traffic conditions. In real life, the speed of vehicles in a city is not only subject to speed limits but greatly by traffic conditions as well. For this reason, it is used a reducing factor that is proportional to the number of vehicles in the street segment the vehicle is moving to. Besides that, there is a maximum capacity regarding the number of vehicles in a segment at any given time. This capacity is calculated based on an estimate vehicle length and the segment length.

Traffic plays an important role in the movement behavior of the network since it affects not only the movement speed but the density around the network. It is believed that, with traffic awareness, the UMM represents with higher fidelity the movement aspects of real life scenarios.

Table 3.3 summarizes the values of the main parameters for the generation of the 32 distinct instances of the Urban Mobility Model. It is important to point out that, although the speed is initially randomly chosen with the defined range, vehicles may move slower than the lower limit since the final speed is subject to traffic conditions. The reducing factor is a function on the current number of vehicles in a segment and it is only used if there is more than 5 vehicles in such segment.

3.1.2.2 Results and Conclusions

Figures 3.2 and 3.3 shows the results of the data it has been gathered in these simulations on the urban scenario. In Figure 3.2, it is shown how the clustering coefficient and network diameter vary for different lengths of the time window T . The degree distribution for vehicles grouped based on their average speed is shown in Figure 3.3.

The first observation in Figure 3.2 is that the network diameter decreases extremely fast with increments of T . This means that vehicles carrying packages to forward in different regions of the network for a short period of time would be enough to reach the whole area with few transmissions. After 30 seconds, the diameter of the network already reached the natural logarithm of the number of nodes level. Another interesting conclusion is that for delay-tolerant applications, it is possible a network region with the same dimensions using one single intermediary node (for T greater than seven minutes).

In Figure 3.2, it can be seen that mobility initially decreases the high clustering coefficient of a static scenario. Nevertheless, this decrease is not substantial and, with time, mobility starts to increase again the clustering coefficient since vehicles continue meeting and forming more cliques among neighbors.

Regarding Figure 3.3, it is important to explain that considering longer windows, the vehicles average speed converges more to the speed range mean (for this reason, for T greater than two minutes, not all speeds are plotted). The expected result would be of increasing degrees for faster vehicles since they would cover larger portions of the network at the same time. However, this is only observed for average speeds up to 15m/s. The reason for the degrees decrease after that is due to the fact that in a city environment vehicles are subjected to traffic which significantly decreases their speeds. A vehicle in a congested street would be surrounded by several other vehicles and a vehicle with a high speed average has not got stuck into traffic.

With these results, it can be seen that with mobility, the topology similar to a lattice when nodes are static transforms into scenario more accurately represented as a Small-World but does not lead to a Random Network since the communication among nearby nodes still prevails. These conclusions can be used for future design of more suitable solutions to this scenario.

3.1.3 Highway Scenario

The behavior of vehicles changes notably from a city environment to a highway scenario. Highways are used to connect farther locations which are either different cities or simply

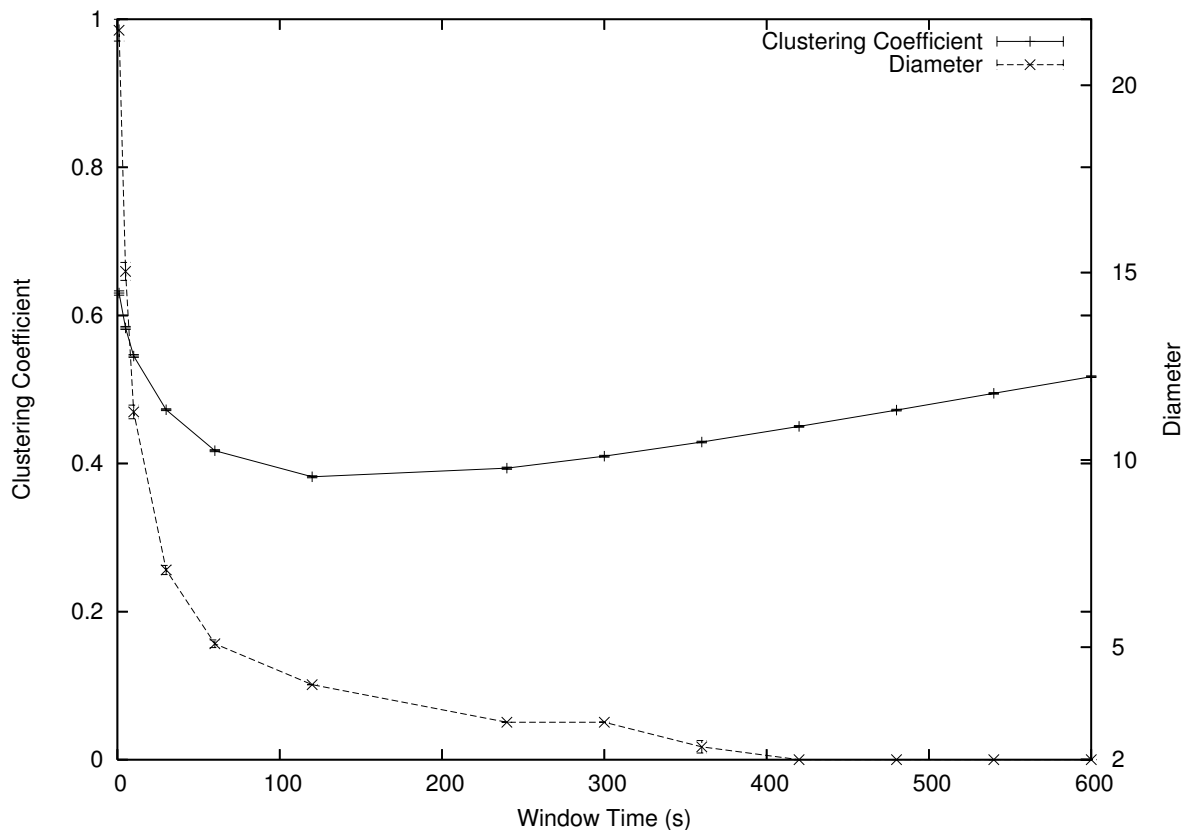


Figure 3.2: Urban Scenario - Time Window $T \times$ Clustering Coefficient/Diameter

distant regions within a large city. Therefore, they have to provide the means for vehicles to move faster in more straight directions and vehicles.

Highways differ from cities' streets and avenues by being usually broader, having higher speed limits, fewer traffic lights and fewer intersections that require a full stop. Vehicles movement in a highway scenario is less erratic than in an urban one since roads do not have abrupt changes of direction as paths followed in a city.

In the following subsection, the mobility model used to simulate this environment is discussed. It is an abstract representation that offers reasonable fidelity to the real life scenario.

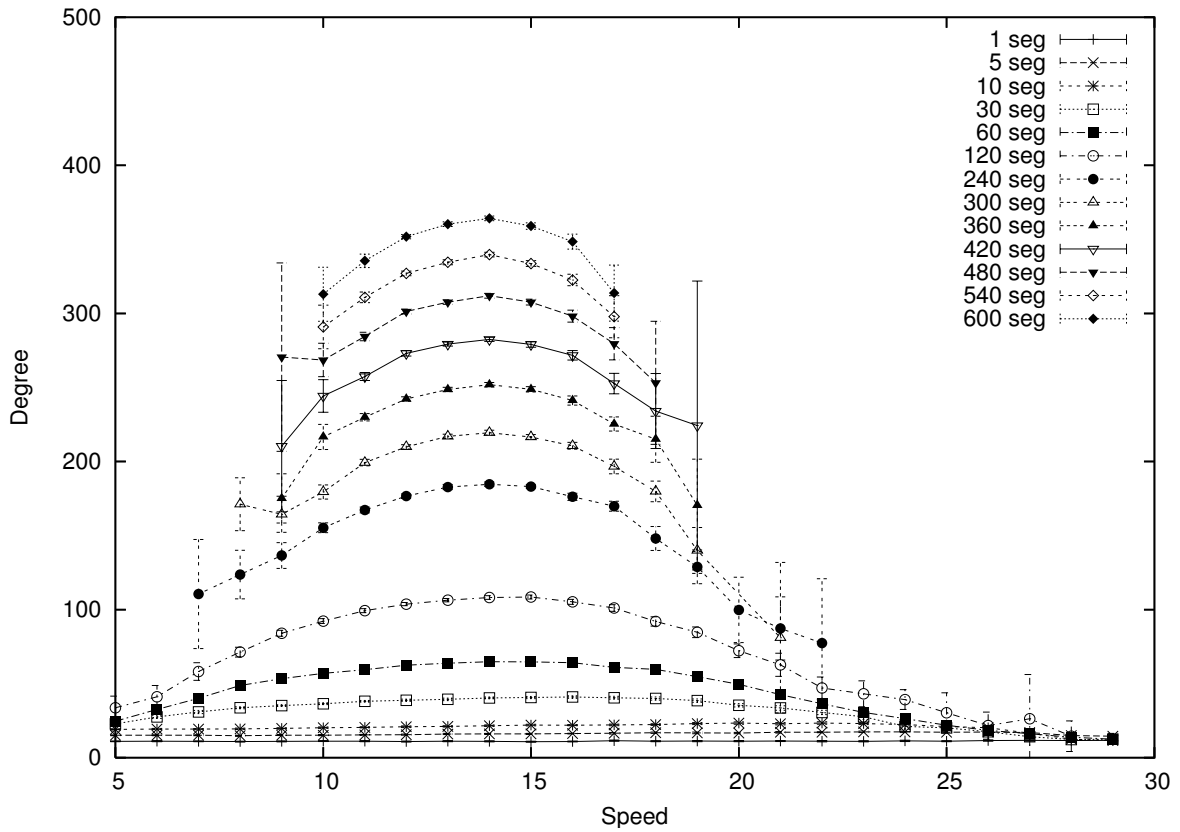


Figure 3.3: Urban Scenario - Average Speed \times Average Degree

3.1.3.1 Mobility Model - Freeway+

The most commonly used model for a highway scenario is the Freeway model [8]. However, an unrealistic aspect of this model is that vehicles do not cross other vehicles once they reach a slower vehicle in front of them; instead they reduce their speed once they are within a certain threshold distance from this vehicle. The resulting scenario would be characterized by a synchronization of speeds and a constant distance between vehicles in the same lane –that is, more stable topologies. This unrealistic behavior would lead to biased and inaccurate analysis of the network topology.

Therefore, this model has been modified so that it supports faster vehicles crossing slower ones. The enhanced model, Freeway⁺, is composed of straight lanes for both directions (curves do not need to be represented since VANETs use short range communications) and a same number of lanes per direction. Each lane has a minimum and

Parameter	Value
# Density	10 vehicles/km
Total Length	150km
Region Evaluated Length	75km
Lanes per Direction	3
Lane Width	5m
Slowest Lane Speeds	5 to 15 m/s
2 nd Slowest Lane Speeds	10 to 25 m/s
Fastest Lane Speeds	20 to 40 m/s
s_c	60s \pm 10%

Table 3.4: Freeway⁺ Parameters

maximum speed, and vehicles speeds are chosen randomly and change every s_c seconds. When nodes reach one of the two extremes, a reset method is called, and the nodes are replaced on the other extreme and in the same lane.

Nodes are distributed uniformly on the road –that is, always within only one lane. Table 3.4 shows the parameters of the mobility scenario used in this work. It is important to notice that the different speed limits are for the three distinct lanes in each direction, thus, for the whole simulation these same limits were used.

The evaluation of the network topology of this scenario would be compromised if it did not handle the issue that when a vehicle reaches an extreme it is placed on the opposite extreme and continue moving. This is done in order to maintain the network density and when placed on the other extreme this node represents a new incoming vehicle. If this issue is disregarded, links would have been considered between vehicles that would never be able to come within reach of each other in a real life scenario. In order to avoid this problem, the simulated road has been prolonged and it was considered solely the communications performed within a limit region of the road. The simulation lasts 30 minutes, thus, only the results in the middle 75km out of the total length of 150km are considered. In this way, a vehicle that reaches any of the extremes of the considered region would never reach the opposite extreme of this region within 30 minutes.

3.1.3.2 Results and Conclusions

Figures 3.4 and 3.5 summarizes the results of our experiments in the highway scenario. Once again, the results are divided into two figures where the first (Figure 3.4) shows

the evolution of the clustering coefficient and diameter for different values of T , while the second (Figure 3.5) shows the degree distribution based on vehicles average speed.

It can be seen in Figure 3.4 that the clustering coefficient suffers insignificant variations for the different lengths of windows. This is an interesting observation and it reflects that although in a highway vehicles move at faster speeds, the road imposes direction restrictions that result in more stable topologies. Vehicles moving to the same direction with similar speeds remain close to each other for long periods (see [19] for a deeper discussion on this phenomenon).

The network diameter in a highway scenario decreases abruptly with further vehicles mobility, but in a different scale than what it has been observed in urban environments. In a highway, it takes longer to observe shorter paths but the natural logarithm level of number of nodes is still reached (after around 10 minutes of movement).

In Figure 3.5, it is shown the degrees distributions for vehicles with different speed averages for different values of T . We can clearly notice that the speeds are grouped in three portions and they are related to each of the three lanes with their respective speed limits. These results are also subject to vehicles having their average speeds closer to the mean of each lane speed range. This happens specially with greater values of T , and in this case, the behavior of extreme speeds (further from the lane average), represents the results of vehicles that were for short periods in the analyzed section of the highway. For this reason, in these cases, the degrees of nodes with speed average closer to the lane range mean represents better the behavior of vehicles. With these considerations, it can be observed that degrees increase slightly but consistently for faster vehicles.

Once again, it has been noticed that mobility impacts the topologies in this VANET scenario making them behave similarly to Small-Worlds.

3.2 Localization through neighboring nodes' perspective

The vast majority of applications and protocols designed for VANETs assume that a vehicle's geographic localization is already provided. Nodes' position is used throughout many layers of the network stack, from the MAC layer [29], through routing [71] to the majority of applications. Therefore, for the deployment of these networks in a real environment, it is fundamental that all issues related to the localization of vehicles be understood and fully addressed.

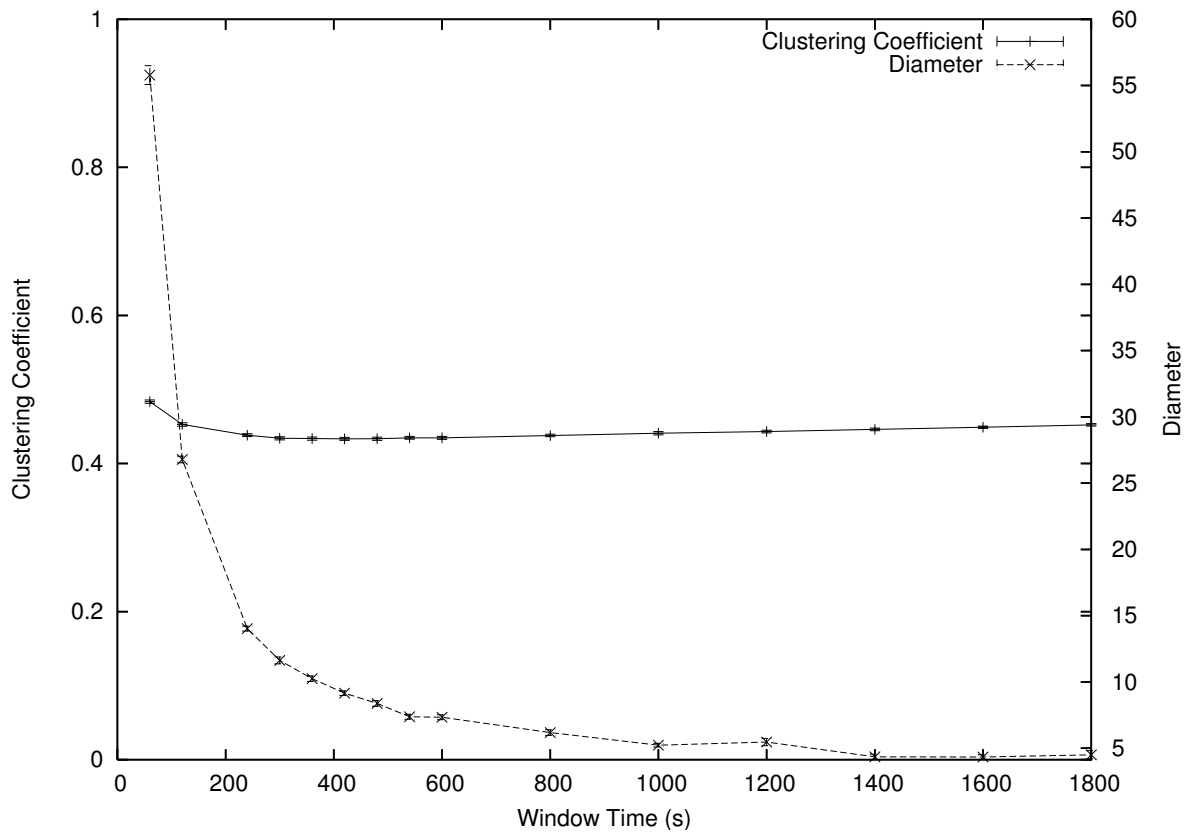


Figure 3.4: Highway Scenario - Time Window $T \times$ Clustering Coefficient/Diameter

There are many localization approaches that mainly handle the trade-off between cost (e.g. bandwidth consumption, calibration, equipment price) and accuracy. In networks similar to VANETs, also with no infrastructure, the cost plays a more crucial role; however, VANETs adopt mechanisms that provide more precise information instead. Killer applications, such as collision avoidance, driver assistance and automatic parking, require highly accurate localization schemes [21, 16], sometimes even more precise than that provided by standard GPS.

Despite this need for accurate location information, to the best of my knowledge, there is no work in the literature that adequately deals with the problem of outdated information regarding neighbors position in mobile networks. This issue is aggravated in these networks because the location of a neighbor changes quickly. Those existing protocols that require precise locations handle this issue by increasing the frequency of periodic messages (beacons) that in turn contain nodes' positions. However, this

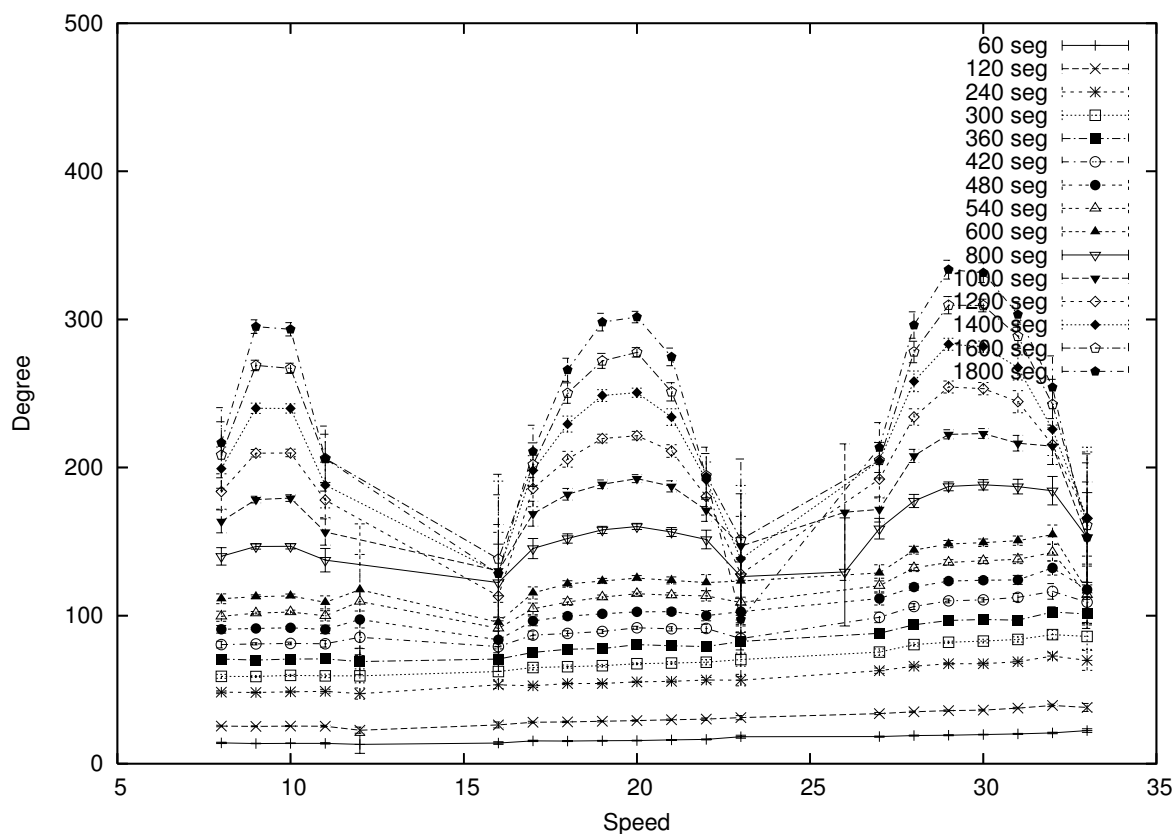


Figure 3.5: Highway Scenario - Average Speed \times Average Degree

solution leads to a high number of messages exchanged, and, even worse, to a high channel occupancy, thus, to an increased number of packets collisions.

My attempt to handle this issue is based on including enough information into beacons for vehicles to not only know the sender’s current position, but also for them to predict its location in the near future. It is understandable that the movement of vehicles can be reasonably predicted for the near future (by a few seconds) based on information such as recent past movement, neighbors’ movement, roads restriction or popular routes. Through prediction, we intend to exchange periodic messages at a lower frequency, then occupying the channel for a much shorter period of time while providing a more accurate localization of nodes’ neighbors.

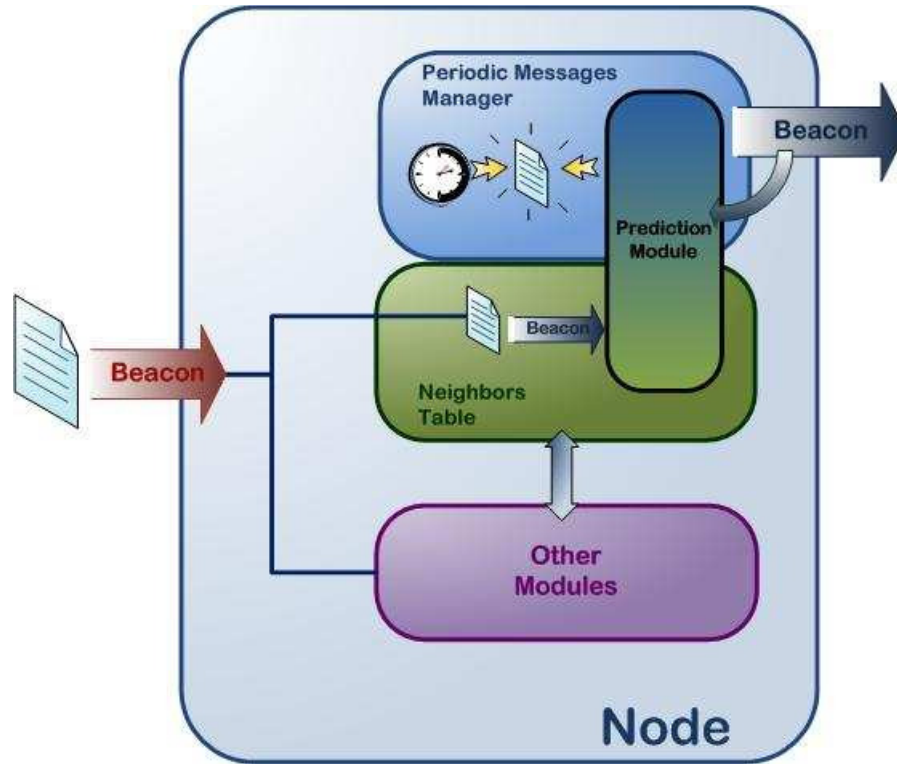


Figure 3.6: Flow of Information and Modules Interaction within Node

3.2.1 Proposed Neighbor Localization Protocol

All previously mentioned localization schemes (see Section 2.3) focus on nodes' own position accuracy. However, in most cases the location of a vehicle in a VANET is used by neighboring nodes as well. Greedy location-based routing algorithms [56], for instance, require that each node know the position of every single neighbor. Moreover, most location-based routing algorithms require that at least the source node know the position of the destination node, which may be more than one hop away from it [59]. Therefore, it is crucial that vehicles are made aware not only of their own precise location, but also of the accurate position of other nodes.

In this work, we have tackled the problem of how to make available accurate localization of one-hop neighbors at any moment for any vehicle². Previous solutions only increase the frequency by which localization related information is broadcast to neighbors

²In order to extend the proposed protocol to solve the issue of keeping accurate localization of other nodes (e.g. a destination node), the only modification is to means of forwarding the proper packets in a multi-hop manner.

and they are not suitable, since they are not scalable to the dense scenarios common in VANETs (due to traffic, accidents, stop lights, and so on). Furthermore, vehicles may rely on inaccurate positions when two previously reachable nodes move away from each other and can not update their mutual location information anymore.

The solution here consists of adding to beacons, besides the usual node's position, information that can be used to predict a vehicle's location into the near future. The furthest into future a vehicle would have to predict another vehicle's position is until a node is removed from a node's neighbors table. This time is usually within a few seconds. Additional information that can be stored in beacons are previous positions, speed and direction, or even routes within a shared road or city map. Global shared information may also be used in order to predict vehicles' future positions, such as popular chosen roads, avenues and streets; traffic conditions; or maps that delimit vehicles' movements.

Several distinct prediction models may be used for the purpose of estimating vehicles' positions. They can be as simple as vector estimations based on previous positions and speed, or as complex as Markov Chains and Artificial Neural Networks. In order to increasing accuracy, prediction models tend to become more complex, requiring higher processing power, memory or bandwidth. The most appropriate model for any scenario is the one that better exploits the trade-off between accuracy and cost.

Figure 3.7 shows the movement of one node and the position considered by a neighbor node reachable for at least from t_0 to t_3 . The table on the top left shows the real current position of the node (R), the predicted (P) and the one that would be used in a naïve approach (N). A beacon is broadcast by the moving node at t_0 and t_3 . It is clear that the predicted position is more accurate than the naïve solution during the time between consecutive beacons are received.

Algorithm 1 Broadcasting Beacon

- 1: *Request* Prediction Module for information required to predict this node's position
 - 2: *Assemble* Beacon with current position, information required for prediction, Beacon Sequence Number and any other periodic information that must be exchanged
 - 3: *Broadcast* Beacon
 - 4: *Request* Prediction Module to keep track of distance between this node's predicted position and current position
 - 5: *Increment* Beacon Sequence Number
-

In my protocol, whenever a vehicle requires the location of another vehicle, it uses the predicted position instead of the one initially informed through the beacon. The goal

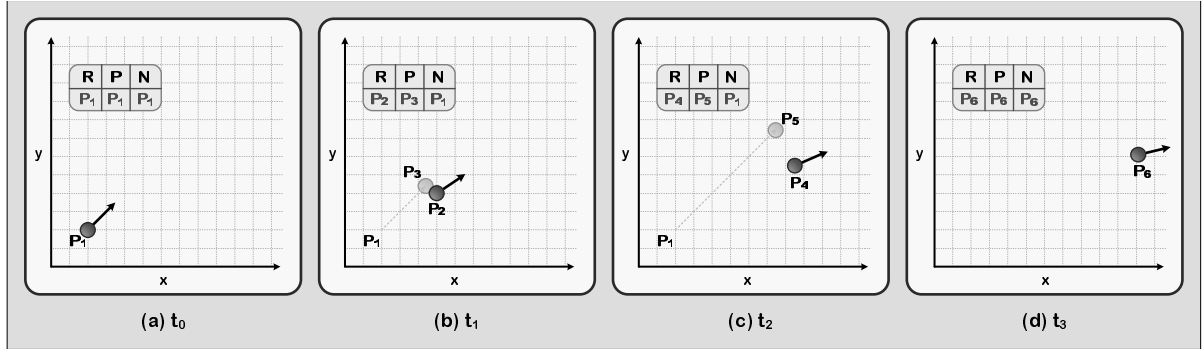


Figure 3.7: Neighbor Localization Protocol

Algorithm 2 Upon Received Beacon

- 1: *Forward* the Beacon to any other module that requires periodic information
 - 2: *Forward* the Beacon to Neighbors Table
 - 3: **if** Source Node is not on Neighbors Table **then**
 - 4: *Create* new entry on Neighbors Table
 - 5: *Request* Prediction Module to create new object to predict source node's position based on the information within the Beacon
 - 6: **else**
 - 7: *Update* neighbor timestamp on Neighbors Table
 - 8: *Forward* new information for prediction from Beacon to the Prediction Module
 - 9: **end if**
-

is to improve the accuracy of the localization of neighboring vehicles while decreasing the necessary number of beacons.

Another mechanism we have implemented ensures that, when a node sends the beacon with its position and the information necessary for the other vehicles to predict its future positions, the sender also store this information, thus, determining the error between the predicted and the actual positions. Consequently, a threshold δ is defined which is used to trigger the broadcast of a new beacon with updated information. In other words, when the difference between the predicted and actual positions is greater than δ , the node assembles a new beacon with the current information and broadcasts it updating neighbors' predictions. If global information is used for the prediction of vehicles' positions, this mechanism can only be used if this information is shared among all nodes involved.

Figure 3.6 illustrates the flow of information and triggers inside a node which happens in two circumstances to broadcast a new beacon: periodic or due to large error between predicted and real position. Since the localization mechanism is considered as an essential aspect of VANETs, and the exchange of messages is solely among reachable nodes, this protocol can be incorporated into the MAC layer. Algorithms 1 and 2 describe the procedure to broadcast a beacon and the actions taken when one is received, respectively.

An example of how the proposed protocol works is shown on Figure 3.7. In the first step t_0 , a beacon is broadcast by the mobile node. In this initial moment, our proposed solution based on prediction would estimate the same position as the naïve approach, both would consider the real position since the location information is updated. On the second step t_1 , the prediction model at a neighbor node would use the information attached to the beacon to estimate the position of the node. Although the estimation P_3 is not perfect, it is certainly better than the naïve solution P_1 . With time, the distance between the actual position and the estimated one tends to increase (Fig. 3.7(c)). In the last step t_3 , another beacon is sent by the node, thus, the localization information is updated and the cycle starts again.

3.2.2 Performance Evaluation

In order to evaluate the protocol's effectiveness in exploiting the trade-off between accuracy and cost for the localization of neighbors in a VANET, we have implemented it using Network Simulator (ns2) [85]. In the following subsection, we describe the simulation environment in detail. In Section 3.2.2.2, the statistical methods used and the metrics evaluated is explained, and the results of the simulation are shown. Then, in Section 3.2.2.3, these results are discussed.

3.2.2.1 Simulation Setup

In Table 3.5, we summarize the values of the parameters used in the experiments. Note that the radio power (which determines the radio range) is the default value and it is always used unless a different value is specified. The mobility model used was the Freeway+ (see Section 3.1.3) and the topology details are listed on table 3.6.

Many results from simulations revealed the impact of the Cold Start effect, where the scenario at the beginning of the simulation has still not reached a stable state. We have ensured three conditions in order to avoid this effect: i) in the first 10 minutes nodes only move around; ii) results are based on exchanges of messages that occurred after the first

Parameter	Value
Radio Propagation Model	TwoRayGround
Mac Layer	IEEE 802.11
RXThresh ₋	1.92278e-08(100m)
Antenna	OmniAntenna
Simulation Time	60 min
δ	0.5; 1; 3; 5; 10; 15 (s)
Π, Δ	0.25,1; 0.5,1.5; 1,3; 5,15 (s)

Table 3.5: Simulation Parameters

Parameter	Value
# Nodes	600
Length	12km
Lanes per Direction	3 - 5m wide each
Lane Width	5m
Speed Limits (m/s)	5-15;10-25;20-40
s_c	60s \pm 10%

 Table 3.6: Freeway⁺ Parameters

kilometer and before the last one, to avoid road extremities issues, thus, the evaluated road length is 10km with 50 nodes per kilometer and an average of 500 nodes; and iii) the first 10 minutes of beacons exchanges are performed but not evaluated. With these measures in place, the results shown here are free of Cold Start and extremes bias. The 60 minutes of simulation considered are, therefore, the 60 minutes after the 20 initial used to avoid these aforementioned issues.

The focus is on how to provide accurate localization of vehicles, from the perspective of a neighbor vehicle. We do not handle the localization issue of the node itself from its perspective. For this reason, we do not consider the error of the initial localization mechanism. In the simulated scenario, vehicles are able to obtain their own position precisely. The initial vehicle localization is beyond the scope of this work.

The prediction model is also an important part of the simulation. We have decided to use a model with low complexity so that beacons would be of only a few bytes and would not incur much overhead, in terms of both bandwidth and computational power. The model here involves calculating a vector $v = (s_x, s_y)$ that indicates movement direction

and speed based on the last broadcast position $p_0 = (x_0, y_0)$ at time t_0 and the current one $p_1 = (x_1, y_1)$ at time t_1 . Therefore, the vector v can be calculated as shown:

$$\begin{aligned} s_x &= (x_1 - x_0)/(t_1 - t_0) \\ s_y &= (y_1 - y_0)/(t_1 - t_0) \end{aligned}$$

A beacon holds, in addition to the node id, the position p_1 and the vector v . Whenever a beacon is received, this information and the current timestamp are stored. When a vehicle n_r , that has received the beacon from node n_s at T_0 , wants to use the geographic position n_s at time T_1 , the position $P = (x_P, y_P)$ here used is given by the following equations:

$$\begin{aligned} x_P &= x_1 + s_x * (T_1 - T_0) \\ y_P &= y_1 + s_y * (T_1 - T_0) \end{aligned}$$

It is important to notice that no global time synchronization is needed since the speed can be calculated by any node using only the time difference between consecutive beacons, and since the predicted position is based only on the difference between the current local time and the local time when the beacon was received. This can be done because the delay of a one-hop transmission is inexpressive when compared to the movement of a vehicle.

One parameter that fundamentally influences the performance of this protocol is the frequency f by which beacons are sent. We have evaluated different frequencies by varying the beacon period $\Pi = 1/f$. Another important parameter is the time Δ that a vehicle remains on the another vehicle's neighbors table if no other beacon is received during this time. The value chosen for Δ is strongly related to Π and Δ is usually around three times Π . Table 3.5 shows the values used in this work for the distance threshold δ (see Section 3.2.1) and the pair Π, Δ . Besides these parameters, we have also evaluated two different values for the radio range r (50m and 100m) in order to understand the impact of network density on the overall performance. Therefore, an instance we had run assumed a configuration that can be defined by the quadruple (δ, Π, Δ, r) and there are 48 distinct possible configurations³.

³Although Π and Δ are distinct parameters, they are mutually dependent; thus, they do not add another dimension to the possible configurations.

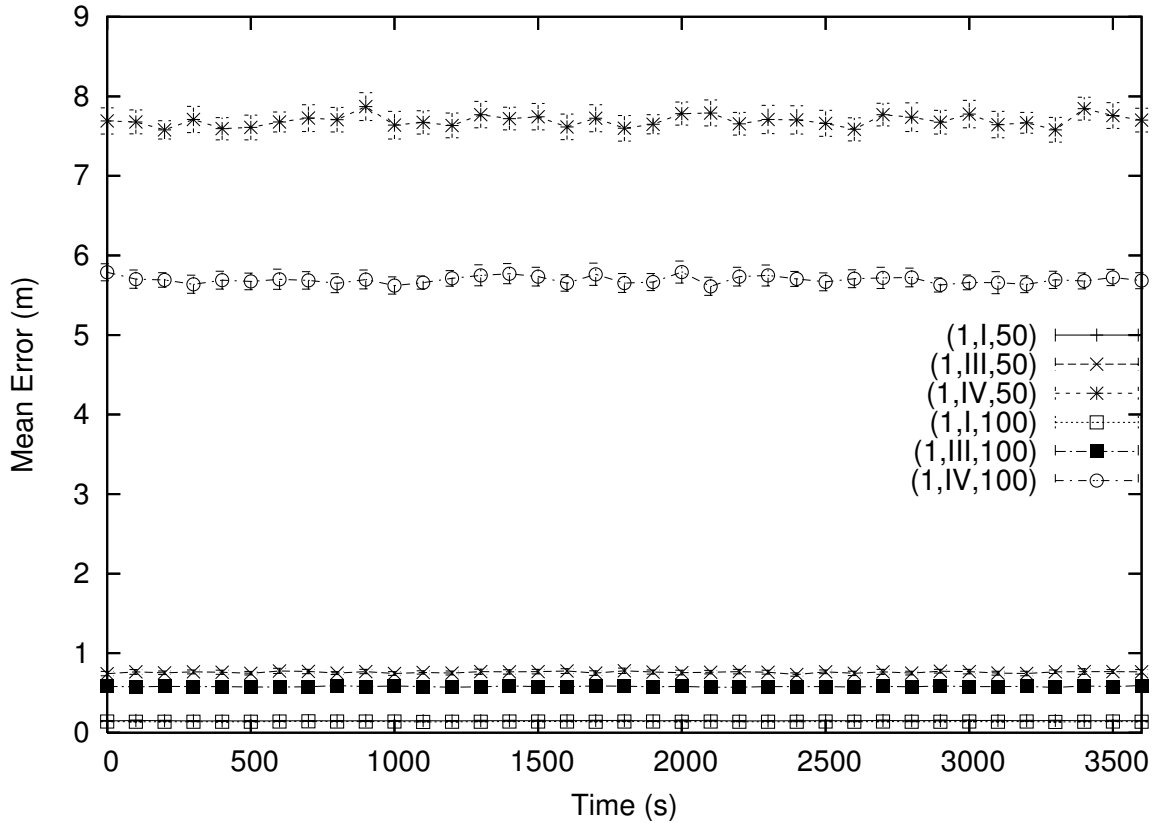


Figure 3.8: Performance Evaluation - Time x Mean Error

3.2.2.2 Experimental Results

Each configuration was executed 32 times; for this reason, the Normal Distribution⁴ could be used to calculate the confidence intervals. Each point plotted on the following figures was an average of these 32 runs and, with all of them, confidence intervals at a confidence level of 99% are plotted.

We mainly want to evaluate the trade-off between accuracy and cost; accordingly, we have defined two metrics, one related to mean error and number of beacons, respectively. The error on any node is the average between all neighbors on the predicted position and the actual one. The mean error is the average of this error between all vehicles in the network. The number of beacons is the average number of beacons sent among all nodes in the network; therefore, it is a value per node and node for the whole network.

⁴Or z-Distribution.

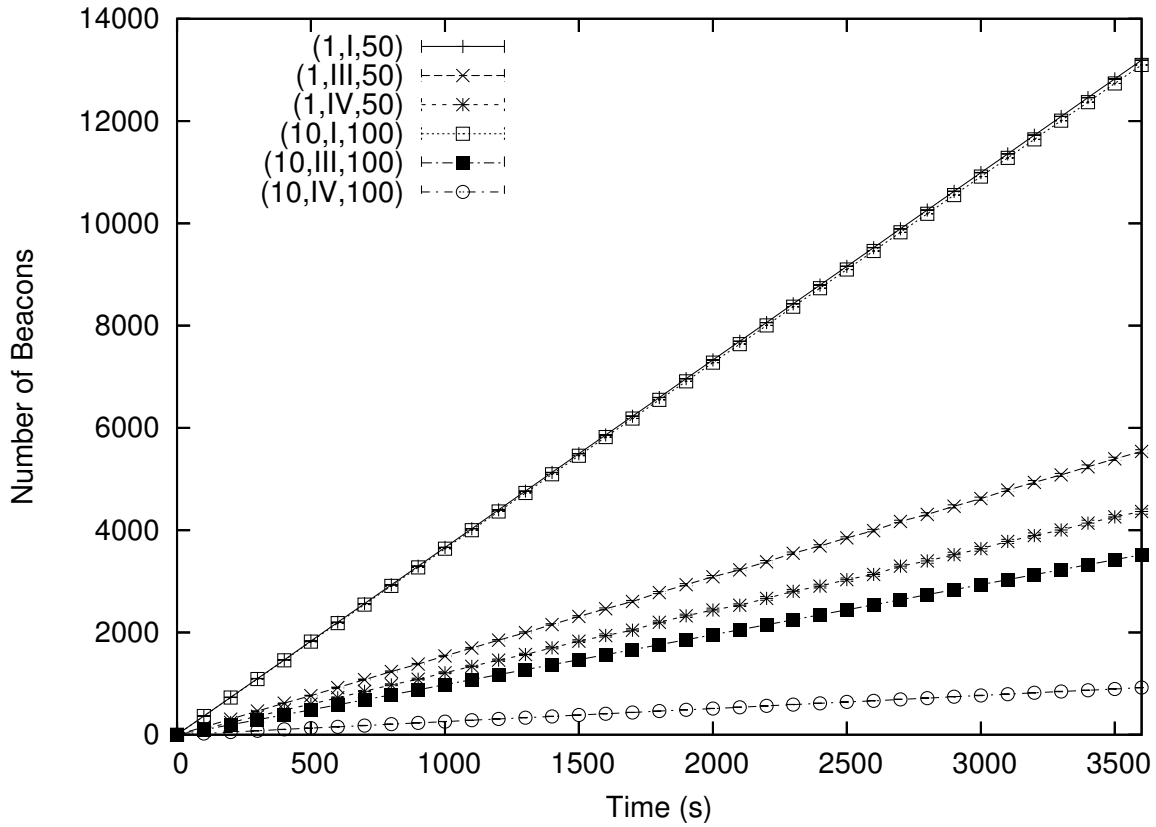


Figure 3.9: Performance Evaluation - Time x Number of Beacons

The first analysis is of the performance of the protocol through time. In Figures 3.8 and 3.9, it is noticeable that the behavior of the network, in terms of the two aforementioned metrics, does not alter through time. For this reason, in the remainder of this paper, the mean errors considered are the average of the 37 samples collected (one for each 100 seconds of the 1 hour simulation time plus one at the beginning). The number of beacons sent is the total number of beacons sent for the whole hour simulated.

Before the performance evaluation of the protocol, it is important to point out that beacons are not only used to update localization information to neighbors, but also to update the reachability status among nodes. As mentioned, after a period of time (in this work, Δ) during which a node does not receive any new beacon, it is removed from the node's neighbors table since it is likely out of reach. Figure 3.10 shows the average number of neighbors in nodes' neighbors table for different Π . The network density is of 50 nodes per km, and as each node covers the length of $2r$ meters, the expected number

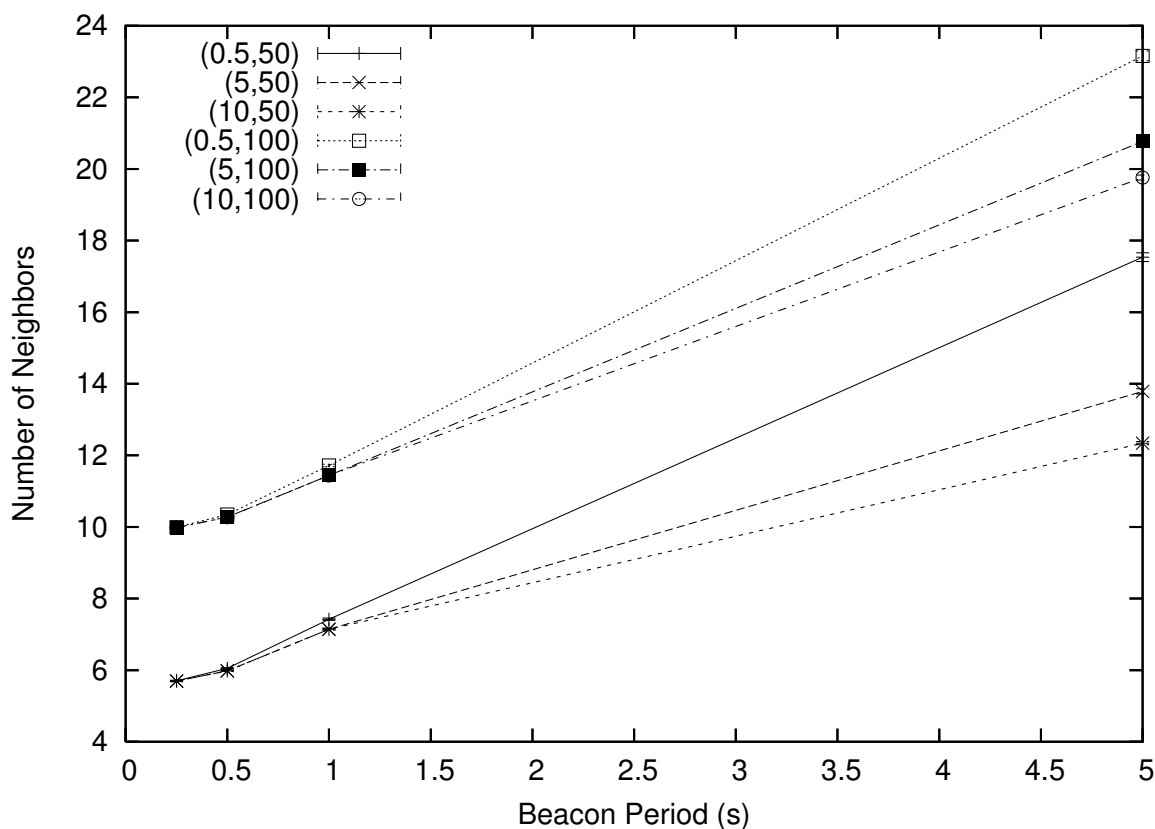


Figure 3.10: Performance Evaluation - Number of Neighbors

of neighbors is 10 when $r = 100$ and 5 when $r = 50$. In Figure 3.10, we can see that as shorter as the period between two consecutive beacons is, the most reliable a node's neighbors table in representing the real environment is. However, we propose here an accurate mechanism for neighbor localization, thus, the vehicles' positions can be used to estimate whether two nodes are still mutually reachable.

Figure 3.11 shows the performance of this protocol regarding its cost. Each curve represents a configuration and it is labelled by the pair (Π, r) . The results follow the expected behavior where increasing δ the number of beacons decreases (converging to the scenario where beacons are exchanged only when Π expires) and for shorter beacon periods Π , more beacons are sent. The radio range r clearly has an impact on the number of beacons sent.

An interesting observation on the performance of this protocol comes from the analysis of the results plotted on Figure 3.12. This figure shows the mean error when the Error

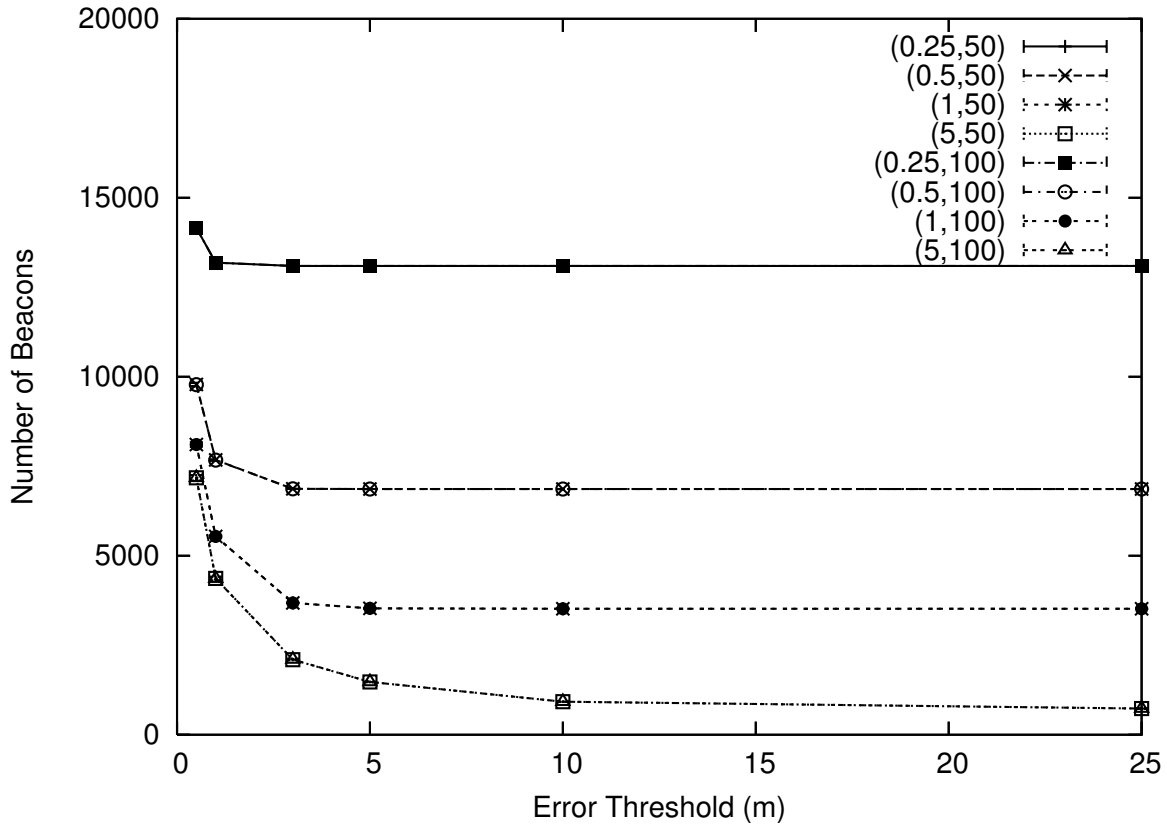


Figure 3.11: Performance Evaluation - Error Threshold (δ) x Number of Beacons

Threshold δ varies. For small values, when δ grows, the mean error increases too, as expected. However, for long beacon periods Π , if δ is continually increased, the mean error surprisingly begins to decrease. In order to understand the reason for this, it should first and foremost be clear that the neighborhood of vehicles in a road scenario is mainly composed of vehicles traveling in the same direction and with similar speeds. Moreover, prediction errors in this work in a road scenario happen mostly due to vehicles changing speed. Therefore, when a vehicle changes its speed, it changes its neighborhood as well. With small values of δ , this change is partially informed to the vehicle's current neighborhood, but the vehicle will soon not be able to properly inform its new movement pattern. With bigger values for δ , the vehicles takes longer to inform its new speed and it broadcasts more accurate information before leaving its previous neighborhood. For this reason, for the remainder of this paper, all the results plotted have $\delta = 25m$.

In Figure 3.13, we compare the accuracy of our protocol with the naïve approach

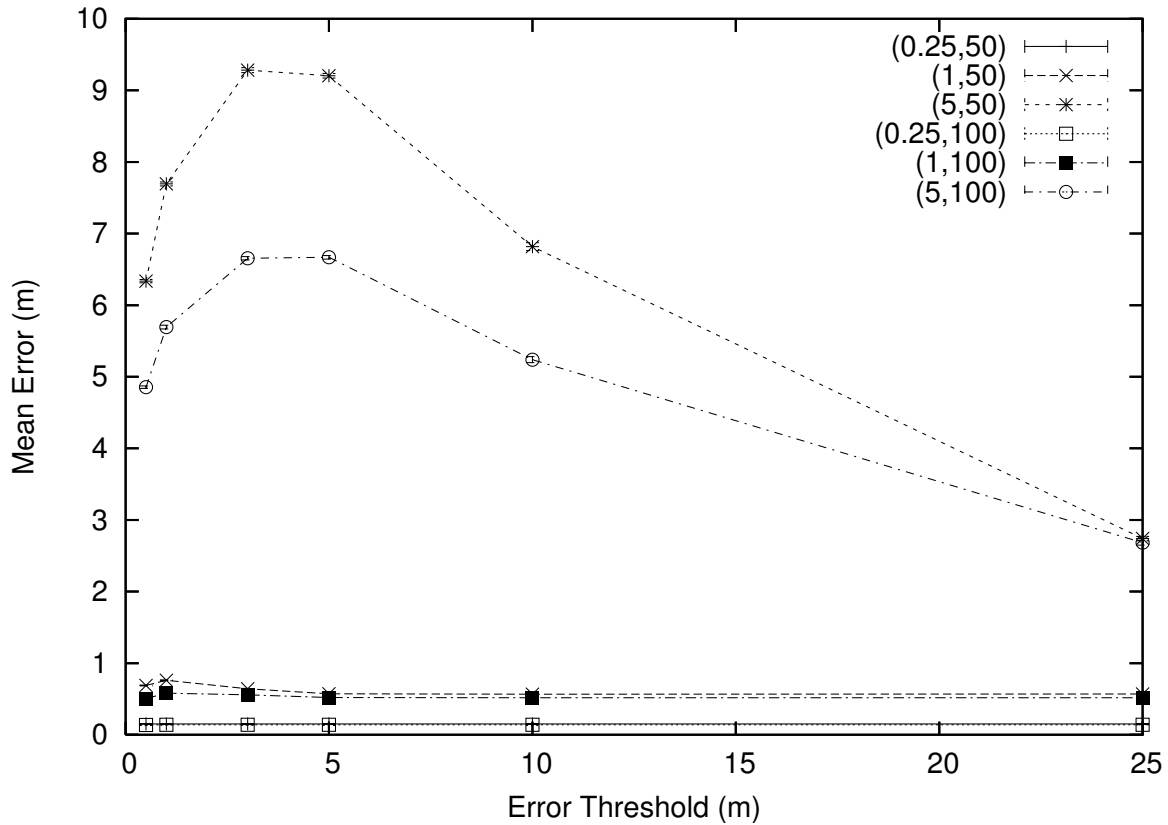


Figure 3.12: Performance Evaluation - Error Threshold (δ) x Mean Error

based solely on the positions informed by beacons. It is clear that adding a mechanism to predict vehicles' positions greatly increases the accuracy of the localization of neighbors. The radio range r has a greater impact on the naïve approach than on mine. The increase of error with longer periods between beacons is also slower when prediction is used than when it is not.

3.2.2.3 Discussion

In these experiments, it has been observed the counter-intuitive result that a larger value for δ led to more accurate localization (see Section 3.2.2.2 for a more detailed explanation). However, in a scenario where vehicles move more erratically than in a road scenario (e.g. in an urban scenario), smaller values of δ would incur a smaller error than for large values. This unexpected behavior happens only because of vehicle proximity in road scenarios, as explained earlier.

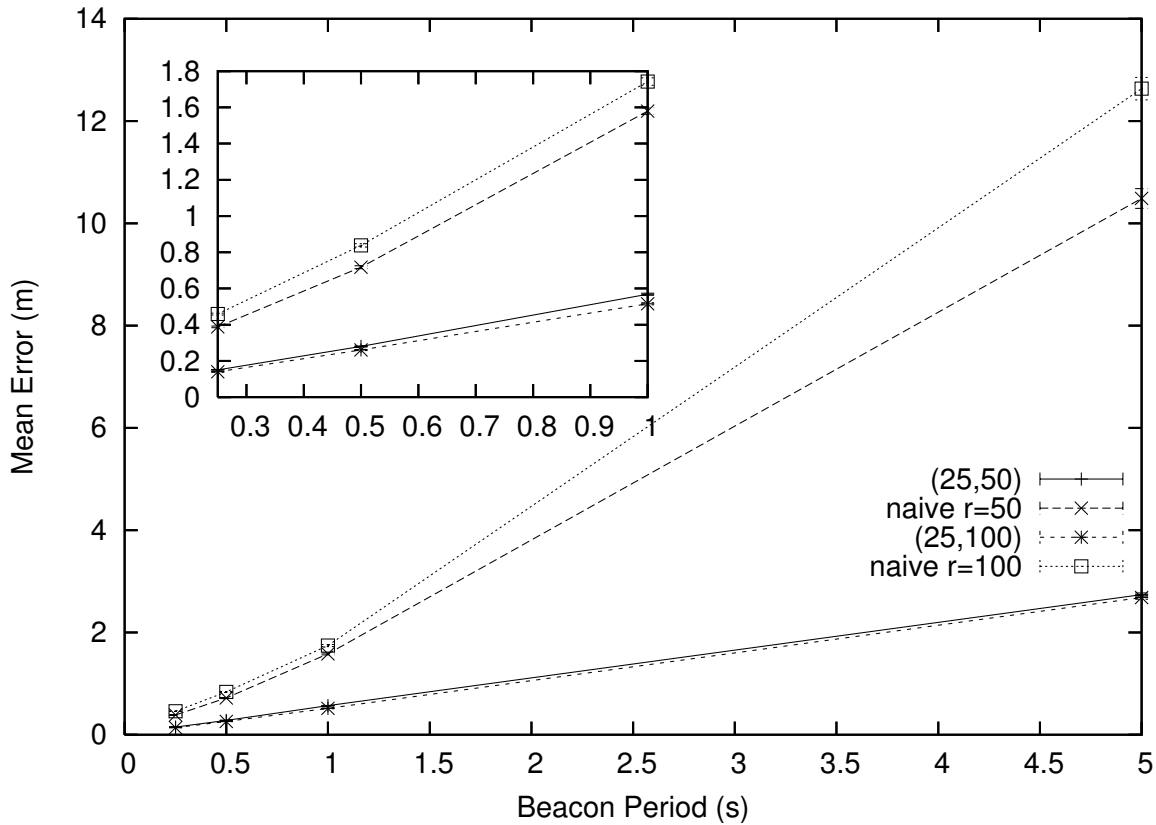


Figure 3.13: Performance Evaluation - Beacon Period x Mean Error

The results have shown that position prediction dramatically increases the accuracy of the localization of neighbors. For the same period Π between consecutive beacons, the mean error was at least half when prediction was used (for $\Pi = 5s$ and $r = 100m$, the error was less than one fifth of the naïve approach). For a mean error of only 50 centimeters, using prediction, a quarter of beacons are sent. More importantly, such accuracy could be achieved in a feasible scenario where the wireless channel is not constantly occupied for beacons exchange as in the naïve approach. The results in this work were under a prediction model of low complexity. It is still possible to design other models that can achieve even more accurate results.

Nevertheless, beacons are not only used for localization purpose. An important purpose of beacons exchange in VANETs is to update vehicles' neighbors table, thus, assuring that routing protocols do not rely on nodes that are no longer available. Therefore, although accurate localization of neighbors could still be achieved while decreasing the

beacons broadcast frequency (using prediction), this decrease could result in an unreliable neighbors table. This issue is easily solved by using the vehicle's position to determine the distance between a vehicle and its neighbors, and to use that information to remove distant nodes from the neighbors table.

3.2.3 Results Summary

We have tackled a serious issue present in Vehicular Ad Hoc Networks that has been neglected by most researchers. This problem is that of how to provide accurate vehicles localization from the perspective of a neighboring node. This is an important issue, since, for most applications and location-based routing protocols, the position of neighbor nodes is used as frequently as the own node's position, if not more frequently.

The solution here to handle this issue is to add, into periodic messages that contain vehicle positions, information that can be used to predict nodes' near future positions (a few seconds). By doing so, any time a vehicle requires the position of another vehicle within range, the position utilized is not that which was initially informed but instead a predicted position.

Through extensive simulations, it has been shown that using a prediction model of low complexity was enough to achieve significantly more accurate positions. For the same frequency of exchange of beacons, mean errors that were at least 50% to 80% lower were achieved. For an accuracy of 50 centimeters from the locally obtained position, the frequency of beacons was decreased from an unsustainable 4 beacons per second to a feasible one of 1 beacon per second.

3.2.4 Neighboring Prediction

A node's neighborhood is composed by the nodes it can communicate with. In VANETs, it is of utmost importance to understand the neighboring status among nodes. Two fundamental pieces of information regarding the neighborhood among nodes are occurrence and duration. Occurrence relates to when two vehicles are close enough so they can exchange messages between themselves with no intermediate nodes, while duration is for the period that these vehicles remain within reach.

Now my goal is to efficiently and effectively predict neighborhood occurrence between two nodes. We believe that such mechanism can be used in order to enhance significantly the overall performance of VANETs. For example, it can be used for resource reservation,

routing continuity despite path breaks or to aid handoff procedures. However, the scope of this work is limited to the provision of the neighborhood prediction mechanism.

We have developed a Neighborhood Prediction Protocol (NPP) in which prediction models make use of information attached to periodic messages (beacons) that are broadcast further than one-hop neighbors. Thereafter, the prediction model tries to determine if the source of the received beacon is potentially a future neighbor. If so, the node estimates when the neighborhood will start and stores this information. In this work, it is shown that NPP provides an efficient and highly accurate neighborhood prediction.

In [70], the authors suggest the advantages of using motion prediction algorithms to assure service continuity in a mobile network. This work focus on enhancing the handoff procedure in Cellular Networks. Their prediction mechanism (Mobile Motion Prediction - MMP) is divided into two models based on two levels of movement length, one for long term and another for routine movement among cells, the Movement Circle (MC) and the Movement Track(MT), respectively. The authors utilize long term movement history to predict future position of nodes. The predicted movement is for a long period of time as well, different from our approach that is based on short time movement pattern for the prediction of the location of near future positions. Thus, the NPP is much more suitable to VANETs than the MMP.

A different work [89] also proposes a hierarchical mobility prediction model (Hierarchical Location-Prediction - HLP) with two different levels of precision. HLP is designed for wireless ATM networks, thus, the network is divided into cells. The high level is based on regular daily user movement among cells while the low level is based on previous speed, direction and cell geometry. The low level does introduce a better precision, however, the authors goal is to predicted what it is going to be the next cell the node will move to. Therefore, the precision requirements for this scenario are much lower than the requirements for VANETs as it was proposed.

A survey on mobility prediction [25] shows a comparison between some of the first solutions for wireless networks. Besides the two previously mentioned works, it compares also three other ideas [14, 66, 51]. These early works have defined most of the challenges and have proposed initial solutions. However, all this solutions are still based on a scenario with a previous deployed infrastructure and of long term movement patterns

In [109], the authors consider a different approach for mobility prediction based on context aware instead of movement history. This work describes how user context information should be gathered, stored and used by the prediction model. Personal information, interests, tasks details and environment characteristics are examples of the

type of information used in order to predict future location of nodes. Although it is an interesting idea, the granularity of the localization is still based in cells and therefore not suitable for an infrastructureless VANET.

Previous works in the literature regarding mobility prediction in mobile networks is mostly developed for scenarios where a previously deployed infrastructure exists. Vehicular Ad Hoc Networks have distinct peculiarities when compared to other mobile networks which demand different solutions. Besides that, these existing solutions usually consider a long term movement pattern and our idea is that prediction of location of vehicles in a near future have a better potential to improve the overall performance of the network.

3.2.4.1 Neighborhood Prediction

In this work, it is proposed a Neighborhood Prediction Protocol (NPP) which extends a previous neighbors localization scheme (described in Section 3.2) by relaying further the location and movement information that was initially broadcast only to nodes one-hop away. By this manner, the information required to keep neighbors' location updated without the need of extra beacons can be used to predict if distant vehicles will be within reach and when.

As the neighbor localization scheme, the NPP prediction model is based on vehicles' movement vectors in order to estimate their future positions. These vectors are calculated based solely on the last broadcast and current positions. Such vectorial model has the advantages of demanding extremely low computational resources (e.g. processing power and available memory), reflecting instantly changes and requiring little bandwidth when broadcast to other nodes. More complex prediction models may lead to more accurate results, however, the vectorial model exploits better the trade-off between cost and accuracy and certainly attends the requirements of the majority of applications.

For a node to predict its future neighbors, it is fundamental to be able to estimate its range of communication. We have assumed that the exchange of messages between vehicles is uniformly distributed in the circle centered by the node with radius equals to its radio's range. Therefore, the radio range r of a node is estimated as twice the average ρ of its distance to nodes that have directly sent a message.

$$r = 2 \times \rho \tag{3.1}$$

The distance average ρ is a weighted average of its current value and the node's distance to the source a newly received beacon. In this work, a node periodically assembles

a beacon with its location and other information necessary for the mobility prediction. Although this beacon is forwarded to further nodes, for radio range estimation, only the first hop transmission is considered. Considering that a vehicle located at p_1 receives a beacon created at a second vehicle at p_2 , the distance $\delta_{p_1:p_2}$ between these points is calculated. Then, the new radio range estimation is given by the following equation:

$$\rho = \Delta_\rho \times \rho + (1 - \Delta_\rho) \times \delta_{p_1:p_2} \quad (3.2)$$

The value of Δ_ρ determines the influence of changes in the network that would affect a vehicle's radio range. Since it is expected that a radio range does not vary often, its value is defined with $\Delta_\rho = 0.99$.

The NPP estimates when two nodes are going to be within range combining the mobility prediction with the range estimation in a way that the future distance between nodes is compared to the communication radius. Consequently, the neighborhood prediction is divided into two parts: future distance estimation and vicinity estimation.

For neighborhood prediction, the time dimension is added to the calculation of the distance between vehicles. Therefore, in NPP, the distance between two vehicles is the distance between two vectors instead of the distance between two static points. Each vehicle v_i has its position vector \vec{p}_i defined by the following equation:

$$\vec{p}_i = (x_i + s_x t, y_i + s_y t) \quad (3.3)$$

where t is the time elapsed since the initial position $\vec{p}_i = (x_i, y_i)$ was retrieved and $\vec{s}_i = (s_{ix}, s_{iy})$ is the speed vector of vehicle v_i . Therefore, the function of the distance square $\delta^2(t)$ is calculated as follows:

$$\begin{aligned} \delta^2(t) &= (\vec{p}_{1x} - \vec{p}_{2x})^2 + (\vec{p}_{1y} - \vec{p}_{2y})^2 \\ \delta^2(t) &= [(x_1 - x_2) + t(s_{1x} - s_{2x})]^2 + \\ &\quad [(y_1 - y_2) + t(s_{1y} - s_{2y})]^2 \end{aligned} \quad (3.4)$$

considering $\Delta_x = (x_1 - x_2)$, $\Delta_y = (y_1 - y_2)$, $\Delta_{s_x} = (s_{1x} - s_{2x})$ and $\Delta_{s_y} = (s_{1y} - s_{2y})$:

$$\delta^2(t) = t^2(\Delta_{s_x}^2 + \Delta_{s_y}^2) + 2t(\Delta_x \Delta_{s_x} + \Delta_y \Delta_{s_y}) + (\Delta_x^2 + \Delta_y^2) \quad (3.5)$$

The equation 3.5 is a polynomial equation of the second degree assuming only non-negative values. For this reason, the smallest value of $\delta^2(t)$ occurs when its derivative $\delta^2'(t)$ equals zero and this happens when:

$$\bar{t} = \frac{-(\Delta_x \Delta_{s_x} + \Delta_y \Delta_{s_y})}{(\Delta_{s_x}^2 + \Delta_{s_y}^2)} \quad (3.6)$$

Neighborhood prediction makes sense only for vehicles that are not currently neighbors, thus, \bar{t} gives us already two scenarios. If \bar{t} is positive, it means that the vehicles are getting closer to each other and that the smallest distance between them has not been reached yet. Otherwise, if \bar{t} is non-positive, it means that the vehicles are moving apart of each other and that the distance between them will only increase. In this later case, there is no need to proceed with the neighborhood prediction since it is assumed with the available information that they will not be close enough to communicate directly.

In case where \bar{t} is positive, it is used in Equation 3.5 to determine the smallest distance $\bar{\delta}$ between the two considered vehicles. This distance is then compared to a value that is called vicinity radius Γ which is given by the following formula:

$$\Gamma = \gamma \times (2 \times \rho) \quad (3.7)$$

where $(2 \times \rho)$ is the estimated radio range (as in Equation 3.1) and γ is the vicinity coefficient which has a strong impact on the performance of NPP as it is shown in the experiments (Section 3.2.2).

The predicted time τ when two nodes will be close enough to communicate is calculated using predicted smallest distance between them $\bar{\delta}$, the time this distance is predicted to occur \bar{t} and the vicinity radius Γ . First of all, if $\bar{\delta}$ is greater than Γ , it is assumed that the vehicles will not be close enough to be within their radio range. It is also defined the speed σ as the speed by which the distance between these vehicles decrease and it is given by the following equation:

$$\sigma = \frac{\delta(0) - \bar{\delta}}{\bar{t}} \quad (3.8)$$

with $\delta(0)$ being the distance between vehicles by the time when the prediction is being made. Finally, the predicted time of neighborhood between both vehicles τ is:

$$\tau = \frac{\delta(0) - \Gamma}{\sigma} \quad (3.9)$$

Besides the neighborhood prediction, NPP requires that the periodic messages containing vehicles information regarding localization and movement pattern are forwarded further than the one-hop neighbors. For this reason, a beacon is flooded to other vehicles distant at most of H hops. Since simple flooding where all nodes within $H - 1$

hops broadcast further the beacon would lead to a large number of transmissions, a gossiping-based approach is adopted in order to minimize the number of transmission and yet reach most nodes within H hops. By this manner, a node forwards a beacon under a predefined probability θ .

Algorithm 3 describes the procedure taken when a beacon is received. If the beacon was created and sent by a vehicle that is already a neighbor, only neighbor localization is updated and no neighborhood prediction is made. Otherwise, \bar{t} and $\bar{\delta}$ are calculated in order to determine if the beacon source is moving closer to this node and, thus, it is a future neighbor. In case the beacon user is predicted to be a future neighbor, the time τ (see Equation 3.9) when it is predicted that they will be within reach is calculated and this information is stored on the Predicted Neighbors Table – PNT. At last, the beacon is broadcast further with probability θ .

Algorithm 3 Receive Beacon at NPP

```

1: if Hop count equals 1 then
2:   Use beacon solely for neighbor localization as in Algorithm 2
3: else
4:   if Beacon source is predicted to be a future neighbor5 then
5:     Calculate time  $\tau$  predicted to vehicles to be neighbors
6:     Store this information on Predicted Neighbors Table
7:   end if
8: end if
9: if Hop count  $\leq H$  then
10:  With probability  $\theta$ , forwards beacon
11: end if

```

The performance of NPP depends on three mentioned parameters: gossiping broadcast probability θ , vicinity coefficient γ and maximum number of hops H . Therefore, an instance of NPP is defined by the triple (θ, γ, H) . In the next Section, NPP will be evaluated for different combinations of this triple.

3.2.4.2 Experiments

We have decided to use the NS-2 simulator [85] because it is a widely adopted network simulator that has been extensively evaluated. In Table 3.5, the values used for the most important parameters are shown.

Parameter	Default Value	Range varied
θ	0.4	0.2 - 1.0 (step 0.2)
γ	0.75	0.1 - 2.0 (step 0.1)
H	5	2,3,4,5,7,10,15 and 20

Table 3.7: NPP's Parameters

The idea proposed is based on the properties of vehicles' movement; it is therefore important to use a reliable and realistic mobility model. This mechanism is evaluated in a road scenario, since mobility models can represent this environment with higher fidelity. The Freeway+ model defined in Section 3.1.3 is used. Table 3.6 shows the parameters of the mobility scenario used in this work. It is important to notice that the different speed limits are for the three distinct lanes in each direction, thus, for the whole simulation these same limits were used.

Many results from simulations revealed the impact of the Cold Start effect, where the scenario at the beginning of the simulation has still not reached a stable state. We have ensured three conditions in order to avoid this effect: i) that the only event in the first 10 minutes of simulation is nodes' movement; ii) that all results be based on an exchange of messages that occurred after the first kilometer and before the last one, to avoid bias due to road extremities, so that the evaluated road length is 10km with a density of 50 nodes per kilometer and that an average of 500 nodes can be expected; and iii) that the first 10 minutes of beacons exchanges and predictions are performed but not evaluated. With these measures in place, we provide the results free of Cold Start and extremes bias. The 60 minutes of simulation considered are, therefore, the 60 minutes after the 20 initial used to avoid these aforementioned issues.

Every plotted result is an average of 16 runs on 16 distinct mobility traces and 16 different seeds for the random numbers. We have used the Student's t-distribution to calculate confidence intervals with a confidence level of 99%. Therefore, all our results are trustworthy and support well our analyses and conclusions.

As mentioned in the previous Section, NPP's performance depends on the triple (θ, γ, H) . Table 3.7 shows the default values for each parameters and the values used throughout the simulations. We have considered that γ and H are mutually independent, therefore, only combinations of each with θ were evaluated.

We call a Hit, the event of detecting a new neighbor at a time within 60 seconds of the neighborhood predicted time. In other words, a hit occurs when a vehicle receives a

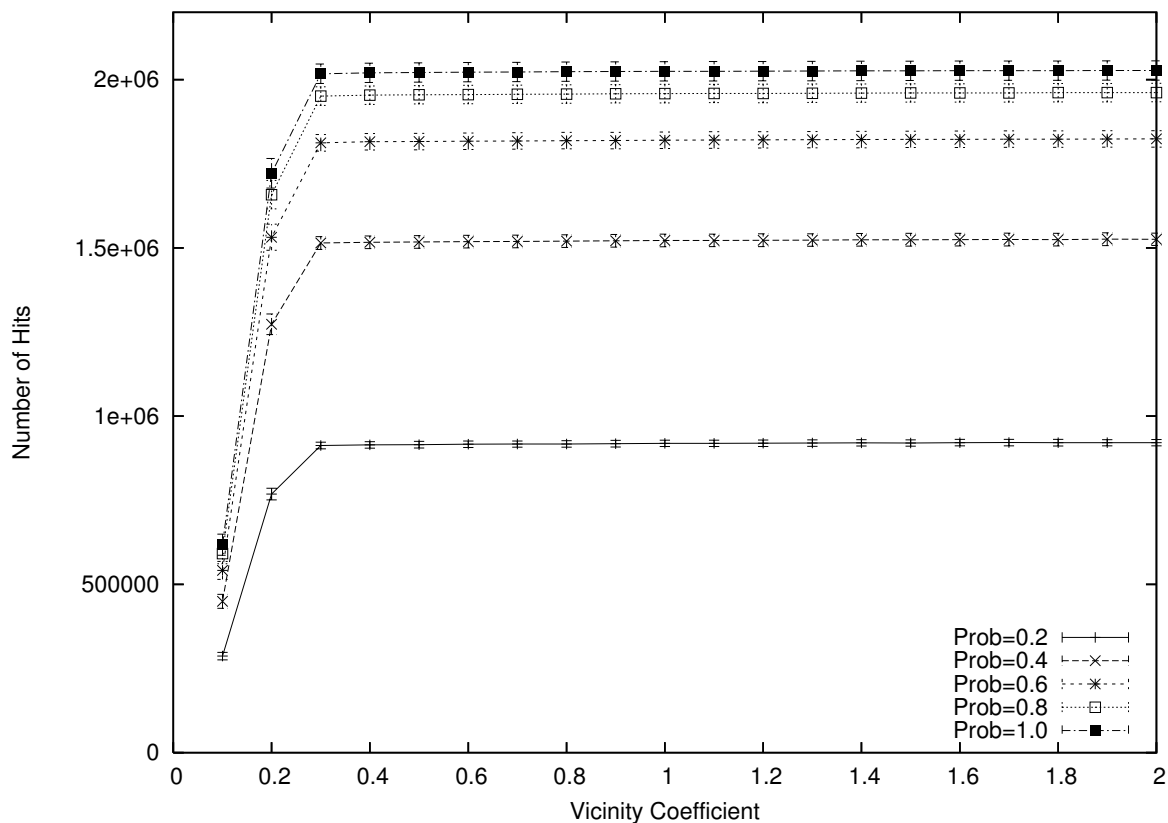


Figure 3.14: Hits - Vicinity Coefficient x Number of Hits

message (data or beacon) for the first time from a specific node which is on the Predicted Neighbors Table and its predicted time τ is within 60 seconds of the current time. We classify hits into Early Hits, when a Hit happens before the predicted time τ , and Late Hits, that happens after the predicted time.

Figures 3.14 to 3.21 shows the results of NPP regarding the occurrence of Hits. In Figure 3.14, it is shown that the vicinity coefficient only influences the total number of hits if it is too small. In this case, predictions and hits occur only when both vehicles get extremely close to each other. The maximum number of hops has a slight impact on the number of hits with larger H values leading to small increases on the number of hits. Larger values of flooding probability θ logarithmically increase the number of hits.

In Figures 3.15 and 3.16, we can observe the impact of the vicinity coefficient γ on the number of early and late hits. These results behave as expected since larger γ leads to a prediction time τ calculated based on reachability at larger distances, while a smaller γ

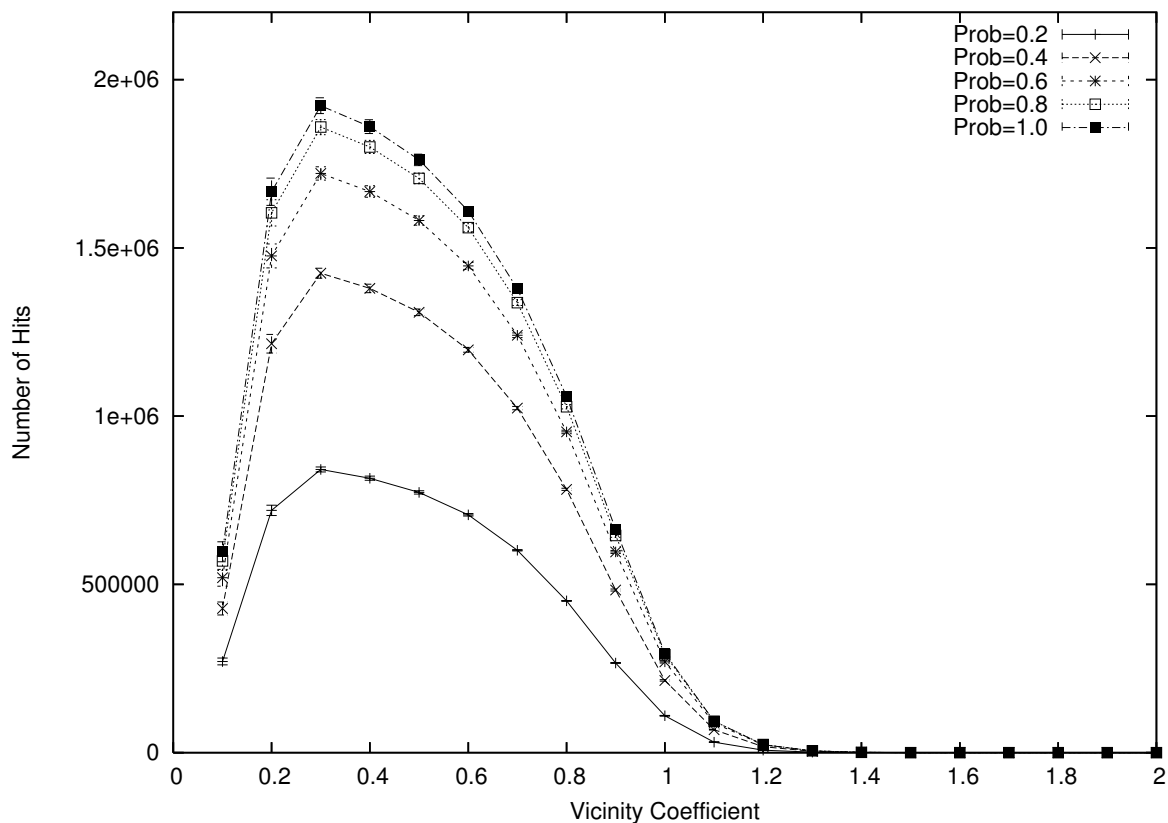


Figure 3.15: Hits - Vicinity Coefficient x Number of Early Hits

requires nodes to be much closer. Therefore, the vicinity coefficient shifts the predicted time in a way that larger γ moves τ earlier (causing more late hits) and smaller γ move τ later (leading to more early hits). The designer can choose the vicinity coefficient that better attends applications' specific requirements.

Figures 3.19 and 3.20 shows that the maximum number of hops H does not have a strong impact on the number of early and late hits. However, if we observe Figure 3.21, the prediction span – which is the average of the time between a hit and when the prediction was first added to the PNT, it is clear that with larger values of H earlier predictions are created and stored at the PNT.

In order to evaluate the cost of NPP, we have measured how many beacons were sent per node (either originally or just forwarding). In Figures 3.22 and 3.23, we can see that the vicinity coefficient has no impact on the bandwidth consumption. How-

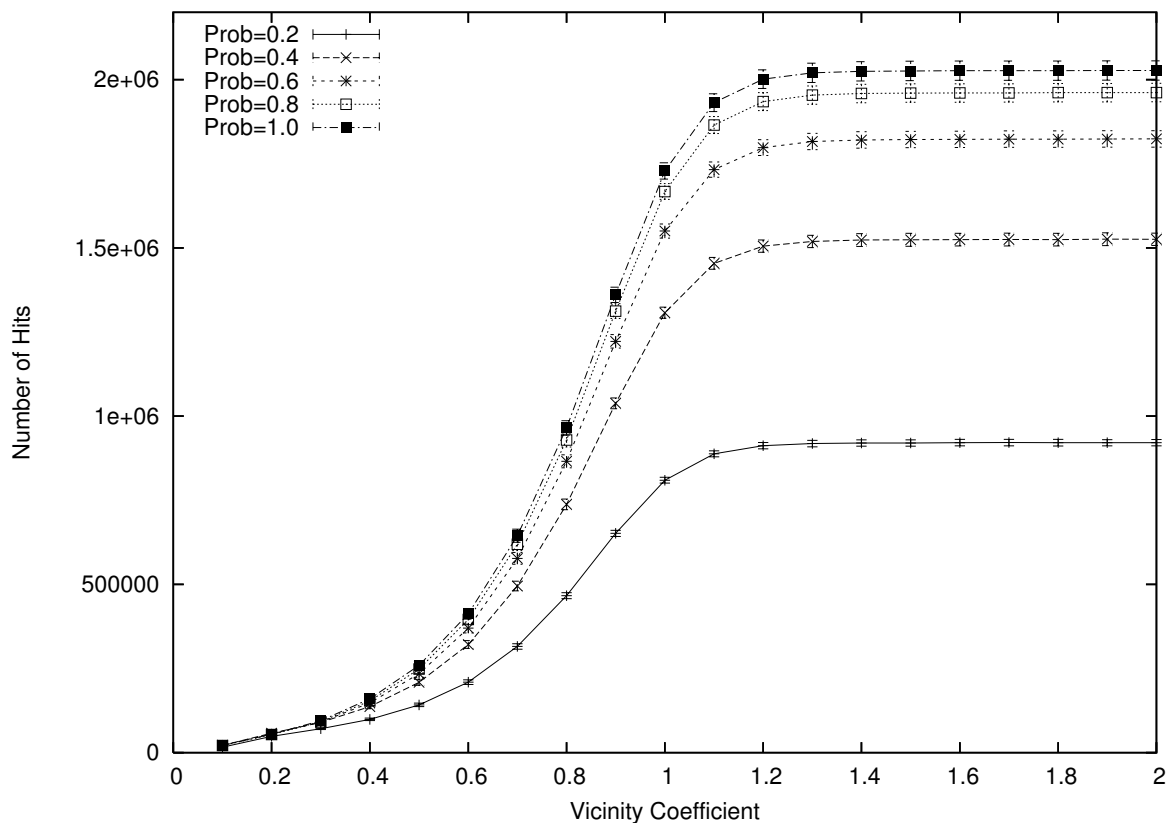


Figure 3.16: Hits - Vicinity Coefficient x Number of Late Hits

ever, the flooding probability is exponentially related to the overhead due to number of transmissions, as expected.

Figures 3.24 and 3.25 show that the maximum number of hops also leads to an increase on the number beacons sent. Nevertheless, the increase is much slower than the impact of the flooding probability. We have also measured the average number of times a prediction is updated since beacons are constantly broadcast.

3.2.4.3 Limitations and Advantages of NPP

In our experiments, it became clear that the parameter with stronger impact in the total number of hits is the probability θ of broadcasting further a beacon in the gossiping-based approach to flood it within H hops. The explanation is straightforward which is that as larger the probability is, more vehicles are reach and, thus, more predictions are added to the Predicted Neighbors Table. Besides that, short connections among vehicles (such

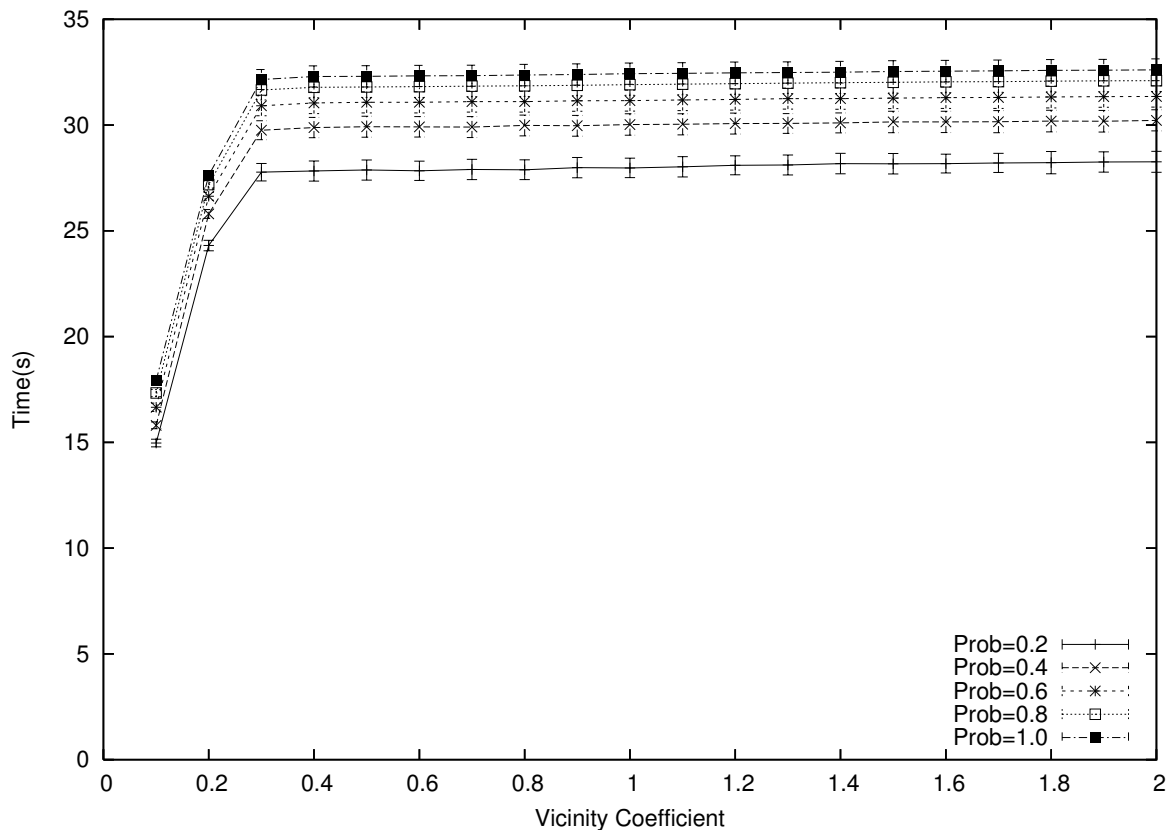


Figure 3.17: Hits - Vicinity Coefficient x Prediction Span

as the ones of vehicles moving in opposite directions) are both predicted and detected more often with higher flooding probabilities.

The distribution of Early and Late hits is very interesting and has a significant impact on the performance of applications. An early hit means that the neighborhood between two vehicles was predicted to happen after it really started. And a late hit leads to predict the ability of two vehicles to directly communicate before it is actually possible. This presents as a duality as in one side a period of connection is wasted since the prediction is late (early hit) and the assumption of a yet non-existing link between two vehicles due to an early prediction (late hit). For this reason, it is up to the service designer to choose the vicinity coefficient that better suits the application peculiarities.

It is important to understand the cost benefit ratio in the Neighborhood Prediction Protocol. Our goal is to use neighborhood prediction to attenuate the instability in VANETs caused by the highly dynamic topology and lack of infrastructure. Therefore,

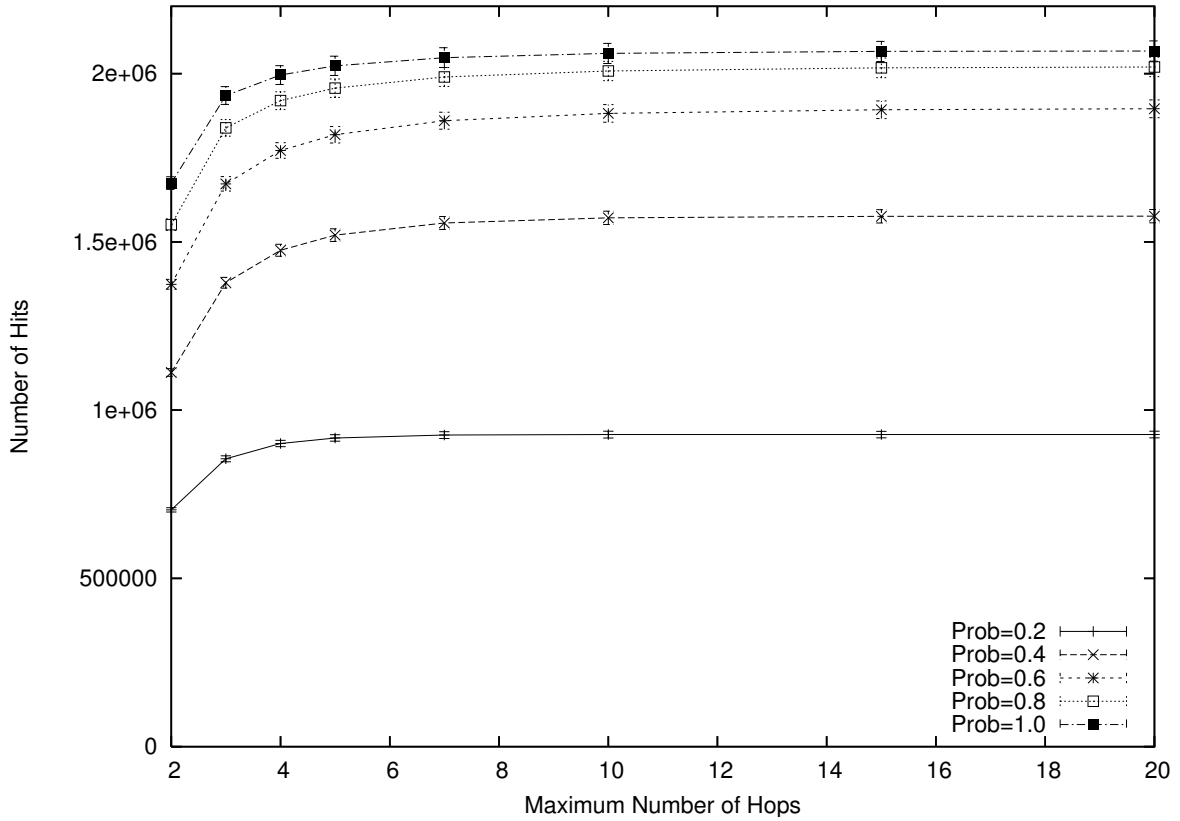


Figure 3.18: Hits - Maximum Number of Hops x Number of Hits

the main benefit of NPP is to be able to anticipate the presence of future links which can be used to sustain continuity of services running over VANETs. The cost of NPP is the channel occupancy by control messages (beacons) instead of data messages.

Both θ and H influences the cost benefit ratio regarding the cost metric of number of beacons per node and the benefit metrics of number of hits and prediction span. The flooding probability θ increases logarithmically the number of hits, however, leads to exponentially more transmissions. For this reason, we understand that a lower value of θ (around 40%) exploits better this trade-off. In terms of prediction span, both θ and H mutually affects this metric. Therefore, in order to keep a low cost and yet a reasonable prediction span, we suggest that a low θ is chosen with a H between 10 and 15. An average prediction span of above 30s is considered reasonable since it is longer than the average connection duration in VANETs of around 20s [22].

Furthermore, another dimension of cost and benefit is in regards to the prediction

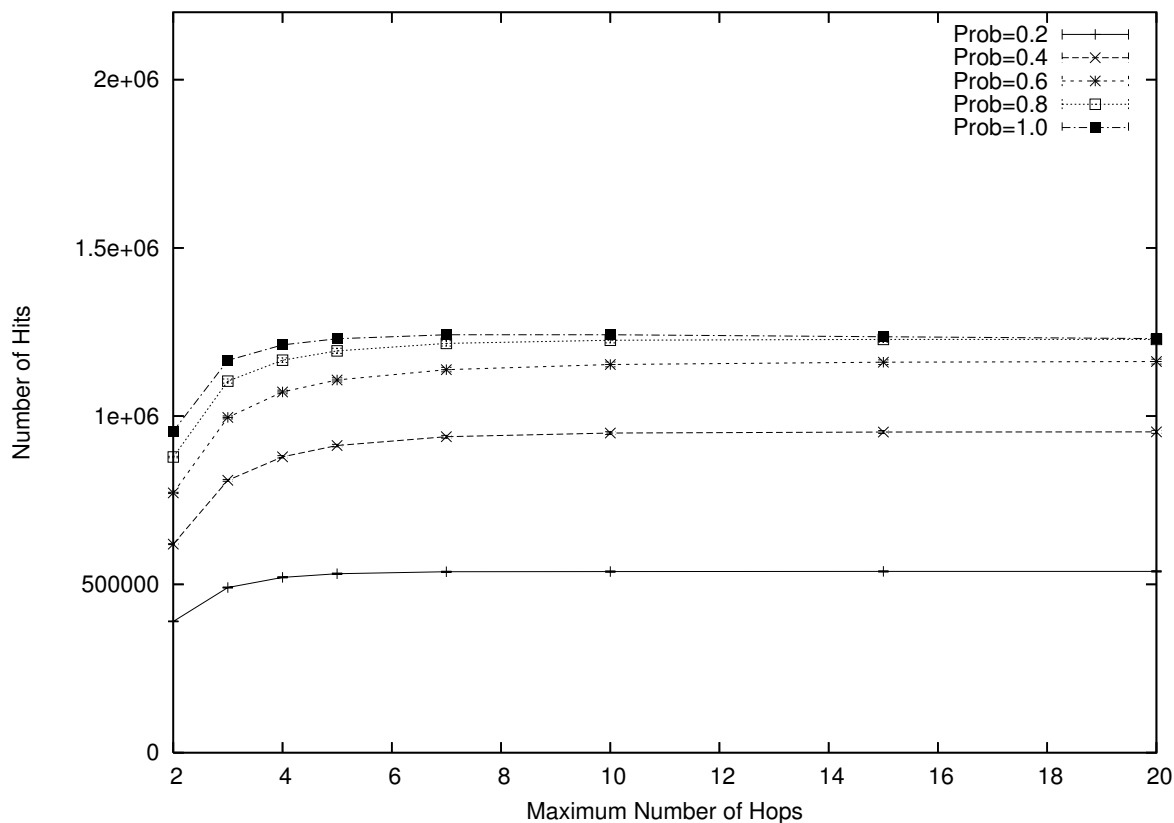


Figure 3.19: Hits - Maximum Number of Hops x Number of Early Hits

model used. In this work, we have used a vectorial model that uses positions and speed vector to predict future positions and estimate time of neighborhood based on predicted proximity. It is a simple model with low computational cost that was able to achieve reasonable accuracy. More sophisticated prediction models may be used for higher accuracy, however, it is necessary to estimate possible increases in computational cost as well as further exchange information. NPP can use any prediction model and future research may indicate the most suitable option for VANETs.

The limitations of NPP are based on its characteristics specially considering the parameters θ and H as well as the prediction model used. Therefore, these limitations are flexible and have to be evaluated adequately to the services deployed as well as the environment considered.

Vehicular Ad Hoc Networks are envisioned as a promising technology, they pose intrinsic challenges due to their highly dynamic topology and the lack of infrastructure.

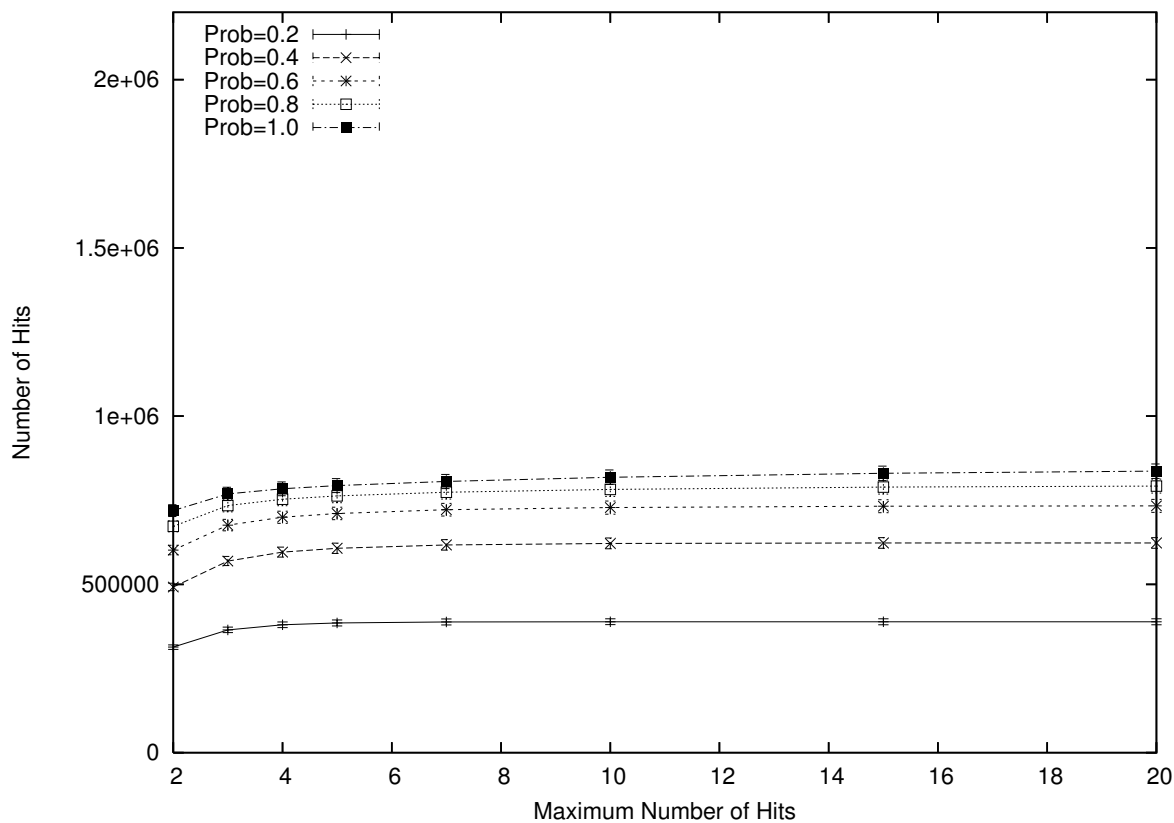


Figure 3.20: Hits - Maximum Number of Hops x Number of Late Hits

We have proposed that the ability to anticipate the occurrence of links in the near future between vehicles yet out of reach of each other can be used to overcome the instability inherent to such environments.

For this reason, we have designed and evaluated the Neighborhood Prediction Protocol (NPP), which extends a previous work in which we solve the issue of outdated information regarding the location of neighbors through mobility prediction. In this work, we have used the same Vectorial Mobility Model of our previous work and it achieves accurate results with little overhead. Our extensive set of experiments has shown that the NPP is both effective and efficient.

As future work, we want to provide enhanced solutions in different areas of VANETs by taking advantage of the information provided by the NPP. Using our Predicted Neighbors table, it is possible to improve the selection of intermediary nodes between source and destination in routing paths.

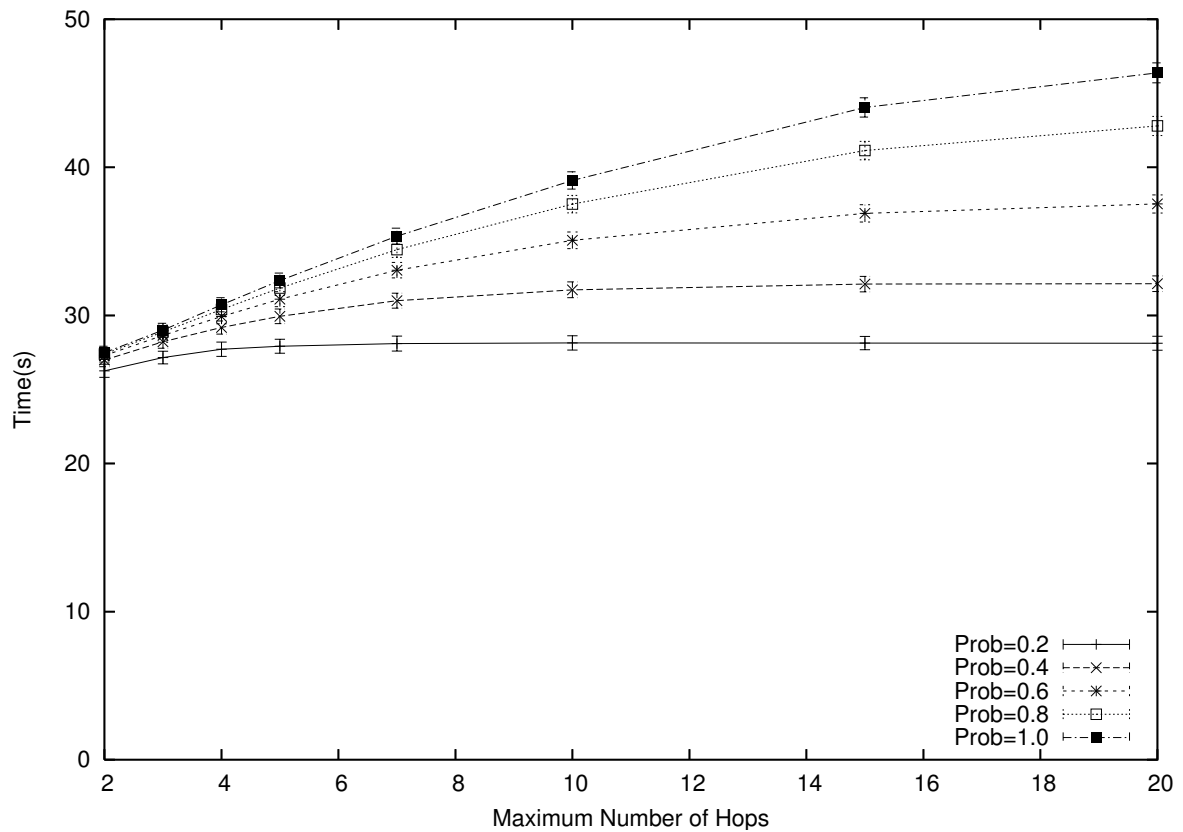


Figure 3.21: Hits - Maximum Number of Hops x Prediction Span

3.3 Quality-of-Service through link reliability based on link duration

There are several services that could be applied to VANETs in order to enhance drivers' and passengers' experiences, and each of these services may have distinct requirements. Examples of applications for VANETs range from drivers' assistance (such as traffic condition monitoring, accident alerts and route planning) to automated driving (emergency breaks, speed limit control, automatic pilot) and on-board videoconferencing. This wide variety of applications must be handled according to their specific requirements. Therefore, it is of utmost importance that protocols should support Quality of Service (QoS) policies in order to properly handle each application and to provide the necessary resources to fulfill their requirements.

In order to satisfy applications' end-to-end requirements, it is important to under-

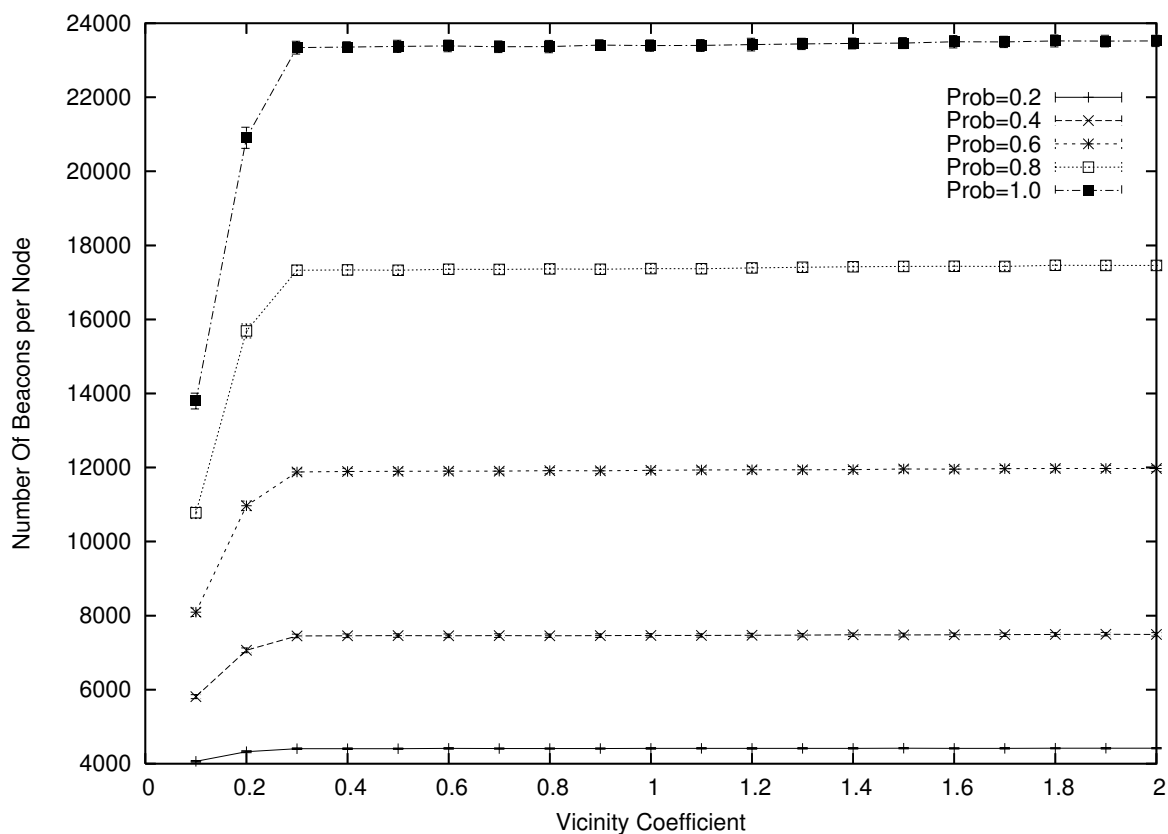


Figure 3.22: Performance through Time - Vicinity Coefficient x Number Beacons per Node

stand the behavior of message exchanging between intermediary vehicles. The connection between a reachable pair of nodes in VANETs has different characteristics due to different relative speeds, destinations and routes. Some studies show that the distribution of connection duration between vehicles and static access points has a mean of only two dozen seconds but, a large standard deviation [22]. Thus, links can sustain connections that last from a few seconds to up several minutes. A connection's duration can consequently be used to estimate how reliable a link between any two vehicles is, since its duration is related to the probability of a current available link remaining valid in the future.

Here, we propose using link reliability to provide QoS support for any protocol designed to VANETs based on a unicast relay of packets. My idea is based on the understanding that the movement pattern in VANETs is not completely random and that

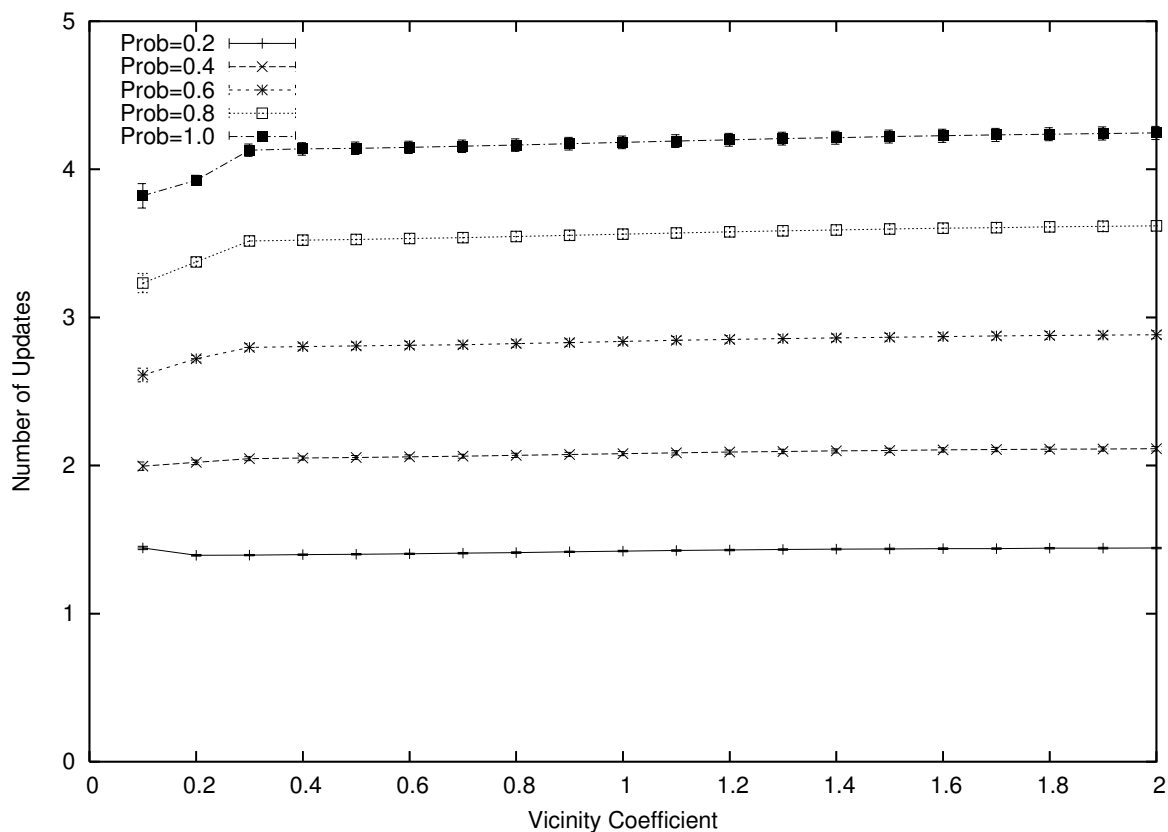


Figure 3.23: Performance through Time - Vicinity Coefficient x Number of Updates per Prediction

vehicles often follow certain flows. Therefore, vehicles following the same flow may have connections that last longer and are more reliable than the connections between vehicles in different flows. Figure 3.26 shows an example of this phenomenon in a highway scenario where a packet is sent from a node on the far right to another one on the far left. The lightning represents the exchange of beacon messages, while the arrows represent the relay of packets. Figure 3.26(a) shows the exchange of beacons and the arrival of a packet: Figures 3.26(b) and 3.26(c) point out two links, one still available and one already out of range.

My idea is to first develop a mechanism to estimate link reliability based solely on a sparse exchange of beacons and to then use these estimations to classify links based on their reliability, with different queues where applications with stronger requirements relay packets through queues with more reliable links. This work shows that the use

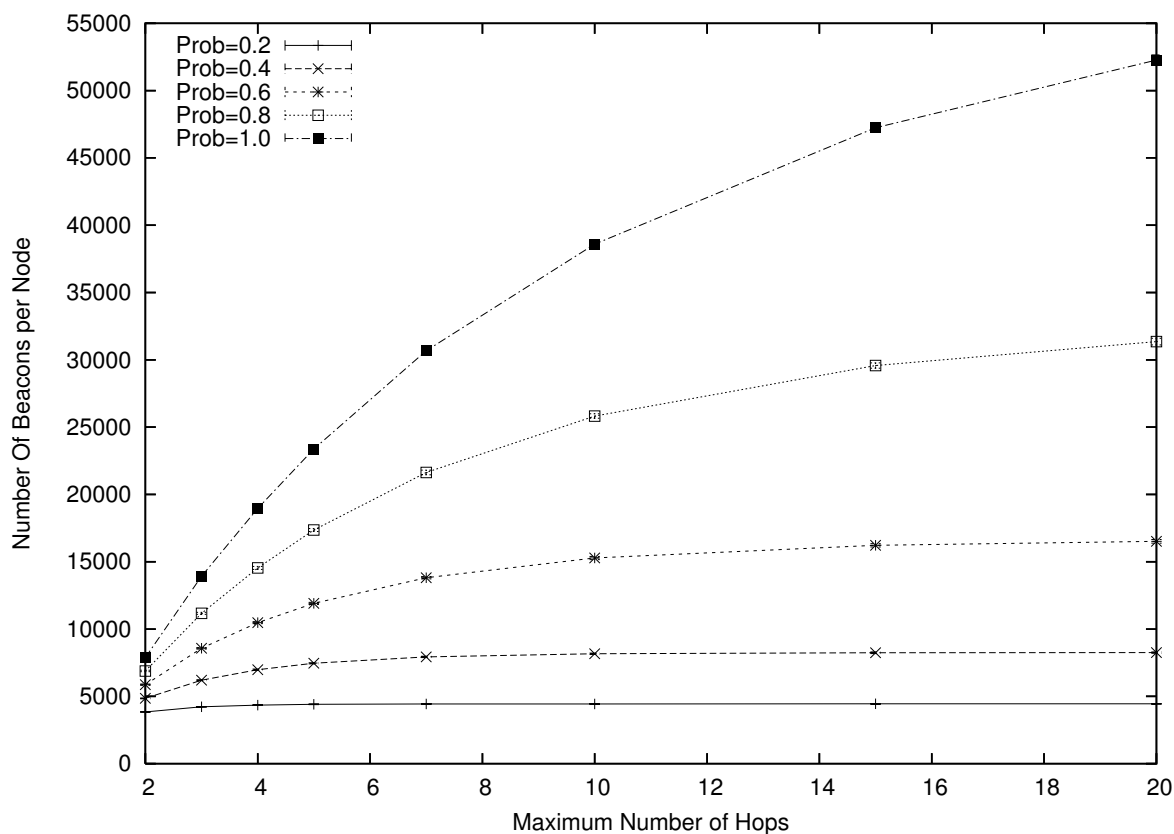


Figure 3.24: Performance through Time - Maximum Number of Hops x Number Beacons per Node

of this simple mechanism to estimate link reliability could help one distinguish between links that provide successful transmission rates ranging from 10% to close to 90%.

Several link reliability models have been proposed in the literature [54, 108, 84]. In [54, 53], the authors propose a model that predicts future availability of links using information regarding users' movement such as speed and direction. A link reliability model for VANETs is proposed in [84] and the authors suggest that large scale factors such as road density and vehicle flow should be considered in order to obtain a more realistic model. In this work, it is proposed a less complex link reliability model that does not require additional exchange of messages and it is proven in this article to achieve acceptable results as it effectively classifies links into different groups of expected future availability.

The provision of QoS support has been widely studied in several wireless networks

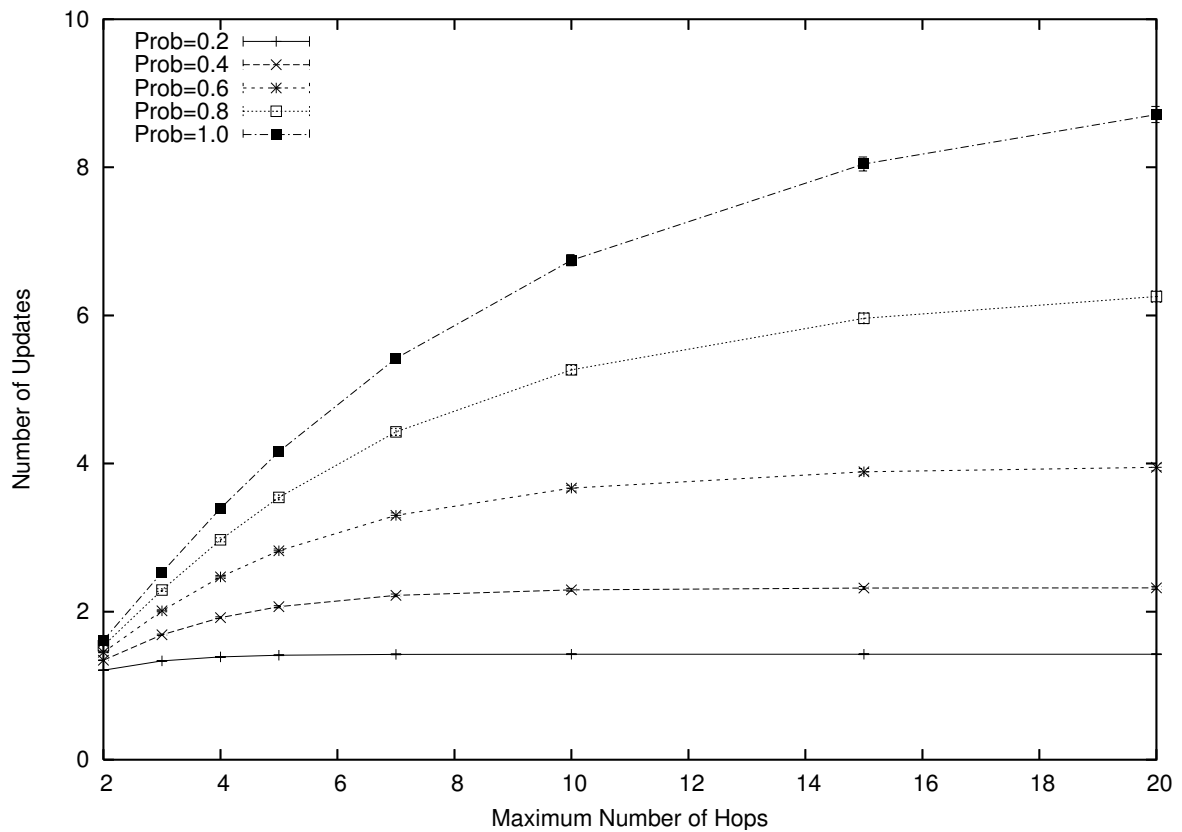


Figure 3.25: Performance through Time - Maximum Number of Hops x Number of Updates per Prediction

architectures, including Sensor Networks [26], Ad Hoc Networks [97] and WiFi Networks [83], however this is still an open topic for VANETs, and different approaches have been proposed. A mechanism based on multipath exploitation is proposed by Ramirez and Veiga [95]. In [117], the authors make use of driving route information to discover delivery routes and to sustain a desired level of quality. Niu et al. propose that link reliability estimations could be used to support QoS routing [84], as proposed here. However, their mechanism require information regarding global knowledge of the network which is not explained how it can be obtained by individual nodes. Besides that, the high complexity of the model incurs in a significant overhead to the network.

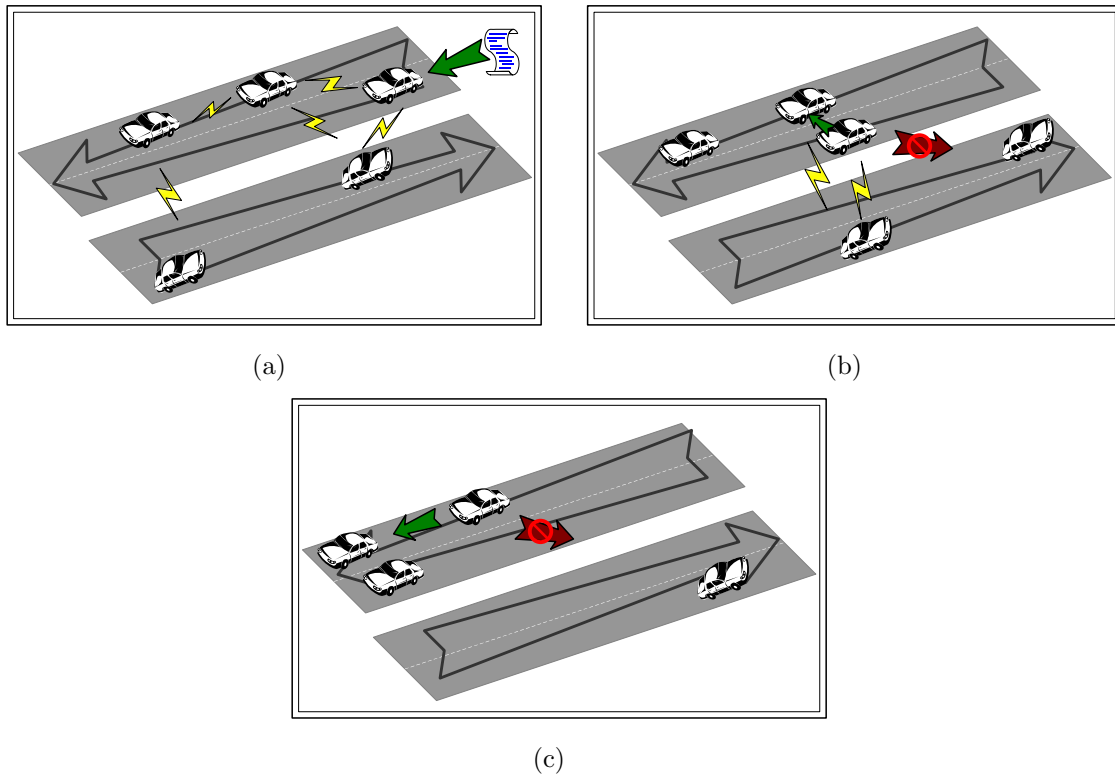


Figure 3.26: Example of Link Reliability

3.3.0.4 Link Reliability

Link Reliability is considered here as the probability of a link performing a successful transmission of packets. In existing literature, several parameters have been used to estimate link reliability in VANETs, such as previous duration, predicted duration, speed, route and density [84, 108]. Although using many parameters results in a more accurate model, we believe that simplifying this process reasonable results can be achieved while adding significantly less overhead.

Link reliability is estimated based only on how long the link has been available thus far. It is understood that a vehicle's movement is limited by street/road boundaries and that it follows human migration patterns. For example, in an urban scenario, cars usually move from residential areas toward business centers or downtown during the first hours of a weekday, and in the opposite direction at the end of the business day. The same phenomenon occurs on highways, where there is dominant movement towards large urban centers on weekdays and towards leisure areas on weekends and holidays. Therefore, the longer a connection between any two vehicles lasts, the stronger the similarity between

these vehicles' movement patterns. For this reason, there is a higher probability that this link would be available in the future.

The estimation of the duration of connectivity between any two vehicles is based on an exchange of beacon messages. Several existing protocols make use of beacon exchange in order to provide nodes with necessary information about their surroundings [56]. This estimation therefore adds little or no overhead to the network.

Different levels of reliability are defined, and each link is classified based on for how long they have been on the node's neighboring table. Beacons are exchanged each b_p seconds, and when a beacon is received from a specific node for the first time, an entry on the receiving node's neighbor table is created. The timestamp of the creation and the timestamp of the last update are both stored. This said, an entry is discarded if the update timestamp is older than b_{ttl} seconds, and a link is classified into the i -th level if its time of creation is older than l_i seconds. Because levels are ordered in such a way that $l_i < l_{i+1}$, a link classified on the i -th level is also classified into all k -th levels for $k < i$ and $k > 0$. The 0-th level is used to represent all links that were created in less than l_1 seconds; in this work, referred as intermittent links.

3.3.0.5 Simulation Setup

The mobility model used is the Freeway+ which is previously described in Section 3.1.3. It was used the same scenario as specified on Table 3.6.

We have decided to use the NS-2 simulator [85] because it is a widely adopted network simulator that has been extensively evaluated. In Table 3.5, the values used for the most important parameters are shown with the only difference that here the simulation time is of 40 minutes. The displayed radio power (which determines the radio range) is the default value and it is always used unless a different value is specified. The radio range is varied in order to evaluate the performance of our proposal under different conditions.

Many results from simulations revealed the impact of the Cold Start effect, where the scenario by the beginning of the simulation has still not reached a stable state. Three things have been ensured to avoid this effect: i) the only event in the first 10 minutes of simulation is nodes' movement; ii) that all results are based on exchange of messages that occurred after the first kilometer and before the last one avoiding bias due to road extremities, so that the evaluated road length is 10km with 500 nodes, assuming a homogeneous distribution of nodes; and iii) that the first ten minutes of beacons exchanges are performed during no event other than nodes' movements. With these measures in place, results free of Cold Start and extremes bias are obtained.

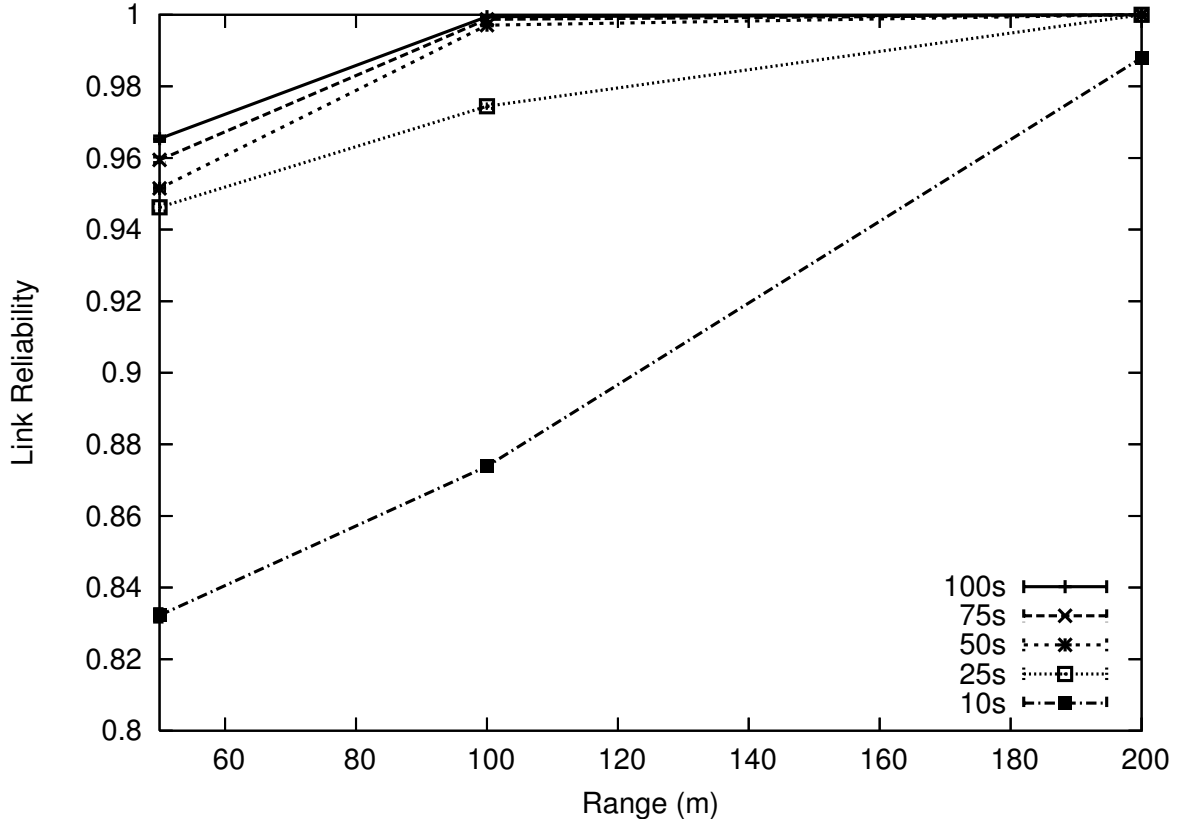


Figure 3.27: Link Reliability Estimation - Link Reliability x Range

We have evaluated scenarios with different beacon periods b_p (the beacon expiration time b_{ttl} was always $3 \times b_p$) and different ranges r . In order to have statistically acceptable results, each combination (b_p, r) was executed for 32 instances, and each had different random seeds and different instances of the same mobility scenario. This allowed us to calculate confidence intervals by using the normal distribution; confidence levels of 95% were used. It is important that, to avoid synchronization of beacon exchanges, the period between two subsequent beacons is a random value uniformly distributed between $0.9b_p$ and $1.1b_p$.

3.3.0.6 Results

The behavior of this proposed mechanism is evaluated for different values of b_p and r . With a beacon period of 1.5s, three different radio ranges r were used: 50m, 100m and 200m. A radio range of 100m was used to evaluate four different beacon periods b_p : 0.5s,

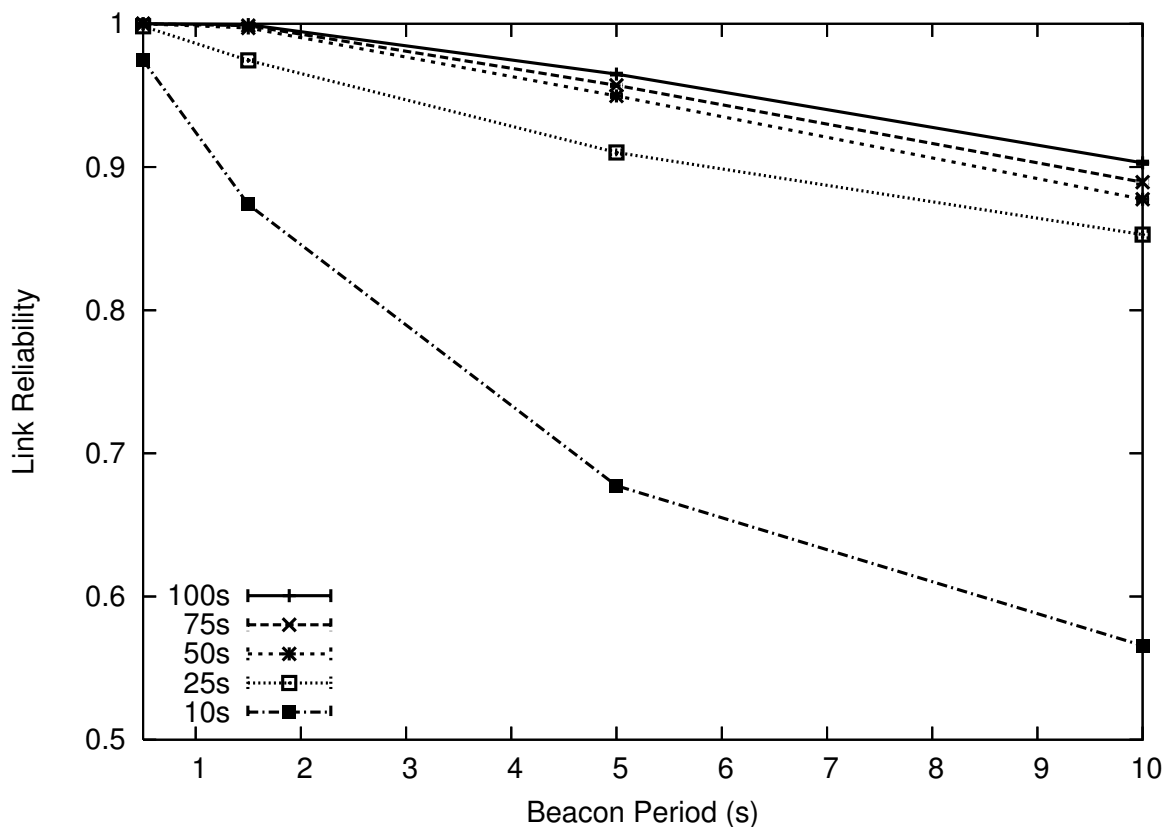


Figure 3.28: Link Reliability Estimation - Link Reliability x Beacon Period

1.5s, 5s and 10s. We have analyzed five different levels, with l_i equals to 10s, 25s, 50s, 75s and 100s, and i for 1 to 5, respectively.

Link reliability was calculated based on the ratio of nodes in a specific level i that are still within range (there was no exchange of packets, only a global evaluation of distance between nodes). The final value of each instance from the 32 executions is an average of 120 samples taken 10s seconds apart during the last 20 minutes of simulation time (the first 20 minutes were used to avoid Cold Start obstacles).

Figures 3.27 to 3.29 show the results with a link reliability range of 0 to 1; the number of links in each level is the sum of the number of links in each node. The first observation is that reliability of links for $l_i > 50s$ is similar despite the value of l_i , varying both range and beacon period (see Figures 3.27 and 3.28). The beacon period has a stronger impact on link reliability; with $b_p = 5s$, link reliability of 25s is still above 90%. With a range of 200m and a small beacon period of 1.5s, a large percentage of links are reliable despite the

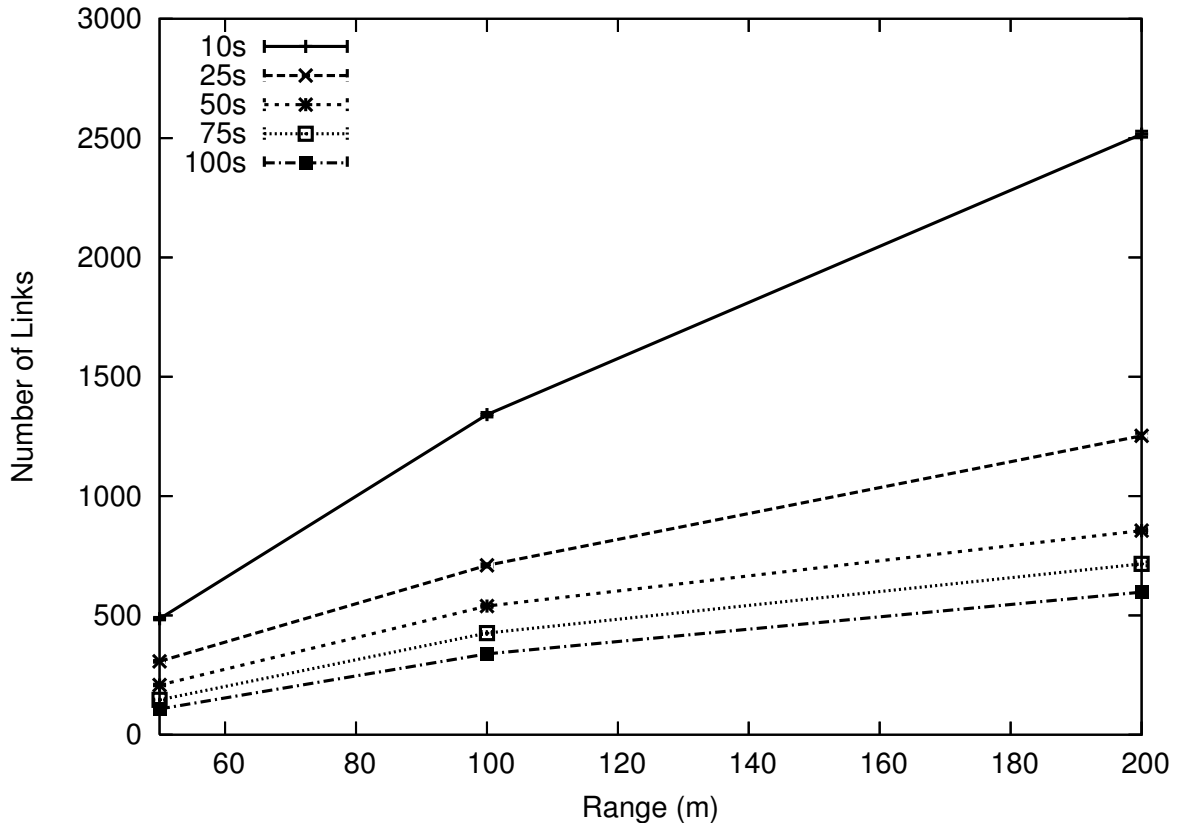


Figure 3.29: Link Reliability Estimation - Number of Links x Range

level of reliability. This was to be expected, since large radio ranges increase the number of nodes in each level, as shown in Figure 3.29. This reduces the impact, percentage-wise, of nodes within the boundaries of reachability. Although the number of links is strongly affected by the value of r , b_p does not affect this property (the figure with these results was omitted for all practical purposes). Another important observation is that, for l_i bigger than 50s, the average number of links per node for each level is smaller than 1, even with $r = 200m$.

These experiments suggest that the proposed mechanism for estimating link reliability can be used to classify links into different levels of reliability. Long beacon periods can be used without compromising the necessary tools to support QoS in VANETs. The proposed mechanism utilizes a relatively insignificant amount of bandwidth and requires little additional computation, yet it has been proven to define classes of links with distinct reliability. The main disadvantage is that the estimation of how reliably a link can be

used to transmit a packet is based on characteristics of incoming transmissions, and it has already been shown that communication properties are not shared in both directions.

3.3.1 QoS Through Link Reliability

A wide variety of applications is expected to be developed for VANETs. These applications have different requirements for properties such as delay, jitter, bandwidth, throughput and security. Most of these properties are strongly influenced by the successful transmission rates between intermediary nodes. Therefore, a mechanism that offers a way of choosing among options with distinguished successful transmission rates expectations can be used to support policies that provide different levels of end-to-end quality for distinct applications.

In this section, the goal is to show how the Link Reliability model proposed in the previous section can be used to achieve different successful transmission rates, and to provide the foundation necessary to support QoS in future protocols. This can be achieved if the levels defined in the link reliability model are used to group links into queues so that packets from applications with higher priorities are forwarded through links in higher-level queues. The use of acknowledgments or retransmissions is not considered; the scope of our goal is the probability of success of a single transmission. Routing protocols can use this mechanism and implement retransmissions or any other measure to increase the end-to-end delivery ratio.

An evaluation of the probability of successful packets relay is performed through simulations with the same scenarios, parameters values and statistical methods as those described in the previous section. In order to simulate the relay of packets, for each execution, five nodes were chosen randomly to transmit continuous packets with a payload of 1kb, at a rate of 25 packets per second for each queue. These transmissions begin ten minutes after the exchange of beacons and are interrupted while nodes are on the first or last kilometer (avoiding Cold Start and extremes bias). A packet is only transmitted if there is at least one node in the respective queue, and an unsent packet is not used to calculate the successful transmission rate. The second round of experiments were conducted for values of r for 50m to 300m and b_p for 0.5 and 5 seconds. In the previous section, it was observed that for l_i values greater than 25s, too few links were detected; for this reason, the following values for l_i were chosen: 5s, 10s, 15s, 20s and 25s.

In Figures 3.30 and 3.31, it is shown the sum of the number of packets that were not transmitted due to the respective queues being empty. The total number of packets to

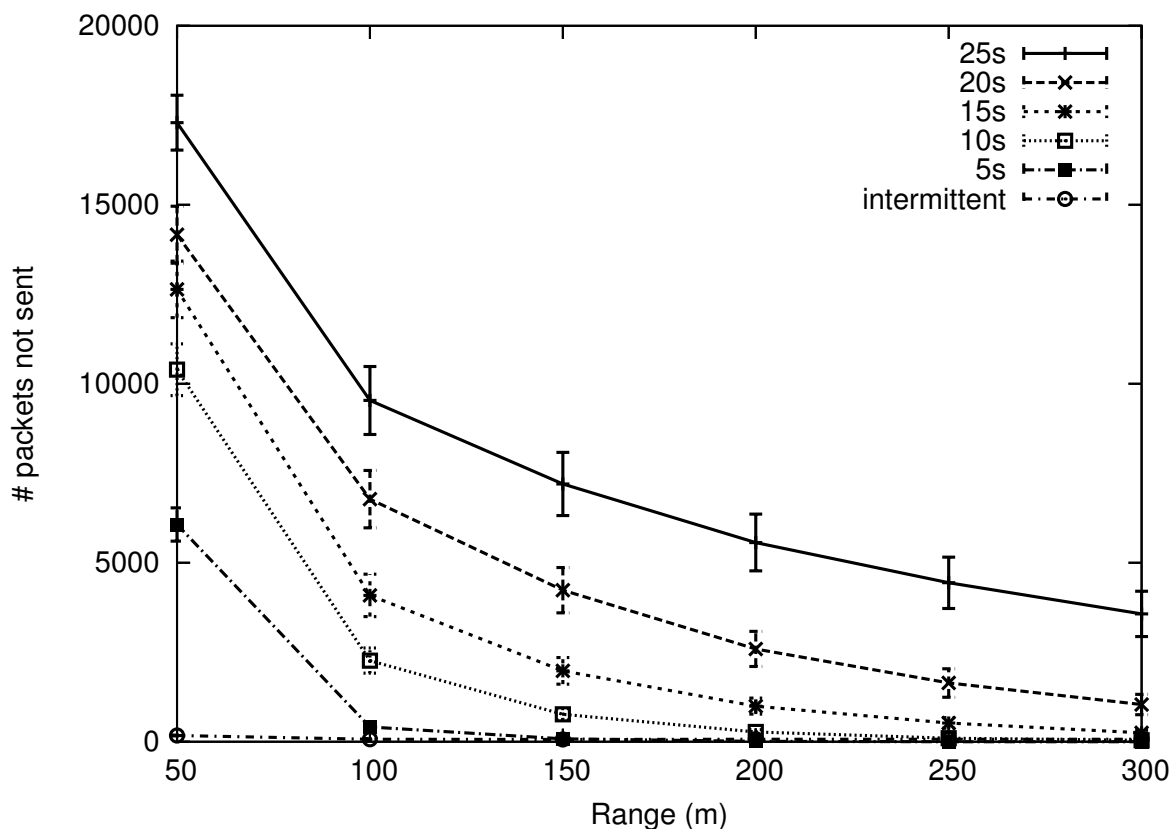


Figure 3.30: QoS Support for Packet Relay - Number of Packets x Range - Period 0.5s

be transmitted was always close to around twenty five thousand. For r not inferior than 100m, more than 50% of the transmissions were triggered –even for the highest level queue. A key observation was that the results were very similar for both values of b_p , suggesting that the beacon period has little impact on the number of detected links.

A small value for b_p (e.g. 0.5s) incurs in a exaggerated number of beacons leads to high overhead, not of energy consumption (as in MANETs) but of channel occupancy. This leads to poor network performance generally. Therefore, a beacon period of 5 seconds is much more suitable for VANETs, and Figure 3.32 shows that, for all values of r , the higher level queues have higher success rates than lower level queues.

Figures 3.30 to 3.32 show that while it is clear that queues with great values of l_i hold links with higher reliability (Fig. 3.32), they are much rarer though (Fig. 3.30 and 3.31). This could lead to an ambiguity on the choice of which queues offer links with better quality. However, QoS-based protocols could always attempt to use the links on the queue of desired quality (considering only the reliability) and if it is empty it would

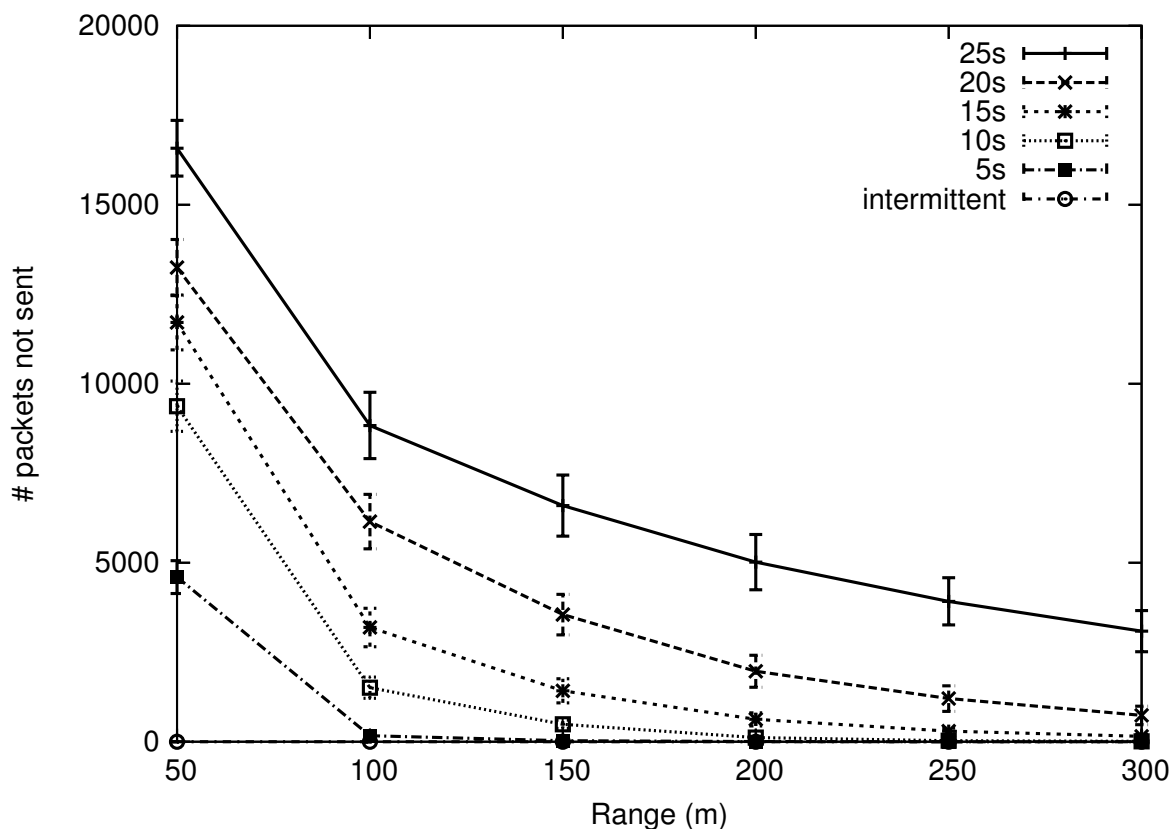


Figure 3.31: QoS Support for Packet Relay - Number of Packets x Range - Period 5.0s

search for links on immediate lower queues until a non-empty one is reached.

These results confirm that link reliability can be used to provide QoS support in VANETs. Both proposed mechanisms, the link reliability model and the queues with different levels with their respective l_i , are of extremely low complexity which leads to insignificant overhead while still providing means of offering distinct levels of quality.

3.3.1.1 Discussion

The motivation for this work was the need to develop a mechanism that would offer a way of to address properly and distinctly the wide variety of services that have been suggested for Vehicular Ad Hoc Networks. Protocols designed for VANETs must consider specific application requirements in order to provide reasonable Quality of Service, regardless of what their demands are. QoS policies can also be used to provide different levels of experience for users willing to pay the higher price of a better service.

The goal was to first define a model to estimate link reliability in VANETs, and to

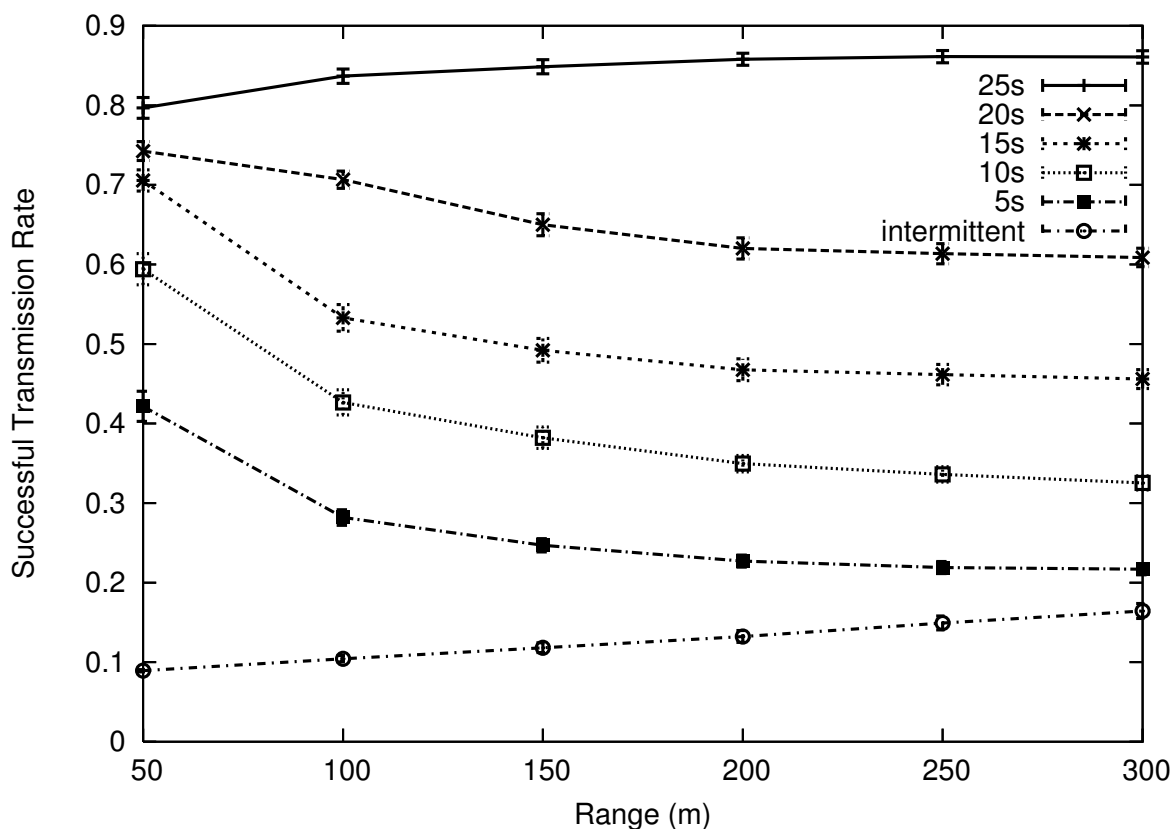


Figure 3.32: QoS Support for Packet Relay - Successful Transmission Rate x Range - Period 5.0s

then use this model to implement packets forwarding based on groups with distinct link reliability. The link reliability model is of extremely low complexity and incurs in almost no overhead. The estimated reliability of a link in this model is based on how long it has been available, which can in turn be calculated with sparse exchange of beacons. In the second part of this work, it was shown how this model can be used to define queues with different levels of reliability and use them to provide differentiated levels of QoS.

After a meticulous and extensive simulation process, it can be seen that both the link reliability estimation model and the relay mechanism have proven to be useful in offering different quality levels for successful transmission rates. While the queue whose links had the highest levels of reliability achieved rates of close to 90%, those whose links had lower reliability levels achieved rates around 70%, 60%, 40% and 30%.

Therefore, we have pointed out the necessity of QoS support in VANETs, defined an efficient process for estimating link reliability, and demonstrated an effective use of this

model for the provision of different levels of expected quality while relaying packets.

3.4 Conclusion

The contributions in this chapter are based on the particular improvements in understanding the whole of mobility; studying the issue of localization through the perspective of neighboring nodes as well as extend the proposed solution for neighborhood prediction; and investigating the use of link duration as a metric for link stability.

It was observed that mobility plays an interesting whole in connectivity. VANETs were evaluated through the perspective of Complex Networks with vehicles as nodes and the exchange of beacons determine the links between these nodes. It was noticeable that high clustering coefficients in inherent to VANETs due to the shared wireless medium between nearby nodes. Mobility played an interesting role as it acted as a random rewiring process and with time changing a lattice network to a Small-World.

The use of a simple vectorial movement prediction model was sufficient to improve the accuracy of the localization of neighbors. With the proposed protocol, it was possible to reduce significantly the frequency of exchange of beacons while maintaining high accuracy. Furthermore, the propagation of received beacons was used for developing a solution that predicts the occurrence of future links. This information is valuable for routing algorithms to react properly to topology changes.

A correlation was established between the current duration of a link between neighboring nodes and its future stability to offer connectivity between such nodes. It was observed that older links have a higher chance to remain valid as links with similar movement patterns tend to be within reach for a longer period of time. A mechanism was proposed to divide links in queues based on their current duration and older links could be prioritize to more important services.

Besides the specific contributions in the aforementioned solutions, these works were fundamental for a deep and insightful understanding of VANETs. The knowledge gathered in these works was important to the design of suitable solutions for video streaming in VANETs. These solutions are described in the next chapters.

Chapter 4

Video Dissemination in VANETs

In this chapter, the focus is on the task of disseminating video content over a VANET. Dissemination is considered as the process of broadcasting data to all nodes within a distance to the source node. This assumption can be easily adapted to a geocast premise where data are broadcasted to all nodes within a defined region. A unicast solution can be used for the transmission of the packet to one node in the destination region and then the same dissemination techniques as shown in this chapter can be applied.

Video dissemination can be used for a variety of services where interest in video content is shared among vehicles in the same region. Examples of services that require or are greatly enhanced through the use of video dissemination are the broadcast of local traffic to incoming vehicles, a video of nearby crashes so drivers can assess safety conditions, the notification to users of local events that are currently happening or commercial services that are provided around users' vicinity.

One specific example of the value of video dissemination over vehicular networks is that of the dissemination of videos for the purpose of warning drivers of animals crossing the roadways. In the United States alone, it is estimated that there are between one and two million accidents involving wildlife/vehicle collisions [47]. Cameras and sensors could be deployed in more dangerous spots where animal crossing occurs more often and drivers' visibility is reduced so that when movement alongside highways is detected, captured video is disseminated and displayed to drivers. This provides richer information than the simple broadcasting of an alert which could be neglected by drivers and, besides that, with a video drivers can distinguish more easily a real animal crossing from a false positive.

The challenges regarding the provision of video streaming dissemination over vehicu-

lar networks are due to the combination of video's stringent requirements and vehicular networks' dynamic topology. Video streaming requires the timely transmission of a large portion of data under a small rate of loss [118]. The movement of vehicles causes the network topology to change constantly which reduces significantly the duration of the connection between two neighboring nodes. Furthermore, the wireless nature of communication is strongly prone to packet loss specially at higher rates of data exchange of necessary for the transmission of videos of a higher quality.

Section 4.1 describes in detail the REACT-DIS protocol and shows a preliminary evaluation on the impact of its defining parameters. Section 4.2 describes an improved solution for video dissemination, namely REDEC. A performance comparison of these two solutions and two other state-of-the-art approaches is presented in Section 4.3. Conclusions are presented in Section 4.4.

4.1 REACT-DIS Protocol

We have designed a Reactive, Density-aware and Timely Dissemination protocol (REACT-DIS). REACT-DIS is implemented to fulfill the aforementioned requirements of a successful video-streaming dissemination service. For this reason, we have used three premises to guide the development of this solution: reactivity, density-aware and timely.

The first principle is that any protocol for VANETs must be reactive and respond to constant topology changes (e.g. links breakage and links creation). There are several solutions to MANETs that already take in consideration the necessity to be reactive. However, many of these solutions still rely on some sort of neighboring table, AODV [92] and DSR [55] are some examples. This kind of solutions is not reactive enough to VANETs' dynamism.

A more suitable paradigm is the receiver-based approach. Through this perspective, the selection of relaying or forwarding nodes is performed at the receiver's side instead of at the sender's. The most common way by which this is performed is that any forwarding node simply broadcasts the message and any node within range triggers a mechanism to decide if it is going to broadcast further such received message. This mechanism consists of nodes scheduling themselves to make the decision of forwarding further a packet in t time in the future. The value of t is chosen from a range $[\tau, \Gamma]$ based on a heuristic that determines nodes' suitability as forwarding nodes (lower values of t to better candidates). Before t expires, all scheduled nodes observe their own channels keeping track if the same received message is forwarded by any other node. When t

expires, nodes take into consideration the overheard broadcasts to decide if they should forward further the received message or not.

The majority of existing receiver-based solutions use geographically greedy solutions. In these solutions, t is inversely proportional to the distance between the receiving and forwarding nodes¹. REACT-DIS chooses t as a simple linear transposition of the distance between the nodes divided by the node communication range², which can be defined by the following equation (where $\delta(n_s, n_r)$ is the distance between sender and receiver nodes):

$$t = \tau + \left[\left(1 - \frac{\delta(n_s, n_r)}{R} \right) \times (\Gamma - \tau) \right] \quad (4.1)$$

The distribution of vehicles throughout a city or a highway varies significantly. In highways, it can be observed that vehicles with similar mobility patterns (i.e. speed and direction) form connected clusters that may be disconnected from other clusters though. Besides that, constructions, traffic or other particular events create spots of high density while other regions become sparsely populated. Non uniform density is even more evident in urban environments. In a macro perspective, traffic seasonality, popular neighborhoods (either for commercial, entertainment or residential reasons) or common routes tend to attract concentration of nodes from some other areas. Furthermore, lights, intersections or stop signs cause density fluctuation to be even more dynamic.

The main problem with density non-uniformity is that solutions usually try to be optimized for the trade-off of overhead and effectiveness and this become complicate with such wide density variety, for example, routing protocols focus on achieving high delivery ratios with the least amount of transmissions. In order to be able to successfully delivery packets from sources to destinations, a routing protocol has to be able to relay packets through low density regions but solutions for these lead probably to a unnecessary highly overhead over denser regions.

The density-aware aspect of REACT-DIS comes into play when nodes have to decide if they are going to forward further received packets after the time t expires. When a unicast solution adopts the receiver-based approach, the reception of the same packet forwarded by a node closer to the destination cancels the scheduled transmission. However, REACT-DIS is a dissemination solution and it is not expected that a single node should be responsible to continue the dissemination by itself. Therefore, the decision of a node in

¹This distance is used by dissemination solutions, unicast approaches have t rather directly proportional to the distance between the receiving node and the destination node

²In this work, we consider the communication range to be know by receiving nodes. This value can be easily estimated based on previous received messages or included in each packet's header.

REACT-DIS to forward a packet is based on the number of overheard retransmissions of duplicated packets. Each node keeps track of how many duplicates messages are received during the time slot of t seconds. Then, a node forward the packet with a probability ρ inversely exponentially proportional to the number of overheard copies c . This probability follows equation 4.2.

$$\rho = \frac{1}{\Upsilon^c} \quad (4.2)$$

By this manner, the relay of a packet depends on nodes' suitability to be a forwarding node (based on its distance to the node in the last hop) and also on the density of its vicinity. Regions with a high density of vehicles are going to have only nodes with a low value of t forwarding packets while low density regions are going to permit that less suitable candidates relay further the message. This is the expected result which dynamically balances the cost of transmissions with the need of high reachability.

The problem with receiver-based solutions for video dissemination is that the waiting time t at each hop leads to an excessive end-to-end delay. In order to have a timely solution, REACT-DIS tackles this issue through the perspective that in each hop there is a competition to determine which nodes are suitable to be forwarding nodes. As many successive packets are transmitted in video dissemination and repeated competitions are unnecessary, in REACT-DIS, whenever a node *wins* as one of the suitable forwarding nodes, it is considered that these nodes continue to be the best options to relay packets for a predefined amount of time Φ . Therefore, within this time window, nodes are selected as relay nodes and any packet received is immediately forwarded. This solution does not impact the ability to react to link breaks, if a relay node is no longer within reach of the previous relay node (or the source node), other eligible neighboring nodes have higher chances of forwarding the packet and to consider themselves as new relay nodes.

REACT-DIS is a non-deterministic solution as nodes are subjected to probability tests in order to decide if they are going to relay further received packets. When a node decides to forward a packet it continues forwarding packets that are received subsequently. During this time, an excessive number of nodes might consider themselves suitable to relay packets. For this reason, we have also adopted the density-aware principle for the forwarding of packets by relay nodes. This is done by using a probability ϱ to decide if specific packets are forwarded. This probability is given by the following function:

Parameter	Value
Radio Propagation Model	TwoRayGround
Mac Layer	IEEE 802.11
Radio Range	300m
Antenna	OmniAntenna
Packet Payload Size	1,000 bytes

Table 4.1: Simulation Parameters

$$\varrho = \begin{cases} 1.0 & \text{if } c \leq k \\ 1.0 - [(c - k) \times \Lambda] & \text{if } c > k \end{cases} \quad (4.3)$$

We have chosen k based on how many relay nodes are expected to be present per hop. We understand that if more than four nodes are relay nodes within the same broadcasting zone of another relay node, its transmission is likely not crucial. For this reason, k is chosen to be equal to 4. Although the choice of k is not empirically checked, experiments are performed varying the value of Λ and its impact on REACT-DIS's performance is analyzed.

Algorithm 4 shows the steps taken by each node when a packet is received. If the packet has already been received, it simply checks if the node is currently scheduled to be a relay node or if it is already one, in these cases, it increments the counter c of duplicated packets. However, if it is the first time the node has received this packet, it follows different steps based on the node's status. If it is a relay node (meaning that it has broadcast a packet in the near past), it immediately forwards further the packet with probability ϱ and it resets the counter c . In case the node is scheduled to broadcast another packet, the new packet is then included in the buffer of received packets. Finally, if the node is idle, it schedules itself to try to forward the received packet in t seconds.

In the next section, the peculiarities of REACT-DIS' implementation are described.

4.1.1 Implementation

In order to evaluate REACT-DIS' effectiveness and efficiency in VANETs, it was implemented using the Network Simulator (ns2)[85]. The Two-Ray Ground [96] was used as the propagation model, IEEE 802.11 for the link layer and a radio range of 300 meters. In Table 4.1, the values of the parameters used in this experiments are listed.

Before we continue describing the simulated scenario, it is important to point out a

Algorithm 4 REACT-DIS - Receiving packet p

```

if  $p$  has not been received before then
  application handles packet  $p$ 
  if node is a relay node then
    forward packet  $p$  with probability  $\varrho$ 
    reset counter  $c$ 
  else
    if node is scheduled to try to broadcast then
      insert  $p$  into buffer of packets to send
    else {Node is idle}
      Schedule to try to forward  $p$  in  $t$  seconds
    end if
  end if
else { $p$  has been received before}
  if Node either is a relay node or it has schedule to try to broadcast then
    increment counter  $c$ 
  end if
end if

```

mechanism that is often omitted in other receiver-based works. As forwarding nodes are chosen locally by receiving nodes themselves, simultaneous transmissions³ happen often which leads to many collisions. The most common and effective solution to this issue is to add a delay that is randomly chosen between 0 and θ . The value of θ is subject to a trade-off between low end-to-end delay and collisions avoidance. We have modeled a scenario where n nodes are placed uniformly in a region where all nodes are mutually reachable with a one-hop communication. θ is varied and the results are analyzed in terms of the delivery ratio of packets triggered to be broadcast at the exactly same time by all nodes (with additional random delays within the mentioned range). We have analyzed this under four different data rates (80kbps, 400kbps, 800kbps and 1600kbps). Figure 4.1 shows the results observed and it can be seen that for $\theta = 10ms$ an either satisfactory or converged delivery ratio is reached if n is less or equal to 10 nodes. For this reason, $\theta = 10ms$ is the value chosen for the remainder of this thesis.

³Transmissions are considered simultaneous if any two or more transmissions are performed by different mutually reachable nodes with a time difference between them smaller than the one necessary for all of them to hear each other.

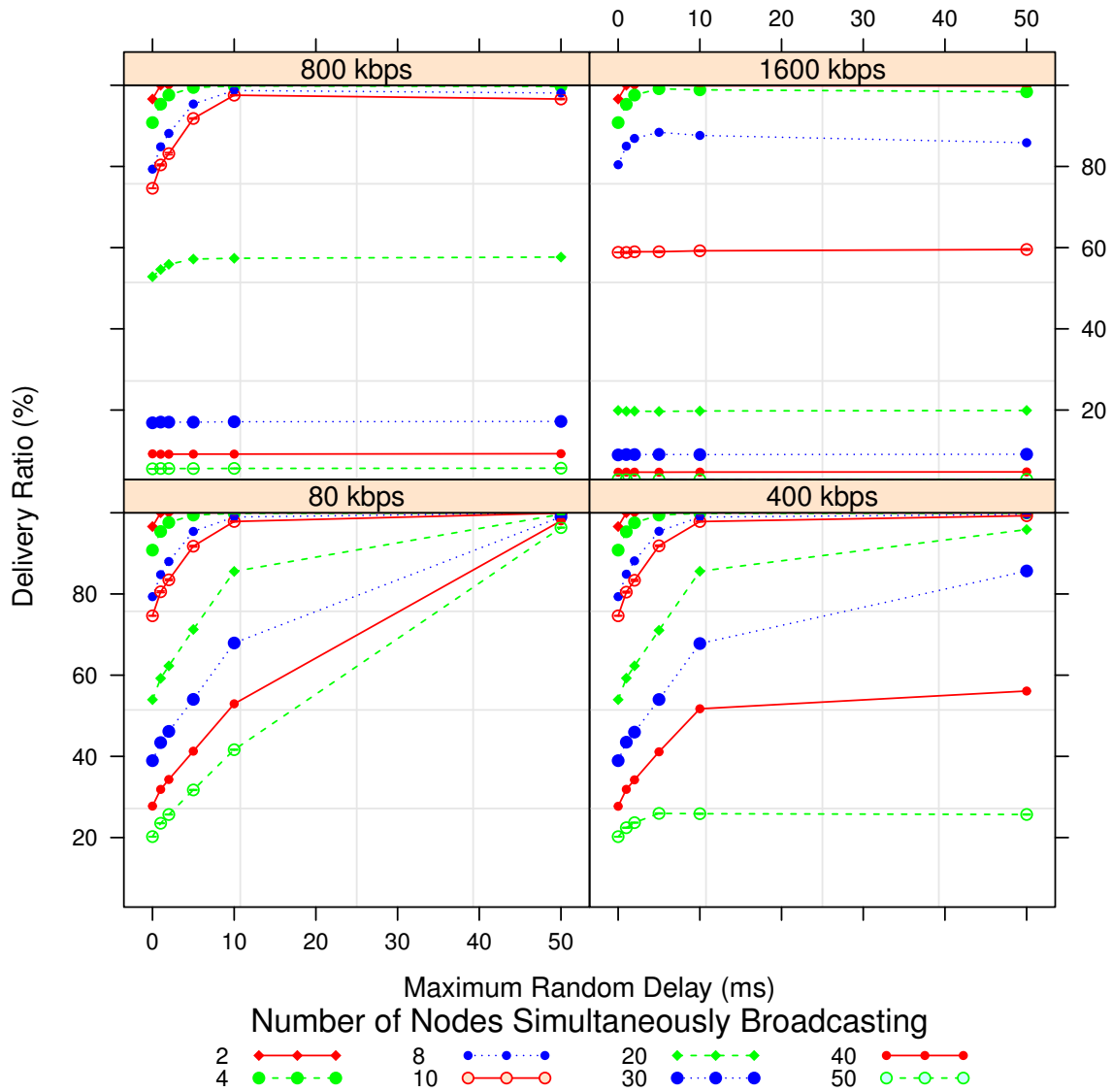


Figure 4.1: Impact of Random Delay on Simultaneous Transmissions

For the mobility model in the simulations in this section, we have used the Urban Mobility Model (UMM) described in Chapter 3 Section 3.1.2.

Table 4.2 summarizes the values of the main parameters for the generation of the 32 distinct instances of the Urban Mobility Model. It is important to point out that, although the speed is initially randomly chosen within the defined range, vehicles may move slower than the lower limit since the final speed is subject to traffic conditions.

The reducing factor is a function on the current number of vehicles in a segment and it is only used if there are more than 5 vehicles in such segment.

Parameter	Value
Number of Vehicles	1,000
Area	3,000m x 3,000m
Segment Length	100 m
Speed Range	5 to 30 m/s
Segment Maximum Capacity	20 vehicles
Reducing Factor	$5^{-[(\#vehicles/5)-1]}$

Table 4.2: Urban Mobility Model Parameters

The video source is an extra static node in the network. It is placed in a corner of the network area instead of the center of the simulated area. There is no particular reason to believe that the performance in different quarters of the network around a disseminating node in the middle would not be symmetrical. Besides that, a source node placed in a corner forces the network to create longer paths to reach farther distances.

It has been considered that all nodes in the simulation are interested in the disseminated content. The majority of services envisioned are composed of videos that are of the interests of nodes 4,300 meters (the farthest possible distance in the used network topology) or less apart from the source node. The use of this solution for dissemination over a smaller region would only require an additional field on packets headers that delimits the dissemination range.

As mentioned in the previous section, the time t that nodes wait to try to forward incoming packets is chosen within $[\tau, \Gamma]$ based on their distance to the node that has lastly broadcast the packet to them. The values assumed by τ and Γ are greatly influenced by the value of θ . In order to prevent new nodes from broadcasting packets in the place of previously selected ones, $\tau = \theta = 10ms$ so any relay node forwards further the received packet before any new candidate. Different values of Γ were evaluated and its impact on the performance of REACT-DIS was analyzed, the results are shown in the next section.

The process of buffering packets depicted in Algorithm 4 is necessary as the transmission data rate is usually large enough so that nodes receive multiple packets before their waiting time t expires. If any packet is received before t expires, it is stored in this buffer. For this reason, whenever t expires and the node has to calculate its probability ρ of forwarding buffered packets, the attenuator c (number of duplicates) is divided by

the number of packets in the buffer. The value used is the largest previous integer to this division. Therefore, with s as the number of packets in the buffer, a more precise description of the equation used to calculate ρ is:

$$\rho = \frac{1}{\Upsilon_{[c/s]}} \quad (4.4)$$

Once a node decides to forward buffered packets, it does following the same data rate as the packets were sent by the source node. If new packets are received before all buffered packets are broadcast, the new incoming packets are added to the end of the buffer.

Through preliminary experiments, it has been observed that as many packets are sent, nodes with very low probabilities ρ of forwarding eventually become relay nodes and they keep forwarding packets for a long period of time at regions with already enough relay nodes. In order to avoid this, ρ is rounded to zero if it is less than 1%. Besides that, it has also been noticed that the initial process of determining the first relay nodes have a great impact in the dissemination of the first packets. It has been decided to broadcast a *null* message one second before starting to disseminate the video content. This additional delay is definitely acceptable and it prevents the loss of many initial packets.

Although it is important for relay nodes to be subjected to a forwarding probability based on density, these probabilities should not be too prohibitively to the dissemination of packets. For this reason, it was defined a lower bound for ρ which is of 40% in this work.

In the next section, the metrics used for the evaluation of REACT-DIS are described and the results are discussed.

4.1.2 Evaluation

REACT-DIS's performance is evaluated through simulations in the Network Simulator (ns2), as mentioned. Each plotted result is an average of 20 to 32 runs, each with a different instance of the same mobility model and different seeds for the generation of random numbers. Confidence intervals are also plotted and they are calculated based on Student's t-distribution with a confidence level of 95%. All graphs and statistical measurements are made with the use of the free software environment for statistical computing and graphics called R [94]. It has been observed that these considerations were enough to achieve trustworthy results as the calculated confidence intervals are

Parameter	Value
Name	Akiyo.cif
Resolution	360x486
Compression	MPEG
#Frames	300
#Packets (1,000 bytes)	353

Table 4.3: Video Parameters

short and compared results can be statistically differentiated.

In this work, we have used EvalVid –*A Video Quality Evaluation Tool-set* [58] –in order to get results relevant to video streaming. The video transmitted in the simulations is well-known and widely available online (akiyo.cif). It is a MPEG video with resolution of 360x486 composed of 300 frames that could be fitted into 353 packets each with a payload of 1,000 bytes (as listed in Table 3.5). These specifications are listed in Table 4.3.

REACT-DIS performance is greatly influenced by the configuration of its main four parameters. These parameters are the maximum waiting time Γ , the forwarding probability reducing factor Υ , the time a node remains as a relay node Φ and the relay node forwarding probability reducing factor Λ . These four parameters determine REACT-DIS’s configuration quadruple $(\Gamma, \Upsilon, \Phi, \Lambda)$.

EvalVid provide tools to evaluate the transmission of video with metrics such as frame loss, frame delay, jitter, PSNR, SSIM, MIV and MOS. In order to do so, it requires to convert the simulation output which consists of a summary of packets sent by the source and one list of the received packets per node. After the simulation, these lists are used to assemble what would be the received videos. Then, these videos are compared to the original reference video. This process is extremely time consuming and has to be performed 1,000 times per simulation (one for each receiving node).

The tuning of REACT-DIS’s parameters is done through the evaluation of 600 unique combinations of its configuration. The evaluation of all these results using EvalVid’s video’s metrics is unfeasible. Consequently, for this part we have decided to measure the network metrics of delivery ratio, packet delay and number of packets sent.

A crucial distinction on the dissemination of video content rather than other type of data is the high data rate of transmission required for higher levels of video quality. Accordingly, REACT-DIS has been evaluated under four different data rates which support different levels of quality. We have used 100kbps (kilobits per second), 500kbps,

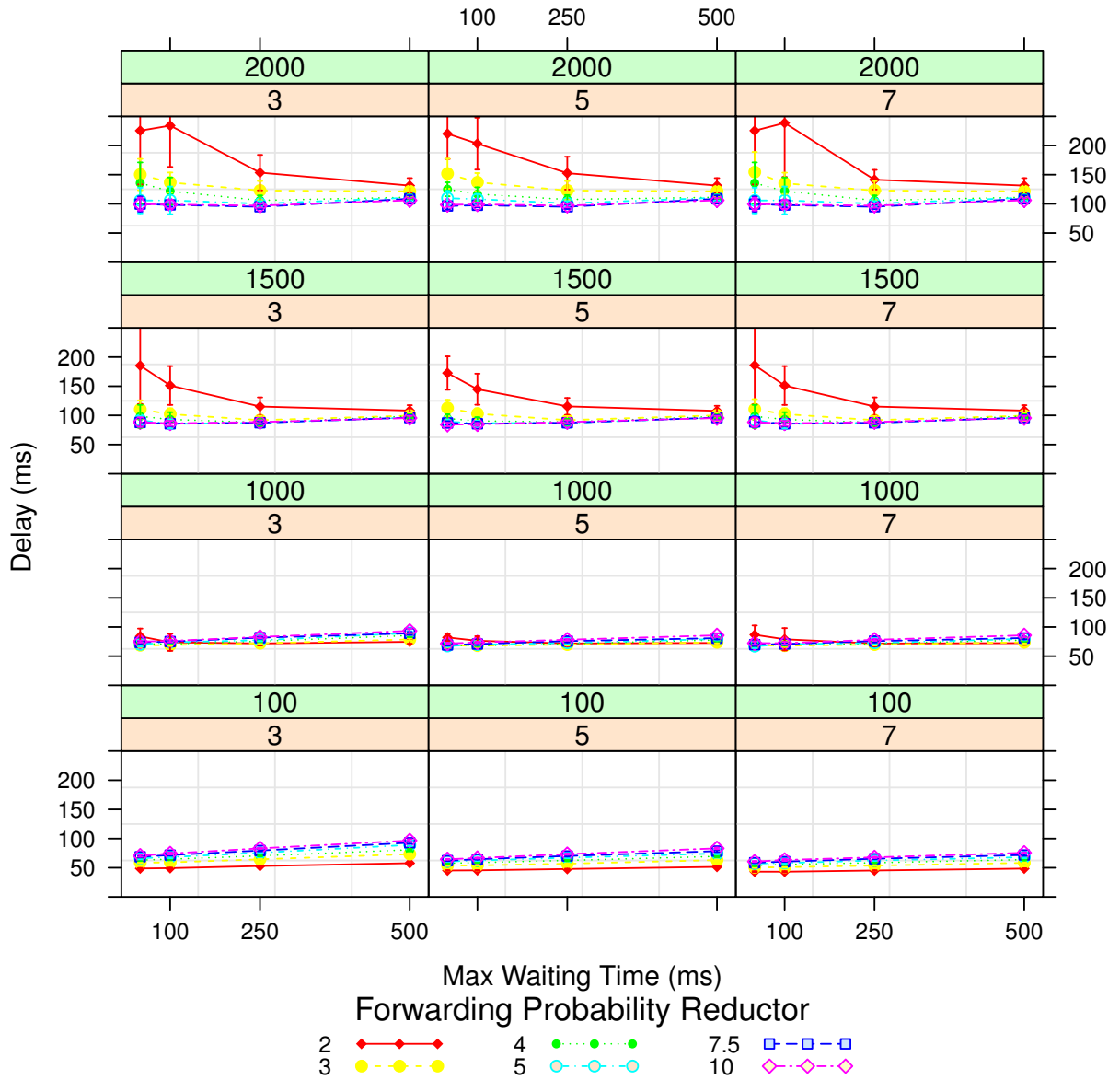


Figure 4.2: Delay in Video Dissemination - Lines represent different Υ , columns vary in Φ and rows are scenarios with different data rates.

1,000kbps, 1,500kbps and 2,000kbps.

The first observation is that REACT-DIS must follow the assumption that the selection of relay nodes should not occur for single packets but rather for a period of time. With $\Phi = 0$, not only the delay exceeds video-streaming requirements of 4 to 5 seconds (as in Table 1.1) but it also incurs into an extremely low delivery ratio (as it is shown later in Figure 4.4).

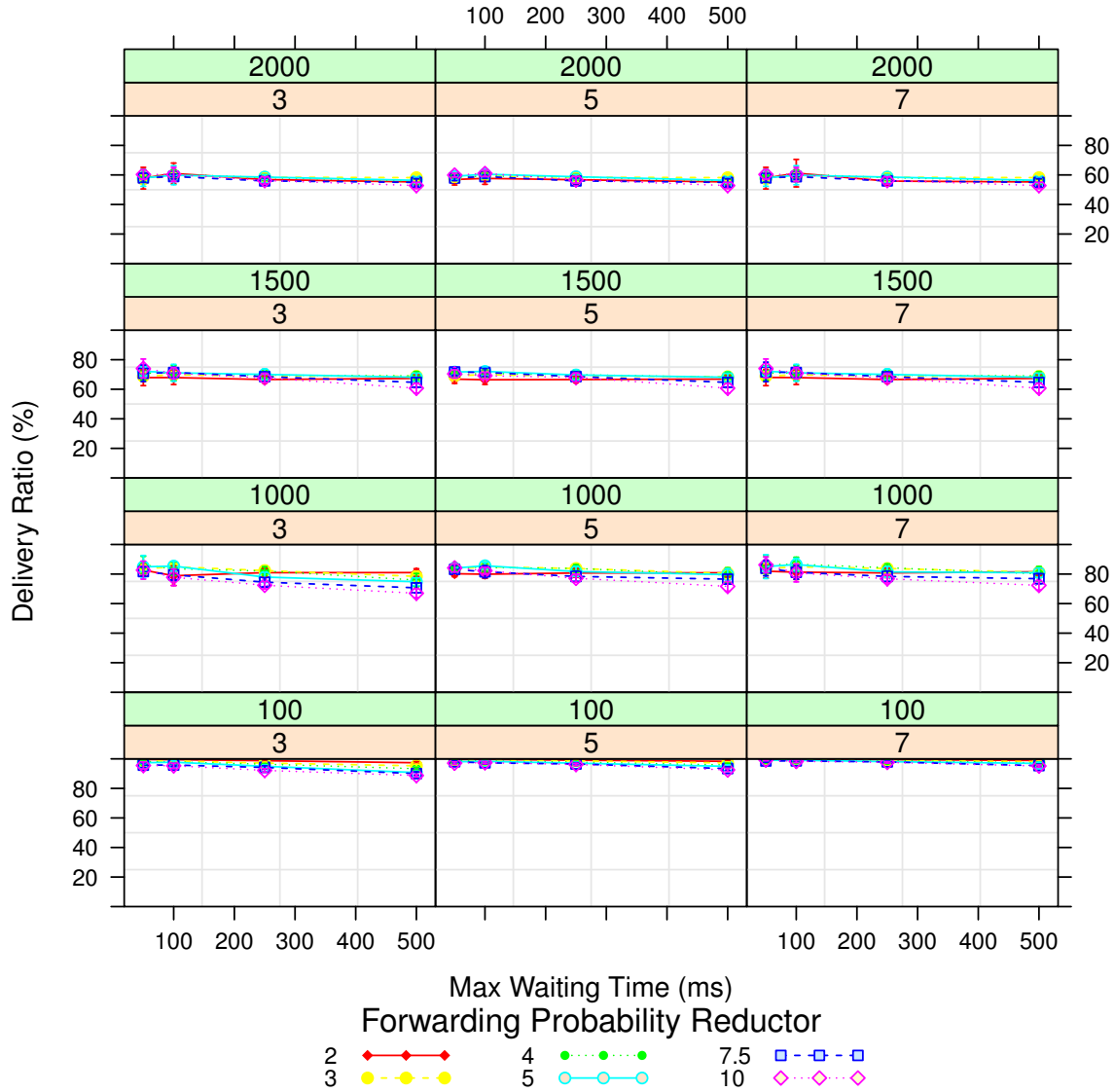


Figure 4.3: Impact of Maximum Waiting Time in Delivery Ratio - Lines represent different Υ , columns vary in Φ and rows are scenarios with different data rates.

In order to have clearer figures, the case when $\Phi = 0$ has been omitted for the evaluation of the impact of the maximum waiting time Γ . Figure 4.2 and Figure 4.3 show respectively the end-to-end packet delay and delivery ratio (for these figures, the relay node forwarding probability reducing factor $\Lambda = 10\%$). It can be seen that for the majority of configurations (excluding those with $\Phi = 0$), the maximum waiting

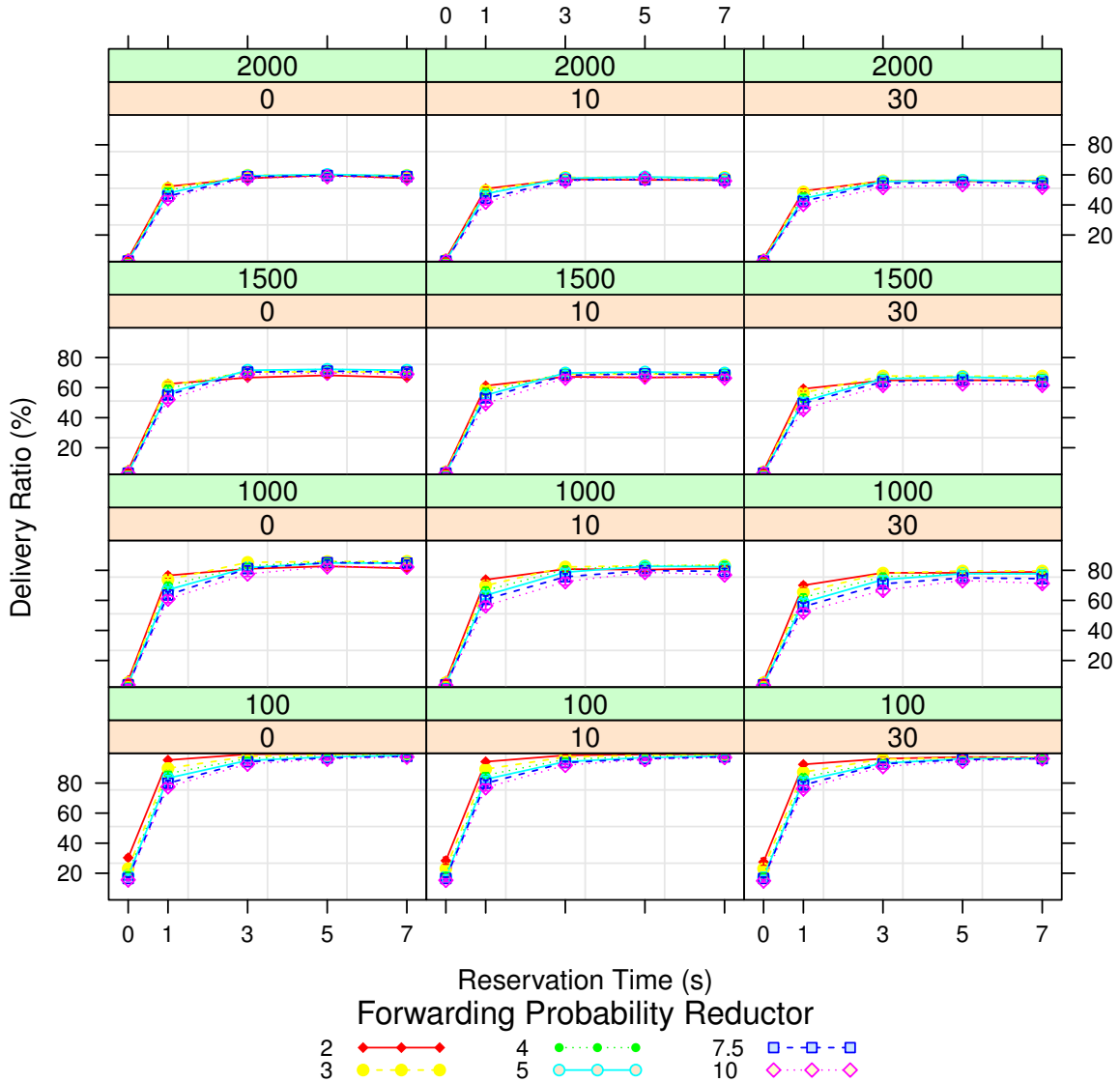


Figure 4.4: Delivery Ratio in Video Dissemination - Lines represent different Υ , columns vary in Λ and rows are scenarios with different data rates.

time has no significant impact. For this reason, it was chosen the optimum value for this parameter with $\Gamma = 250ms$ for all the remaining plotted results (for clarity, one dimension of REACT-DIS's configuration had to be excluded).

The observed end-to-end delay when $\Phi > 0$ is always smaller than the video-streaming requirement shown in Table 1.1. Furthermore, REACT-DIS's performance in terms of

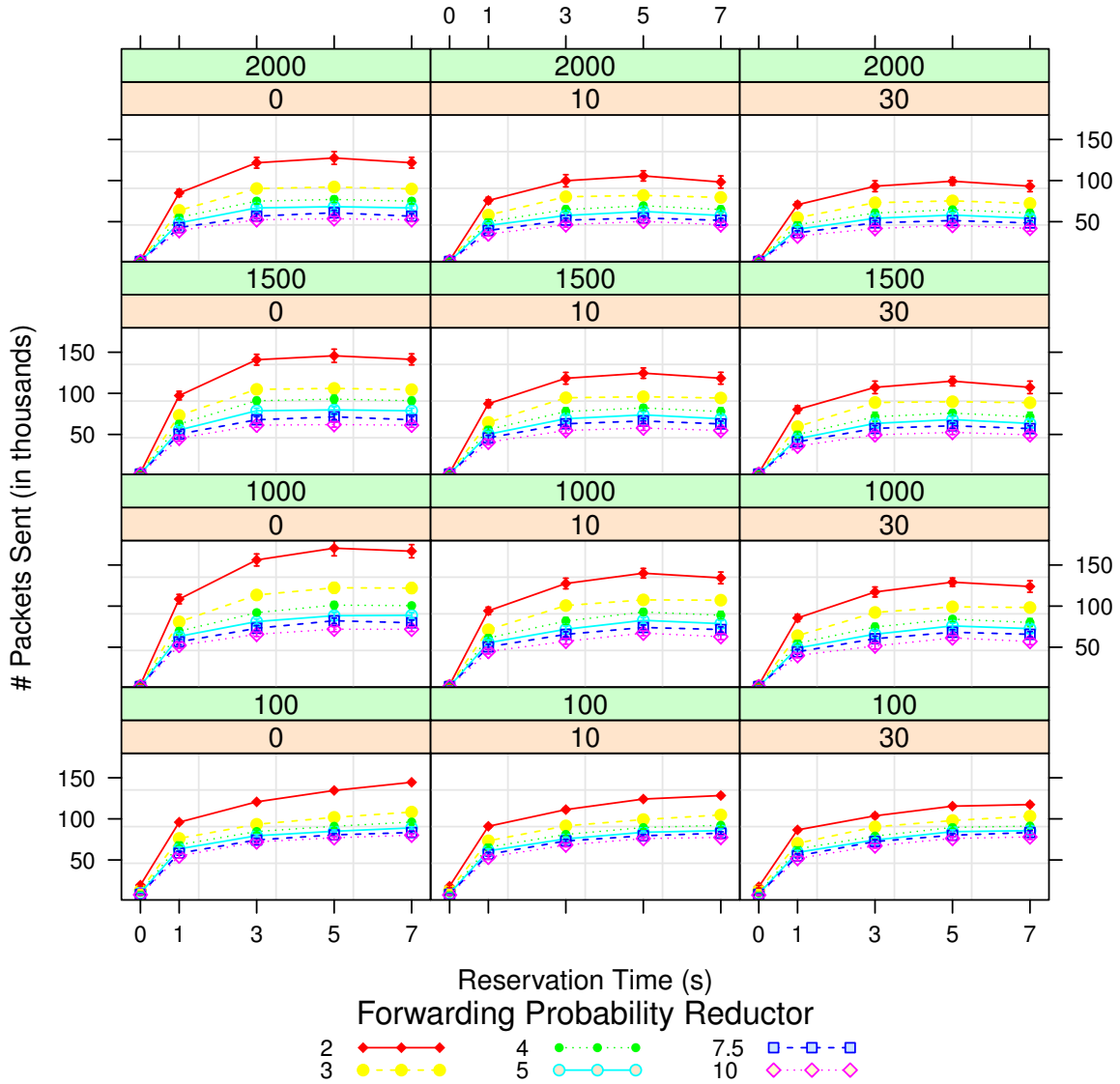


Figure 4.5: Number of Packets Sent in Video Dissemination - Lines represent different Υ , columns vary in Λ and rows are scenarios with different data rates.

delay has shown to comply even with the stronger delay requirement of interactive-video. Slightly worse performances were perceived with either $\Phi = 1$ or $\Upsilon < 4$. It can be conclusively understood that REACT-DIS's approach in extending the selection of relay nodes for more than a single packet but instead to a time period has shown to be extremely successful in its attempt to be suitable to the dissemination of video content.

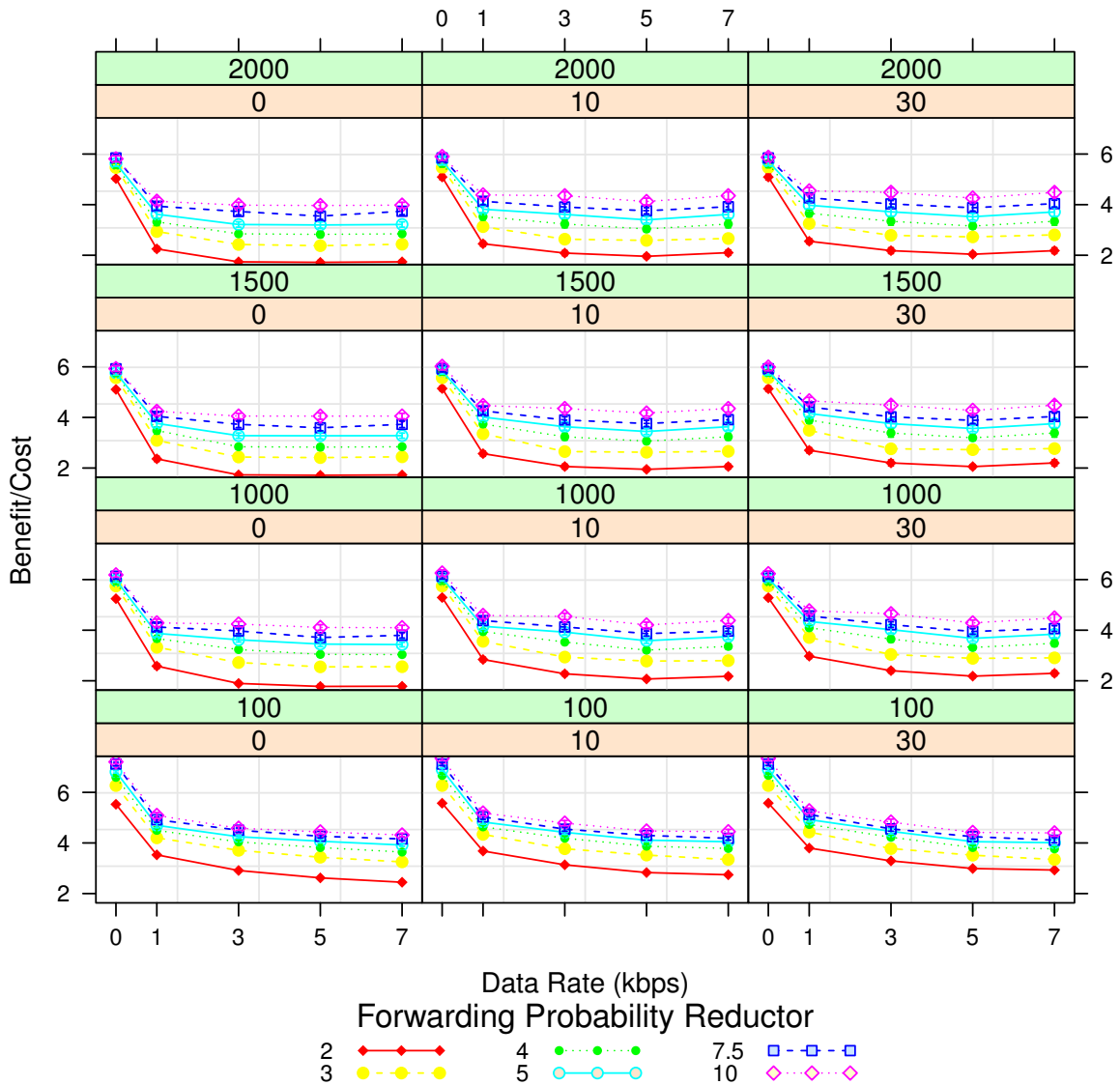


Figure 4.6: Benefit vs Cost in Video Dissemination - Lines represent different Υ , columns vary in Λ and rows are scenarios with different data rates.

Figure 4.4 shows the results for a deeper investigation on REACT-DIS’s ability to successfully delivery packets to receivers. The first surprising observation is that both forwarding probability reducing factors (Υ and Λ) had little impact in the achieved delivery ratio (a slight decrease is observed with the highest value of these parameters). The time Φ that a node considers itself as a relay node, however, influences greatly

REACT-DIS's performance. The highest delivery are reached by values of Φ greater or equals to 3 seconds. Furthermore, delivery ratios high enough to fulfill video-streaming requirements (95-96% - Table 1.1) are not reached with data rates of 500kbps or higher. At 1,000kbps, the delivery ratio is already around 80% and it decreases even further for higher data rates with a level around 60% at 2,000kbps. A solution to increase delivery ratio at higher data rates is discussed in Chapter 6.

The evaluation so far consisted in measuring the benefits of REACT-DIS. In order to estimate its feasibility, it is fundamental to evaluate also its cost. The number of video packets transmitted is the measurement of cost in this work. The results for this metric are shown in Figure 4.5. As mentioned before, higher values of Υ and Λ do not lead to lower delivery ratios, however, in this figure, the efficiency of REACT-DIS can be seen as the same higher values reduce dramatically the number of packets sent.

The trade-off between benefit and cost is clearer seen in Figure 4.6. We have used a metric that divides delivery ratio (already normalized) by a normalized version of packets sent. The later is the division of the number of packets sent by the maximum possible number of packets that can be sent (the number of nodes in the network multiplied by the number of unique packets sent by the source node). Therefore, higher values of this metric reflects a better use of the networks resources. REACT-DIS's efficiency decreases with higher periods of time that nodes remain as relay nodes. However, this is necessary to fulfill the minimum requirements of delivery ratio. The impact of increasing probability reducing factors is significant and leads to more efficient REACT-DIS.

4.2 REDEC

My second solution to video dissemination over VANETs is a REceiver-based approach where the transmission of video content is DECOupled from the selection of relay nodes. This approach is named REDEC and the goal is to combine the reactivity of receiver-based solutions without suffering from issues of relay node selection and their impact upon the transmission and reception of packets carrying video content.

REDEC is a receiver-based solution (like REACT-DIS) in the sense that the determining of which nodes relay further received packets is conducted on the receiver's side rather than on the sender's side. The decision determining a node's suitability to relay received packets is dictated by the amount of time it waits before evaluating if it should broadcast a packet or not. Most suitable candidates should wait a small amount of time while less suitable nodes should wait longer. The calculation of REDEC's waiting time

differs from that of REACT-DIS and it is described in detail in Section 4.2.2.

The transmission of video content requires assembled packets to carry a large amount of data. These larger packets consume a larger portion of the available transmission slots and thus are more likely to be prone to collisions. REDEC minimizes this issue by decoupling the selection of relay nodes from the transmission of video content. Before the transmission of video content starts, the source node disseminates a control packet following a receiver-based approach for the selection of relay nodes. When packets containing video content are sent, nodes simply check if they are relay nodes and if so, they broadcast further the received packet. This control packet is disseminated by the source node periodically in order to update node status according to the current topology.

The time between the dissemination of control packets is α and its value influences how well REDEC handles topology changes while preventing an excessive overhead due to the transmission of control packets. A detailed study on this trade-off is presented in Section 4.2.3.2.

4.2.1 Protocol

REDEC's behavior is based on how nodes decide if they should participate in the dissemination process. A node using REDEC could be in one of the following four states: non-relay, scheduled, relay or scheduled relay. A non-relay node is a node that does not currently participate in the dissemination process and it is only potentially interested in the disseminated content. A relay node is a node that actively participates in the dissemination by broadcasting further any newly received packet. A scheduled node or scheduled relay node is a node that has recently received a control packet; and, it is currently waiting for its timer to expire in order to decide if it is going to become a relay or a non-relay node. It is important to distinguish scheduled relay nodes from scheduled nodes because the former has to forward any new incoming packet even while it is waiting for its timer to expire. Figure 4.7 shows a diagram that illustrates the transition between these four states.

As it can be seen in Figure 4.7, the maximum number of duplicates allowed δ is determinant on the decision of a node to become a relay node. The use of this parameter in REDEC is in order to control the amount of redundancy permitted in the network. If larger amounts of redundancy are accepted, a larger amount of nodes could be potentially reached; however, there could be more collisions and a higher cost in terms of number of transmissions. Although a small value of δ would incur less overhead, it could prevent

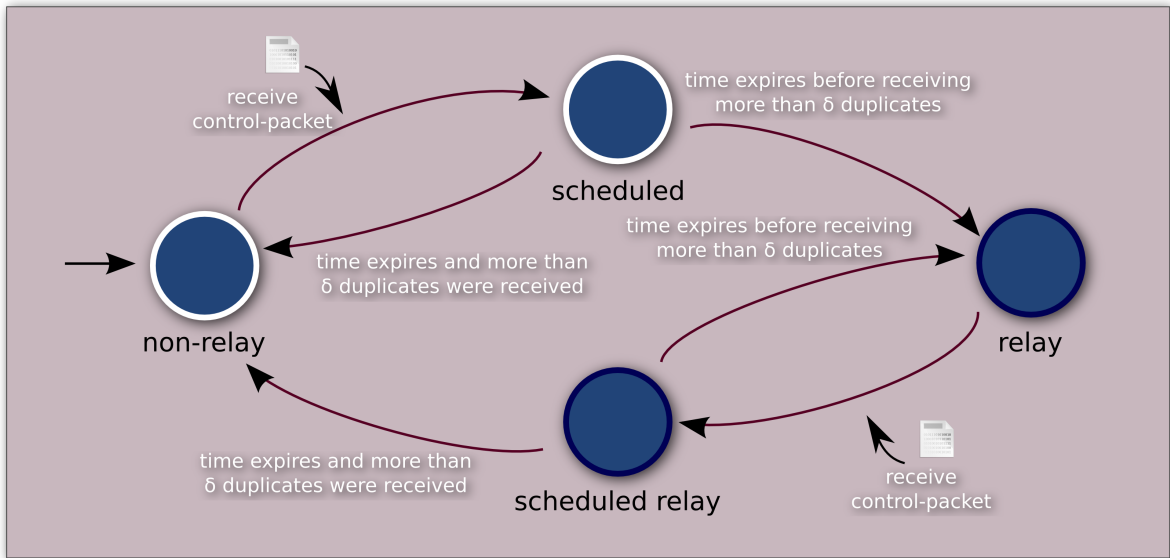


Figure 4.7: REDEC - Diagram of Node's STATES

interested nodes from receiving the disseminated video. The evaluation concerning the trade-off of this parameter is shown in Section 4.2.3.2. It is important to point out that the maximum number of duplicates is not exactly equal to the number of relay nodes in a neighborhood. The reason for this is that different nodes could have similar waiting times which would prevent them from taking a decision prior the reception of the transmission of the other. This is not an issue and the evaluation of different values of δ in Section 4.2.3.2 suffices to find an ideal value.

Algorithm 5 describes in detail the steps taken by REDEC when a packet is received. Lines 2-14 show what happens when a control packet is received. If it is the first time the control packet is received, a node calculates the amount of time γ it is going to wait before deciding if it is going to be a relay node. The node stores the received packet that may be forwarded further if it becomes a relay node. It switches to either scheduled or scheduled relay status depending on its state prior to receiving this control packet. At last, the node schedules to carry out its decision making in γ seconds⁴. In the case where the received control packet has been already received before, the node increments its duplicates count d and then discards the received packet. Lines 16-26 describes the behavior of the node when the received packet is not a control packet. It checks if it is the first time this packet is received. If it is, it forwards the packet to the upper layers in

⁴In this work, we show γ always in seconds but it could be in any scale of time.

Algorithm 5 Node receives packet p

```

1: if  $p$  is a REDEC control packet then
2:   if  $p$  has not been received before then
3:     calculate waiting time  $\gamma$  based on packet  $p$ 
4:     store  $p$  for potential later relay
5:     if this node is currently a relay node then
6:       set status as scheduled relay node
7:     else
8:       set status as scheduled node
9:     end if
10:    schedule to try to become a relay node in  $\gamma$  seconds
11:  else
12:    increment duplicates count  $d$ 
13:    discard  $p$ 
14:  end if
15: else
16:  if  $p$  has not been received before then
17:    if this node is interested in  $p$  then
18:      send packet to upper layer
19:    end if
20:    if this node is either a relay node or a scheduled relay node then
21:      broadcast packet  $p$ 
22:    end if
23:    discards  $p$ , if node is not interested and it has not broadcasted the packet
24:  else
25:    discards  $p$ 
26:  end if
27: end if

```

case the node is interested in its content and broadcasts the packet further if it is a relay or a scheduled relay node. When the received video packet has already been received before, it is discard.

The process followed for a node to decide to become or not a relay node is depicted in Algorithm 6. This process is invoked right after the waiting time γ has passed. The node then checks if the number d of received duplicates is not greater than the maximum

Algorithm 6 Node decision on becoming relay node

Require: γ seconds has elapsed

- 1: **if** number of duplicates $d \leq$ maximum number of duplicates δ **then**
 - 2: set status as *relay node*
 - 3: forward received packet p
 - 4: **else**
 - 5: set status as *non-relay node*
 - 6: drop packet p
 - 7: **end if**
 - 8: reset d
-

number of allowed duplicates δ . In the case where d is less or equal to δ , the node becomes a relay node and forwards the received and stored packet p (Algorithm 5, Line 4). If d is greater than δ , the node's status is updated to non-relay node and the stored packet p is dropped. Finally, either way, the value of d is reset for the next cycle.

The calculation of the waiting time depicted in Algorithm 5, Line 3 is paramount to the definition of a node's suitability as a relay node. In the following subsection, we describe in detail how REDEC calculates a node's waiting time.

4.2.2 Waiting Time

As mentioned before, the time γ a node waits to decide if it is going to forward received packets should reflect its suitability as a relay node. Lower values should be given to better suited candidates while less suitable nodes should be required to wait a longer time. By this method, the most suitable nodes have their timers expire first and they forward the packets preventing less suitable candidates to become relay nodes.

The waiting time γ , chosen by a node, is limited to a maximum value that in REDEC is named Γ . The maximum waiting time Γ impacts the distribution of the waiting time γ of the nodes. Larger values of Γ lead to greater differences of nearby nodes' γ s of nearby nodes but they also incur longer waiting times. The evaluation of the impact of Γ on REDEC's performance is discussed in Section 4.2.3.2.

REDEC adopts the perspective of a relay node to keep this status for a longer period of time than that of a single transmission. For this reason, it is important to consider stability as it is expected for a relay node to remain within reach for a period of time. The choice of the most distant node as a relay node is not recommended because such

nodes are usually shortly out of reach. The waiting time function has to balance between geographic advancement and high reachability and stability for longer periods of connection.

Based on these conclusions, we have defined a non-continuous function that compromises between geographic advancement and stability. Both of these aspects are calculated based on the distance v of the receiving node to the last hop node that transmitted the packet. It is assumed that each node knows its own location and when broadcasting a packet, the node inserts its current location in the header of the packet. For the purposes of video dissemination, the eventual movement of a vehicle during the time between transmission and reception of a packet is negligible.

In REDEC, the normalized waiting time is calculated with the following function $\hat{\gamma}(\hat{v})$, where \hat{v} is the norm of the distance between the node and the last hop (the normalization is based on radio range):

$$\hat{\gamma}(\hat{v}) = \begin{cases} 1 - (0.6\hat{v}) & \text{if } \hat{v} \leq 0.5 \\ 1 - (\hat{v} + 0.1) & \text{if } 0.5 < \hat{v} \leq 0.9 \\ \hat{v} - 0.4 & \text{if } \hat{v} > 0.9 \end{cases} \quad (4.5)$$

the used waiting time is then $\gamma(\hat{v}) = \hat{\gamma}(\hat{v}) * \Gamma$.

Figure 4.8(a) shows the function $\hat{\gamma}(\hat{v})$ plotted. Besides the different behavior in each interval, it can also be observed that there are unused steps of 0.1 length when the waiting time calculation moves from one interval to the other. The idea is to prevent that γ values from different nodes being placed in different intervals are too close to each other. Nodes with very close γ values could make their decision to become a relay node without observing the transmission of the other. Figure 4.8(b) illustrates the distribution of the values of γ for when a node located in the center of the figure broadcasts a control packet. Darker regions reflect smaller values of γ . It shows the boundary values of each interval for the case when $\Gamma = 100m.s$.

The constants in Equation 4.5 are chosen to reflect the aforementioned principles and follow the behavior shown in Figure 4.8.

4.2.3 Preliminary Evaluation

In this preliminary evaluation, the goal is to analyze the impact of REDEC's parameters on its behavior. This evaluation is fundamental to the corroboration of the values chosen for these parameters. Furthermore, it also provides information regarding some aspects

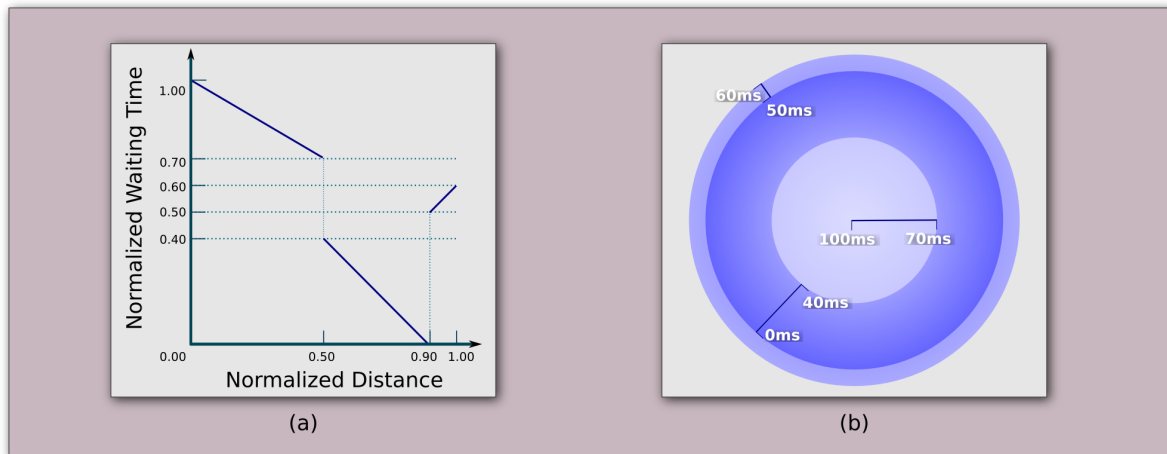


Figure 4.8: REDEC - Waiting Time based on distance to last hop

of the issues of video dissemination over VANETs.

REDEC's behavior is influenced mainly by three parameters: maximum waiting time Γ , periodicity at which control messages are disseminated α and maximum number of allowed duplicates δ . The maximum waiting time Γ has to balance the goal of short end-to-end delays while increasing the difference between the waiting time of different nodes. The periodicity of dissemination of control messages α deals with the trade-off updates to topology changes against overhead and collisions. The maximum number of allowed duplicates δ manages the amount of redundancy permitted in the network; higher values could lead to higher reachability but also to a higher number of overall transmissions.

In the following, the simulation environment and the results of the experiments are presented.

4.2.3.1 Simulation Environment

The computational environment used for the simulations in this work is composed of two clusters. One is a Dell cluster of 24 nodes, each with a Quad-core 2.40 GHz Intel(R) Xeon(R) CPU and 8 GB of RAM. The second is an IBM cluster of 32 nodes, each with a Core 2 Duo 3.4 GHz Inter(R) Xeon(R) CPU and 2 GB of RAM. With this infrastructure, we were able to conduct thorough simulations with a large number of nodes. This is crucial to support the conclusions obtained in this work.

The network simulator NS2 was used again with the same communication setup as the one described in Section 4.1.1. The same Mobility Model was also used (i.e. UMM)

Parameter	Value
Dimensions	2,000m x 2,000m
Number of Vehicles	500 (125/km ²)
Video Source Location	1,000 x 1,000m

Table 4.4: Scenarios Topology

and we have used a scenario of 2,000m x 2,000m, each block 100m wide, streets are used in both directions and there are 500 vehicles (a density of 125 vehicles per square kilometer). Vehicles' speed ranges initially from 5m/s to 30m/s but vehicles are subjected to road traffic. The node disseminating the video content is placed in the middle of the network. Table 4.4 lists the details of the scenario topology. EvalVid was used for the purpose of measuring video transmission on NS2, the same video configuration as the one in Section 4.1.2 was used.

Another measure towards an unbiased simulation is that vehicles initially move for 10 minutes in order to conduct packet exchanges when the mobility model has already reached a steady state [133]. After that, the source node starts sending REDEC's control messages one second before it starts the dissemination of video content. The simulation is ended 100 seconds after the beginning of the video dissemination which is more than sufficient for the transmission and reception of the whole content.

Every result plotted in this section is an average ranging between 20 to 24 runs each using a unique instance of the mobility model described and an unique seed for random number generator. We have also plotted the confidence intervals calculated using Student-t distribution at a confidence level of 95%. The calculation of average, confidence intervals and plotting figures was done using the Statistical Tool R [94].

In regards to the video content disseminated, REDEC's behavior was evaluated according to three metrics: Delivery Ratio, Delay and Number of Transmissions. Delivery Ratio here is given as 100% minus the percentage of video frames lost (calculated through EvalVid). The delay is also calculated from the video perspective and it is the average of the time elapsed between the reception of the necessary information for the assemblage of a video frame and the time that the first packet, containing information of the same frame, was transmitted by the source node. REDEC's cost was measured as the total number of transmissions in the network of packets containing video information. Video quality metrics such as PSNR, SSIM or (Mean Opinion Score) MOS was not used at this point due to the amount of videos that are considered for the many combinations of

parameters evaluated. The evaluation of Delivery Ratio is sufficient to promote a deep understanding of the impact of REDEC's parameters on its behavior.

The quality of streamed videos strongly influences the necessary rate by which the video content has to be transmitted through the network. Video with higher quality requires higher data rates from the network. Therefore, in this work, REDEC's behavior and performance is evaluated with increasing rates of data exchange in the network. By this method, it is possible to investigate the limits on REDEC's ability to support video streaming. The data rate R shown considers solely video content; therefore, the period ρ between consecutively transmitted video packets is given by: $\rho = (1,000\text{bytes} * 8\text{bits}/\text{byte})/R$.

In the next subsection, the obtained results are shown and discussed.

4.2.3.2 Results

In each figure, the plotted curves vary in terms of the maximum waiting time Γ , from 50ms to 1,000ms (1s); and, columns vary according to the periodicity of dissemination of control packets α from 0.5 seconds to 2 seconds, while rows vary in terms of the maximum number of allowed duplicates δ . The x-axis shows increases in the underlying network data rate while the y-axis follows one of the previously mentioned metrics.

Figure 4.9 shows the impact of REDEC's parameters on the delivery ratios it could reach. The first clear observation is that lower delivery ratios are reached when the video is transmitted at higher network data rates. This reflects the effect of collisions caused due to the fast transmission of consecutive packets. We can see that rates close to 100% were achieved for data rates up to 750 kbps. It is interesting to observe that in extreme cases of $(\alpha = 0.5s, \delta = 4)$ and $(\alpha = 2s, \delta = 0)$, the impact of the maximum waiting time Γ is reversed. This happens because when a small Γ is used, there could have been potentially more relay nodes per region than the amount expected regarding the number of allowed duplicates since their timer expires before the transmission of another node could be observed. In a scenario where the choice of relay nodes is frequently updated and many duplicates are allowed $(\alpha = 0.5s, \delta = 4)$, an even higher number of relay nodes, due to a small Γ , increases the number of collisions and decreases the delivery ratio. However, in a scenario where the update is less frequent and no duplicates are allowed, the relay nodes with similar waiting times, due to a small Γ , favor REDEC's reachability.

In Figure 4.10, the end-to-end delay is calculated as the average time between transmitting the first packet, with information of a video frame, and the time when this frame

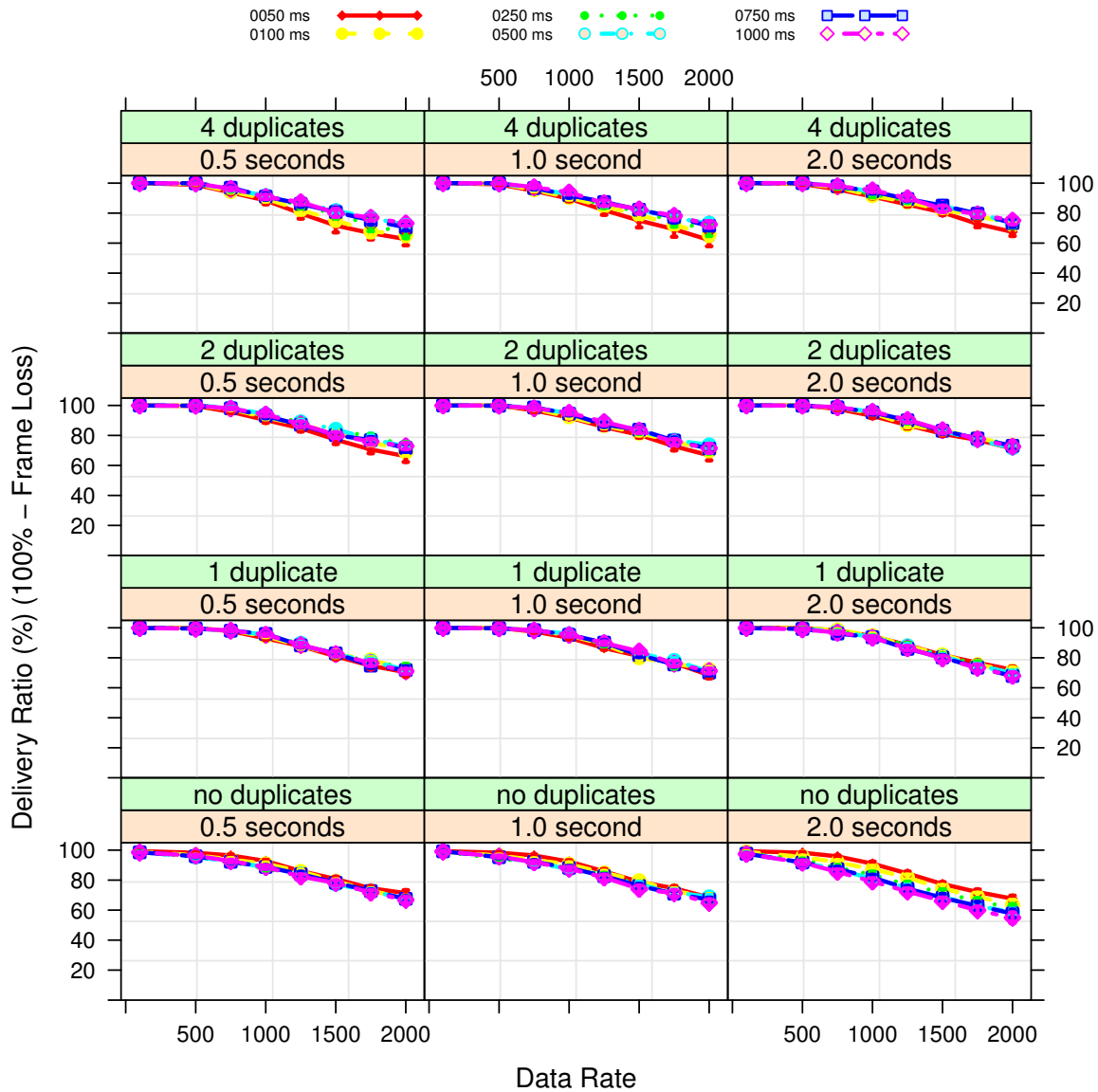


Figure 4.9: REDEC - Delivery Ratio depending on (Γ, α, δ)

is assembled at the receivers. When a node using REDEC receives a packet containing video data, its decision to forward or not is immediately determined depending only on which state the node is (see Figure 4.7). Because of this, REDEC’s end-to-end delay is very low and it is only influenced by the increases of collision. Increases on the number of allowed duplicates and on the smaller values of maximum waiting time lead to a larger number of relay nodes. This fact combined with increases on network data rates lead to

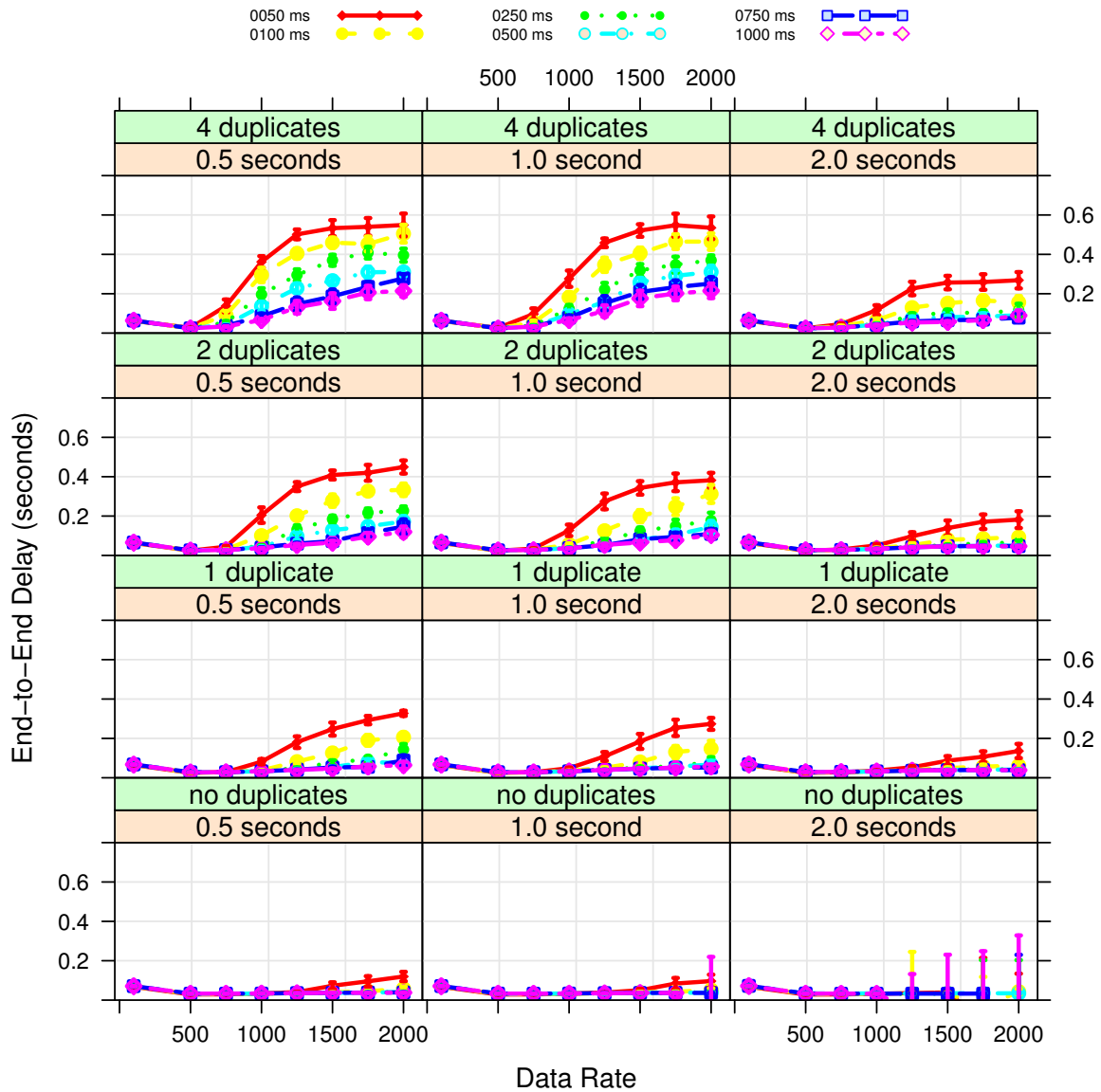


Figure 4.10: REDEC - End-to-end Delay depending on (Γ, α, δ)

more frequent collisions. When collisions are happening, the nodes that had smaller values of γ and which became relay nodes are probably less connected with other nodes; it is for this reason that they have not received the maximum number of allowed duplicates until this certain point and that they have lower rates of collision. These lower values of γ are usually associated with short geographic advancements which increase the number of hops and ultimately the end-to-end delay.

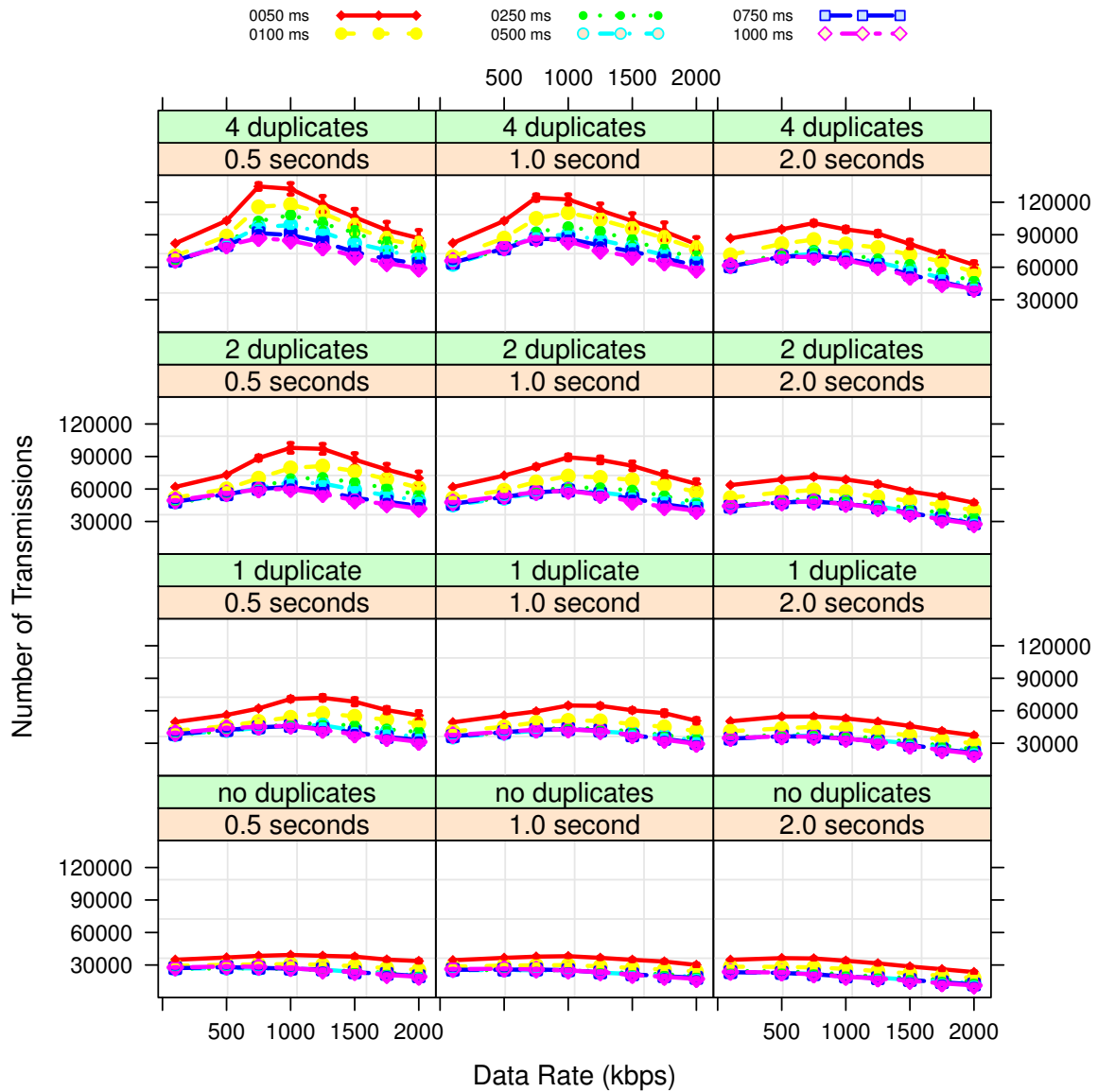


Figure 4.11: REDEC - Number of Transmissions of video packets depending on (Γ, α, δ)

The evaluation of the total number of transmissions of packets containing video content throughout the dissemination of the video is shown in Figure 4.11. For the sake of clarity, it is useful to know that 30,000 transmissions correspond to an average of 17% of nodes participating in the dissemination (30,000 transmissions / 353 packets / 500 nodes). The number of transmissions is directly related to the number of selected relay nodes. Therefore, increases in the number of the maximum allowed duplicates and

smaller values of Γ , which lead to a higher number of relay nodes, also incur higher overhead. There are more transmissions with initial increases on network data rates because although relay node selection is decoupled from video transmission, both compete for available bandwidth. At higher network data rates, the competition for the channel is intensified and the resulting collisions prevent some nodes from observing other relay nodes. In this case, a smaller number of duplicates are observed and a larger number of relay nodes are selected; thus, an overall higher number of transmissions is observed. Smaller values of Γ also lead to a higher number of relay nodes which is reflected by increases in the number of transmissions. The reduction in the number of transmissions with further increases on the network data rate is due to early interruption of packets dissemination; the achievement of a lower delivery ratio (as seen in Figure 4.9) leads to the performance of less transmissions.

Besides packets carrying video content, REDEC also exchanges control packets for the selection of relay nodes. However, the cost due to these transmissions is insignificant when compared to the one associated with the transmission of video content. Control packets do not carry 1,000 bytes of video data and they are sent at a much lower frequency (maximum 2 per second). The percentage of nodes participating in the dissemination of control packets is always inferior to 20% and their transmission is interrupted after the transmission of all video content. Therefore, in the worst case 6,000 control packets are transmitted which corresponds to the transmission of less than 1,000 video packets.

4.3 Performance Evaluation

In this section, REDEC and REACT-DIS performance is evaluated and compared to other state of the art solutions. The behavior of these solutions in different scenarios and the results and conclusions in this section provide a deep insight into the issue of video dissemination over VANETs.

REDEC and REACT-DIS performances are compared to two other existing works. These two solutions are AID [11] and NCDD [90].

The Adaptive approach for Information Dissemination (AID) [11] is another receiver-based solution that conducts relay node selection during the transmission of the disseminated content itself. AID does not consider the availability of location information and nodes' waiting time is uniformly randomly chosen. When this time expires, the decision of a node to become a relay node depends on an comparison between the average rate of reception of duplicates and the actual time intervals between these receptions.

The Network Coding based Data Dissemination (NCDD) [90, 91] suggests the use of Network Coding for an efficient use of the inherent redundancy in dissemination over VANETs. The video content transmitted is encoded into blocks following a random linear coding approach and intermediary nodes wait the reception of a whole block for later forwarding newly encoded packets. By this manner, the reception of content from different intermediary nodes is frequently useful towards the decoding and reception of video content. Besides that, if intermediary nodes perceive the reception of only part of a block, they broadcast a request to their neighbors for the content necessary for decoding such block. By this manner, if a node that has received and decoded a block, moves to a new location and observe these requests, it can carry the information priorly received to this new region.

In the next subsection, the impact of REACT-DIS and REDEC parameters is explained as well as the selected values. The specific details in the simulation environment for performance evaluation are explained in Section 4.3.2. In Section 4.3.3, the comparison between REDEC, REACT-DIS, AID and NCDD is shown and explained. Section 4.3.4 contains a detailed analysis of the results observed.

4.3.1 The impact of parameters

The choice of the parameters used for REACT-DIS and REDEC is based on the trade-off between cost and benefit. Cost is given as the overhead in terms of number of transmissions while the benefit is the achieved delivery ratio that is expected to directly impact video quality. The experiments shown in this chapter in regards to the evaluation of the impact of parameters are conducted in more simplistic scenarios so we avoid selecting the local optimum for performance comparison.

REACT-DIS performance is greatly influenced by the configuration of its main four parameters. These parameters are the maximum waiting time Γ , the forwarding probability reducing factor Υ , the time a node remains as a relay node Φ and the relay node forwarding probability reducing factor Λ . These four parameters determine REACT-DIS's configuration quadruple $(\Gamma, \Upsilon, \Phi, \Lambda)$. REACT-DIS has shown four configurations that better fulfill video-streaming requirements and better exploit the benefit and cost trade-off. These combinations and their results (as seen in Section 4.1.2) are listed in Table 4.5, the delay is omitted as it has shown to be for all the configurations significantly lower than video-streaming requirements (see Figure 4.2). The selected quadruple for the experiments in this section is $(250ms, 5.0, 5s, 10\%)$ aiming at achieving very high

Υ	Φ	Delivery Ratio					Packets Sent				
Data Rate		0.1	0.5	1.0	1.5	2.0	0.1	0.5	1.0	1.5	2.0
5.0	3s	95%	88%	78%	70%	59%	76K	74K	69K	68K	57K
5.0	5s	97%	91%	82%	70%	59%	82K	81K	76K	68K	57K
10.0	3s	92%	82%	72%	68%	56%	68K	63K	56K	55K	45K
10.0	5s	96%	86%	77%	68%	56%	74K	68K	62K	55K	46K

Table 4.5: REACT-DIS Configurations ($\Gamma = 250ms$ and $\Lambda = 10\%$) - Data Rate in mbps

delivery ratios. If a scenario where bandwidth consumption is more critical, the approach with $(250ms, 10.0, 3s, 10\%)$ could be preferred.

In the case of REDEC, the parameters are Maximum Waiting Time, Time Between Control Packets and Maximum Number of Allowed Duplicates (Γ, α, δ). The maximum number of duplicates δ is the most influential parameter in the trade-off between cost and benefit. A larger value of δ leads to slightly higher delivery ratios (as seen in Figure 4.9) but in a substantial increase in number of transmissions (see Figure 4.11). The combination $(500ms, 1s, 1)$ was shown to exploit the best trade-off of reachability and cost. A higher δ could be used to force higher delivery ratios but it would certainly lead to the overall reception of many duplicates.

4.3.2 Simulation Environment

The same computational resources as described in Section 4.2.3.1 was used. The main changes in the simulation environment are the use of a more realistic propagation model and a larger simulated area with different node densities. In this manner, a fair performance comparison is conducted and the behaviour of the solutions is evaluated in different scenarios. Furthermore, the number of instances for each plotted result was increased ranging from 32 to 48; thus, confidence intervals could be calculated using the normal distribution.

The Nakagami propagation model [81] was used because it is accepted as the most realistic propagation model for wireless communication in VANETs [120]. The parameters used for configuring the wireless medium and the propagation model (including the fading model) were based on the analysis in [120, 28], and the scenario of communication based on a 300 meter range. Table 4.6 lists all the parameters that determine the communication model on the simulation, the variables ending with $_n$ are related to the Nakagami distribution.

Parameter	Value	Parameter	Value
Radio Propagation Model	Nakagami	Mac Layer	IEEE 802.11b
Transmission Power	0.1	RXThresh_	3.95e-12
gamma0_	1.9	gamma1_ and gamma2_	3.8
d0_gamma_ and d0_m_	100	d1_gamma_ and d1_m_	200
m0_	3.0	m1_	1.5
m2_	1.0		

Table 4.6: NS2 Parameters for Performance Evaluation

Parameter	Value
Dimensions	3,000m x 3,000m
Number of Vehicles	500 (56/km ²) - 1,000 (111/km ²) 1,500 (167/km ²) - 2,000 (222/km ²)
Video Source Location	1,500m x 1,500m

Table 4.7: Scenarios Topology

The same mobility model as described in Section 4.2.3.1 was used; however, it is based on a larger area and the number of nodes used varied from 500 to 2,000. The goal is to evaluate the performance of the solutions in scenarios with different density. The details of the topologies used are listed in Table 4.7.

Besides the aforementioned metrics of delivery ratio, end-to-end delay and the number of transmissions, in this performance evaluation PSNR and the rate by which video content is received were also measured. Peak Signal-to-Noise Ratio (PSNR) relates to the quality of the video received when compared to the originally transmitted content. PSNR is calculated based on differences between corresponding individual pixels from frames of both the received and original videos. It is calculated with the following formula:

$$PSNR = 10 \log_{10} \left(\frac{\Xi^2}{MSE} \right) \quad (4.6)$$

where, Ξ equals to the maximum possible value of a pixel in the image and the Mean Square Error (MSE) is defined as:

$$MSE = \frac{1}{mn} \sum_{i=1}^m \sum_{j=1}^n [R(i, j) - O(i, j)]^2 \quad (4.7)$$

with R and O as the pixel matrices of the received and original frames, respectively. PSNRs above 37 indicate high quality video (almost perfect), 31-37 values refer to good quality videos, 25-31 fair quality, 20-25 poor quality and <20 bad quality videos [49].

Another aspect of video quality is in regards to the receiving rate of video content. All solutions were evaluated through different rates by which video content is transmitted. However, the impact on video quality is defined by the rate by which video content is received rather than transmitted. Therefore, the average reception rate of video content was measured and compared to the behavior of all solutions.

4.3.3 Results

All the figures in this section display curves that represent each of the four solutions evaluated with the x axis illustrating varying increases in data rates through which the video content was transmitted. Each figure is divided into four figures, one for each of the used number of nodes in the network. As in the previous results, confidence intervals were calculated with a confidence level of 95%.

Figure 4.12 depicts the observed delivery ratio in terms of the percentage of received frames. The initial observation is that all solutions reach lower delivery ratios with increasing data transmission rates. High data rates lead to a higher number of collisions which degrades the ability of nodes to receive and forward data. The variation of density caused a strong degradation on AID's ability to reach vehicles in the network; and, it is explained by the fact that the determining of a node's suitability as a relay node is based on the inter-arrival time of duplicates rather than some indication of density. REDEC and REACT-DIS are the solutions least prone to variations in performance due to different densities because both solutions make use of density-aware mechanisms, though they use different strategies. REDEC and AID have achieved the highest delivery ratios when data is transmitted in up to 500 kbps. With further increases in data rate, REDEC offers the highest delivery ratios for three out of four scenarios while AID matches its performance at the lowest density scenario.

All solutions have achieved very high delivery ratios when video is transmitted at 100 kbps. However, their behavior varies significantly when higher data rates are used. This is a strong indication that solutions for video streaming have to be evaluated under increasing data rates. The performance of these solutions depends on their ability to handle congested scenarios both in terms of vehicles' density and wireless channel occupancy. The higher delivery ratios achieved by REDEC corroborate the advantages

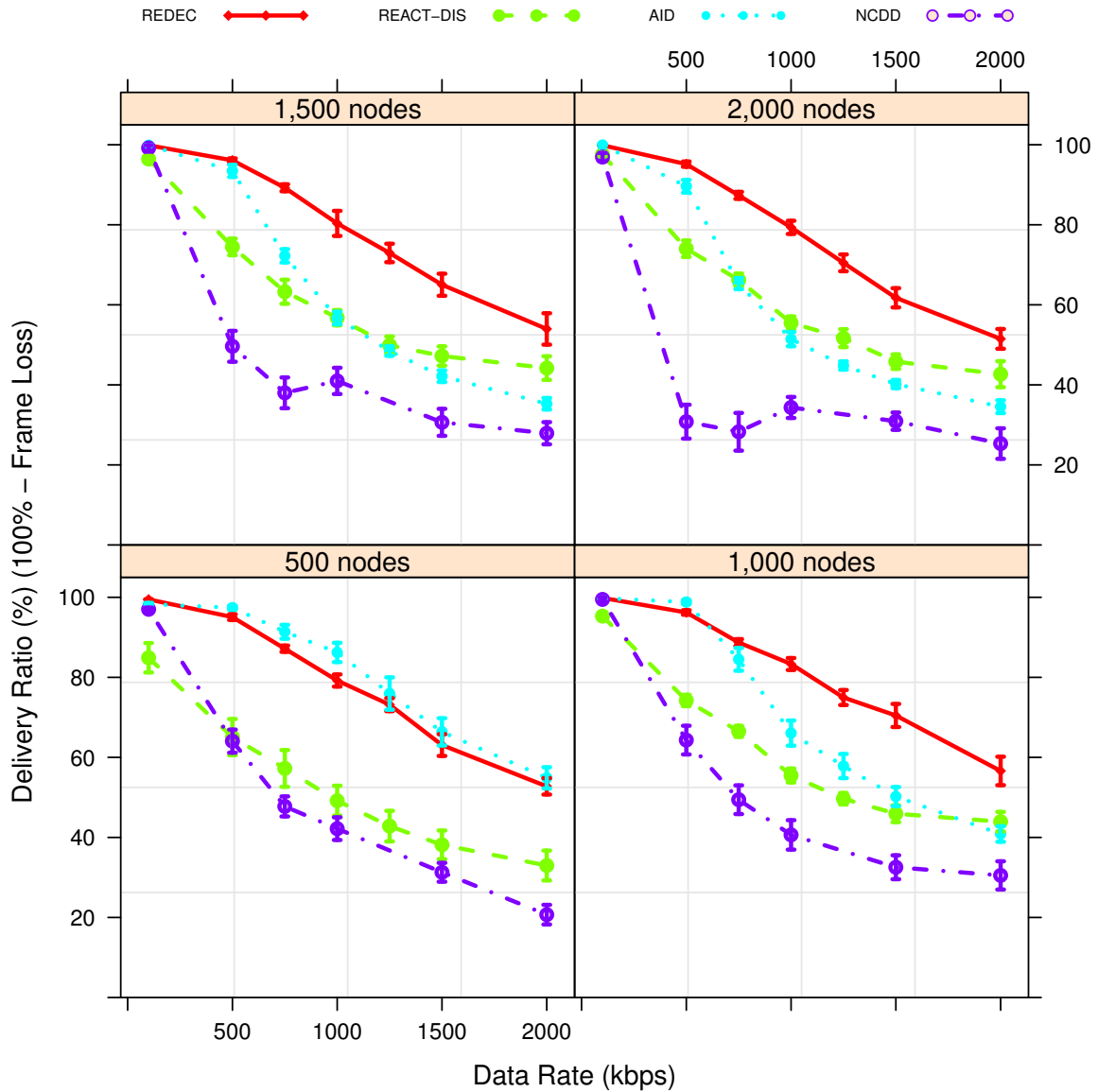


Figure 4.12: Video Dissemination - Delivery Ratio for different densities

of using its mechanism to choose the waiting time of nodes, its simplistic method of deciding if nodes should become relay nodes and its method of decoupling relay node selection from video transmission.

In Figure 4.13, the evaluation of quality of video received in terms of PSNR is depicted. The results shown reflect the results observed in terms of delivery ratio but are aggravated by the impact of frame loss in the overall video quality. Another important

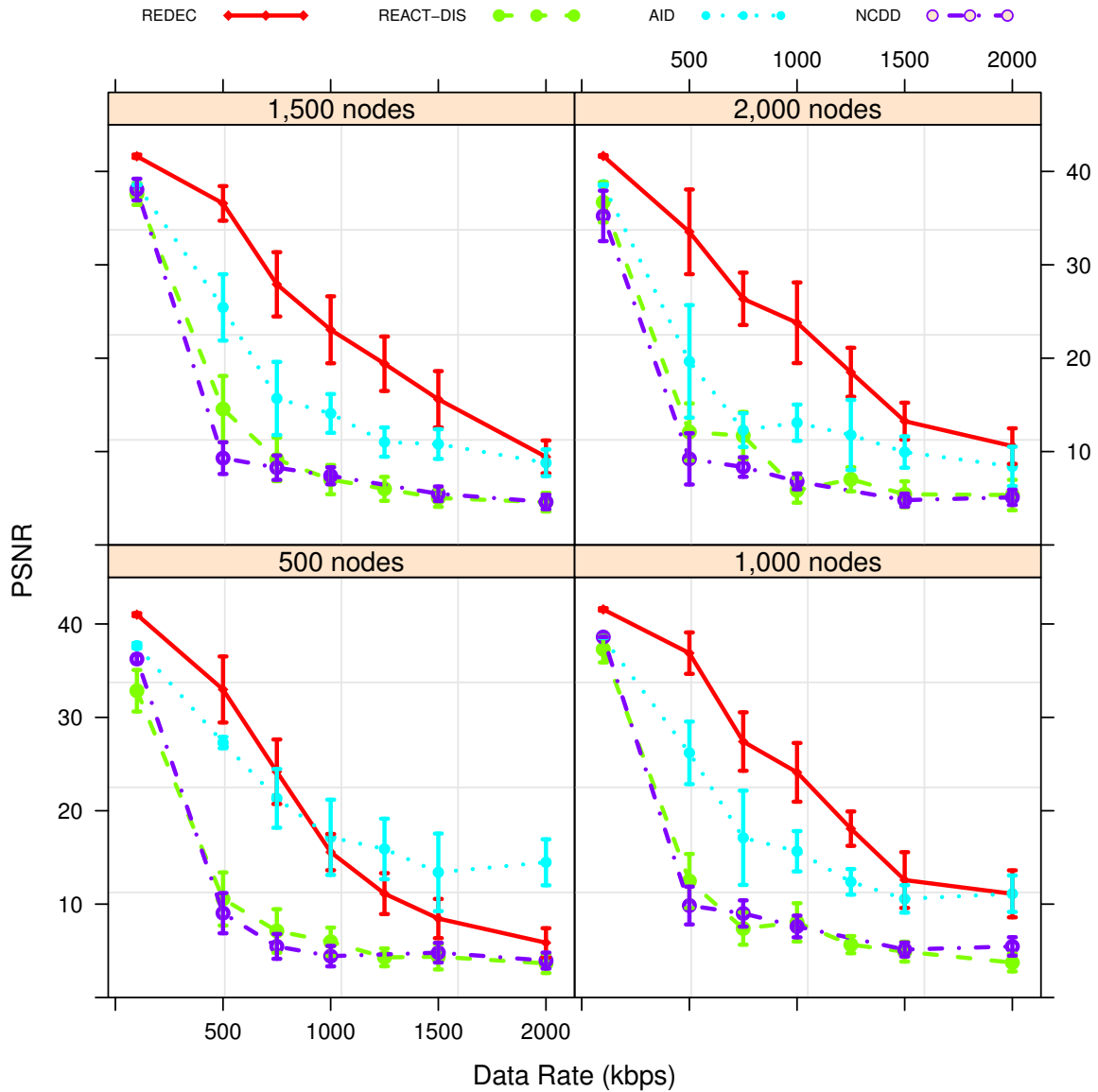


Figure 4.13: Video Dissemination - PSNR for different densities

observation is that the calculated confidence intervals are larger which indicates that results vary significantly. The reason is that although all packets are treated in the same way, they contain information of different frames that have different impacts on the overall video quality. For example, the loss of packets carrying information regarding I-frames deteriorates the quality of all frames within the same Group of Pictures (GOP)⁵

⁵In this work, the GOP is composed of 30 frames

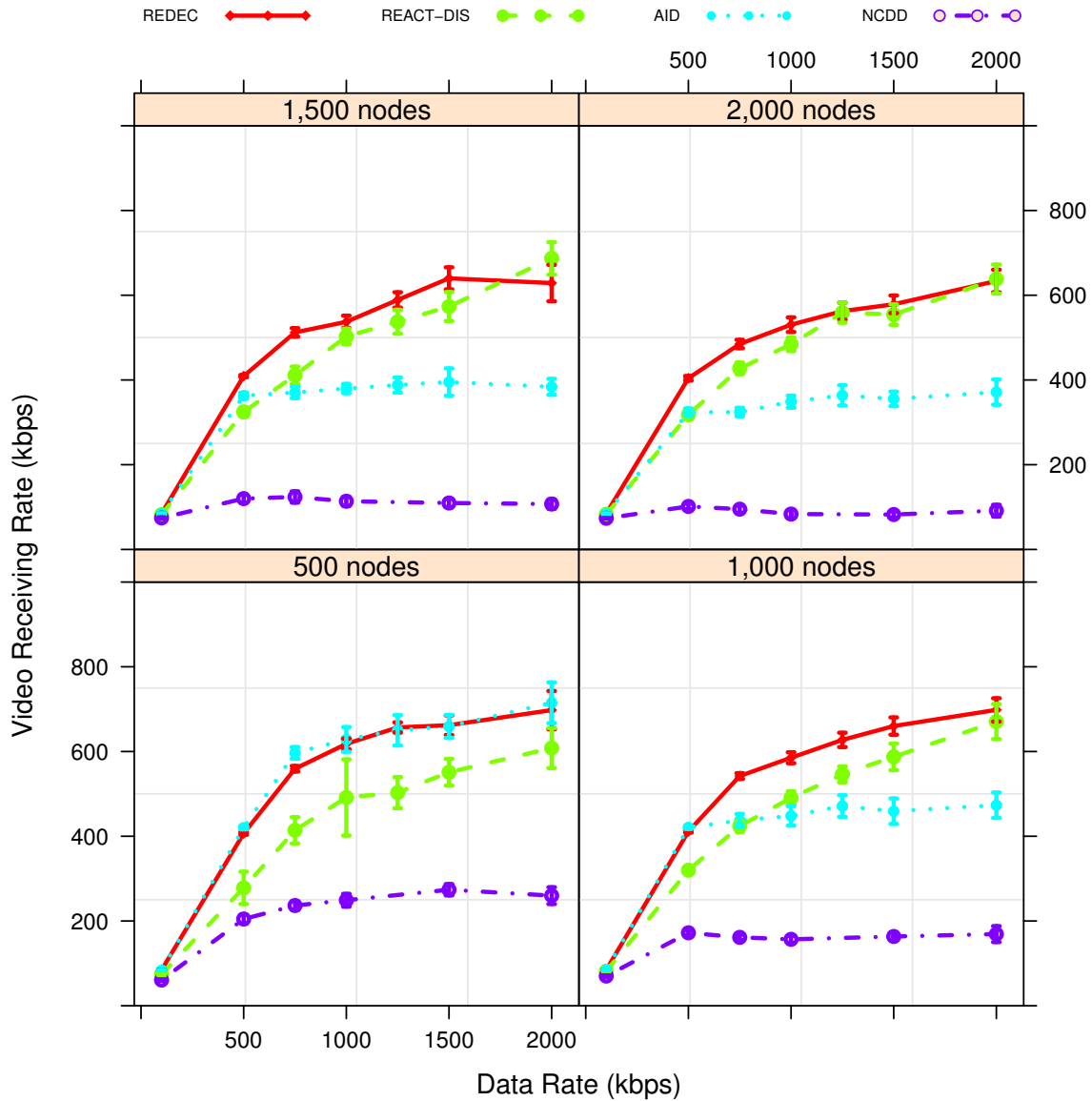


Figure 4.14: Video Dissemination - Video Receiving Rate for different densities

much more intensely than the loss of packets carrying P or B frames.

The evaluation of the performance of these solutions through different data rates for transmission of video content is due to the goal to understand the ability of each solution to handle the transmission of videos of higher quality. Therefore, it is also important to measure the rate by which video content is received as this determines the quality of video that can be displayed to end users.

Figure 4.14 shows the video reception rate of all solutions for each scenario. It can be observed that increases in the data rate by which video is transmitted does not reflect on a proportional increases on the rate by which video content is received. The low rates observed when NCDD is used are because the use of Network Coding requires intermediary nodes to wait for the reception of a whole block before forwarding their newly encoded packets. Besides that, the use of help messages and carry-and-forward strategies limits the rate by which video content is received. The rates by which video content is received by nodes using AID is also restricted in scenarios with higher density. This happens due to the way a node decides to become a relay node which is based on the variance of packets' arrival time. This promotes a reduction in the overall transmitting rate when congestion (in terms of packets transmission) happens.

REDEC and REACT-DIS were the solutions that obtained the best video reception rates. However, increases in the transmission data rates higher than 1,000 kbps resulted in slightly higher video reception rates. With further increases, packet loss increases significantly which restricts the achievement of higher video reception rates.

The results regarding end-to-end delay are shown in Figure 4.15 where the y axis is in log scale due to the excessively large values observed when NCDD is used. NCDD's high delay is caused by the need of intermediary nodes to wait for the decoding of a whole block before further propagation of video content. The use of carry-and-forward with assist of help messages also increases the overall end-to-end delay.

The comparison of other solutions depends on the data transmission rate. When it is of 100 kbps and all solutions perform at their best, REDEC has the lowest end-to-end delay since the transmission of video content by intermediary nodes is always immediate as relay node selection is performed separately. Although REACT-DIS uses the perspective of relay node selection for a time window rather than for every single transmission, at 100 kbps the transmission of video lasts longer and the topology changes more; this requires that a greater amount of transmissions of video content triggers the selection of relay nodes. At higher data rates, all three receiver-based solutions suffer from collisions at nodes with small waiting times which leads to higher successful transmission rates at nodes that wait a little longer. In REDEC, due to its waiting time function (see Section 4.2.2), this leads to larger end-to-end paths composed of more hops. At higher data rates, the time of transmission of video is reduced and REACT-DIS transmission of video content requires fewer updates on relay node selection. AID's end-to-end delay is always slightly higher than the one observed by REDEC.

Figure 4.16 shows the number of transmissions of packets carrying video content and

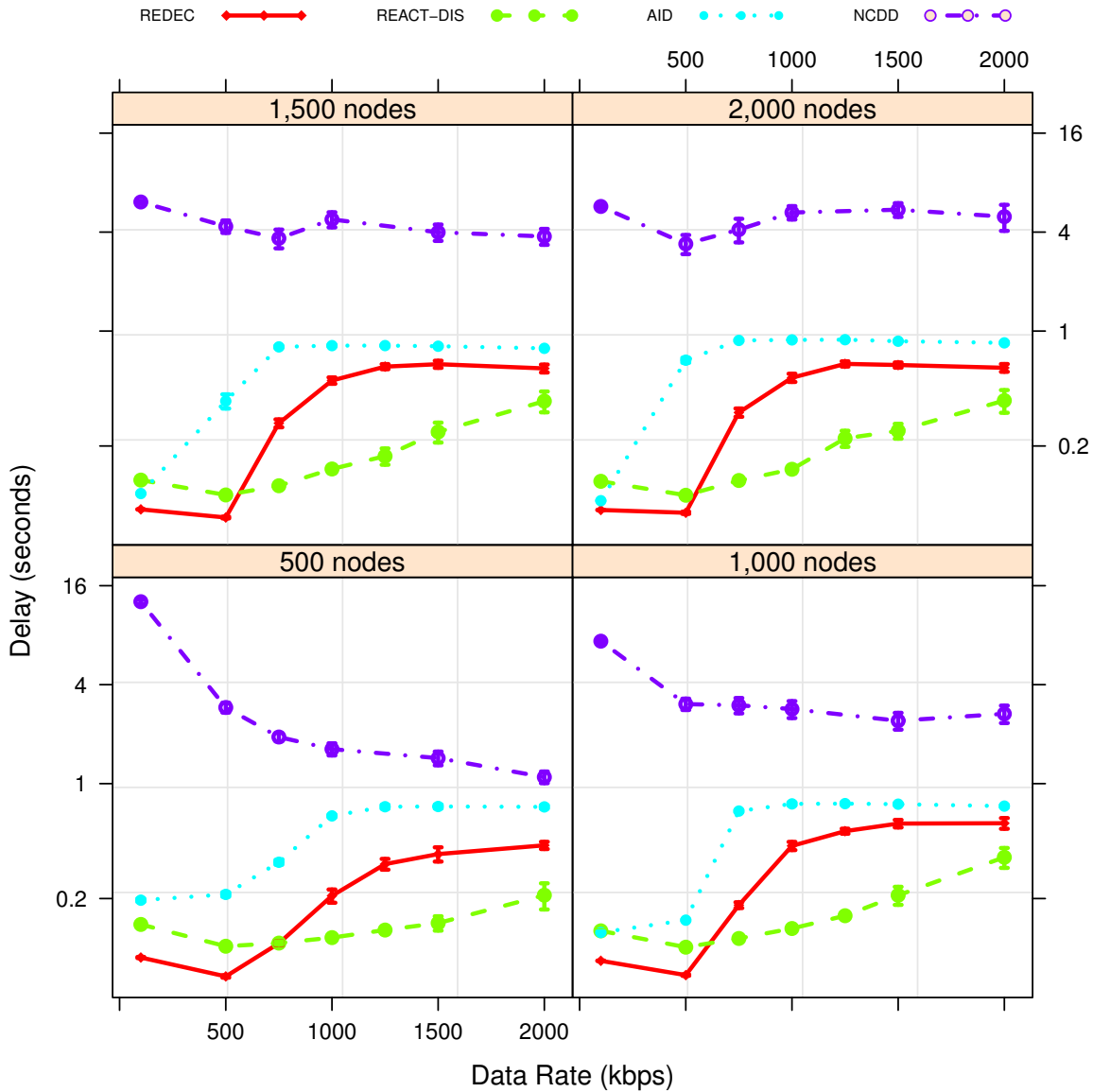


Figure 4.15: Video Dissemination - End-to-end Delay for different densities - in logarithmic scale

it is also in log scale due to NCDD’s excessive number of transmissions. NCDD does not perform any sort of relay node selection and every node in the network participates in the dissemination process. This is the cause of the extremely large number of transmissions when density increases. REDEC and AID have similar performance in terms of the number of transmissions. REACT-DIS exhibits the lowest number of transmissions,

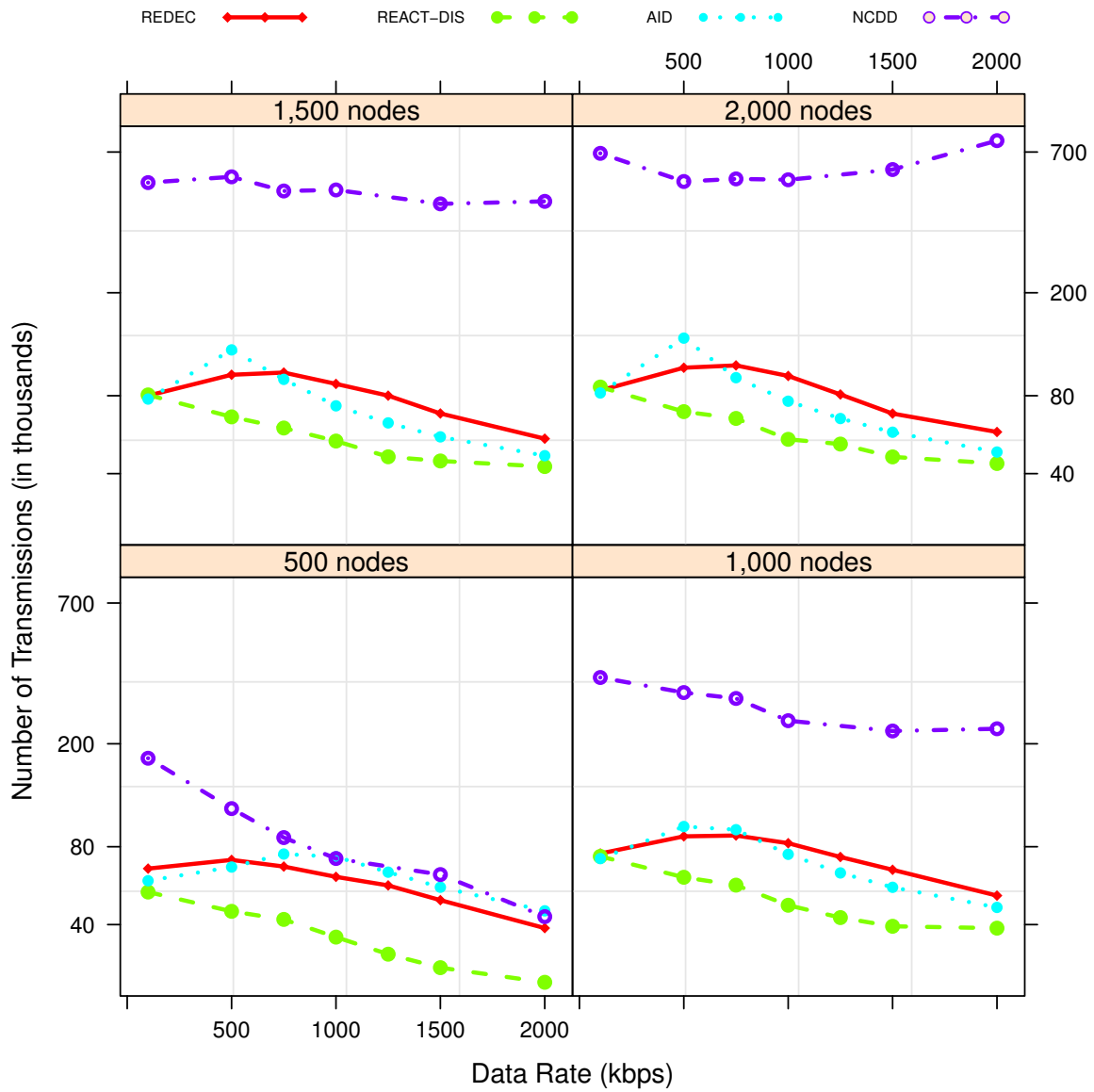


Figure 4.16: Video Dissemination - Number of Transmissions (in thousands) for different densities - in logarithmic scale

however, this is caused by a large number of packets' loss that does not trigger the transmission of packets at nodes farther away from the source.

4.3.3.1 Real city Topology

The main changes in the simulation environment in this part is the use a topology based on the real distribution of streets, avenues and highway of a city. We used SUMO [12] as a mobility model for vehicle movement in a urban scenario. We have used a topology based on the downtown region of Ottawa (Ontario), in Canada. The scenario includes traffic lights, a portion of a highway, street capacity and speed limits. It reflects, with a high fidelity, the distribution and movement of vehicles in a real city. The dimensions of that area are $2,556 \text{ m} \times 3,004 \text{ m}$. The video source location is a static node located in a popular intersection (it could be illustrated as a camera in a traffic light) at the location (1578 m,1844 m); this is slightly northeast of the center. For the sake of analysis on the impact of vehicles density, we used that topology with two different densities: 400 and 600 vehicles in the whole network.

We consider dissemination as the task of delivering the content (in our work, a video) to all nodes within a certain distance to the source node. In our simulations, we have considered a range that includes all nodes in the network. This allows us to evaluate the performance of solutions in a larger scale, including the use of paths with a larger number of hops. Therefore, once again, the results are based on an average of all vehicles in the network.

All the figures in this section (Figures 4.17 to 4.22) display curves that represent each of the four solutions evaluated (including REDEC) with the x axis illustrating varying increases in data rates through which the video content was transmitted. Each figure is divided into two figures, one for each of the used number of nodes in the network. As in the previous results, confidence intervals were calculated with a confidence level of 95%.

Figure 4.17 depicts the observed delivery ratio in terms of the percentage of received frames. The initial observation is that REDEC, REACT-DIS and NCDD reach lower delivery ratios with increasing data transmission rates. High data rates lead to a higher number of collisions which degrades the ability of nodes to receive and forward data. AID was able to maintain close to the same level of delivery ratios for most increases on transmission rates but a decline on these ratios are observed at the highest transmission rates. AID relay node selection mechanism tries takes into consideration into arrival time of packets, so, at higher transmission rates, it distributes the transmission of packets through nodes waiting time. However, this incurs lower receiving rates as explained later in this work (see Figure 4.21).

The variation in density has shown that all solutions perform better at higher densi-

ties. This is due to the better connected topologies in denser scenarios. Lack of connectivity is an important issue for the provision of real-time video streaming over VANETs. Although some proposals [61, 74] suggest the use of store-carry-and-forward approaches for handling periods without connectivity, its use for video streaming is questionable as it incurs substantial increases on delay.

All solutions have achieved very high delivery ratios when video is transmitted at 100 kbps. However, their behavior varies significantly when higher data rates are used. This is a strong indication that solutions for video streaming have to be evaluated under increasing data rates. The performance of these solutions depends on their ability to handle congested scenarios both in terms of vehicles' density and wireless channel occupancy.

REDEC has shown overall higher delivery ratios and improvements of up to 8 percentage points from REACT-DIS and 16 percentage points from AID. NCDD has achieved the lowest delivery ratios (specially at higher transmission rates) mainly due to the issue of not providing partial recovery of the contents of a block when Network Coding is used. When not enough packets are received for decoding a whole block, all the received packets are useless towards the reception of video content. The significantly higher delivery ratios achieved by REDEC corroborate the advantages of using its mechanism to choose the waiting time of nodes, its simplistic method of deciding if nodes should become relay nodes and its method of decoupling relay node selection from video transmission.

In Figure 4.18, we evaluate the quality of video received in terms of PSNR. The results shown reflect the results observed in terms of delivery ratio but are aggravated by the impact of frame loss in the overall video quality. Another important observation is that the calculated confidence intervals are large which indicates that results vary significantly. The reason is that although all packets are treated in the same way, they contain information of different frames that have different impacts on the overall video quality. For example, the loss of packets carrying information regarding I-frames deteriorates the quality of all frames within the same Group of Pictures (GOP)⁶ much more intensely than the loss of packets carrying P or B frames. Another interesting observation is that although NCDD achieved significant lower delivery ratios, it has by comparison achieved better results in terms of PSNR. This happens because the use of Network Coding in NCDD leads to the reception of packets in blocks. The successful reception of larger number of consecutive packets leads to higher quality GOPs. Therefore, the pattern of packet loss has an impact on the quality of received videos.

⁶In this work, the GOP is composed of 30 frames

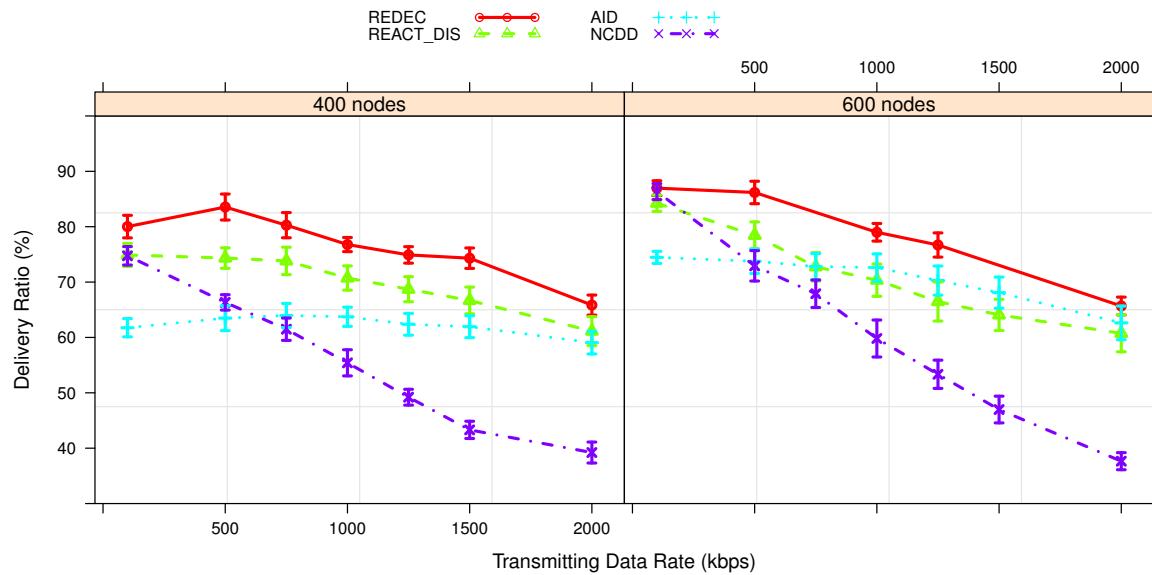


Figure 4.17: Real City Topology - Delivery Ratio

Another metric regarding video quality is Structure Similarity (SSIM) [126]. SSIM differs from PSNR as it estimates structural distortion rather than pixel-by-pixel errors. The concept of structural information is that pixels have strong spacial locality since they are inter-dependent to provide useful information to human eyes. SSIM is calculated through several $N \times N$ windows of an image. The measure between windows images x and y of different images (i.e. original and received) is given by:

$$SSIM(x, y) = \frac{(2\mu_x\mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + C_1)(\sigma_x^2 + \sigma_y^2 + C_2)} \quad (4.8)$$

where, μ_x is the average of x ; μ_y is the average of y ; σ_x^2 is the variance of x ; σ_y^2 is the variance of y ; σ_{xy} is the covariance of x and y ; $C_1 = (k_1L)^2$ and $C_2 = (k_2L)^2$ are two variables to stabilize the division with weak denominator; L is the dynamic range of the pixel-values⁷; and, $k_1 = 0.01$ and $k_2 = 0.03$ by default. A SSIM of 1.0 would only be achieved if the received video is exactly the same as the transmitted one. Therefore, the better the quality, the closest it is to 1.0.

The results considering SSIM are shown in Figure 4.19. They follow the same tendency observed in terms of delivery ratio (Figure 4.17) and PNSR (Figure 4.18). Similarly to PSNR, it is shown that video quality is significantly affected by data loss. We can see

⁷It is usually 2^k with k equals to the number of bits per pixel.

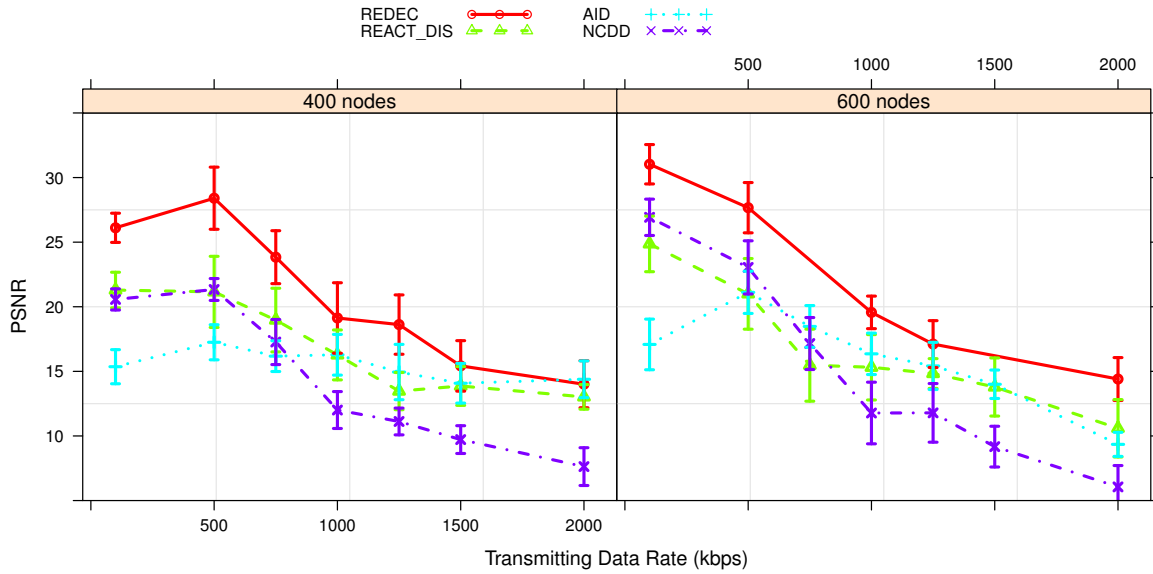


Figure 4.18: Real City Topology - PSNR

that REDEC outperforms the other solutions at lower data rates where packet loss is not as substantial as when transmission rates increase. In those cases, the difference between the performance of these solutions are narrower since they all suffer from congestion. In the scenario with 600 nodes, the topology is better connected, higher values of SSIM are observed and REDEC’s advantage is more pronounced.

The results regarding end-to-end delay are shown in Figure 4.20 where the y axis is in log scale due to the excessively large values observed when NCDD is used. NCDD’s high delay is caused by the need of intermediary nodes to wait for the decoding of a whole block before further propagation of video content. The use of carry-and-forward with assist of help messages also increases the overall end-to-end delay. REACT-DIS and REDEC obtained the lowest end-to-end delay (between 10 ms and 20 ms for data rates of 500 kbps or higher) because they switch the perspective of receiver based solutions of selecting relay nodes for every single transmission for the duration of a time window instead.

The evaluation of the performance of these solutions through different data rates for transmission of video content is explained by the goal to understand the ability of each solution to handle the transmission of videos of higher quality. Therefore, it is also important to measure the rate by which video content is received as this determines the quality of video that can be displayed to end users.

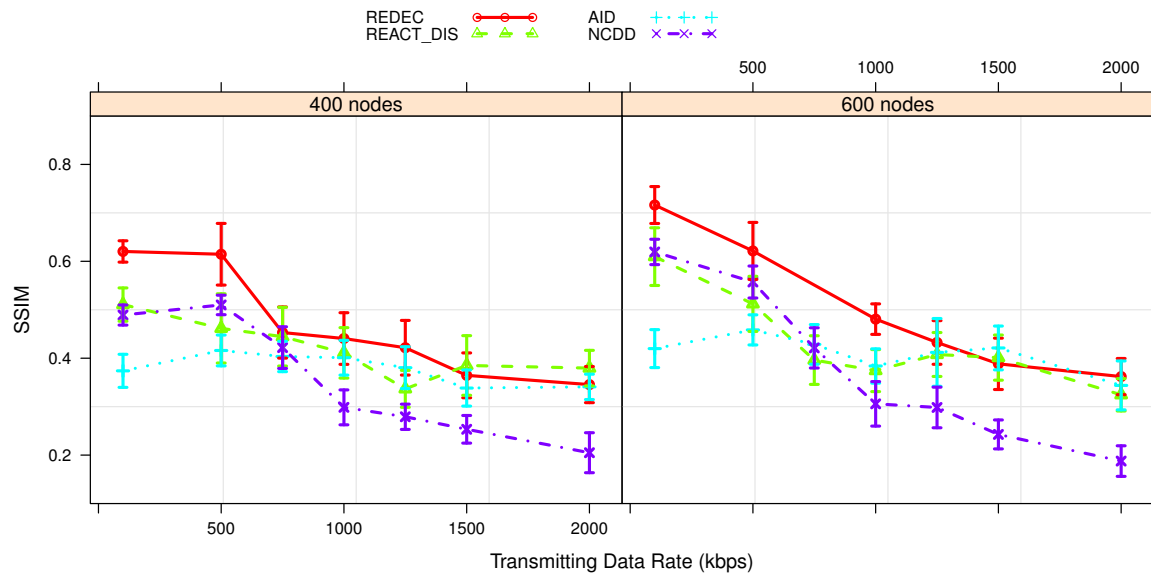


Figure 4.19: Real City Topology - SSIM

Figure 4.21 shows the video reception rate of all solutions for each scenario. It can be observed that increases in the data rate by which video is transmitted does not reflect on straightforward increases on the rate by which video content is received (5:4 at 500 kbps to 5:3 at 2,000 kbps). The low rates observed when NCDD is used are because the use of Network Coding requires intermediary nodes to wait for the reception of a whole block before forwarding their newly encoded packets. Besides that, the use of help messages and carry-and-forward strategies limits the rate by which video content is received. The rates by which video content is received by nodes using AID is also restricted. This happens due to the way a node decides to become a relay node which is based on the variance of packets' arrival time; this promotes a reduction in the overall transmitting rate. REDEC obtained slight improvements in the receiving rates when compared to REDEC but up to 20% and 90% when compared to AID, at 2,000 kbps transmission rates with 400 and 600 nodes, respectively.

Figure 4.22 shows the number of transmissions of packets carrying video content and it is also in log scale due to NCDD's excessive number of transmissions. NCDD does not perform any sort of relay node selection and every node in the network participates in the dissemination process. Furthermore, it relies on negative acknowledge messages that incur into even more transmissions. REDEC and REACT-DIS have similar performance in terms of the number of transmissions which is under 20,000 for 400 nodes and slight

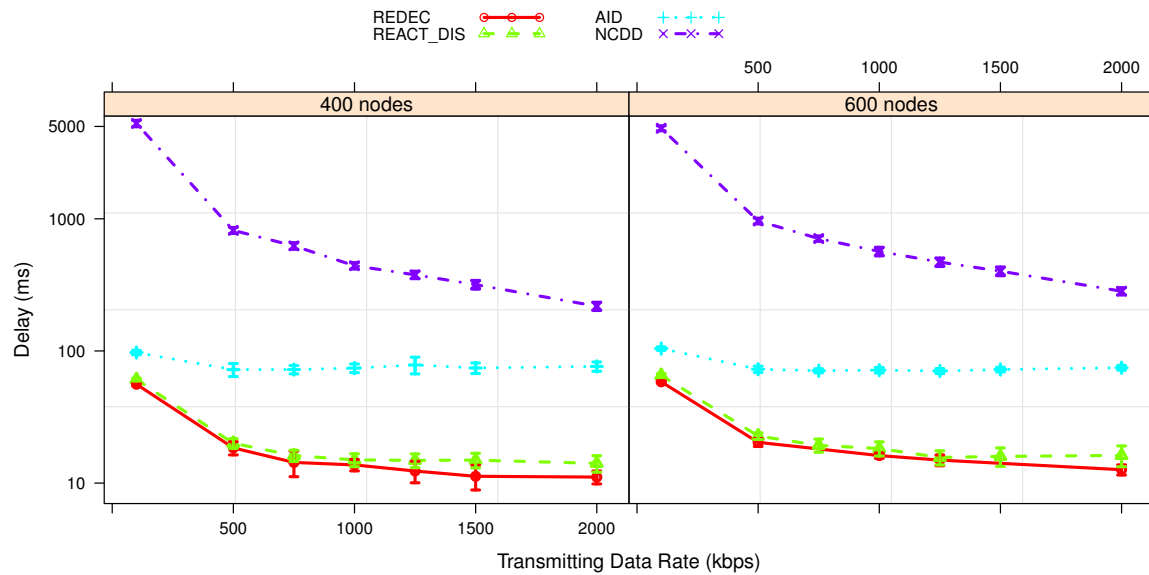


Figure 4.20: Real City Topology - Delay

above it for 600 nodes, which corresponds to under 15% and 10% of nodes participating in the dissemination process, respectively. AID exhibits the lowest number of transmissions which shows that using inter-arrival time reduces the number of duplicates but it also leads to lower receiving rates which are fundamental to high quality video streaming (as aforementioned).

In the next Section, we summarize the conclusions that can be taken based on the results presented here.

4.3.4 Conclusions

Many valuable conclusions can be made based on the extensive evaluations shown in this work. The following list discusses the main points:

- REDEC's overall performance:** REDEC displays the best performance when all criteria of Delivery Ratio, PSNR, SSIM, Video Reception Rate, End-to-end Delay and Number of Transmissions are considered. AID's performance matches that of REDEC for the lower density scenario but this is not sustained for the scenarios with higher density. REDEC was shown to offer reasonable levels of service with increases of density and data transmission rate. Its waiting time function incurs the selection of more stable links, its simple mechanism to make

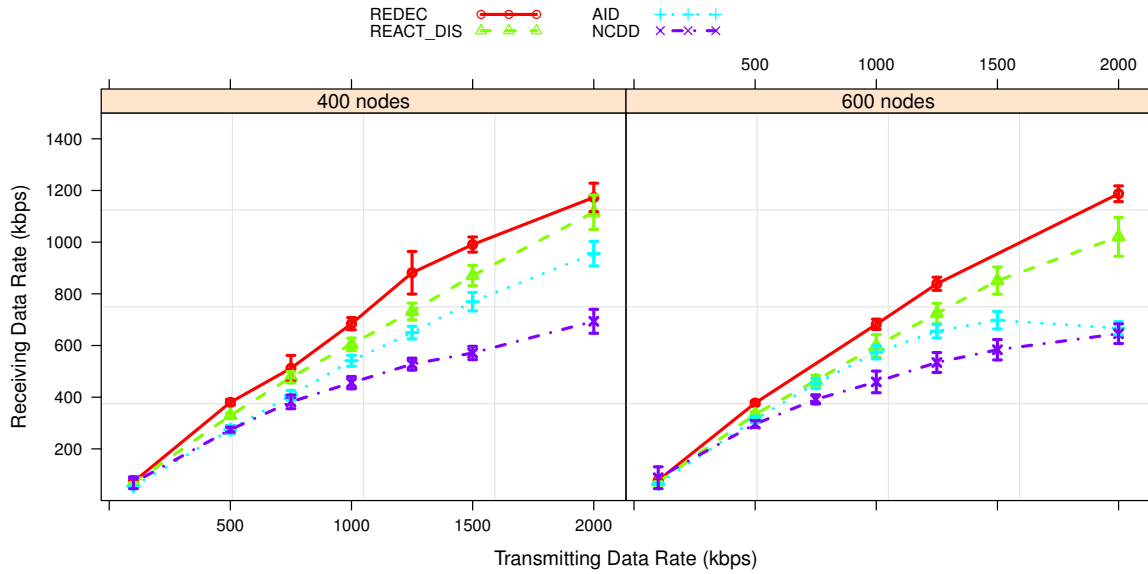


Figure 4.21: Real City Topology - Receiving Rate

nodes decide to relay packets is suitable to manage the trade-off of reachability and transmission cost; and, REDEC’s ability to decouple the transmission of video content to receiver-based relay node selection prevents the issues observed in dense scenarios with high data traffic.

- **REDEC is stable and offers low latency:** REDEC delivers video content at a delay always smaller than one second. This is more than sufficient to fulfill video streaming requirements in terms of latency [118]. Besides that, it was shown that REDEC is able to maintain similarly reasonable levels of transmission cost when compared to delivery ratios of different densities. This indicates that REDEC is a scalable solution and it is suitable for deployment in networks of any size.
- **Transmission rate vs reception rate analysis:** An important evaluation is shown in regards to the ability of the solutions to offer higher rates of video content reception; this is strongly related to the quality of videos that can be reproduced at end users. We have shown that in terms of video dissemination over VANETs, increases in the transmission rate do not result in proportional increases in the video reception rate. Furthermore, we were able to observe that some mechanisms like AID’s inter-arrival time approach, for relay node selection, and NCDD’s use of Network Coding, reduce video reception rates obtained. Therefore, when video

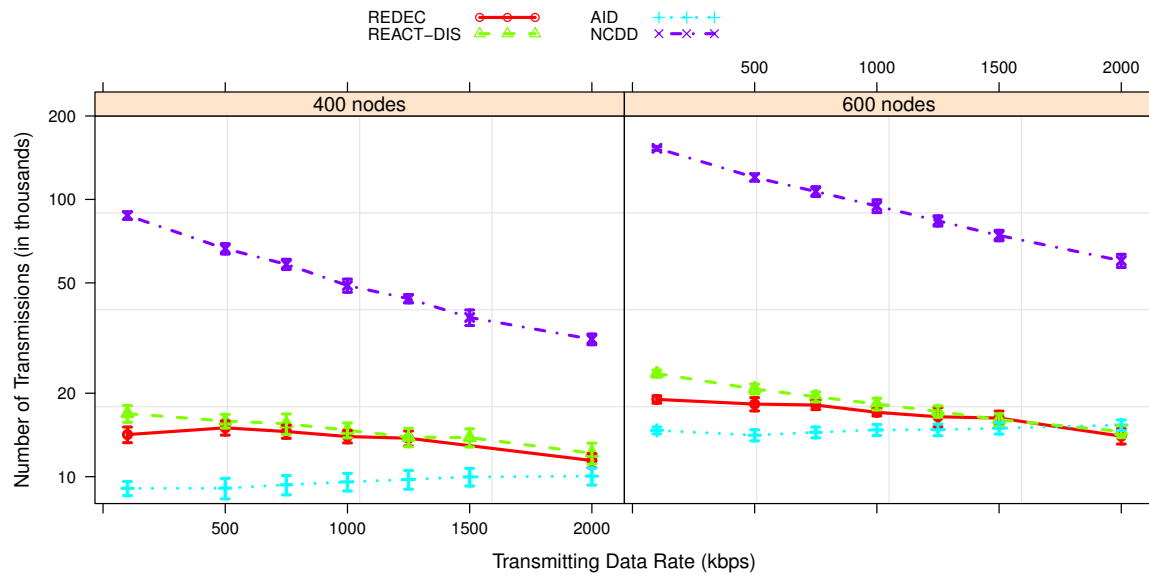


Figure 4.22: Real City Topology - Number of Transmissions

streaming is considered, proposed solutions have to evaluate their impact on receivers' reception rate.

- Network Coding issues:** The use of Network Coding has already been suggested as beneficial for content distribution [68] and even video dissemination [90] over VANETs. However, its use for video streaming requires a deeper investigation due to the delay caused by intermediary nodes' need to wait for the reception of a whole block and the impact on video playback upon partial reception of a non-decodable block.
- Data type and video quality:** We have observed that even with a low variation in delivery ratios, the average PSNR and SSIM varies significantly. This is explained by the differentiated level of importance of the content carried by transmitted packets. When packets that carry more crucial data (such as that of I-frames) are lost, they have a stronger impact on the decrease in video quality perceived by end users.

4.4 Final Remarks

We have tackled the challenging issue of supporting the dissemination of video streaming content over Vehicular Ad Hoc Networks. The difficulties in this task lie in how to fulfill video streaming's stringent requirements over a wireless network with a highly dynamic topology. The provision of this service would be greatly beneficial to enhance users' experience in a variety of applications.

The first solution designed was the Reactive, Density-Aware and Timely Dissemination Protocol (REACT-DIS). In this chapter, REACT-DIS was described in detail and thoroughly evaluated. This extensive evaluation allowed us to properly tune REACT-DIS's parameters and observe different levels of performance by unique configurations. Therefore, different configurations can be used depending on different Quality of Service (QoS) policies. REACT-DIS's performance was also measured under different data rates in order to observe its behavior for a variation of video quality demands.

The second protocol proposed is a REceiver-based solution where video transmission is DECoupled from relay node selection, namely REDEC. This solution takes advantage of the reactive quality of receiver-based solutions where the decision of a node to participate in dissemination is performed at receiving nodes rather than on the previous relay node. However, video messages are composed of a large amount of data and they are sent at a high frequency; this leads to many issues in the ability of receiver-based solutions to prevent unnecessary transmissions and to select relay nodes that are mutually unreachable. Furthermore, it performs relay node selection by using the periodic dissemination of control packets rather than the video transmission itself. By this method, when packets carrying video content are disseminated, all nodes involved in the communication have only to check their current status obtained through the dissemination of the control packets.

This chapter presents an extensive and thorough experimental analysis of simulated large scale vehicular networks. The choice of the values for REACT-DIS and REDEC parameters is based on a thorough evaluation. A performance analysis is conducted along with a performance comparison with other state of the art solutions.

The performance evaluation showed that REDEC has an overall better performance than the other solutions. Both of the solutions proposed in this chapter were able to achieve higher video data receiving rates which is paramount for the display of higher quality videos for end users. Although in specific scenarios end-to-end delay of REACT-DIS and REDEC was always slightly higher than other solutions, it was always under one

second, which is more than sufficient for video streaming requirements [118]. REDEC and REACT-DIS are scalable to increases in density as the same level of service is provided without incurring excessive new transmissions.

This detailed performance evaluation explored many aspects of video dissemination over VANETs. It was shown the behavior of REDEC, REACT-DIS and the other solutions through demanding scenarios that stress their abilities rather than using trivial scenarios such as those with low transmission rates and ideal density. The analysis of the relation between transmission rates and video reception rates is novel for video streaming over VANETs; and, it is valuable to observe that not all techniques offer the same corresponding behavior between both rates. Furthermore, this chapter presents evaluations of networks in a significantly larger scale than other existing works.

Chapter 5

Video Unicast in VANETs

Communication capability is paramount for VANETs applications. Thus, many efforts to make unicast, broadcast, multicast, anycast, and geocast communication models suitable for VANETs environment have been found in the literature. Unicast communication can be classified as proactive, when the communication infrastructure is constructed in advance, and reactive, when the network only builds a communication infrastructure when necessary. Proactive approaches tend to be costly due to the infrastructure maintenance, especially for dynamic networks such as VANETs, while reactive approaches tend to present high communication delay. Regarding path construction, they can be classified as sender based, when the sender decides which(s) neighbor(s) are chosen to relay their packets, and receiver based, when the neighbors themselves decide to relay or not the packets they receive.

Despite these challenges, any video streaming solution has to be able to comply to some Quality of Service (QoS) requirements. Video streaming capabilities are either crucially necessary or greatly valuable for a high level of user satisfaction for the majority of envisioned applications and services over VANETs. Computational devices and display screens available inside vehicles do not suffer from the same restraints imposed to MANETs' usual devices. Therefore, they are capable of reproducing high quality videos which increase the pressure on QoS expected from VANETs. As mentioned before, CISCO has defined some of these requirements [118] for general video streaming. Delay should not be higher than 4 to 5 seconds, while loss should not exceed 5 percent. Bandwidth requirements depend on applications and jitter imposes no significant requirements (see Table 1.1). The transmission of video is expected to demand the use of high amounts of network resources but it cannot be excessive. Therefore, video streaming

solutions for VANETs have to fulfill all of these base requirements limited to a reasonable occupation of the wireless medium.

In this chapter, we discuss my solution to video unicast, namely the Video Reactive Tracking-based UnicaSt (VIRTUS). It adopts a receiver-based strategy where the selection of a relay node is extended to a time window instead of only for a single transmission, similarly to REACT-DIS (see Chapter 4). VIRTUS uses the current location of a vehicle and its future position estimations to better select relaying nodes. VIRTUS balances the suitability of a node to forward packets between the node geographic advancement towards the destination and the stability of its connectivity to the previous node.

Furthermore, VIRTUS is improved with an extension where video transmission is decoupled from the process of relay node selection while a density aware policy is also used. It could be observed that under scenarios of congested communication (mainly due to increases in transmission data rates), the number of collisions rises which impairs the ability of receiver-based solutions to perform cancellations effectively. The retransmission of packets by nodes that should have been cancelled causes even more collisions. The separation of relay node selection from video transmission breaks this cycle. We have added a density-aware mechanism where the observed number of received duplicates is used as an indication of high density and VIRTUS adapt itself to such scenarios. This modification has helped VIRTUS provide a stable performance even with further increases in density. With these modifications, VIRTUS is scalable to increases in transmission rates and in density.

A thorough experimental analysis was conducted through the use of realistic simulations. Based on these experiments, it was possible to provide a deep understanding of the issue of unicast video streaming over VANETs. Besides that, these experiments are essential to corroborate the benefits of VIRTUS.

The peculiarities of VIRTUS are described in detail in Section 5.1. Section 5.2 describes the experimental methodology and the observed results. Final remarks are presented in Section 5.3

5.1 VIRTUS

The Video Reactive Tracking-based UnicaSt protocol (VIRTUS) is a receiver-based solution designed to deliver packets in a timely fashion. It adapts the paradigm on deciding at receivers which nodes to participate in the forwarding process from source to destination according to the requirements of video streaming.

In the next subsection, we explain thoroughly the process of relay node selection used by VIRTUS. Section 5.1.2 explains the extensions implemented towards a solution that scales to increases in communication congestion and in density.

5.1.1 Relay Node Selection

Throughout VIRTUS delivery of packets from source to destination, the selection of relay nodes is optimized in order to attempt the avoidance of unnecessary transmissions by intermediary nodes. The receiver-based approach shifts the paradigm for the selection of relay nodes from senders to receivers; thus, nodes in the network do not need previous knowledge of their local neighborhood for the selection of relay nodes.

A forwarding node in a receiver-based solution simply broadcasts the packet to its neighbors and upon its reception, neighboring nodes schedule themselves to relay the packet further. The first node to expire its waiting time forwards the received packet. This transmission triggers the scheduling of new nodes towards the destination while it cancels the previously scheduled nodes in order to avoid unnecessary transmissions.

The waiting time γ is then related to the node's suitability as a relay node of the received packet. It is the time a node waits to observe the forwarding of the packet by any other node within range which, if perceived, leads this node to cancel the later transmission of the packet. Therefore, nodes considered as more suitable to relay a packet must have a shorter waiting time.

A fundamental concept of VIRTUS is its Forwarding Zone which limits the selection of relay nodes to a sector of the region reached by the communication range of nodes. This sector is defined as the region within an angle β of the line connecting both the forwarding and the destination node (as seen in Figure 5.1). This mechanism prevents the formation of loops (with $\beta < 90^\circ$) and prevents that nodes which are disconnected from each other from deciding to become relay nodes; this would result in nodes not being able to cancel transmissions from other nodes. The choice of the value of β balances the trade-off of mutual connectivity between neighbors and the limitation on nodes that can forward a packet and prevent a path break. We have defined $\beta = 30^\circ$ as this is the maximum angle that can form a forwarding zone where the maximum distance between any two nodes within this zone is limited to the communication range.

A problem with using the receiver-based paradigm for video-streaming is its high end-to-end delay caused by the waiting time necessary to relay incoming packets further. The same problem was observed for video dissemination in the previous chapter; VIRTUS

solves this issue with the same approach by changing the perspective concerning choice of relay nodes for each transmitted packet to a set of packets within a time window. In VIRTUS, when a receiving node decides it is a suitable relay node (i.e. its waiting time expires and no other retransmission of the same packet was observed), it considers itself as a suitable relay node for the duration of a time window of λ seconds. During this time, any newly received packet is immediately forwarded. The duration of this time window is named Reservation Time (λ) and this is the period of time the new relay node is estimated to maintain within the forwarding zone of the previous relay node. The estimation of the time a node is within the forwarding zone of another node is based on the location information received which is stored at the headers of incoming packets. This estimation is described thoroughly in [100].

The decision of VIRTUS regarding the suitability of nodes to relay further incoming packets is a hybrid approach that takes into consideration geographic advancement towards the destination and link stability. Link stability is calculated based on the Reservation Time λ normalized to its maximum pre-defined value of 5 seconds. The suitability of a node to relay a packet is defined by the time γ it waits to decide if it is to become a relay node. Both waiting times are calculated based on only geographic advancements γ_{geo} and stability γ_{stab} ; and, the value of γ is a weighted combination of these two elements. With $\delta(n_i, n_j)$ as the geographical distance between nodes n_i and n_j , n_d as the destination node, n_{lh} as the transmitting node (last hop), n_r as the receiver and r as the radio range, we have the following: $\gamma_{geo} = 1 - \frac{\delta(n_{lh}, n_d) - \delta(n_r, n_d)}{r}$; and, as mentioned, with λ as the reservation time and Λ as the maximum reservation time, we have: $\gamma_{stab} = 1 - \frac{\lambda}{\Lambda}$. With γ_{geo} and γ_{stab} as normalized values, we define γ as:

$$\gamma = \Gamma * [\alpha * \gamma_{stab} + (1 - \alpha) * \gamma_{geo}] \quad (5.1)$$

where Γ defines the Maximum Waiting Time.

Figure 5.1 is a detailed picture that uses the example of when node B relays a packet received from node A. All other cases in Figure 5.1 are explained further in this section.

The effectiveness and efficiency of a receiver-based approach is mainly twofold in the aforementioned calculation of the Waiting Time and the mechanism of cancelling unnecessary transmissions of packets that have already been forwarded. The most simple case of cancellation happens when a node in the forwarding zone of a relay node perceives the broadcasting of the same packet by another node located closer to the destination than itself. In this case, these nodes cancel the scheduled broadcast and drop the packet. Both crossed nodes C in Figure 5.1 exemplify this scenario. However, there are nodes

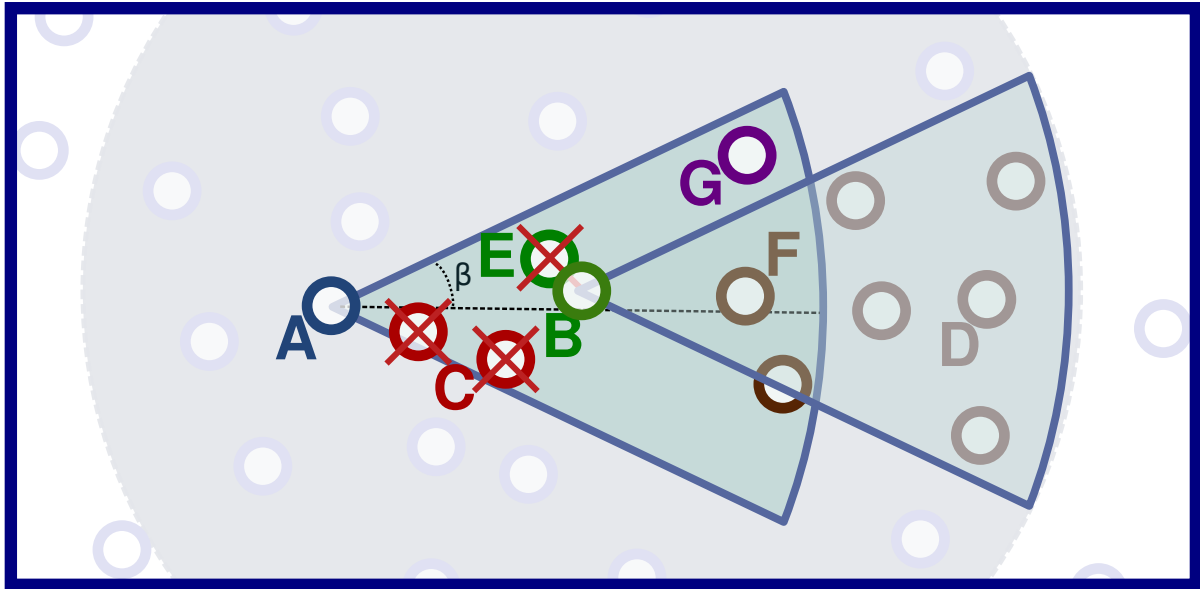


Figure 5.1: VIRTUS - Forwarding, Cancelling and Rescheduling

that perceive this transmission but are located closer to the destination than the relay node. For these nodes (nodes F and G), the relayed packet triggers the rescheduling of the broadcasting of the packet instead of its cancellation.

There are two cases of rescheduling a node to further relay a packet that depend on whether the respective node is inside or outside the forwarding zone of the new relay node. For nodes that are inside the new forwarding zone, they only need to recalculate their new reservation λ and waiting time γ (node F in Figure 5.1). However, it is important to consider the nodes that are located outside of the forwarding zone as there might be cases in which they are the only option to continue the transmission towards the destination. The calculation of a new reservation time would lead to having $\lambda = 0$; this is because it is already outside of the forwarding zone. For this reason, we have considered that the new waiting time take into account the location of the new relay node but that it uses the reservation time calculated previously which is based on the location of the later relay node instead of the new one. Node G in Figure 5.1 is an example of when this kind of rescheduling is necessary.

In VIRTUS, any set of nodes that have a waiting time which differs by less than the maximum random delay θ^1 may forward the same packet before they are able to perceive

¹See Chapter 4 Section 4.1.1 for further details regarding θ .

the transmission by another node; optimally, only one node should be able to forward the packet. For this reason, there is a second level of cancellations that is conducted between relay nodes. It is included in the header of the packets the waiting time used for nodes to become relay nodes. This value is used so that the node with the minimum waiting time is selected as the most suitable relay node.

Upon the reception of a packet by a relay node that has already forwarded it, the node checks if the waiting time it has used is less than that of the waiting time in the header of the packet. If it is, this node remains as the relay node; otherwise, it cancels its status as a relay node and it becomes once again subject to the calculation of new waiting times (node E in Figure 5.1 is an example of this kind of cancellation). This process is performed throughout the transmission of all packets; hence, if there are still multiple relay nodes in the same forwarding zone after the first transmission, with time, only the relay node with the smallest waiting time continues to forward incoming packets immediately.

5.1.2 Density-Aware Relay Node Selection Decoupled from Video Transmission

As in video dissemination, it was observed that the performance of receiver based solutions for video unicast is severely deteriorated with increases on transmissions rates. High transmissions rates incur into more frequent collisions which prevent the transmission by the most suitable relay node to cancel further transmissions by other potential candidates. These unnecessary retransmissions congest even further the shared medium. Video streaming requires transmission of data at high rates specially for higher quality videos.

The separation of relay node selection from video transmission is due to the difficulty in performing cancellations properly when a large amount of data is transmitted at high frequencies. The process of relay node selection in a receiver-based perspective consists in defining short waiting times for nodes more suitable forward received packets and to aim at having only the most suitable node to forward the packet. In video streaming, packets carrying a large amount of data are transmitted in a short period of time. This scenario is strongly prone to collisions and it significantly impacts upon the ability of the best candidates, for packet relaying, to cancel upcoming transmissions by other less suitable nodes. For this reason, it was decided to decouple the process of relay node selection from that of transmitting packets carrying video content.

In this approach, a control packet is transmitted periodically from the source to the destination with the goal of triggering the relay node selection process. The time between control packets consecutively sent by the source node is referred as ρ . The transmission of these control packets follows the relay node selection process described in Section 5.1.1 and the results from this process determine the state transitions from an idle node to a relay node. In this way, when packets containing video content are transmitted, receiving nodes check their previously assigned states and forward these packets if they were set as relay nodes.

Nodes in VIRTUS are in one of three possible states: idle, scheduled or relay. The destination node becomes a relay node when it requests the transmission of video content, remaining in the same state until the end of the transmission. The source node becomes a relay node upon the reception of a video request and it maintains such a state for the duration of the transmission of the whole video. All other nodes begin the video transmission process at an idle state and change their status following the relay node selection process through the transmission of the control packets.

One modification in the relay node selection process when decoupled from video transmission is that when a control packet is received by a node that is currently a relay node, it checks if its remaining duration as a relay node is longer than the periodicity ρ between consecutive control packets. If its time as a relay node expires before the period ρ , although the node maintains its status as relay node for the duration of the transmission of packets carrying video content, it behaves as an idle node for the process of relay node selection through to the transmission of control packets. In this way, it can be ensured that the predicted change of status from a relay node to an idle node does not incur path breaks.

Another cause of increasingly communication congestion is the transmission through regions of high density. VIRTUS has to balance the trade-off of lower end-to-end delay and simultaneous transmissions depending on vehicles density.

We have used in this decoupled relay node selection process a policy that aims to dynamically adapt depending on the local density. Small values to the maximum waiting time Γ in dense regions could lead to a higher number of collisions due to waiting times from different nodes too close to each other. Large values of Γ do not lead to high delays in dense regions, this is because there is a higher chance of having nodes in better situations to relay packets; thus, lower waiting times are achieved. Thus, a mechanism was applied that detects the occurrence of multiple nodes forwarding packets in the same region, which then increases the value of Γ .

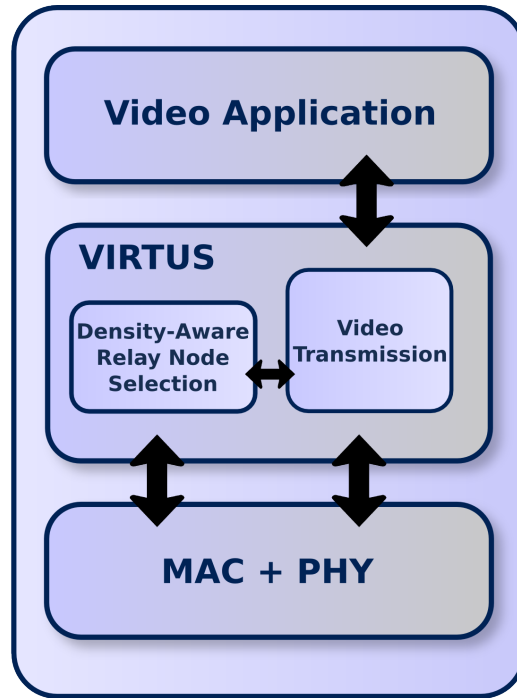


Figure 5.2: VIRTUS Architecture

The observed number of duplicates was used as an indication of local density so the value of Γ is properly adapted. Upon the reception of any control packet that has been previously received, the number of duplicates counter increases. When there are duplicates, it means that the value of Γ is smaller than it should be. Therefore, before a node is scheduled or re-scheduled (see Section 5.1.1), VIRTUS checks if any duplicate was perceived; if this is the case, the value of Γ is multiplied by two. If no duplicate has been received, the value of Γ is multiplied by 0.75; thus, a fast-increase-slow-decrease policy is adopted. The value of Γ is limited between the range of 50ms to 2s, since it can be understood that a delay of 50ms in each hop leads to end-to-end delays compliant with video streaming requirements and 2,000ms is sufficient to guarantee reasonable differences between vehicles' waiting times. The number of duplicates observed by each node is reset after the value of Γ is updated.

Figure 5.2 illustrates VIRTUS architecture with these extensions. Relay node selection and video transmission are separate modules; their interaction consists only in the video transmission module requesting information regarding the node status as a relay node. The relay node selection module never interacts with the video application, the transmission of video content is conducted solely by the video transmission module.

5.2 Performance Evaluation

The protocol for the video streaming process follows a method in which the destination node initially sends a message to the source of the video requesting the video content. After this, the node source of the video content starts both the process of transmitting of the video and of exchanging location information with the destination node (which also sends its location to the source node periodically). The assumption here then is that the video requester knows the location of the node with the content it is requesting. In a scenario where cameras are located at intersections, it is reasonable to assume that the location of cameras is shared among nodes in the network. For scenarios where this is not feasible, a Location Discovery solution is necessary; but, this solution is outside of the scope of this work.

In order to evaluate VIRTUS behavior, a thorough experimental analysis of its performance was conducted. We have divided these experiments into three groups: preliminary, tuning and performance comparison. The preliminary analysis provide an initial understand of the advantages of VIRTUS. The second group (tuning) aims at providing a deep understanding of VIRTUS behavior with the density-aware relay node selection decoupled from video transmission as well as analyzing the impact of its parameters. With this information, it is possible to support the choice of values for VIRTUS parameters and then compare its performance with its version without the extensions and with another state of the art solution. The performance comparison is run in a topology with a greater fidelity to real scenarios and through different levels of vehicles density.

5.2.1 Preliminary Analysis

In this preliminary analysis, the goal is to observe the advantages of using a receiver-based approach where geographic advancement and link stability is considered. This version of VIRTUS includes the perspective of increasing the duration of the decision of a node to relay packets to a time window rather than for a single transmission. The location prediction mechanism is used both to consider updated positions of nodes and the duration of mutual reachability². Furthermore, the impact of the movement of source and destination node is studied through 4 different scenarios. In the first case, both are static, the second case considers a static source and a moving destination. The third scenario considers moving source and a static destination. A fourth scenario considers

²The decoupling of video transmission and relay node selection as well as the density-aware mechanism are not used in this preliminary analysis.

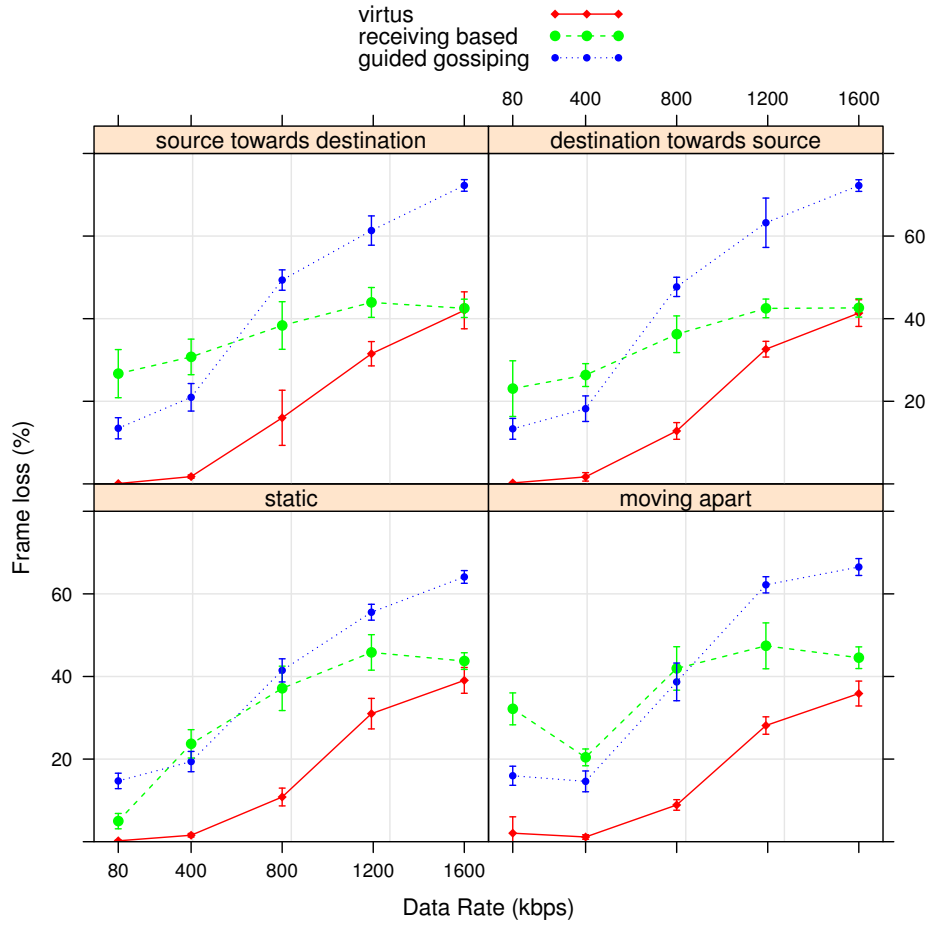


Figure 5.3: VIRTUS - Preliminary Analysis - Frame Loss

that both source and destination are moving apart of each other. For a more detailed description of the simulation setup see [103].

VIRTUS performance is compared to two baseline solutions. The first consists of an adaptation of a flooding mechanism which can offer lower bounds to delay even if it incurs into high overhead. This solution is referred as guided gossiping and it consist of a dissemination directed towards the destination. Another baseline is a standard geographic receiving-based solution that is based solely on a geographic greedy approach.

The performance of the protocols is measured according to frame loss and delay. Besides that, their feasibility in terms of cost is considered by measuring the rate between the total number of transmissions and packets sent. Frame loss is the percentage of frames that could not be reproduced at the receiver. Delay is the average end-to-end latency

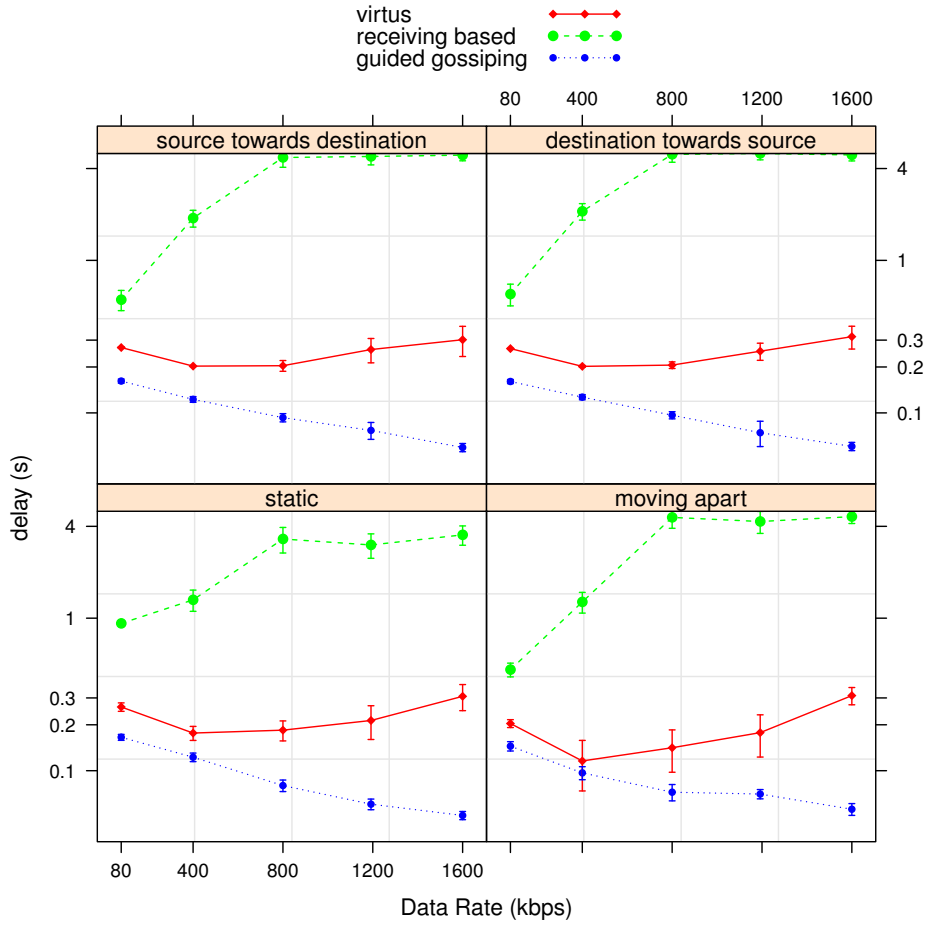


Figure 5.4: VIRTUS - Preliminary Analysis - Delay

of all received frames. For the cost estimation, the total number of transmissions at the VIRTUS level is divided by the number of packets sent by VIRTUS at the source.

All solutions have used the same protocol where position updates are exchange between source and destination. This protocol was proven to be effective as the different movement patterns of source and destination did not incur into a noticeable impact on the results (Figures 5.3 to 5.5).

Figure 5.3 shows how VIRTUS has achieved the lowest frame loss among the evaluated solutions. At 400 kbps, VIRTUS frame loss is still close to 0% while the other two solutions suffer from 20% or more of frame loss. At the highest data rate, its performance is matched by that of the naive receiver based solution at around 40%.

The end-to-end delay observed by VIRTUS in Figure 5.4 is close to a practical lower

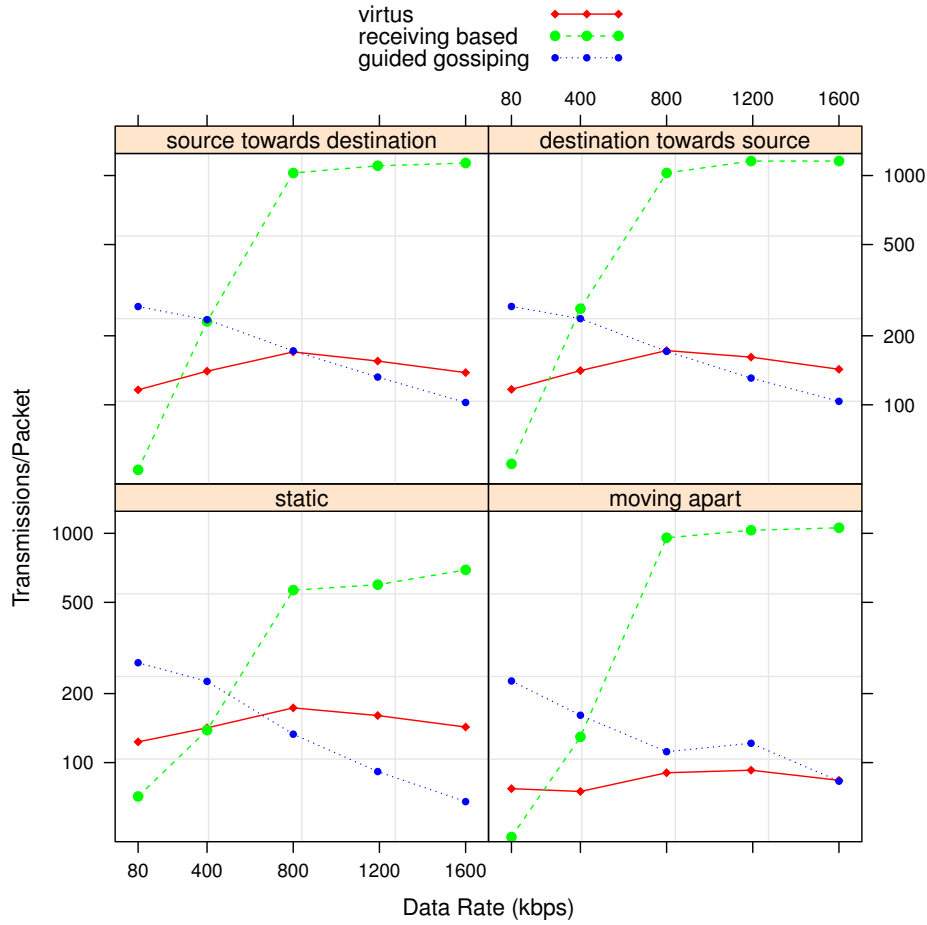


Figure 5.5: VIRTUS - Preliminary Analysis - Cost

bound of the guided gossiping solution since the later does not require ever for intermediary nodes to wait to relay packets further. The naive receiver based solution incurs excessive end-to-end delay reaching orders higher than that observed for VIRTUS (Figure 5.4 was plotted in logarithmic scale for that reason). This shows that the change in perspective for the duration of the selection of a node as a relay node achieves its goal to offer a timely transmission of video content.

VIRTUS is shown to refrain from excessive overhead as seen in Figure 5.5. The scenario used consists of communication paths varying from 35 to 40 hops, thus, this initial version of VIRTUS requires 3 to 5 transmissions per hop. This is reduced with transmissions of video content decoupled from relay node selection and the inclusion of the density-aware mechanism. This is further discussed in Section 5.2.4.

VIRTUS has shown to outperform baseline solutions as it is able to deliver a higher percentage of packets resulting in fewer frames lost at the receiver. The delay level achieved is within the quality of service requirements of real-time video streaming. Although the amount of resources used is not ideal, it is still reasonable and within feasible real life scenarios.

5.2.2 Simulation Environment

The deployment of VIRTUS over a real VANET is unfeasible at this point. Because of this, once again the Network Simulator NS2 [85] was used. The communication model used in this chapter is similar as the one in Chapter 4 Section 4.3.2. The Nakagami propagation model was used with the same configuration as the one listed in Table 4.6. However, the IEEE 802.11p standard was used as it is the one indicated for vehicular networks. In its NS2 configuration, it was necessary to decrease the transmission power to maintain the same 300 meters expected communication range. EvalVid was used for the purpose of measuring video transmission on NS2, the same video configuration as the one in Chapter 4 Section 4.1.2 was used.

The simulation of VANET protocols is influenced greatly by the fidelity of the underlying mobility model used to emulate vehicle movements. In this chapter, we have used the road traffic simulation package SUMO [12]. This is a mobility model that takes into consideration several microscopic peculiarities of vehicle movement and provides mobility scenarios with high fidelity to real vehicle behavior. Two distinct topologies were used; a grid-based topology for the evaluation of VIRTUS parameters and one that uses the layout of downtown Ottawa (Canada) for performance comparison. Since different topologies are used, the choice of parameters does not represent the selection of the best outcome possible when VIRTUS is compared to other solutions.

The grid topology used for the evaluation of the impact of VIRTUS parameters consists of an area of 1,200m per 400m with 400 vehicles in the network and blocks of 100m length. In the preliminary analysis, it was shown that the protocol used to update both the source node and destination node with the information concerning the location and speed of the other node prevents the movement of either node from influencing VIRTUS performance. For this reason, in this evaluation, static nodes were as both the source and destination. In this grid scenario, the source node is placed at (0, 200) while the destination is at (1200, 200). In this manner, they are 1,200m distant from each other.

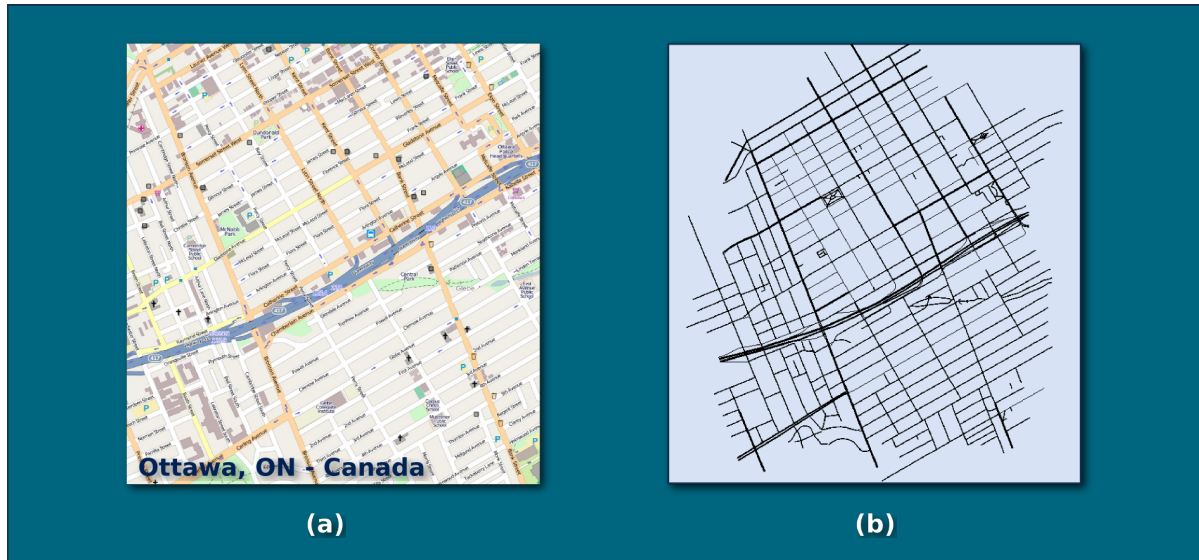


Figure 5.6: SUMO Roads Topology

Parameter	Grid Topology	Downtown Ottawa
Dimensions	1,200m x 400m	2,556m x 3,004m
Number of Vehicles	400	400 - 600 - 800 - 1,000
Video Source Location	0m x 200m	1,578m x 1,844m
Video Destination Location	1,200m x 200m	2,126m x 444m

Table 5.1: SUMO Scenarios

The performance comparison was conducted using a real city topology. A section of the downtown area of Canada's capital, Ottawa was chosen. Figure 5.6(a) displays the map from which the topology was built and the specific topology used is depicted in Figure 5.6(b). It can be noticed that the chosen region includes streets and avenues with different speed limits and even a section of a highway. Furthermore, traffic lights are also used based on available information. The source and destination nodes are placed on a stretch of 1,500m along Bank Street. VIRTUS performance was compared in different densities of vehicles that varies from 400 nodes to 1,000 nodes. Table 5.1 summarizes the details of the mobility scenarios used.

For the proper simulation of an environment in video-streaming, the performance of solutions was analyzed under different data rates. This is necessary as the transmission of video content requires data rates much higher than the ones used in applications such as accident alert messages. The used transmission rate used ranged from 100 kbps to

2,000 kbps. The evaluation of the performance of video transmission for these different rates has proven to be valuable for an in-depth understanding of the applicability of proposed solutions to different levels of video quality.

All results shown next are an average of 20 to 32 runs in the context of the evaluation of the impact of VIRTUS parameters and 30 to 48 runs for the performance comparison. Each run uses a different instance of the used mobility model; furthermore, an unique seed is used for the random number generator of each run. Besides the average, confidence intervals were plotted with a confidence level of 95%. The Student's t-distribution is used when less than 30 runs were used; otherwise, the normal distribution was used. For summarizing the results and plotting the figures, the statistical tool R [94] was used.

5.2.3 The impact of parameters

This part of the evaluation consists of understanding the impact of VIRTUS parameters on its performance. In here, VIRTUS implements the density-aware relay node selection decoupled from video transmission. This evaluation is also important for the provisioning of some initial insights into the issues of video streaming over VANETs. The evaluation of this wide variety of combinations of its parameters permits us to observe some of VIRTUS advantages.

For this initial evaluation, it was chosen to observe VIRTUS performance under three different metrics: Delivery Ratio, End-to-end Delay and Transmission Cost. Delivery Ratio is given by 100% minus the percentage of lost frames. Although Delivery Ratio is a network measurement, it is strongly associated with video quality especially since frame loss was used instead of packet loss³. End-to-end delay is the average delay calculated as the time between the transmission at the source, of the first packet containing information of a frame, and when the frame is assembled at the destination. In order to conduct a cost/benefit analysis, the total number of transmissions of video packets is considered for each combination of parameters. In this manner, it is possible to evaluate what combination provides the best delivery ratio under low end-to-end delays with a reasonable cost in terms of the number of transmissions.

VIRTUS performance is dictated by three parameters: Weighting Factor α , Initial Maximum Waiting Time Γ and the Time Between Control Packets ρ . The weighting factor α defines the extent to which waiting time of nodes is based on geographic ad-

³For the performance comparison, PSNR was measured which is a specific metric in regards to video quality.

vancement or link stability ($\alpha = 0$ has a waiting time based only on geographic advancement while $\alpha = 1$ has link stability as the only factor). The Initial Maximum Waiting Time Γ is the value used that nodes start with for their Maximum Waiting Time. The Maximum Waiting Time varies from node to node through the execution and is based on their observed number of duplicates (see Section 5.1.2). The selection of relay nodes is decoupled from the transmission of video content by having separate control packets, that are periodically sent from source to destination, that trigger relay node selection. The periodicity ρ by which these control messages are sent by the source node is the last parameter.

Figures 5.7 to 5.9 show the results of the variety of combinations of the aforementioned parameters. In these figures, the y-axis is established in regards to the metrics evaluated while the x-axis shows different values in the transmission data rate. Each curve represents results for different values of the weighting factor α . The columns represent variations of the initial maximum waiting time Γ and the rows represent variations in time between the transmission of control packets to trigger relay node selection ρ .

The delivery ratio reached by VIRTUS is shown in Figure 5.7. The decrease in delivery ratio with increases in data transmission rates is expected because higher data rates through which video content is transmitted lead to a more intense competition for the use of the shared wireless medium. Variations in the weighting factor α have also incurred noticeably different levels of achieved delivery ratios.

VIRTUS uses the perspective of prolonging the selection of a node as a relay node for a time window rather than for the transmission of a single packet; furthermore, it performs this relay node selection only during the transmission of control packets instead of during the transmission of video content. Therefore, the use of a heuristic function for the calculation of the suitability of a node to relay packets based solely on geographic advancement ($\alpha = 0$), is not satisfactory. This is because it could lead to the selection of nodes that do not maintain connectivity throughout this time window. This is corroborated by the results in Figure 5.7, as the curves when $\alpha = 0$ display the lowest delivery ratios. The deterioration of VIRTUS delivery ratios with $\alpha = 0$ is more strongly pronounced with increases in the periodicity at which control packets are transmitted because the longer the time is between consecutive relay node selections, the higher the chances are of breaking the link between previously selected nodes.

The highest delivery ratios were reached with $\alpha = 1$; thus, this occurred when relay node selection is based solely on link stability. However, this is not due to the selection of the best candidates for packets forwarding but rather because of the selection of

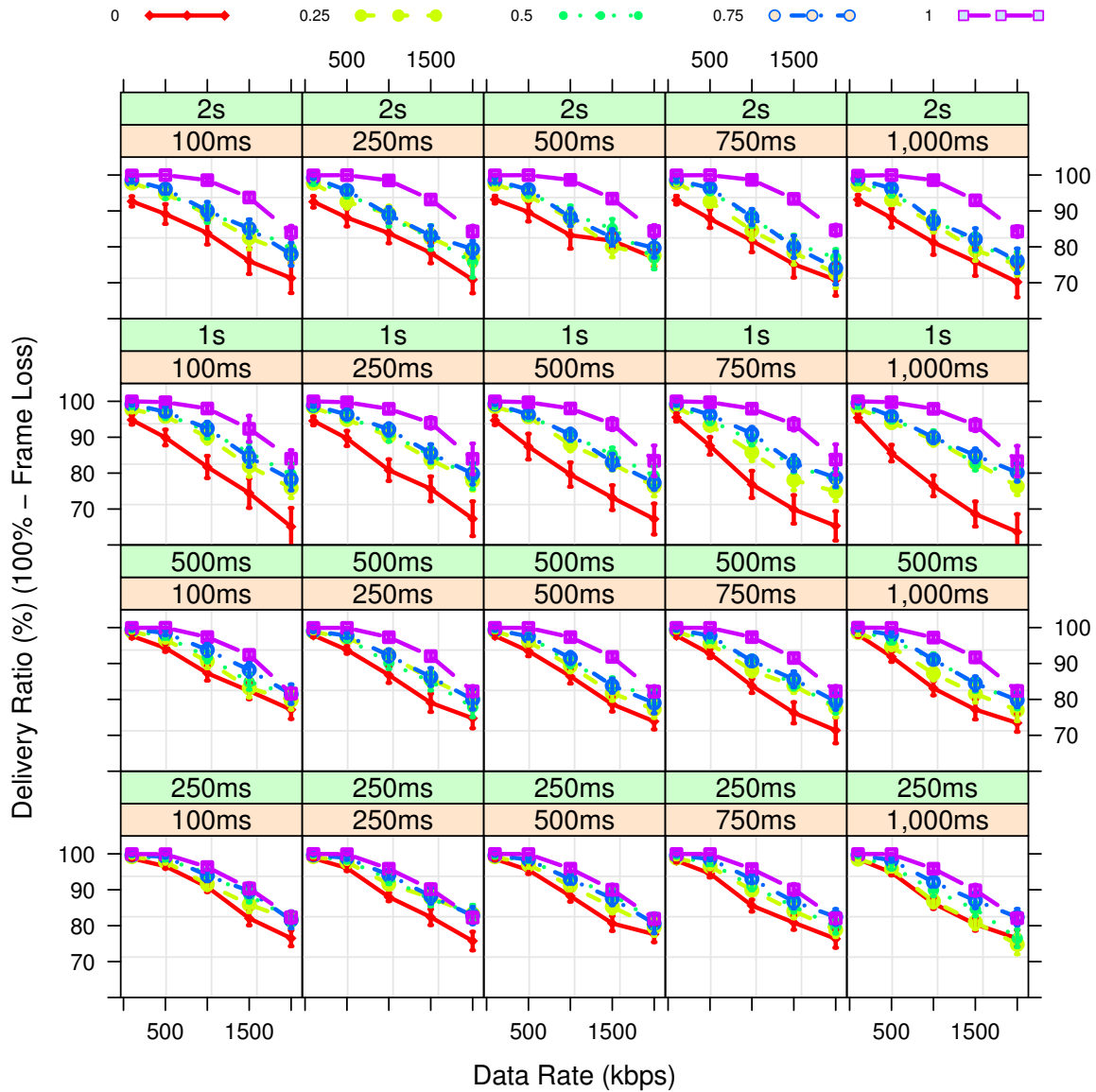


Figure 5.7: Delivery Ratio - Curves vary in the weighting factor α , rows in time between transmission of control packets ρ and columns in maximum waiting time Γ

many of them. When $\alpha = 1$, all nodes that have been estimated to remain within the forwarding zone of the previous relay node for a period equal to or longer than the maximum reservation time (5 seconds, see Section 5.1) have their waiting time set to zero. Therefore, all of them forward the received packet which causes collisions between many of them but increases the chances of at least one successful transmission.

The periodicity ρ of the transmission of control packets that triggers relay node selection affects the delivery ratio reached by VIRTUS. The shorter this periodicity is, the higher the delivery ratios obtained are. The decoupling nature between relay node selection and video transmission of VIRTUS diminishes its receiver-based ability to handle topology changes. Therefore, a short period of 250ms is recommended as it updates the relay nodes selected frequently enough to topological changes without incurring the transmission of an excessive number of control packets.

The value of the initial maximum waiting time Γ has shown to have little impact on the delivery ratios. This corroborates the concept that the mechanism of dynamically adapting the local maximum waiting time based on an indication of density by the observed number of duplicates is effective.

Figure 5.8 shows the observed end-to-end delay achieved by the different combination of VIRTUS parameters. It can be seen that VIRTUS has achieved very low end-to-end delays for any combination of parameters (always inferior to 200ms). There is very little variation in the observed end-to-end delays for different parameters. The only observable difference is when $\alpha = 1$. As mentioned before, when only link stability is considered, many potential candidates are selected as relay nodes. The increase in end-to-end delay at higher data rates indicates that among the selected relay nodes, the ones that have their transmission successfully received are the ones which have used a higher random delay on the lower layer. This random delay is used to avoid collisions by simultaneous transmissions. Therefore, it can be already observed the deviations resulting from the use of a relay suitability heuristic that is uniquely based on link stability.

The cost, in terms of number of transmissions of packets containing video information, is shown in logarithmic scale in Figure 5.9. Once again, the only influencing parameter is the weighting factor α . As mentioned before, when $\alpha = 1$, many candidate nodes are selected as relay nodes and this leads to an excessive number of transmissions which limits VIRTUS scalability. However, for all the other values of α , reasonable amounts of transmissions are performed with an average of 2 to 4 transmissions per communication hop⁴. There are slight increases on the transmission cost at higher values of α but transmission costs still remain within reasonable levels for α up to 0.75. These increases are caused by the larger number of hops between source and destination when stability is emphasized in detriment of geographic advancement.

⁴353 packets are sent through an average of 5 hops between source and destination.

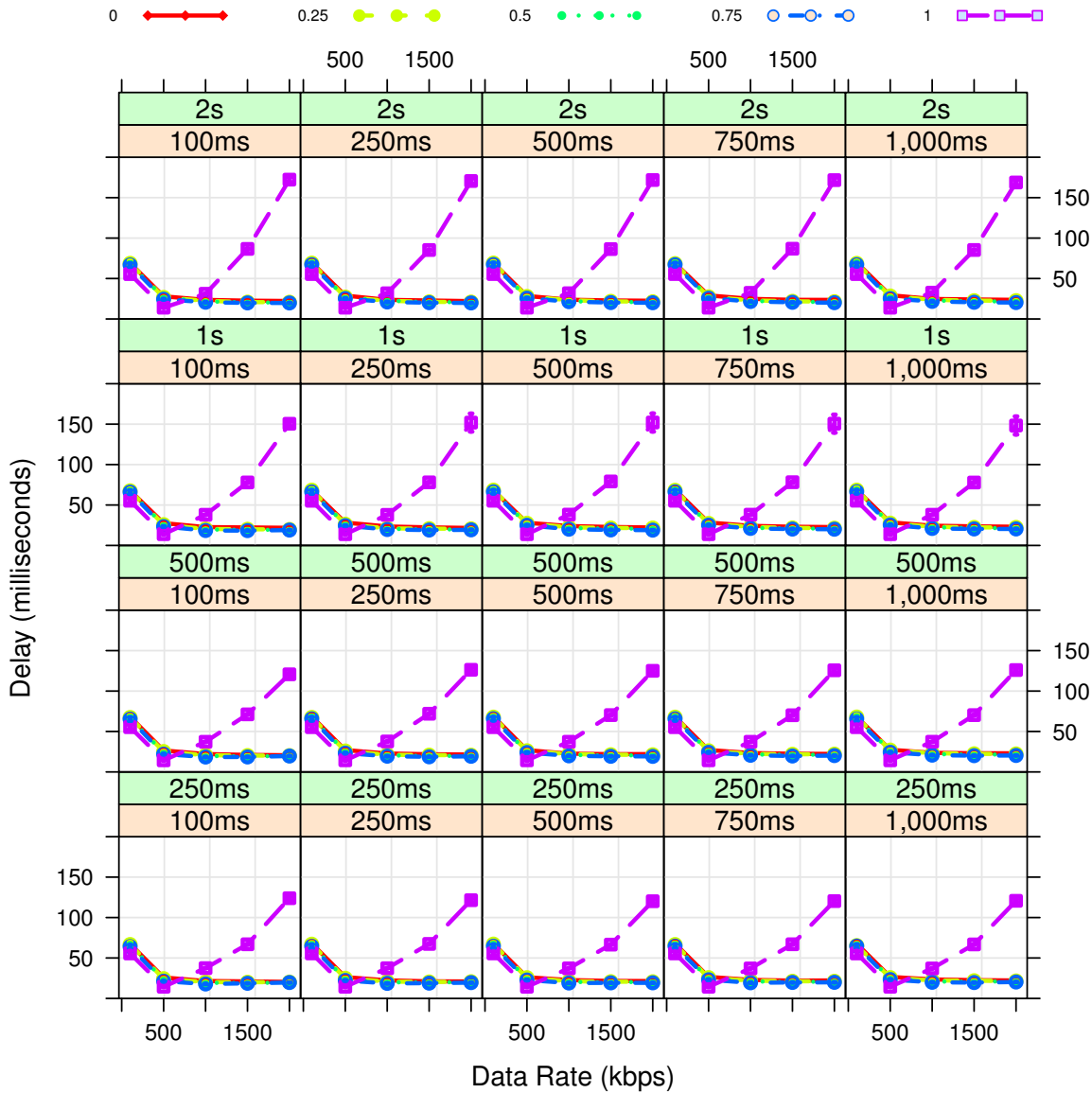


Figure 5.8: End-to-end Delay - Curves vary in the weighting factor α , rows in time between transmission of control packets ρ and columns in maximum waiting time Γ

5.2.3.1 Summary

Based on the entirety of this discussion, the values selected for the parameters were $\alpha = 0.50$, $\Gamma = 500ms$ and $\rho = 250ms$. The weighting factor α at 50% balances evenly the process of relay node selection between geographic advancement and stability. At this level, it was possible to achieve high delivery ratios with low end-to-end delay at

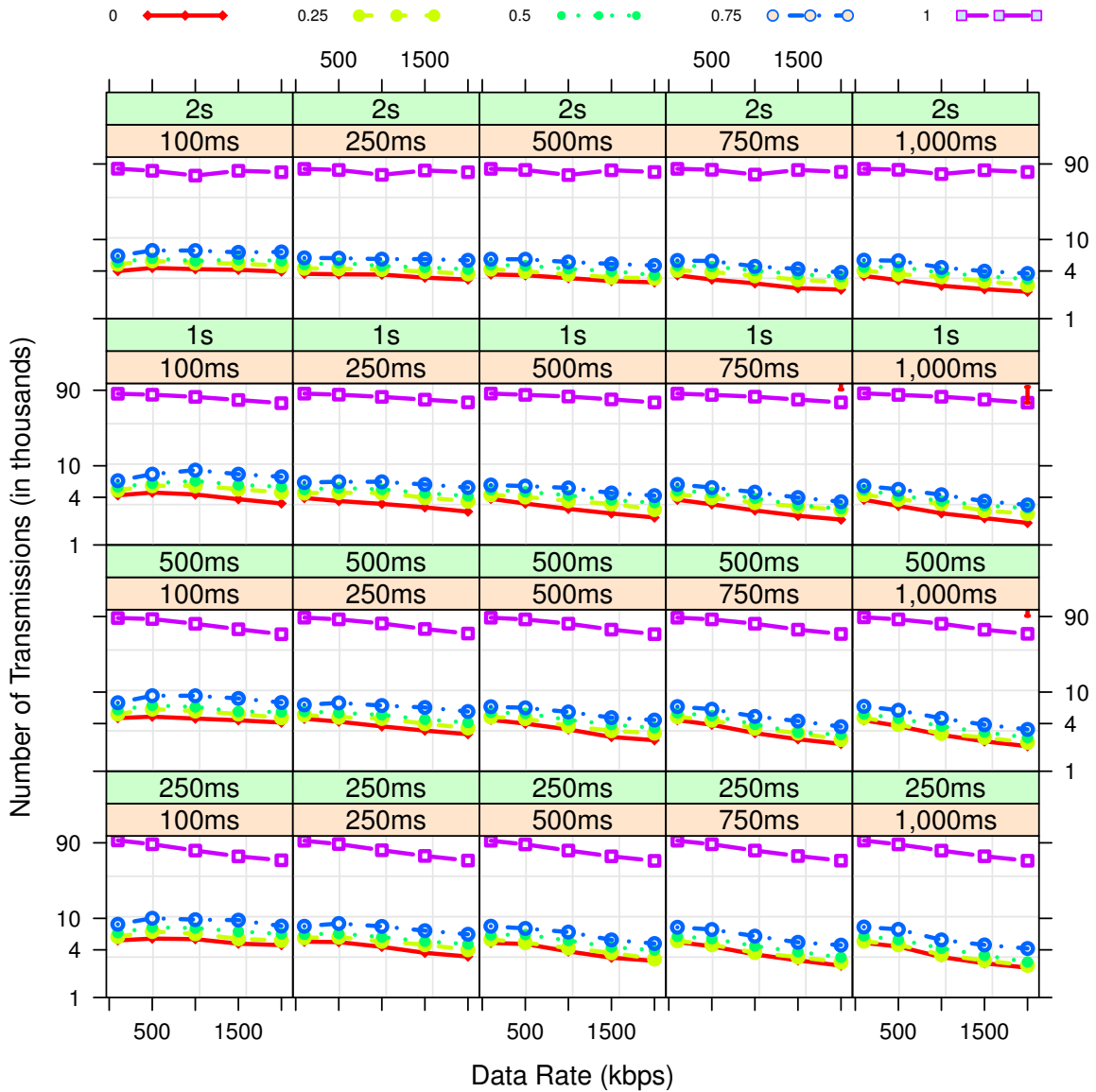


Figure 5.9: Number of Transmissions - Curves vary in the weighting factor α , rows in time between transmission of control packets ρ and columns in maximum waiting time Γ

the cost of a fewer number of transmissions. The use of 500ms as an initial value for the maximum waiting time does not necessarily impact VIRTUS performance; this is a median value which is adapted dynamically depending on the observed number of duplicates. The transmission of control packets for relay node selection at a frequency

of four per second ($\rho = 250ms$) is ideal to handle topology changes and it does not incur excessive overhead.

Although these values were selected for the next references to VIRTUS, these parameters are flexible to adapt to different network conditions. In a more stable network (high density of vehicles uniformly distributed in a well-planned city), a lower α as well as a higher ρ could be used so fewer hops would be used since geographic advancement would have higher priority while less frequently updates of relay nodes are necessary. In the other end, a higher value of α in combination with a lower value ρ could lead to higher delivery ratios and faster updated selection of relay nodes even if it incurs in higher overhead.

5.2.4 Performance Comparison

In this section, VIRTUS performance is compared with and without the Density-Aware Relay Node Selection Decoupled from Video Transmission (DADVT) extension and also to a well-known state-of-the-art solution. The goal is to show the advantages on video streaming over VANETS with a receiver-based decoupled approach for the selection relay nodes through a heuristic approach that weights both geographic advancement and link stability. VIRTUS with DADVT is compared to VIRTUS without DADVT and to CBF; and, the results demonstrate that VIRTUS without DADVT outperforms traditional receiver-based solutions and that VIRTUS with DADVT improves even further by delivering successfully video content in a timely and scalable fashion.

Contention-based Forwarding (CBF) [36, 37] is a receiver-based solution where relay node selection is based solely on geographic advancement. Every transmission through CBF triggers the relay node selection process; and, when a node decides it is suitable to forward further a received packet, this decision is valid only for this respective transmission (which is different from VIRTUS). The area-based suppression scheme of CBF makes use of the Reuleaux triangle to define its forwarding zone.

In addition to the three metrics used previously (Delivery Ratio, End-to-end Delay and Number of Transmissions), video quality as the average PSNR and Video Receiving Rate were also evaluated. PSNR is a metric that measures the quality of received frames when compared to the original content. PSNR is directly proportional to the observed video quality and a PSNR of 40 reflects a received video that matches closely the perfection of the original video. We evaluate the performance of these protocols for increasing network data rates with the goal of understanding their performance in the context of the transmission of a higher quality video. However, the most important element is video

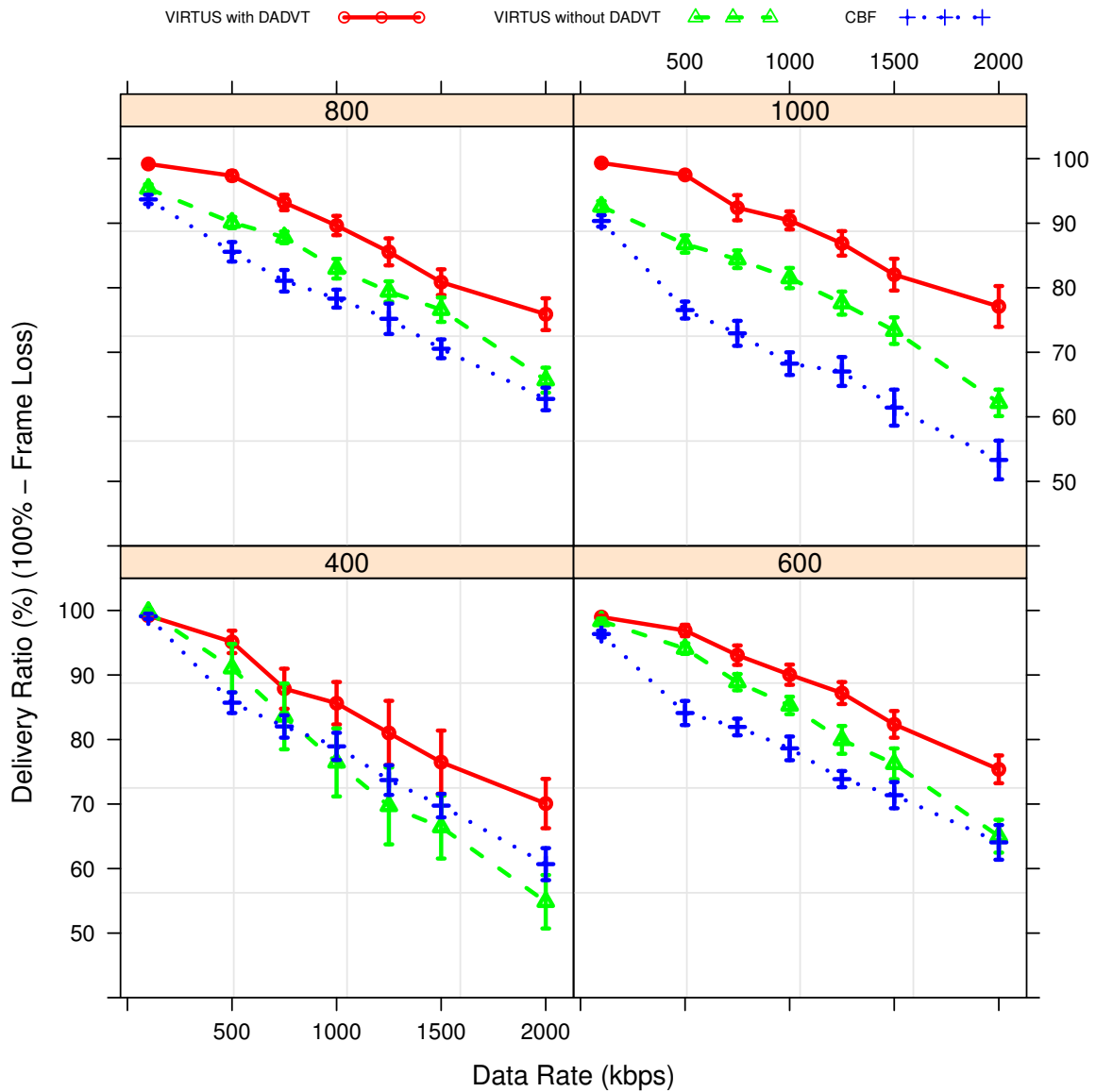


Figure 5.10: Delivery Ratio

quality that can be displayed at the end users. For this reason, the rate at which video is received at the destination was considered.

Figures 5.10 to 5.14 display the results of the aforementioned metrics on the y-axis, while the x-axis varies in the used network data rate for transmissions at the source node. Each curve represents one solution and each graph corresponds to different densities varying in topologies from 400 to 1,000 vehicles.

The delivery ratios achieved by each solution at each scenario are shown in Figure 5.10. As expected, increases in network data rates lead to lower delivery ratios due to more intense competition for the wireless channel. VIRTUS with DADVT achieves higher averages in all scenarios. We can observe that at a lower density (400 vehicles), the confidence intervals are larger and this is explained by the fact that, at this density, the network is not always connected. Therefore, depending on the instance of mobility used, connectivity between source and destination varies significantly. At higher densities, it is noticeable that the performance of VIRTUS with DADVT is more stable with further increases in density than VIRTUS without DADVT which is more stable than CBF. This is a result of preventing the frequent selection of relay nodes. CBF conducts this selection for every single transmission; thus, in denser scenarios, too many vehicles decide to become relay nodes which causes collisions. VIRTUS with DADVT only conducts a receiver-based relay node selection through the transmission of control packets sent at a much lower frequency than packets carrying video content. Combined with the dynamic adaptation of the maximum waiting time, VIRTUS with DADVT maintains its performance with increases in density.

Figure 5.11 shows the PSNR achieved by each solution. These results are closely related to that observed in terms of delivery ratio but they are intensified. Video coding aims to achieve high compression rates so transmitted data carries as much information as possible. For this reason, small amounts of lost data incurs severe losses of video quality. Large confidence intervals are also observed; this great variance of results is due to the different impact on video quality that is directly linked to the type of data contained in packets. H.264/MPEG-4 codec uses different types of frames; in this codec, a few high quality frames (i.e. I-frames) are used as a base for lower quality frames (i.e. P and B frames). The pattern of packet loss in these solutions is highly uniform; thus, the high variance in PSNR is due to the fact that depending on which packets are lost under the same packet loss percentage, different PSNR averages are observed.

We have also used SSIM as a video quality metric to evaluate the performance of these unicast solutions, shown in Figure 5.12. The behavior of the solutions in terms of SSIM is similar to PSNR, however, low loss ratios lead to less severe degradation since SSIM measures distortion which is more resilient. With further increases in losses (as observed in Figure 5.10), VIRTUS without DADVT and CBF observed stronger degradation in SSIM. This happens specially in denser regions because these solutions suffer from the issue of problems cancelling other transmissions which lead to even further collisions. This phenomenon also incurs in bursts of losses which have a stronger impact

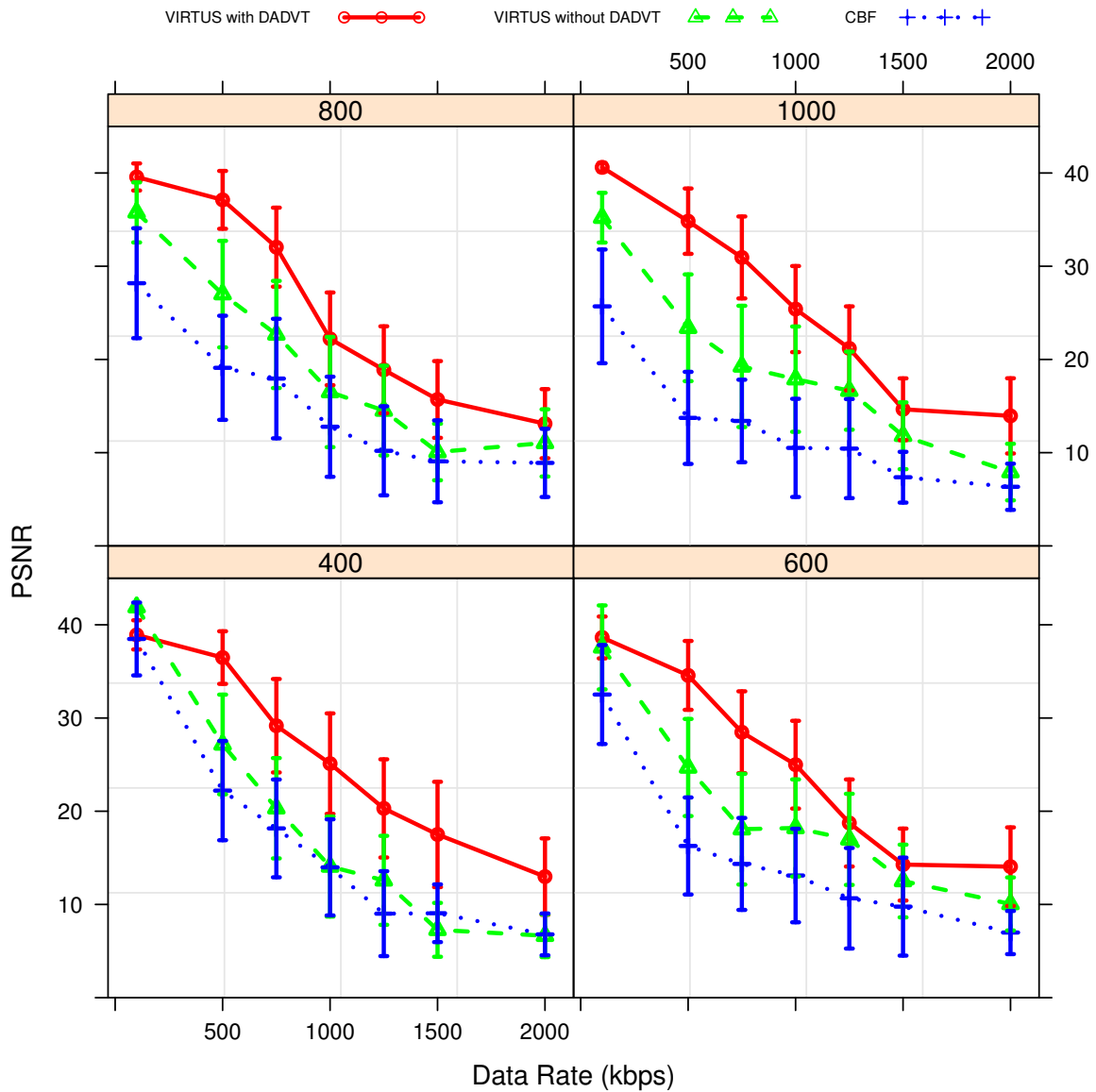


Figure 5.11: PSNR

on SSIM than scatter loss which is more common in VIRTUS with DADVT. These results corroborate that VIRTUS with DADVT is able to delivery better quality videos to the destination.

The end-to-end delay is shown in Figure 5.13 and it can be seen that all of the solutions fulfill video streaming delay requirements (according to [118] delay for video streaming should not exceed 5 seconds). Nevertheless, it is also noticeable that VIRTUS

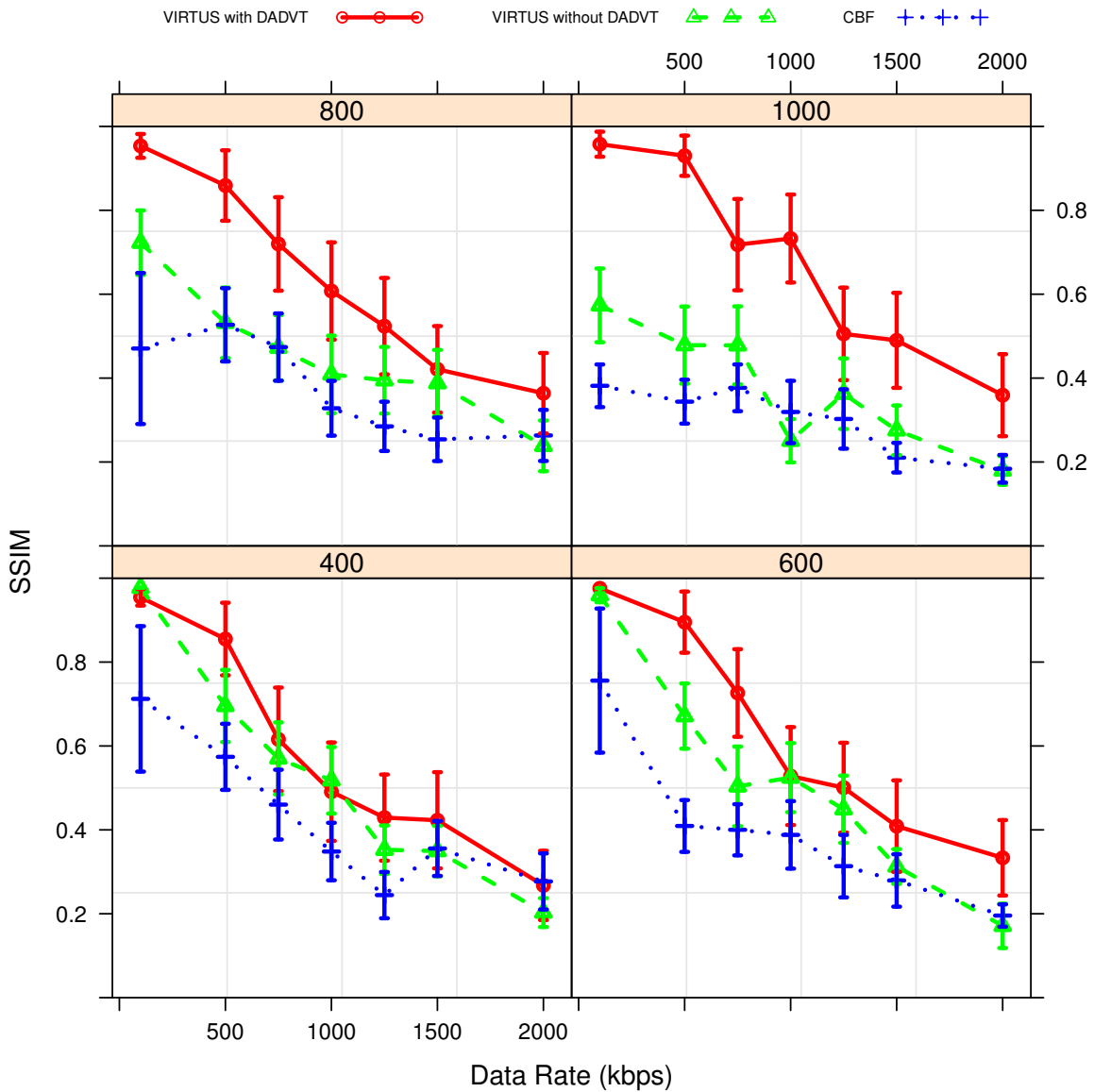


Figure 5.12: SSIM

with DADVT achieves the lowest end-to-end delay. This is expected because unlike the other solutions, video packets are always immediately forwarded by relay nodes, since the selection of these nodes is, instead, conducted through the transmission of control packets. The increases in delay observed by VIRTUS without DADVT and CBF at higher data rates is caused by the increases in the number of collisions of nodes that use a short waiting time and the prevalence of successful transmissions by nodes with a

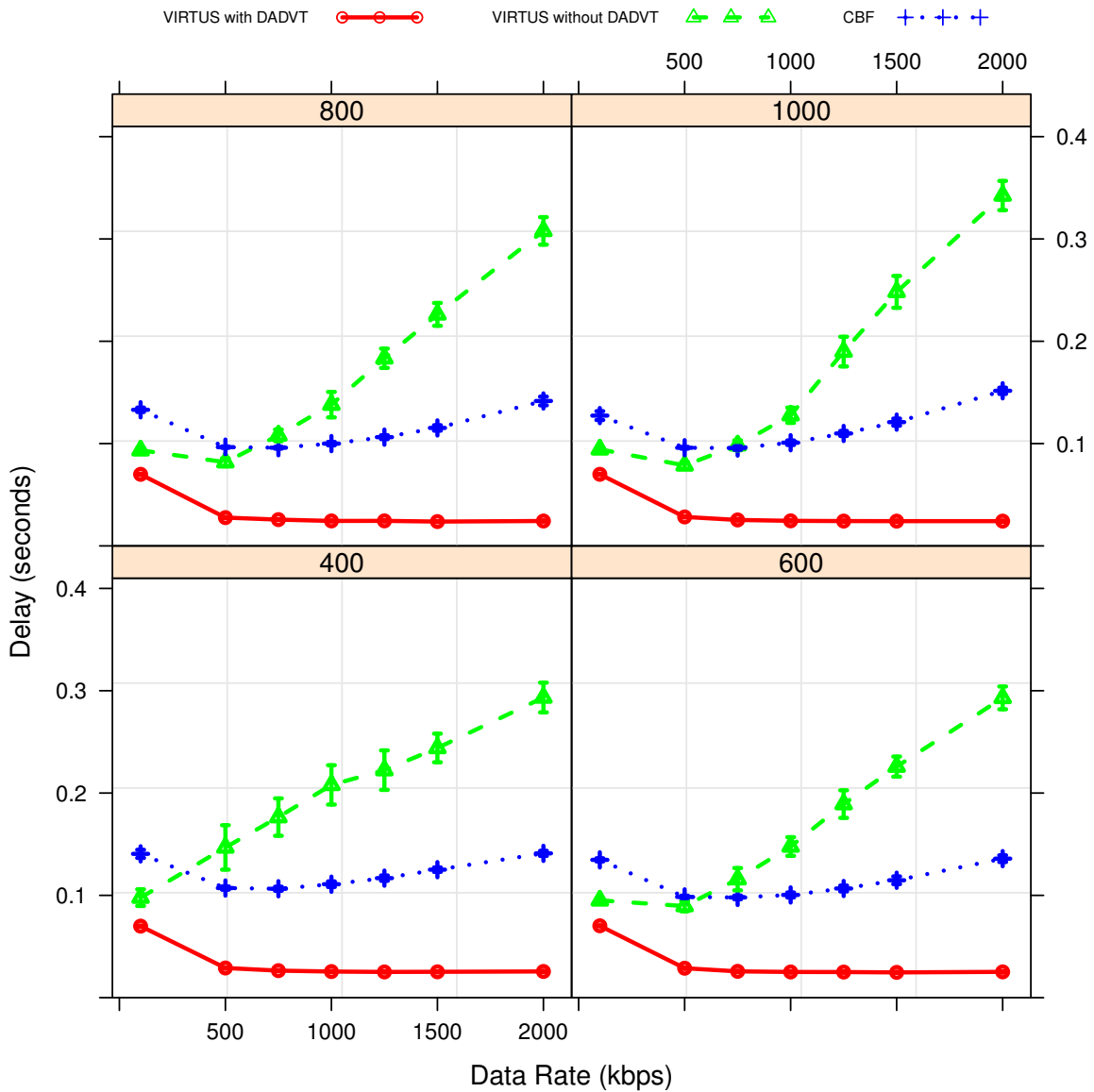


Figure 5.13: End-to-end Delay

longer waiting time.

Figure 5.14 displays the Video Receiving Rate by each solution. It is noticeable a proportional correlation between the Data Rate used to transmit the video; however, the transmission rate is not 100% converted to the video receiving rate (e.g. transmitting at 2,000 kbps never led to a video receiving rate above 1,500 kbps). This discrepancy is caused by packet loss and by a receiver-based approach where intermediary nodes post-

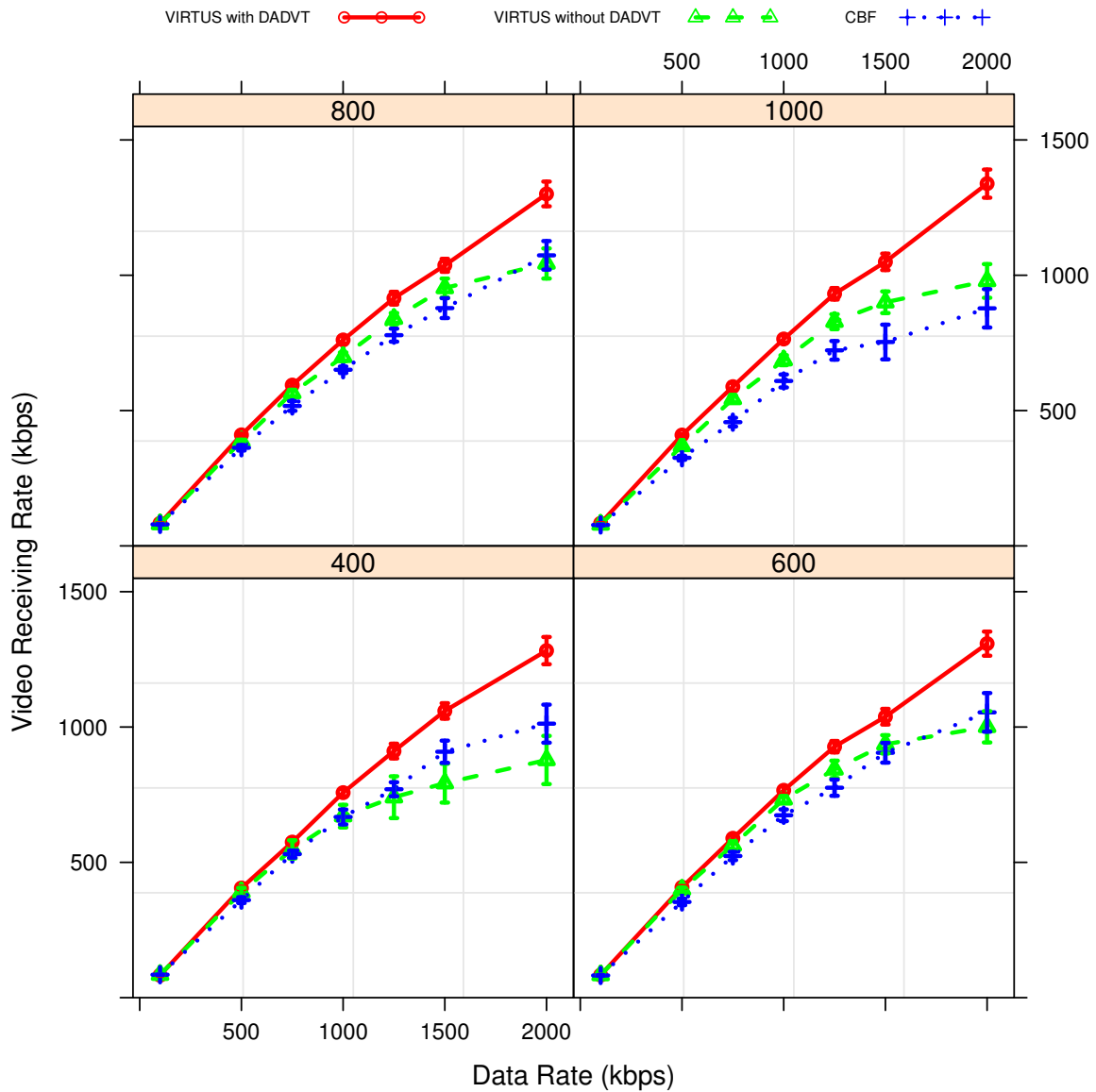


Figure 5.14: Video Receiving Rate

pone forwarding received packets. VIRTUS with DADVT achieves the highest delivery ratios and it does not require intermediary nodes to wait to forward further received packets. Because of this, VIRTUS with DADVT was able to achieve the highest video receiving rates.

We have compared the performance of these solutions in terms of scalability to increases in vehicles density and data traffic. Figures 5.10 to 5.14 already show the im-

improvements of VIRTUS over CBF with variations of vehicles density. VIRTUS with DADVT shows the best improvements since it adapts the maximum waiting time according to density. In Figure 5.15, we compare the performance of the three solutions in how they scale in cost (number of transmissions) with increases on density. It can be seen that VIRTUS with DADVT sustained the same level of cost while VIRTUS without DADVT and CBF observed significant increases in number of transmissions, the later with a steeper increase. The reason for this is due to the difficulty in performing proper cancellations when density is high and different nodes have similar waiting times. This leads to more simultaneous transmissions which incur collisions that degrade further the cancellation process. Since VIRTUS adopts the perspective of the selection of a relay node to last for a period rather than a single transmission, the issue is minimized. Furthermore, DADVT module of VIRTUS handle this problem with both an adaptive maximum waiting time that increases in dense regions, and, the decoupled transmission of video content from relay node selection. The later prevents that high transmission rates of video impact the cancellation process.

In order to evaluate the solutions scalability to increase in data traffic, we have run simulations where all nodes in the network transmit noise data (irrelevant content) at specified rates. Figures 5.16(a) and 5.16(b) show the results for increasing noise transmission rates in terms of delivery ratio and PSNR, respectively. In these simulations, the transmission rate of video content is of 500 kbps and the topology is used with 600 vehicles. Although all solutions observed decreases in delivery ratio and PSNR for higher noise rates, CBF deterioration was significantly steeper. Increased data traffic causes collisions and this impacts the solutions in different ways. In CBF, these collisions prevents successful relay of packets to cancel other transmissions. Furthermore, the unnecessary transmissions lead to more collisions creating a cycle that significantly degrades the protocol performance. VIRTUS without DADVT suffers from a similar problem but the mechanism of previously selected relay nodes to forward packets immediately prevents from falling into this cycle of increasing collisions. The problem with VIRTUS with DADVT due to increasing data traffic is due to collisions that prevent a successful relay of video content. However, the results show that this lead to the lowest deterioration of performance.

This thorough examination of VIRTUS performance and its performance comparison in highly realistic simulations proves the benefits of using VIRTUS (specially with DADVT). The main motivation in the use of DADVT on VIRTUS is to improve scalability in terms of both increases on transmission rates and increases on density. With

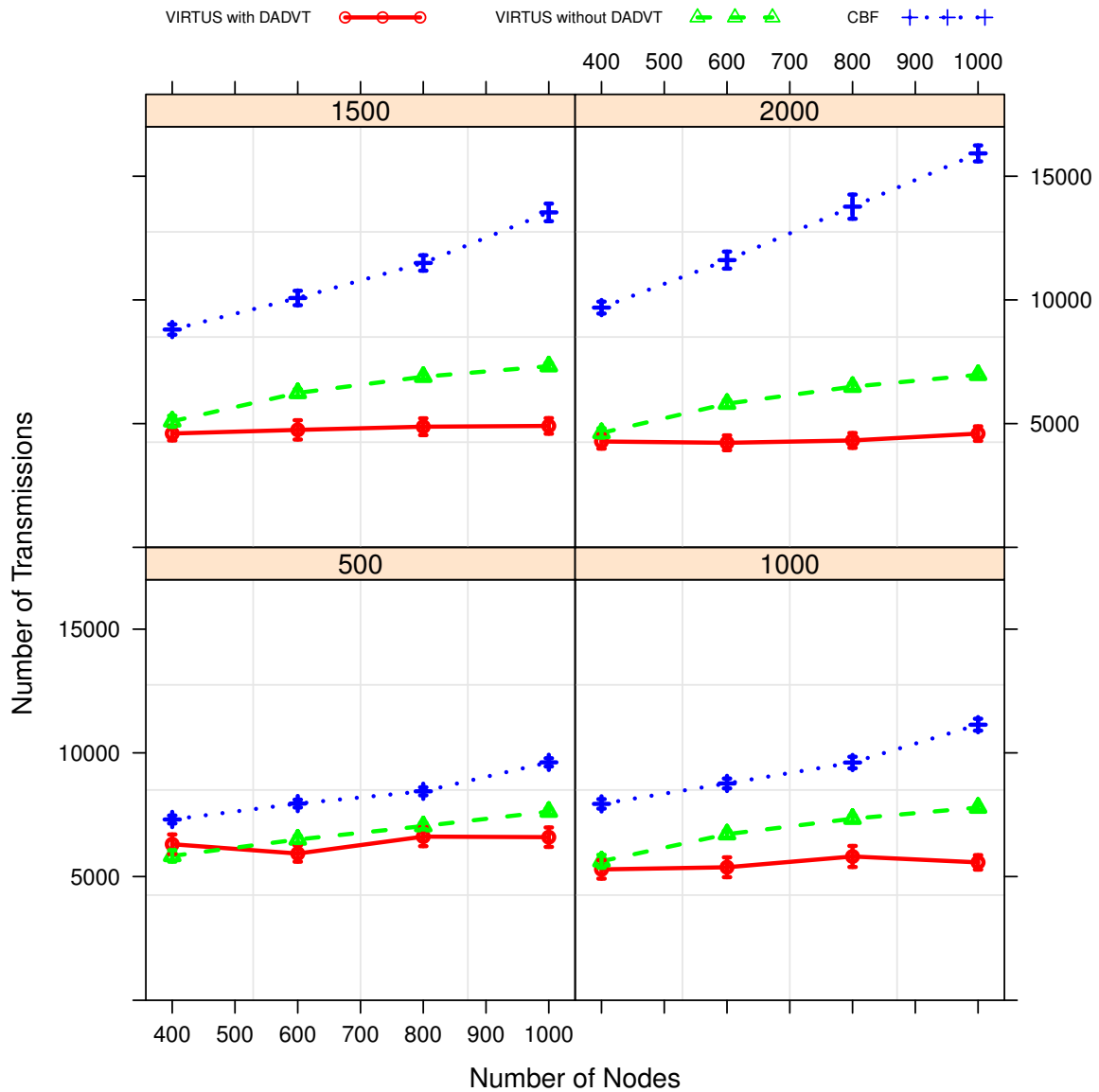


Figure 5.15: Number of Transmissions

a video transmission decoupled from relay node selection, higher transmissions rates do not cause collisions on the cancellation process of receiver-based solutions. This mechanism combined with a density-aware approach lead to the improvements perceived by VIRTUS with DADVT over VIRTUS without DADVT. VIRTUS perspective on the receiver-based paradigm with a policy on relay node suitability weighted between geographic advancement and connection stability combined with a longer duration of relay

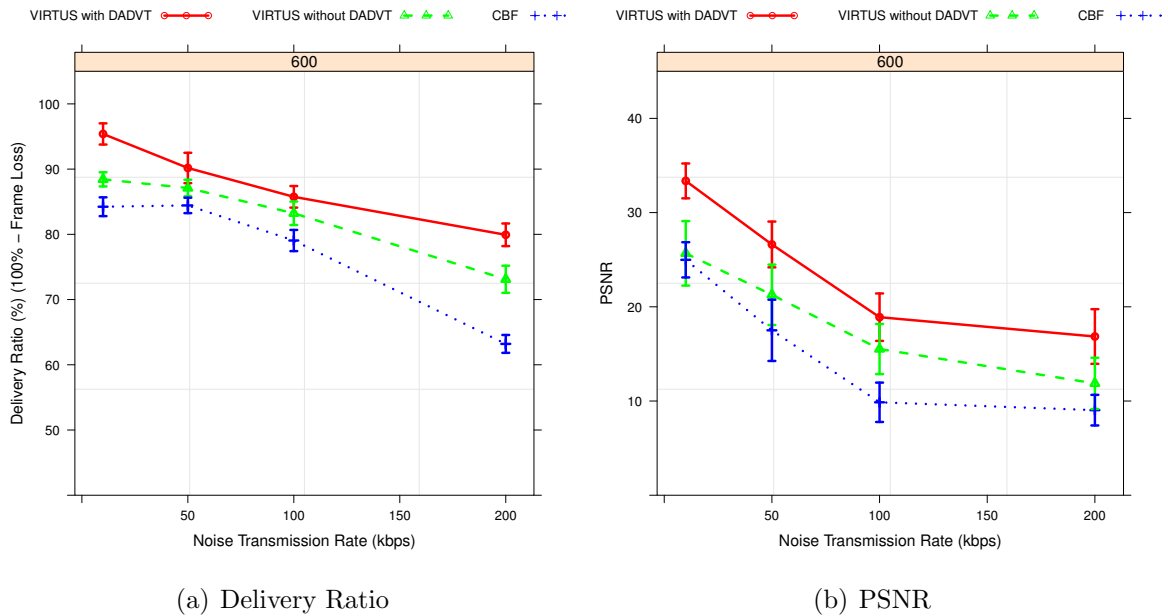


Figure 5.16: Scalability in regards to data traffic

node selection (instead of being for only a single transmission) was shown to be effective for video transmission over VANETs when compared to CBF.

5.3 Final Remarks

Unicast video streaming is essential for the deployment of valuable services over VANETs. However, its stringent requirements apply a significant stress on VANETs' challenges. In this chapter, we have presented and evaluated a highly reactive solution, namely VIRTUS.

VIRTUS takes into consideration the peculiarities of video streaming and extends the duration by which a node is considered suitable to forward packets in a receiver-based approach to a time window instead of only for a single transmission. In this new approach, VIRTUS determines the suitability of a node to relay packets based on a balanced decision between geographic advancement towards the destination and connectivity stability. VIRTUS is shown to outperform traditional receiver-based solutions for unicast video streaming over VANETs.

Connectivity stability in VIRTUS is estimated based on predicted duration of geographical proximity between vehicles. As explained in [100], the prediction model used is a bayesian state estimation with a motion model based on particles filter. The use

of such prediction model dictates the balance between achieved accuracy and computational cost. Although this impacts VIRTUS performance, the protocol is flexible for the use of any other prediction model. The results observed show a suitable exploitation of computational power for the achieved accuracy.

VIRTUS is also extended by separating the process of relay node selection from that of video transmission. This was shown to be beneficial as it solves the issue of performing cancellations properly even when video content is sent at high data rates. Furthermore, VIRTUS notices duplicated transmissions and correlates this information to vehicle local density estimations; and, based on this estimation, it adapts dynamically the maximum waiting time to avoid simultaneous transmissions. This Density-Aware Relay Node Selection Decoupled from Video Transmission extension was shown to be greatly beneficial.

This chapter offers an in-depth understanding of the issues on the provisioning of unicast video streaming support over Vehicular Ad Hoc Networks. Extensive experiments were conducted over highly realistic simulations that support the valuable conclusions reached.

A detailed description of VIRTUS was provided and it has been thoroughly evaluated. We have showed that VIRTUS improves on the previous solutions and presents itself as an efficient and effective mechanism to stream video from one node to another over VANETs. It is clear in the results that receiver-based solutions are highly suitable to react and handle the frequent topology changes in VANETs. VIRTUS perspective of extending relay node selection for a time window was shown to be greatly beneficial. Furthermore, VIRTUS strategy on decoupling the process of relay node selection from that of video transmission was proven to obtain the best results in terms of the quality of videos received, end-to-end delay and transmission cost.

Chapter 6

The Impact of Redundancy

The use of redundancy to achieve higher delivery ratios in VANETs has already been suggested [125, 67, 111]; but, in this chapter we go through an extensive analysis of its benefits for the specific case of video streaming. We discuss the advantages and disadvantages of using Erasure Coding and Network Coding for an efficient use of redundancy. This chapter covers the scenarios for both video unicast and video dissemination.

The contributions in this chapter are divided in mainly 4 parts: i) a thorough study on the issues inherent in using redundancy for video streaming over VANETs for both unicast and dissemination; ii) an evaluation on the benefits of two novel solutions: XOR-based Coding and the Hybrid solution; iii) the demonstration of the improvements on a novel approach that uses additional redundancy selectively in I-frames data only; and, iv) an extensive comparison provided on solution performance through the perspective of the receiving rates of unique video content.

The importance of the latter contribution is due to the strong correlation between the video quality that can be displayed to users and the data rates by which videos can be received at applications on receivers. The use of additional redundancy by Erasure Coding particularly impacts the transmission rate of unique video content; and, it is important to study the trade-off between improvements on delivery ratio and the decrease on this rate.

Section 6.1 provides a summarized discussion regarding the use of coding strategies for an efficient use of redundancy. The peculiarities involved in the use of redundancy for video unicast and video dissemination are discussed in Sections 6.2.1 and 6.2.2, respectively. Section 6.3 describes the selective use of redundancy in I-frames and presents a thorough performance comparison of the different strategies for both video dissemination

and unicast. The conclusions and future work are presented in Section 6.4.

6.1 Redundancy

Vehicular Ad Hoc Networks are prone strongly to packet loss mainly due to intermittent connections between nearby vehicles and communication congestion. Therefore, it is necessary to provide mechanisms that are able to recover from frequent losses. This is particularly important for video streaming that requires high rates of successful data delivery.

Interactive error correction mechanisms are not suitable to video streaming over VANETs because the exchange of messages between receivers and senders are not necessarily reliable or timely. The delay caused by the time spent detecting the loss of content at receivers, notifying the source node and retransmitting such information is prohibitive for a continuous playback at receivers. This issue is aggravated in a video dissemination scenario as this would incur excessive use of the available bandwidth for notifying and retransmitting.

The use of redundancy is an elegant asynchronous way of handling packet loss. It does not require any interaction between receivers and video transmitters. In the next sections, the important peculiarities surrounding the use of redundancy for video streaming over VANETs are discussed. The most important aspects of these different strategies are summarized in Table 6.1.

6.1.1 Coding Techniques

The most naïve approach for handling packet loss is conducted through the transmission of simple copies of every packet sent. In this manner, when a packet is lost, it can be eventually recovered through the reception of another copy that was transmitted. Nevertheless, the transmission of copies incur excessive overhead and its effectiveness is subject to the pattern of packet loss.

A more efficient approach in terms of entropy can be provided through the use of some coding techniques [43, 72]. These techniques use information theory to improve the use of redundant transmissions; this is done by encoding the original content in such a way that partial reception of all encoded information sent incurs higher delivery ratios of the original content. These coding techniques tackle uniquely how to assemble encoded packets.

The majority of well-known coding techniques can be classified in the following two groups: in the first some variation of linear coding is considered; while, in the second, XOR bitwise operations are used. In the next sections, these two groups are presented.

6.1.1.1 Random Linear Coding

Linear Coding consists of dividing the original data content into blocks that are further divided into segments of the same size; these segments are then linearly combined into encoded packets that are used to solve the linear system at the receiver end for a full decoding of the original content. The different Linear Coding approaches are mainly distinguished by how coefficients are selected to encode each packet.

Random Linear Coding [43] (RLC) chooses randomly the coefficients to encode a packet; this has the advantage of presenting a very simple complexity while it maintains an extremely low probability of using linearly dependent vectors of coefficients. In this work, the vector of coefficients used to assemble the encoded information in a packet is defined by one single seed number employed by the same pseudo-random number generator. In this way, the need for an excessively large packet header is avoided.

RLC may impact video streaming end-to-end delay depending the pattern of packet loss it observes. A block of the original information is only completely decoded upon receiving the last necessary encoded packet. For this reason, if the delay in the reception of the necessary number of packets for the full decoding of a block is significant, the delay in the reception of video content could be excessive [77]. The use of RLC for video streaming causes the received packets to be grouped into blocks which changes the pattern of packet loss.

6.1.1.2 XOR-based Coding

The properties of exclusive or (XOR) are suitable for combining arrays of unique data into a single array which is later useful for gathering the original information at receivers. The solutions that employ XOR operations for an efficient use of entropy differ mainly in respect to the distribution of the number of parts and the particular parts used for composing encoded packets.

There are some well-known coding techniques based on XOR operations, such as LT Code and Tornado Code [72]; and, Raptor Code [115]. These coding techniques are

designed for networks with lower packet loss rates than those of VANETs; thus, they are intended to receive the whole original content. In a network with higher packet loss rates like that of a VANET, it is necessary to design coding solutions that provide partial recovery of content with partial reception of a block [73].

We have developed a simple degree distribution and segment selection policy that considers partial, rather than only full recovery. Our strategy is to initially send all packets of a block in the form of one-degree packets (i.e., not encoded) and to encode the additional packets using the smallest degrees while maintaining an uniform distribution of the original packets. Through this manner, we have increased the likelihood for received packets to result in useful information independent of how many packets per block were received.

The degree of the remaining packets depends on the amount of additional redundancy τ . All extra packets should cover uniformly all η segments of each block. With the number of packets sent per block equals to κ , the number of additional packets is $\kappa - \eta$ and the additional redundancy τ is calculated as $\tau = \frac{\kappa}{\eta} - 1$. In this thesis, additional redundancy up to 100% is considered and both the degree distribution and segment index selection depends on the indexes (i) of the extra packets. The idea is that up to 50% of redundancy (i.e. extra packet index smaller than $(\kappa - \eta)/2$), the packets combined are chosen based on a modular function of their indexes. When $\tau > 50\%$, the extra packets of index greater than $(\kappa - \eta)/2$ select packets sequentially. The degree distribution is given by:

$$d_i = \begin{cases} \max(\lceil \eta/(\kappa - \eta) \rceil, 2) & \text{if } i < \lfloor 0.50\eta \rfloor \\ \max(\lceil \eta/(\kappa - \eta - \lfloor \eta/2 \rfloor) \rceil, 2) & \text{otherwise} \end{cases} \quad (6.1)$$

And the choice of segments used for combination in each packet is either based on an interleaved or sequential pick. If the extra packet index i is less than half of the number of segments in each block, segments are selected in an interleaved manner depending on the modulo of their indexes j . Otherwise, the d_i consecutive segments are chosen. The test to determine if a segment s_j belongs to the set which will be combined to form the additional packet p_i can be described by the following equation:

$$s_j \text{ used at } p_i = \begin{cases} j = i \bmod d_i & \text{if } i < \lfloor 0.50\eta \rfloor \\ \lfloor j/d_i \rfloor = (i - \lfloor 0.50\eta \rfloor) & \text{otherwise} \end{cases} \quad (6.2)$$

For example, the additional packets for $\eta = 10$ and $\tau = 100\%$ are $p_0 = \{s_0, s_5\}$, $p_1 = \{s_1, s_6\}$, $p_2 = \{s_2, s_7\}$, $p_3 = \{s_3, s_8\}$, $p_4 = \{s_4, s_9\}$, $p_5 = \{s_0, s_1\}$, $p_6 = \{s_2, s_3\}$, $p_7 = \{s_4, s_5\}$, $p_8 = \{s_6, s_7\}$ and $p_9 = \{s_8, s_9\}$. If $\eta = 10$ and $\tau = 80\%$, the first 5 extra

packets (p_0 to p_4) would be the same while the 3 remaining would be $p_5 = \{s_0, s_1, s_2, s_3\}$, $p_6 = \{s_4, s_5, s_6, s_7\}$ and $p_7 = \{s_6, s_7, s_8, s_9\}$.

The ability of XOR-based coding to offer partial recovery of a block is beneficial to video streaming because it prevents the wasting of large amounts of received packets that can not be decoded into video content.

6.1.2 Where to Encode?

A second classification of error correction mechanisms that use redundancy has been established on the basis of where newly encoded packets are generated. The two approaches consist in either limiting encoding to only the source node or permitting and using re-encoding by intermediary nodes. Both of these solutions are discussed in the following subsections.

6.1.2.1 Erasure Coding

Wireless Erasure Networks are defined as wireless networks where links between adjacent nodes have a significant probability of losing packets transmitted through it [32]. VANETs are certainly wireless erasure networks since transmissions are strongly prone to losses, due mainly to mobility, interference and collisions.

Erasure Coding (EC) is highly suitable for erasure networks because it encourages increasing the amounts of data sent by the source node to represent the same amount of information; the idea is that the loss of a part of transmitted data does not influence the ability of receivers to obtain the original content. In EC, the original packets are encoded into a larger amount of data at the source; and, intermediary nodes may decode received packets for their own benefit (i.e. in the case of video dissemination) relaying exactly the same received packets.

XOR-based Coding is particularly well suited to EC as it is designed for assembling encoded packets composed of a larger amount of data than the minimal amount necessary for defining the original content. Furthermore, the XOR-based Coding property that allows partial recovery of block content is advantageous for the erasure nature of VANETs. The advantages of XOR-based Coding over RLC can already be seen in Section 6.2.1.1.

An extremely important point with respect to the use of EC for video streaming is the relation between the amount of additional redundancy and the rate at which video content is received in the application layer. Video streaming quality is highly correlated

to the rate at which video content can be received. Higher quality videos require higher rates. When the original video content is encoded into a larger amount of data, the reception rate of video content is potentially decreased. This issue is thoroughly discussed in Section 6.3.

6.1.2.2 Network Coding

An important aspect of VANETs communication is that transmissions are always shared among nearby vehicles. This shared communication medium creates an opportunity in the sense that single transmissions can be used for the benefit of many reachable nodes. The majority of solutions for either unicast or broadcast in VANETs consider the occurrence of redundant transmissions by neighbor nodes that share the same wireless medium.

Network Coding (NC) [2] and [69] in VANETs is aimed specifically at making more efficient use of the shared medium by requesting that intermediary nodes transmit newly encoded packets [65, 91]. Through this manner, transmissions observed by neighboring nodes are always valuable towards gathering the original content transmitted, instead of gathering simply duplicates. In NC, intermediary nodes wait for the reception of enough packets before decoding a block, and re-encoding the original content into newly encoded packets which are then transmitted further. NC techniques have to offer great diversity in the packets newly encoded by intermediary nodes and to make sure that the reception of such packets is relevant to gathering the original information at receivers.

Because of this need for diversity, Random Linear Coding (RLC) is highly suitable for use in NC. Intermediary nodes can use the decoded content to encode packets using a new vector of random coefficients. In a field of a reasonable size, it is highly unlikely that any two vectors of random coefficients are linearly dependent. XOR-based Coding could be used, however, the options for efficient degrees and segments selection are restrictive in terms of diversity.

The use of NC for video streaming is prone to increasing delays the further a vehicle is from the source of the video content. At each hop of communication, the time spent by intermediary nodes waiting for the reception of enough packets to decode a full block could be prohibitive as it accumulates.

		Advantages	Disadvantages
Coding Technique	Random Linear Coding	high diversity; packets have same role towards decoding	received packets may not lead to useful video content
	XOR-based Coding	allows partial recovery of a block	low diversity; requires additional redundancy
Where to Encode?	Erasure Coding	an asynchronous mechanism for retransmission of eventual lost content	decreases the transmission rate of unique video content
	Network Coding	takes advantage of inherent redundancy in multiple transmissions of nearby nodes	increases delay as nodes are further away from source

Table 6.1: A summary of the impact of redundancy on video streaming over VANETs

6.2 Redundancy in Video Streaming

Video streaming poses stringent requirements specially regarding successful delivery ratios and end-to-end delay [118]. Video streaming consists of streaming video content in a close to real-time manner in which delay can not exceed a few seconds. It is also fundamental to provide solutions that delivery the vast majority of the content transmitted since error correction mechanisms that requires interaction between receivers and transmitters may deteriorate prohibitively the experience end-to-end delay.

VANETs are particularly a challenging scenario for video streaming due to its highly dynamic topology, shared wireless communication medium and bandwidth constrains. The combination of VANETs' challenges to the requirements of video streaming requires the investigation of novel solutions for packet delivery.

In the next sections, the discussion on the impact of the use of redundancy in video streaming is divided according to video unicast (Section 6.2.1) and to video dissemination (Section 6.2.2).

6.2.1 Redundancy in Video Unicast

Unicast solutions over VANETs aim to achieve high delivery ratios with the least amount of transmissions possible. For the sake of scalability, it is important to provide unicast

solutions that prevent the frequent occurrence of multiple retransmissions of the same packet.

The undesirability of multiple retransmissions in unicast solutions reduces the applicability of NC. NC requires intermediary nodes to decode and re-encode new packets with the purpose of increasing the value of eventual duplicates. Since these duplicates are limited in unicast solutions, the use of NC for unicast purposes is not practical.

On the other hand, EC is highly suitable for video unicast over VANETs since it does not depend on multiple retransmissions but rather on redundant transmissions from source to destination. Other error correction mechanisms for unicast solutions rely on interactions between destination and source which is problematic since such interactions are also highly susceptible to loss.

6.2.1.1 Preliminary Analysis

In this preliminary evaluation, an initial study on the use of XOR-based Coding and RLC for the sake of video streaming is provided. Aspects of their use such as block size and the amount of additional redundancy are investigated. These coding techniques are evaluated through Erasure Coding (see Section 6.1.2.1) over the video unicast solution VIRTUS without the density-aware relay node selection decoupled from video transmission mechanism (see Chapter 5).

This evaluation was conducted through simulations in the Network Simulator 2 (NS2) [85]. Vehicles use IEEE 802.11b for their wireless communication with a radio range of 300 meters. In the evaluated scenario there is 12 km long highway with 600 vehicles (50 vehicles/km) moving in both directions. The source node is placed at 1 km while the destination at 11 km. The highway scenario already provides a realistic level of packet loss expected to be observed in VANETs. This is important to evaluate the performance of coding techniques.

In this preliminary analysis, the performance is considered in terms of delivery ratio. In these results, delivery ratio was calculated as 100% minus the percentage of lost frames. It is already evaluated the impact of transmissions rates in the use of redundancy; besides its relation to the video quality that can be supported, it offers an opportunity to evaluate the coding techniques under different levels of packet loss. The amount of additional redundancy varied from 0% (no redundancy used) up to 100%, with steps of 20%.

The results in Figure 6.2 when 0% additional redundancy is used represent the performance of the underlying solution (VIRTUS). Therefore, it can be seen a clear decrease in

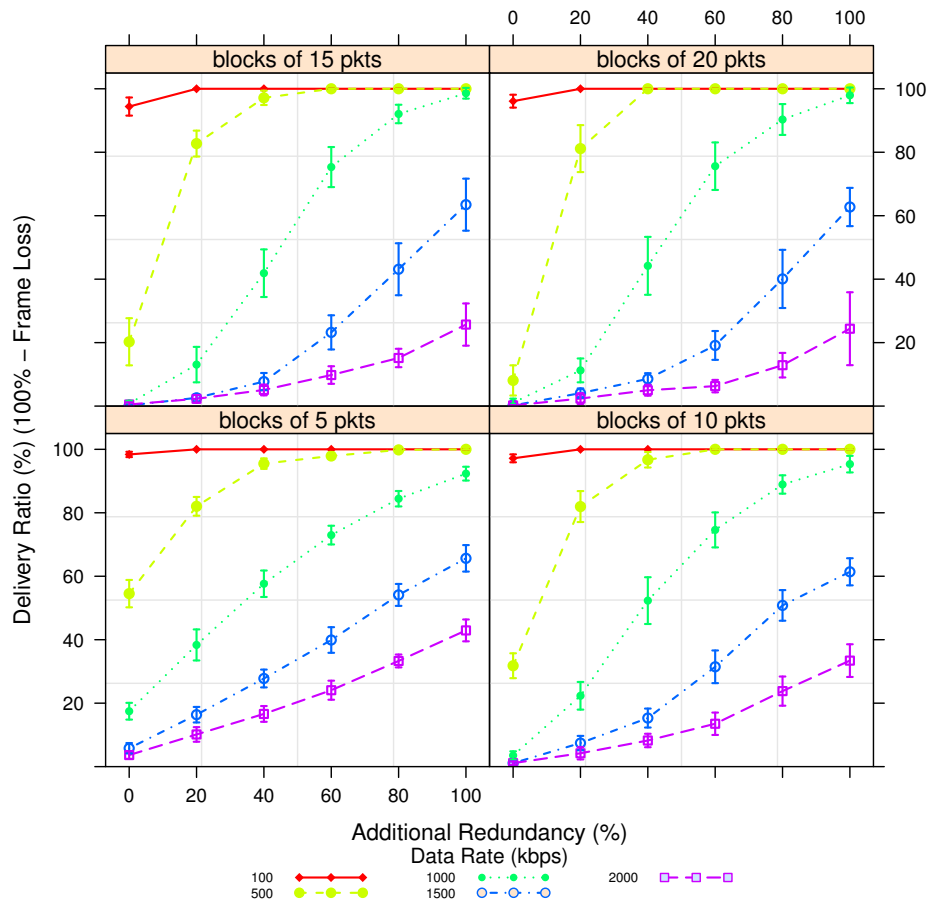


Figure 6.1: Unicast Video Streaming - Delivery Ratio - Random Linear Coding

delivery ratios for higher transmission rates when no redundancy is considered; it drops from close to 100% at 100 kbps to close to 50% at 2,000 kbps. This is due to the fact that at higher rates, the wireless channel is busier; this leads to increases in collisions. However, it is important to evaluate the use of higher transmission rates because higher quality videos require such rates. Later, in Section 6.3, the importance of using instead the receiving rate of video content at the application layer is discussed.

Figure 6.1 shows the delivery ratios achieved with the use of RLC. When the underlying loss of the unicast solution is higher (i.e. higher data rates), the feasibility of the use of RLC is drastically reduced due to its inability to provide partial recovery of a block.

A correlation between the best block sizes and the underlying delivery ratios is noticeable. With lower delivery ratios observed at higher data rates, smaller blocks were

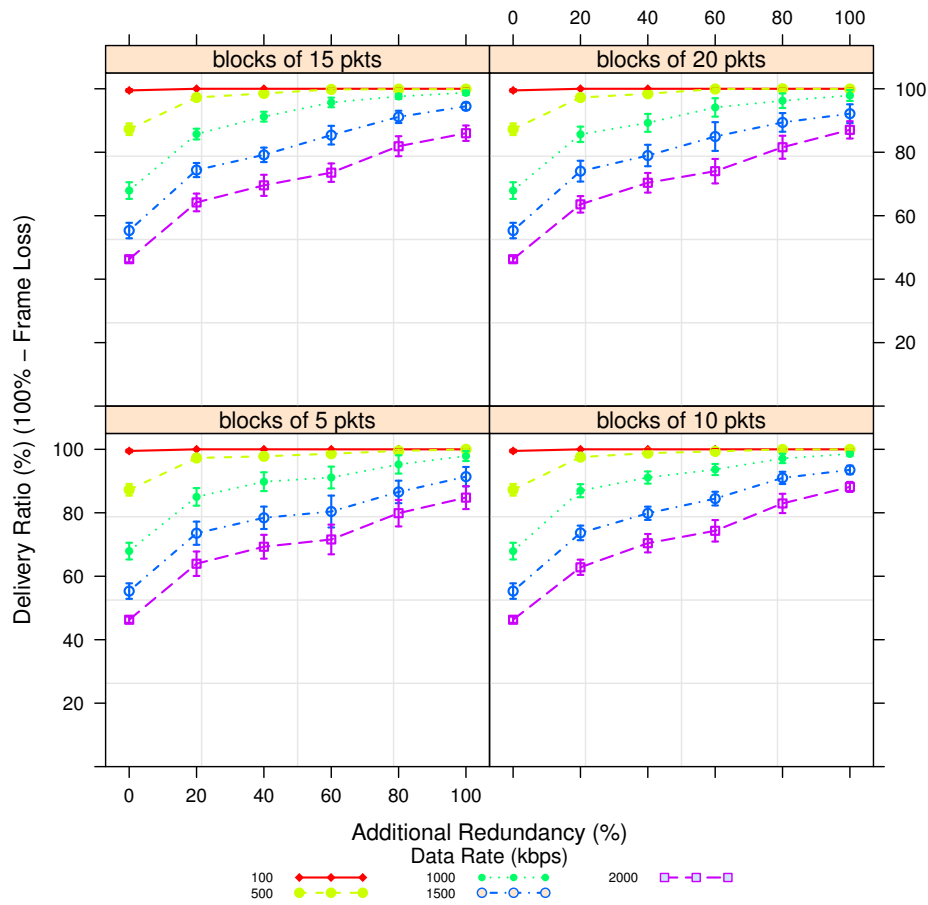


Figure 6.2: Unicast Video Streaming - Delivery Ratio - XOR-based Coding

more favorable. On the other hand, at higher delivery ratios observed at lower data rates, larger blocks should be used. The main concept is that the importance of a single packet is inversely proportional to the size of a block. Therefore, at higher delivery ratios it is more beneficial to decrease the relevance of eventual lost packets; while, at lower delivery ratios, it is better to increase the relevance of less frequently received packets.

XOR-based Coding was able to achieve higher delivery ratios, as seen in Figure 6.2. Although larger amounts of additional redundancy lead to increasingly higher delivery ratios, these amounts require a larger number of transmissions and reduces the rates of transmission of unique video content. This latter topic is further discussed in this chapter (Section 6.3.2.2). It can also be observed in the results that smaller degrees lead to better delivery ratios. This is particularly noticeable if we compare the increase

of additional redundancy from 40% to 60%. Based on the degree distribution, the new packets composed due to additional redundancy above 50% have a degree initially higher than the expected degree 2 of the previous packets. This is the reason for the less step increase in τ from 40% to 60%. Therefore, it can be understood that packets with greater degrees are not as useful as the ones with lower degrees.

When both results are compared (Figures 6.1 and 6.2), for transmission rates up to 1,000 kbps, RLC and XOR-based coding achieved close to 100% delivery ratio. However, RLC required much higher amounts of additional redundancy (at least 20 percentage points more). For higher transmission rates, XOR-based coding achieved close to 90% of delivery ratio while RLC did not offer ratios higher than 70%. As explained, this is due to the lack of support of partial recovery when RLC is used.

6.2.2 Video Dissemination

The task of dissemination in VANETs presents an inherent redundancy since vehicles in the network usually observe the relay of packets from more than one other node. In VANETS, it is usually unfeasible to reach maximum coverage using only transmissions by nodes that would only reach previously uncovered nodes. It is expected that a solution that provides a high coverage, relies on transmissions that cause the reception of duplicates by nodes.

Network Coding (NC) is an opportunistic solution as it takes advantage of this inherent redundancy. With the use of NC, intermediary nodes broadcast newly encoded packets, that are never duplicated data at receiving neighboring nodes. Through this manner, these initially redundant transmissions can be used to overcome the loss of other packets.

Erasure Coding (EC) is also greatly beneficial since the dissemination process in VANETs is also strongly prone to packet loss. Although EC does not rely on an efficient use of the shared medium as does NC, the additional packets may offer better improvements to the delivery ratio.

In the case of video dissemination, we have also considered a novel hybrid approach where EC is used in the first hop of the communication while NC is used throughout further hops. NC performs well in a scenario where content is shared to multiple users that also share communication resources. However, in the beginning of video dissemination, only the source node holds the video information. If a packet is lost in the first hop, no other node in the network can provide another encoded packet to overcome this loss.

Therefore, a whole block of packets could be lost for all the remaining nodes. For this reason, in this hybrid approach, the source node uses EC to send additional redundancy in order to improve the reception and decoding of a block by one-hop neighbors. After that, the intermediary nodes (including first hop receivers) use NC to decode the received block and encode new packets. For the reasons explained in Section 6.1.2.2, RLC is used in this hybrid approach.

6.2.2.1 Preliminary Analysis

We have conducted experiments in NS2 for this preliminary analysis of the use of different strategies on the use of redundancy for video dissemination. Each plotted result is an average of 20 to 32 runs, each with a different instance of the same mobility model and different seeds for the generation of random numbers. Confidence intervals are also plotted and they are calculated based on Student's t-distribution with a confidence level of 95%. All results and statistical measurements are generated with the use of the statistical package R [94]. The simulation environment is the same as the one in Section 4.1.1 with EvalVid as a tool to evaluate video transmission and the same benchmark video. As in such section, the Urban Mobility Model was used for 1,000 nodes spread over a grid of 3,000m x 3,000m.

The size η of the blocks by which the original content is divided into has an impact on the overall performance of these coding techniques. Through preliminary experiments in Section 6.2.1.1, it could be observed that $\eta = 10$ for segments of size of 1,000 bytes has shown to be the best option. This size is sufficient to balance the uniqueness of encoded information and the impact of packets that were received but could not be decoded into useful content. For the Random Linear Coding, the use a finite field F^{32} has proven to be sufficient for a very unlikely occurrence of encoded packets with linearly dependent vector of coefficients.

As the underlying dissemination protocol, REACT-DIS (see Chapter 4, Section 4.1). This solution by itself with no encoding was also evaluated and showed in the results for comparison purposes.

Video quality is strongly related to the network's ability to support transmissions at higher data rates. For this reason, the evaluation in this section is conducted for different levels of data rates. The network data rate is always clearly defined, and for most of the coding techniques, an additional redundancy is included at the source node to make a fair comparison. Therefore, the Unique Content Data Rate (UCDR) is considered instead of the simple network data rate, which is the rate that original unique content

Network	Redundancy	Unique Content	Network	Redundancy	Unique Content
500 kbps	40%	357 kbps	2000 kbps	100%	1000 kbps
500 kbps	20%	417 kbps	1500 kbps	40%	1071 kbps
1000 kbps	60%	625 kbps	2000 kbps	80%	1111 kbps
1000 kbps	40%	714 kbps	2000 kbps	60%	1250 kbps
1500 kbps	60%	937 kbps	2000 kbps	40%	1429 kbps

Table 6.2: Unique Content Data Rate from different Network Data Rate/Additional Redundancy ratios

is disseminated. The Unique Content Data Rate is calculated by dividing the network Data Rate per one plus the additional redundancy. Table 6.2 lists the values used in this work.

In Figures 6.3 to 6.5, the solutions are combination of Erasure Coding (EC) or Network Coding (NC) with XOR-Based Coding (XoR), LT-Code (LT) or Random Linear Coding (RLC). The Hybrid solutions uses EC in the first hop and NC for the remaining process.

The first metric considered is the delivery ratio and the results are shown in Figure 6.3. First of all, it is important to point out that throughout all the results in this section, the performance of Erasure Coding solutions that use additional redundancy at the source node follows erratic curves with continuous increases on unique content data rates. This is because in some cases, higher UCDRs are achieved by higher network Data Rates with higher amounts of extra redundancy. EC-RLC is the solution that is more severely affected by this as it is more sensitive to the problem of nodes being unable to convert the received packets into useful information. EC-RLC requires higher minimum amounts of additional redundancy for a reasonable performance. NC-RLC could not achieve delivery ratios higher than when no encoding technique is used because many times the first hop neighbours do not receive all packets of the same block transmitted by the source, which prevents any other node to receive any data from these blocks. EC-LT also did not outperform the initial solution mainly due to its approach of randomly choosing segments that compose a packet. The problem with this solution is that the η segments of a block are not uniformly covered and many times specific segments came only from packets with large degrees. EC-XOR and Hybrid-RLC improved the achieved delivery ratio for data rates up to 1,111 kbps. Their performance is very similar and statistically undistinguishable.

The next evaluation is in terms of the average delay between the transmissions of any

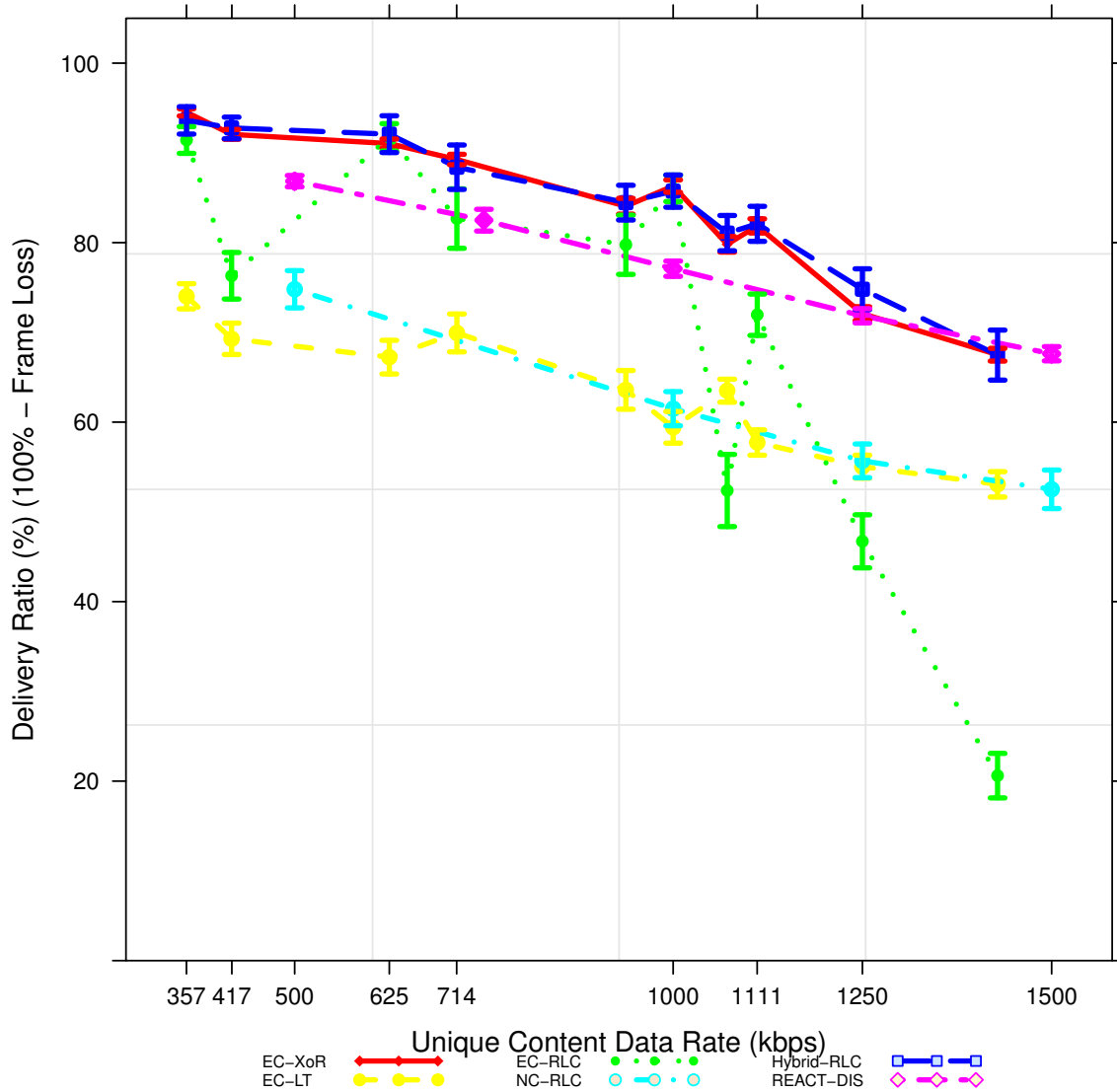


Figure 6.3: Redundancy in Video Dissemination - Preliminary - Delivery Ratio

content of a video frame at the source until its fully decoding at the receivers. Figure 6.4 depicts these results. It is clear that much higher delays are observed by the Network Coding solutions that require intermediary nodes to wait for the decoding of a block before any packet carrying content from such block is forwarded. This delay decreases when high data rates are used as the time to receive enough packets from a block is

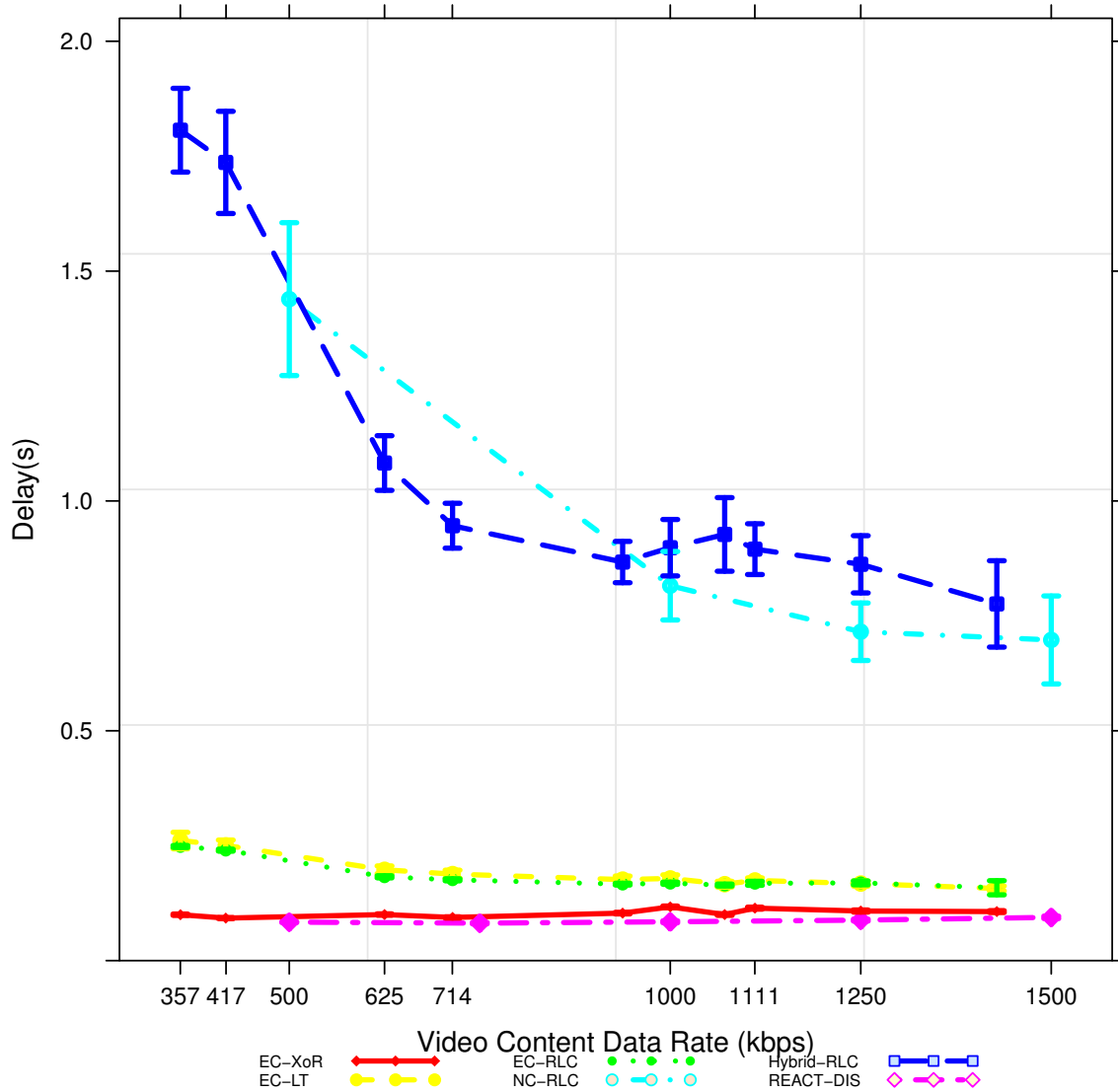


Figure 6.4: Redundancy in Video Dissemination - Preliminary - Average End-to-end Delay

proportionally reduced. Despite being larger than the other solutions, these values fulfill video streaming requirements¹.

¹In [118], CISCO specifies video streaming requirements. Among them, a delay up to 4 to 5 seconds is said to be acceptable.

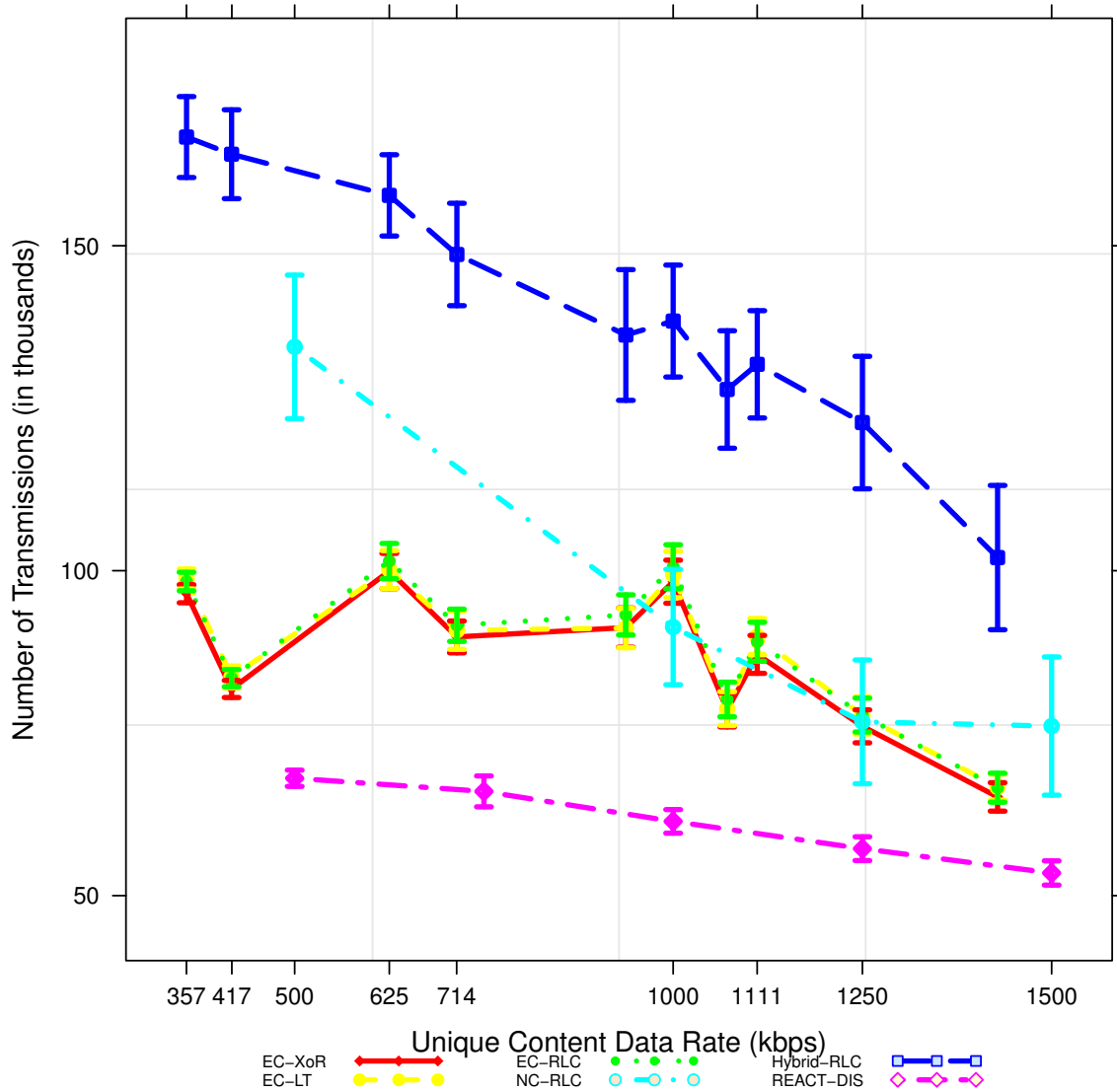


Figure 6.5: Redundancy in Video Dissemination - Preliminary - Number of Transmissions

Delivery Ratio and Delay measure the benefit of these solutions. To evaluate the trade-off between benefit and cost, the number of transmissions performed was measured for each solution. Figure 6.5 shows the observed results. The Erasure Coding solutions that use additional redundancy at the source and do not require any interaction of intermediary nodes with the content itself performed following exactly the same

trends with results being statistically undistinguishable. The reason for this is that the network layer performs exactly the same and the only change is on the content received at the application layer. This shows explicitly how different coding approaches lead to different levels of delivery ratios under exactly the same network performance. NC-RLC and Hybrid-RLC lead to a higher number of transmissions because the transmission perspective shifts from single packets to whole blocks.

The main goal in the use of coding techniques is to achieve an efficient use of redundancy, improve resilience in the presence of packet loss and increase frame delivery ratios and the quality of received video. EC-XOR and Hybrid-RLC were the solutions that achieved significant higher delivery ratios. Their delivery ratios are similar, however, EC-XOR consumes less resources (lower number of transmissions) and delivers video content with lower latency.

6.3 Selective Redundancy

Through an initial evaluation, it was observed that Erasure Coding (EC) and our Hybrid approach have obtained a better result than the use of Network Coding (NC) by itself. In the case of video unicast, it is clear that NC is unfeasible since multiple transmissions by intermediary nodes are strongly avoided. In video dissemination, NC has shown some ability to take advantage of these multiple transmissions but it is necessary to apply EC in the first hop of communication.

One of the focuses of this work is to understand the benefit of using redundancy to the detriment of rates by which video content is received at the application. The quality of video streaming is highly related to the rate by which video content can be displayed at the application layer. Therefore, it is interesting to investigate the performance of the solutions proposed here in regards to what reception rates of video content they can provide over VANETs. The use of EC is expected to have an impact on the receiving data rate because, for the same network transmission rates, less video content is sent in the same time period with increasing amounts of additional redundancy.

Another novel approach discussed in this chapter is based on the different types of transmitted data that composes a video. In this work, the H.264/MPEG-4 AVC codec has been used and it divides videos into frames of mainly three different types: I, P and B. While an I-frame represents its full content by itself, P and B frames are based on predictions of adjacent frames; a P-frame is based on an earlier frame while B-frame prediction is bidirectional. In this manner, I-frames have a stronger impact on the overall

Solution		EC	NC	XOR-based Coding	RLC	Selective to to I-frames
Video Unicast	VIRTUS	no	no	no	no	no
	VIRTUS-Erasure	yes	no	yes	no	no
	VIRTUS-Erasure-I	yes	no	yes	no	yes
Video Dissemination	REDEC	no	no	no	no	no
	REDEC-Erasure	yes	no	yes	no	no
	REDEC-Erasure-I	yes	no	yes	no	yes
	REDEC-Hybrid	first hop	yes	no	yes	no
	REDEC-Hybrid-I	first hop	yes	no	yes	yes

Table 6.3: Summary of the characteristics of considered solutions

video quality than P-frames which in turn have a stronger impact than B-frames. The amount of data needed to represent each frame follows the same hierarchy with I-frames demanding the greatest amount of data.

I propose to selectively use EC only on packets that carry content regarding I-frames. It has already been pointed out that packet loss of I-frames can substantially propagate error to predicted frames [134]. Thus, the idea is that in this way the impact on the receiving data rates can be decreased while maintaining high delivery ratios of crucial data. Besides the impact on receiving data rates, it is also expected to use less resources in terms of number of transmissions.

Table 6.3 summarize the characteristics of the solutions evaluated in this section.

6.3.1 Simulation Environment

All solutions were implemented in the Network Simulator 2 (NS2) [85]. The wireless communication is modelled to be as realistic as possible to what is expected of wireless communication in vehicle networks. The same setup was used as the one presented in Chapter 5 Section 5.2.2 with the Nakagami Propagation model and IEEE 802.11p standard. Besides the communication model, the same mobility model (SUMO) was used as well with the topology based on a region of downtown Ottawa (Ontario), Canada (as depicted in Figure 5.6). The same benchmark video was used and EvalVid [58] served as a framework to evaluate video transmission through NS2.

The dimensions of the used area are 2,556 meters per 3,004 meters. The video source location for both unicast and dissemination is a static node located in a popular intersection (it could be illustrated as a camera in a traffic light) at the location (1578m,1844m); this is slightly northeast of the center. The destination in the unicast scenario is at

(2126m,444m); this is close to the southeast corner of the region of interest. This gives the unicast scenario a distance of 1,500m between source and destination. This topology was used with three different densities: 400, 600 and 800 vehicles in the whole network.

The underlying unicast and dissemination solutions used were, respectively, VIRTUS with the density-aware relay selection mechanism decoupled from video transmission (see Chapter 5) and REDEC (see Chapter 4).

6.3.2 Results and Analysis

Thorough experiments were conducted in the realistic scenario depicted in the previous section. The evaluation took into consideration 3 different amounts of additional redundancy (20%, 60% and 100%), transmission rates ranging from 100 kbps to 2,000 kbps² and 3 different densities (400, 600 and 800 nodes) for 3 unicast solutions (VIRTUS, VIRTUS-Erasure and VIRTUS-Erasure-I) and 5 dissemination solutions (REDEC, REDEC-Erasure, REDEC-Erasure-I, REDEC-Hybrid and REDEC-Hybrid-I). This has led to more than 400 combinations of solutions and scenarios. Furthermore, each combination was run between 32 to 48 times in order to obtain statistically sound averages and confidence intervals (at a confidence level of 95% using the normal distribution). The many hours (adding up to weeks) of execution were only feasible to be conducted due to the availability of two clusters of computers. One is a Dell cluster of 24 nodes, each with a Quad-core 2.40 GHz Intel(R) Xeon(R) CPU and 8 GBs of RAM. The second is an IBM cluster of 32 nodes, each with Core 2 Duo 3.4 GHz Inter(R) Xeon(R) CPU and 2 GBs of RAM.

6.3.2.1 The Cost of Additional Redundancy

The first analysis consists in understanding the impact of different amounts of additional redundancy. The use of additional redundancy is subjected to the trade-off between cost and improvements in delivery ratio. In the case of video streaming, we initially observe how increases in additional redundancy lead to higher delivery ratios and higher quality videos at receivers while making use of a larger number of transmissions (high bandwidth usage) and decreases on the rate of reception of unique video content.

²For the solutions without redundancy (VIRTUS and REDEC), up to 1,500 kbps transmission rates were used; while, an extra transmission rate of 2,000 kbps was used for the other solutions, so that higher receiving rates could be achieved.

The results for unicast video streaming and video dissemination are shown in Figures 6.6 and 6.7, respectively. These results are based on the topology mentioned in Section 6.3.1 with 600 vehicles and a transmission rate of 1,000kbps was used.

Both figures show that the use of Erasure Coding in all packets leads to significant improvements in delivery ratio and PSNR, with larger increases in additional redundancy. In the case of the use of EC selectively on I-frames, shows slight (not statistically significant) decreases on delivery ratio which is caused by the increased competition for resources for packets carry content regarding P or B frames. However, the improvements on PSNR are similar to those when additional redundancy is used for all packets. However, the use of additional redundancy for all packets incurs on the need of substantially higher number of transmissions proportional to the percentage of additional redundancy used. The selective use of redundancy showed a much lower increase on number of transmissions (e.g. 45% for the selective use on I-frames while 135% for all packets at 100% additional redundancy).

For the case of the Hybrid solution in video dissemination, the dissemination protocol is more lenient to redundant transmissions in order to take advantage of Network Coding mechanism. This leads to improvement in delivery ratio for the selective approach as well as for the indiscriminating solution at higher levels of additional redundancy. The REDEC-Hybrid solution shows decreases on delivery ratio when 20% additional redundancy is used do the issue of packets that are received but are not decoded into useful information since not enough packets of the same block were received. This problem is mitigated with higher amounts of additional redundancy. In terms of PSNR, both REDEC-Hybrid and REDEC-Hybrid-I observed smaller increases on PSNR than REDEC-Erasure and REDEC-Erasure-I when the levels of overhead regarding increases in number of transmissions are considered.

Figures 6.6(d) and 6.7(d) show the decrease on the rate by which unique video content is received when additional redundancy increases. Additional redundancy reduces the amount of video content transmitted per time period when the transmission rates are maintained. In video streaming, the receiving rates achieved are strongly related to the quality of video that can be displayed to end-users. Therefore, the cost of using redundancy is twofold into increased number of transmissions as well as the need to use higher transmissions rates for expected receiving rates.

The impact on receiving rates are substantially different between solutions. The selective use of redundancy offers higher receiving rates for same amounts of additional redundancy. Since the receiving rates are crucial to video quality, in the next Section,

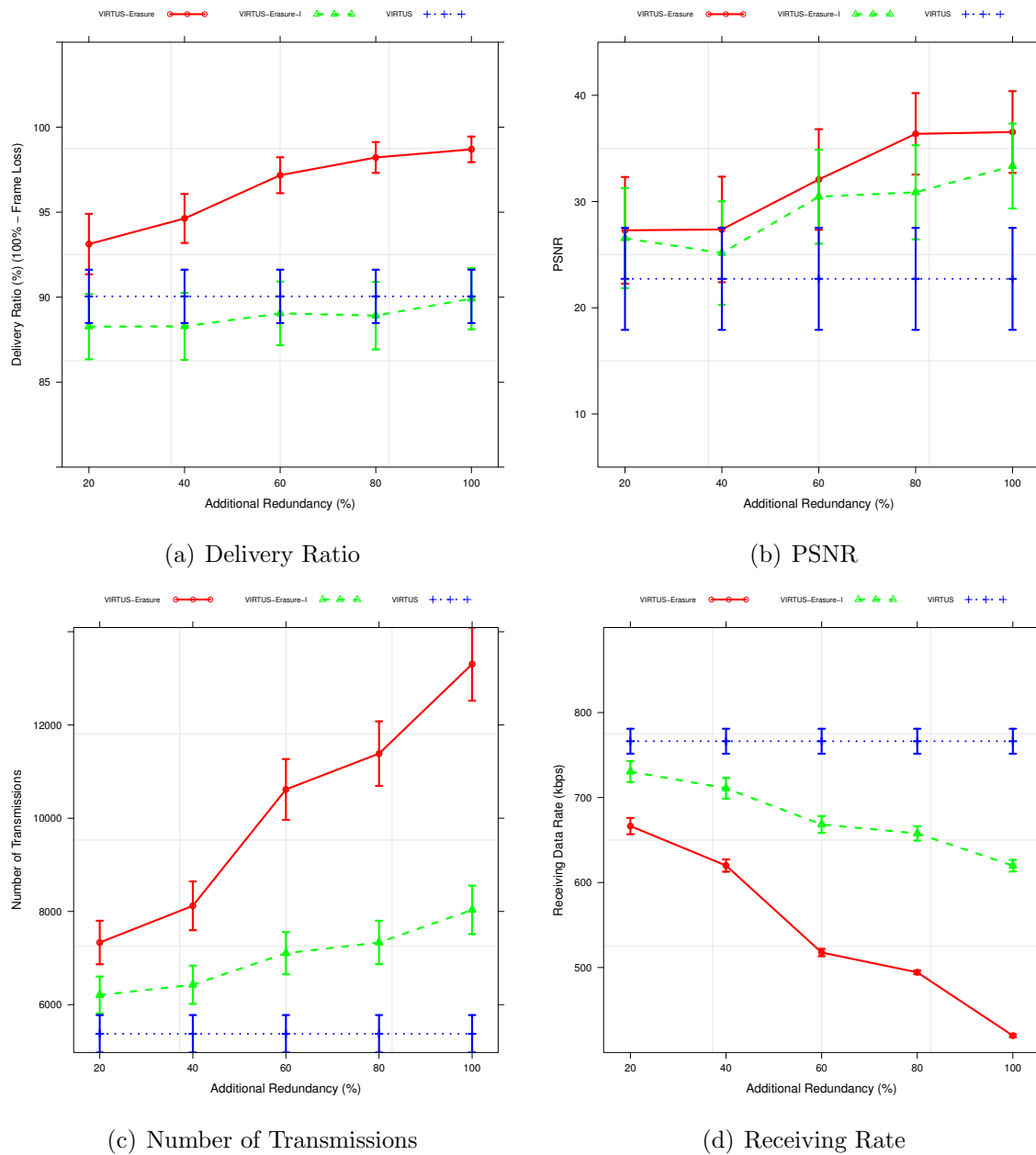


Figure 6.6: Unicast Video Streaming - Impact of Additional Redundancy

we evaluate the performance of the considered solutions through the perspective of these rates.

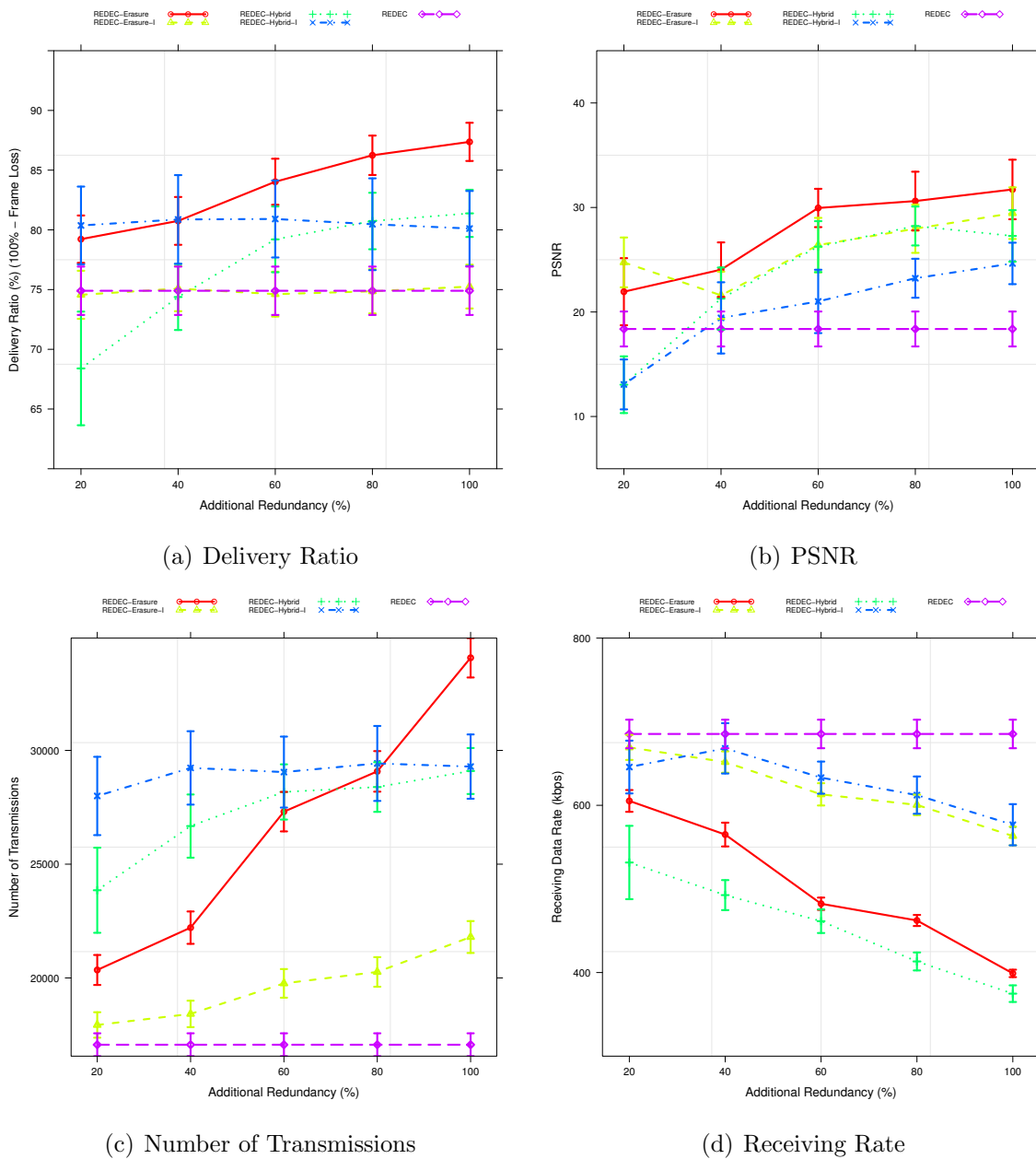


Figure 6.7: Video Dissemination - Impact of Additional Redundancy

6.3.2.2 Receiving Rates

In this section, the observed receiving rates at the application layer for different transmission rates were evaluated. It is important to consider the rates at the application layer instead of lower layers because it is where it fully reflects the reception rate of unique video content. This is particularly crucial when redundancy is considered since

transmission rates and receiving rates at the network level are relative to data that is not necessarily converted into useful and unique video content.

Figures 6.8 and 6.9 show this for video unicast and video dissemination, respectively. The graphs vary in columns by percentage of additional redundancy and in rows by density. The unicast (VIRTUS) and dissemination (REDEC) underlying solutions are plotted through the different amounts of additional redundancy for the sake of comparison despite the fact that they do not use any additional redundancy.

It is noticeable that transmission rates are not fully converted into receiving rates even when no additional redundancy is used (VIRTUS and REDEC). This is caused mainly by packet loss as it can be observed that for higher transmission rates, leading to higher loss, resulted in a ratio worse in the conversion of transmission rate to that of receiving. Solutions with no redundancy decreased from a 80% conversion ratio at lower transmission rates to 60% at higher transmission rates.

It can also be seen that increases on the percentage of additional redundancy lead to lower receiving rates for the Erasure and Hybrid solutions. When 100% of additional redundancy is used, all solutions that apply additional redundancy to all packets (VIRTUS-Erasure, REDEC-Erasure, REDEC-Hybrid) displayed a conversion ratio of 40%. It is interesting that this ratio was maintained independently of increases on the transmission rates because the 100% of additional redundancy reduces frame loss significantly.

The use of redundancy only for I-frames provides a better conversion of transmission to receiving rates than when redundancy is used for all video content. Even at 100% of additional redundancy, the curves of solutions that use redundancy solely on packets carrying I-frames data (VIRTUS-Erasure-I, REDEC-Erasure-I, REDEC-Hybrid-I) were very close to the solutions with no redundancy. The lowest conversion ratio achieved by them was of 50%, superior to the 40% observed by the use of redundancy of all packets.

Figures 6.10 to 6.19 use the same previous graph layout varying in columns by percentage of additional redundancy and in rows by density; however, the x-axis of these figures use the receiving rate of video content shown in the previous figures. The intention is to evaluate the benefits of each solution through the perspective of the receiving data rate at the application layer. As explained, the receiving rate of unique video content at the application layer is fundamental to the support of video streaming of a higher quality. The receiving rate is a metric for evaluation even better than the Unique Content Data Rate (UCDR) previously mentioned. For the remainder of this chapter, receiving rates refer to the receiving rates of unique video content at the application layer.

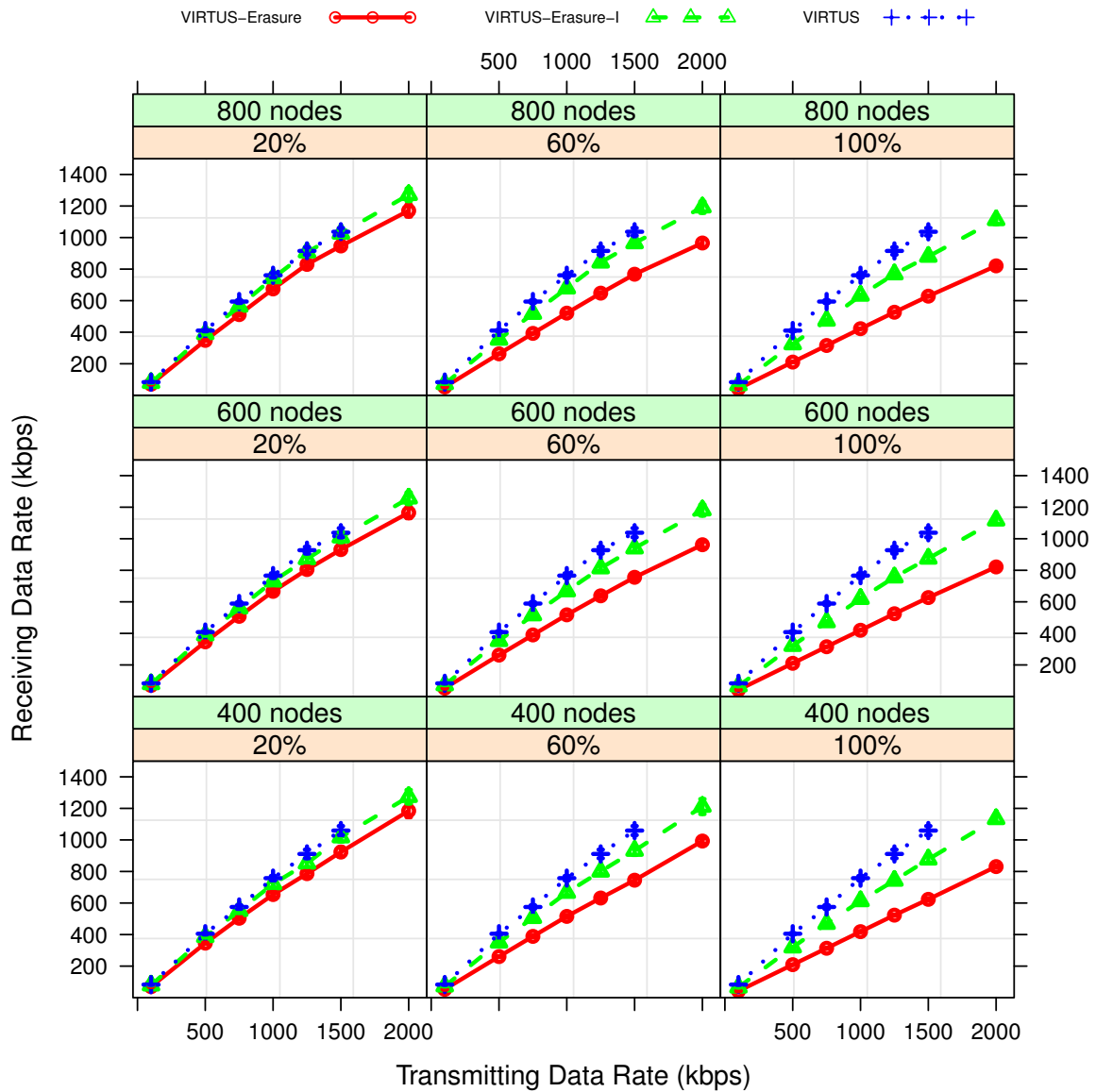


Figure 6.8: Unicast Video Streaming - Receiving Data Rate

6.3.2.3 Delivery Ratio

Figures 6.10 and 6.11 show the delivery ratios achieved by video unicast and video dissemination solutions, respectively. Because the receiving data rate are used on the x-axis, the solutions show points at different lengths for the same transmission rates used. This is clearly noticeable by the shorter curves when redundancy is used for all packets at the high amount of 100% of additional redundancy. This corroborates the importance

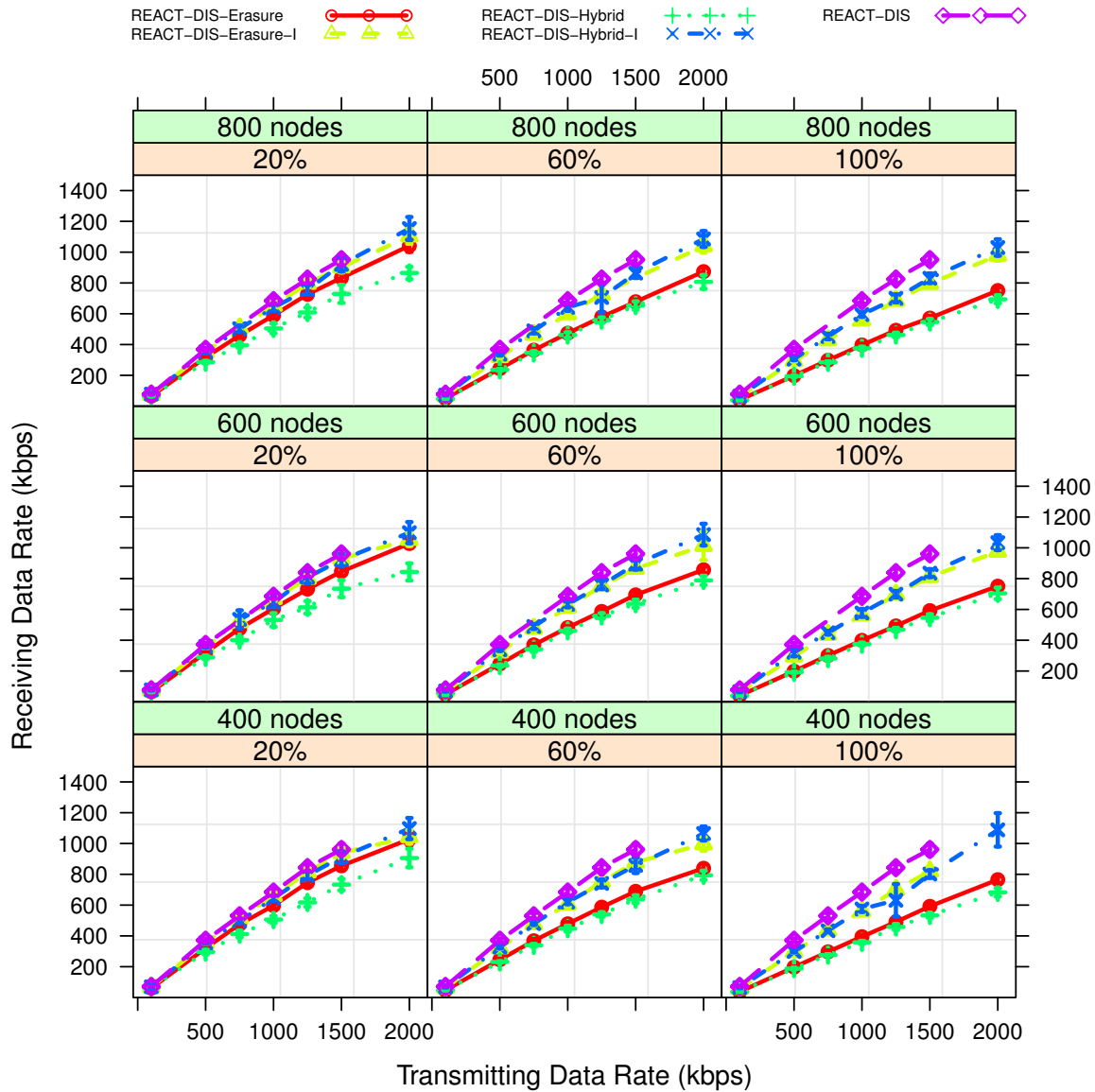


Figure 6.9: Video Dissemination - Receiving Data Rate

of evaluating the solutions performance through the perspective of the receiving rates of video content at the application layer.

It is once again clear that frame loss increases when higher transmissions rates are used to achieve higher receiving rates. In the case of video unicast, the rates drop from close to 100% to the 70%’s level. For video dissemination, the delivery ratios drop from the 90%’s level to the 60%’s level. In video dissemination, some nodes in the network

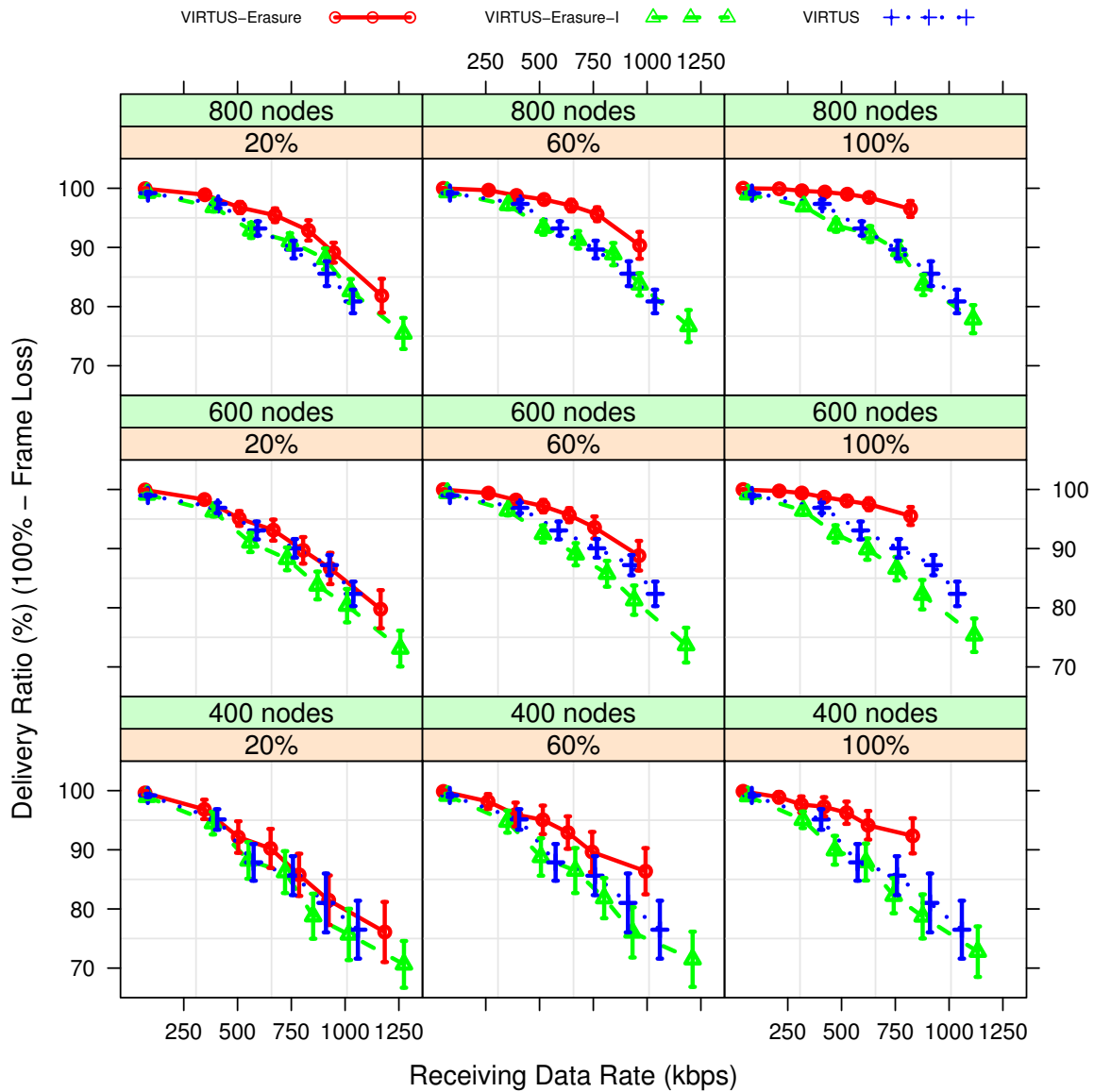


Figure 6.10: Unicast Video Streaming - Delivery Ratio

might not be connected and this can be observed by lower levels (around 80%) observed at low receiving rates and lower density. Another indication of the issues due to lack of connectivity can be observed by the larger confidence intervals in the case of video unicast.

The solutions that use additional redundancy in all packets have shown improvements on delivery ratio in the majority of circumstances even with the need of higher trans-

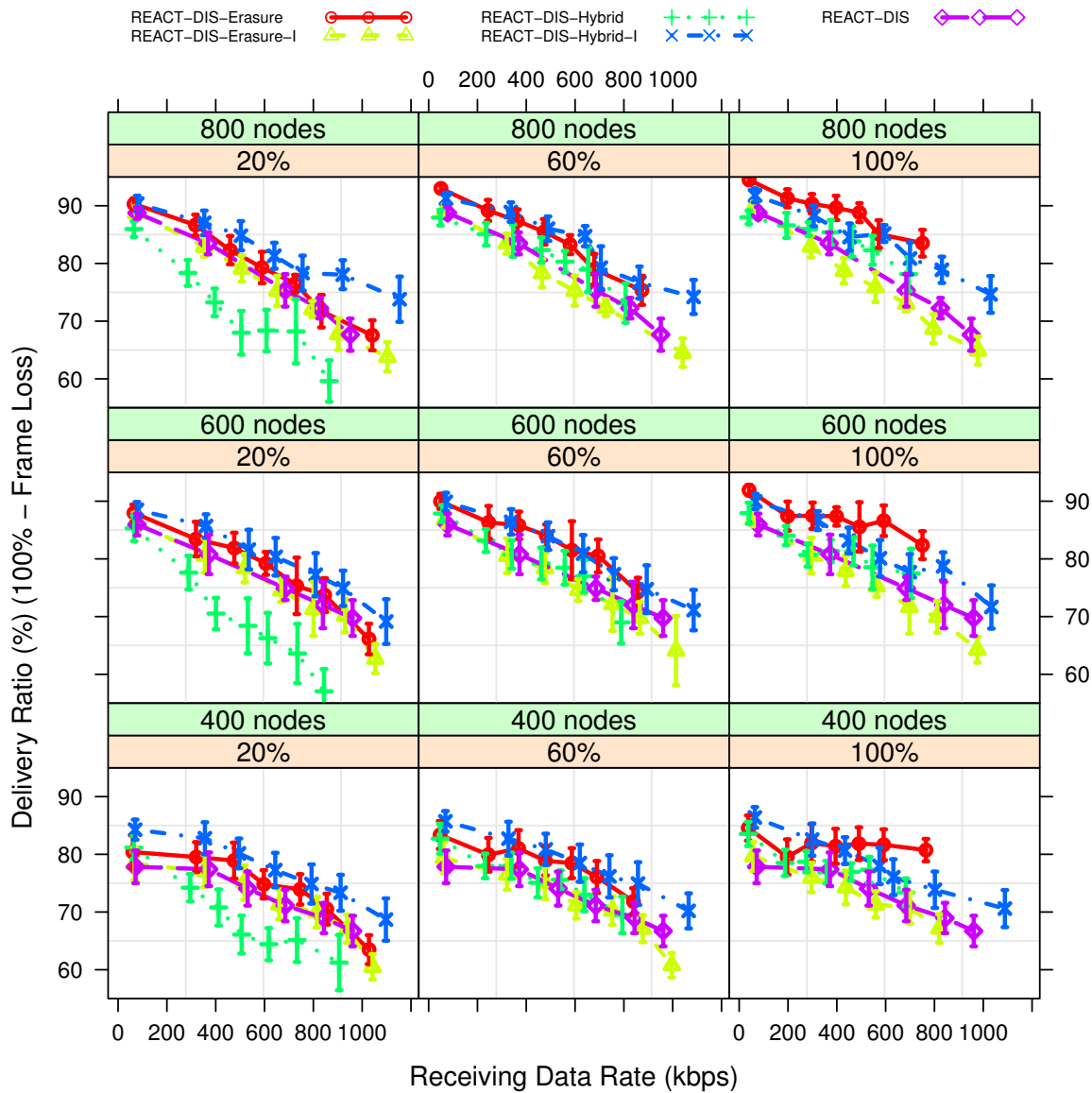


Figure 6.11: Video Dissemination - Delivery Ratio

mission rates for the same receiving rates. These improvements range from statistically insignificant (confidence intervals overlap) to 10 percentage points with 100% additional redundancy at the scenario of high density; the largest improvements were observed at higher amounts of additional redundancy.

The Hybrid solution for video dissemination has achieved a lower delivery ratio when only 20% of additional redundancy was used; this is explained by the occurrence of blocks

that could not be decoded by nodes close to the source since an additional redundancy of 20% was insufficient to guarantee the reception of enough packets. The improvements on delivery ratio due to EC and our Hybrid solution were larger in the case of dissemination than in that of unicast due to the inherent redundancy of dissemination in the favored multiple transmissions of neighboring nodes.

The solutions focusing solely on redundancy for I-frames in most of the situations resulted in a delivery ratio similar to that of when no redundancy is used at all. In video unicast, with further increases on the amount of additional redundancy, the delivery ratios observed by VIRTUS-Erasure-I were slightly (up to 3 percentage points) inferior to that of VIRTUS because higher transmission rates were used to reach the same receiving rates. It is interesting to note that the lower delivery ratio observed by REDEC-Hybrid at 20% of additional redundancy does not happen with the REDEC-Hybrid-I solution; this is because although some I-frames could not be decoded, packets carrying information from other frames were not encoded and they could benefit from the full reception of other I-frames.

6.3.2.4 PSNR

Video quality is initially evaluated as the average Peak Signal-to-Noise Ratio (PSNR) of frames and the results are shown in Figures 6.12 and 6.13. The larger confidence intervals are explained by the high variation of PSNR for small changes in delivery ratio.

In video unicast, although the averages were already clearly higher at 60% additional redundancy (from 15 to around 25), the benefits were more pronounced only when the percentage of additional redundancy was 100% (from 15 to around 30). For video dissemination, the higher delivery ratios achieved by the EC solutions have resulted in significantly higher PSNR (around 30) when compared to the Hybrid solutions (around 20) and to the solution with no redundancy (around 15). The necessary use of RLC for the NC part of the Hybrid solution still poses an issue when not enough packets are received and a whole block of packets is lost.

The most important observation is that the solutions that have used additional redundancy only for packets carrying information regarding I-frames obtained the same levels of PSNR as the solutions that apply the redundancy strategies to all packets. Besides that, the solutions focused on I-frames could reach higher receiving data rates. This is a significant contribution as it is shown that focusing the use of additional redundancy strategically in most crucial information, it leads to the same level of improvements in video quality (despite lower delivery ratios as seen in Section 6.3.2.3) while maintaining

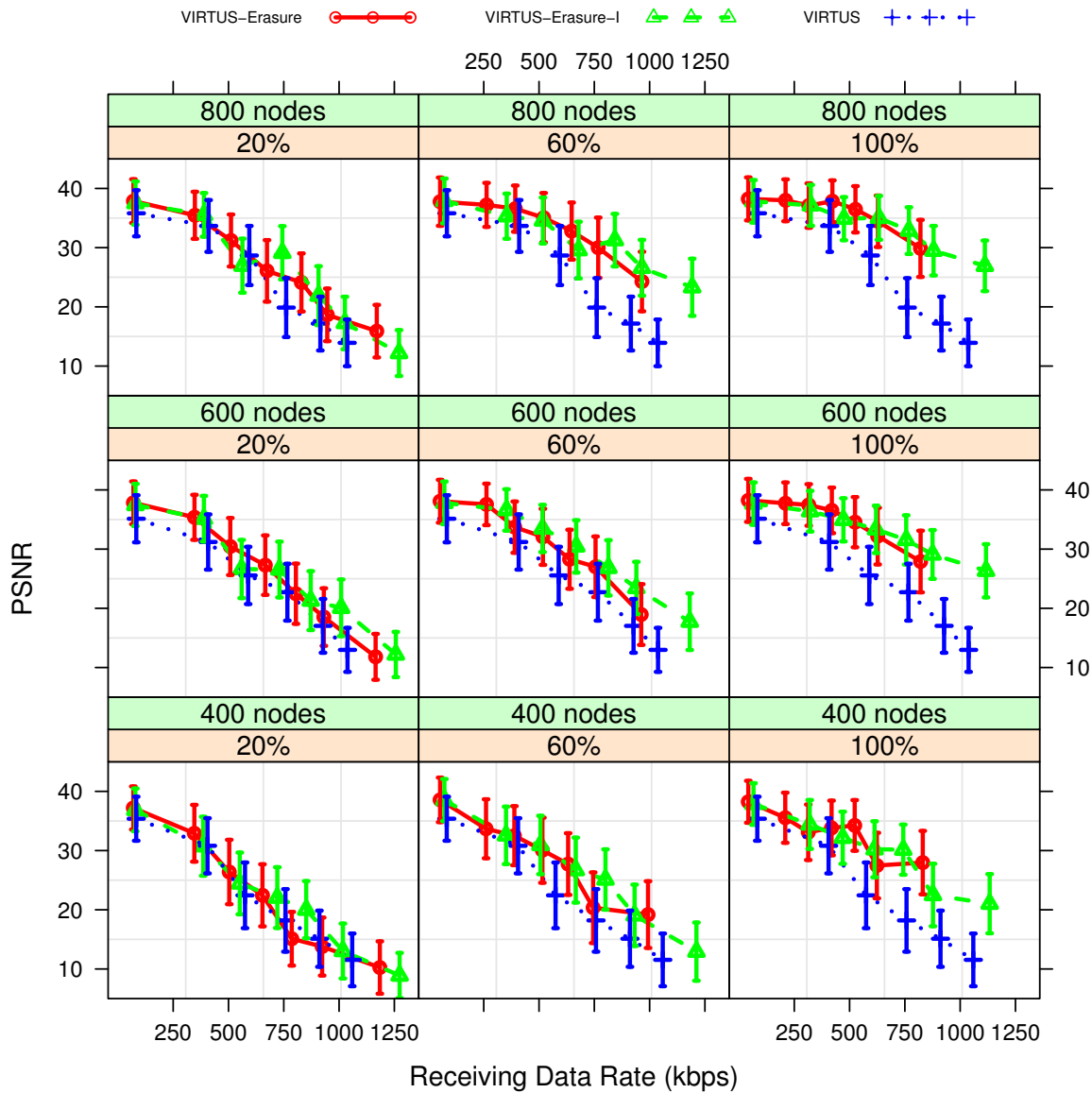


Figure 6.12: Unicast Video Streaming - PSNR

higher receiving rates (Section 6.3.2.2) at lower overhead (Section 6.3.2.7).

6.3.2.5 SSIM

Figures 6.14 and 6.15 shows the SSIM achieved by the unicast and dissemination solutions, respectively. It can be noticed that confidence intervals are narrower than those observed for the PSNR results. This is an indication that SSIM is less volatile to varia-

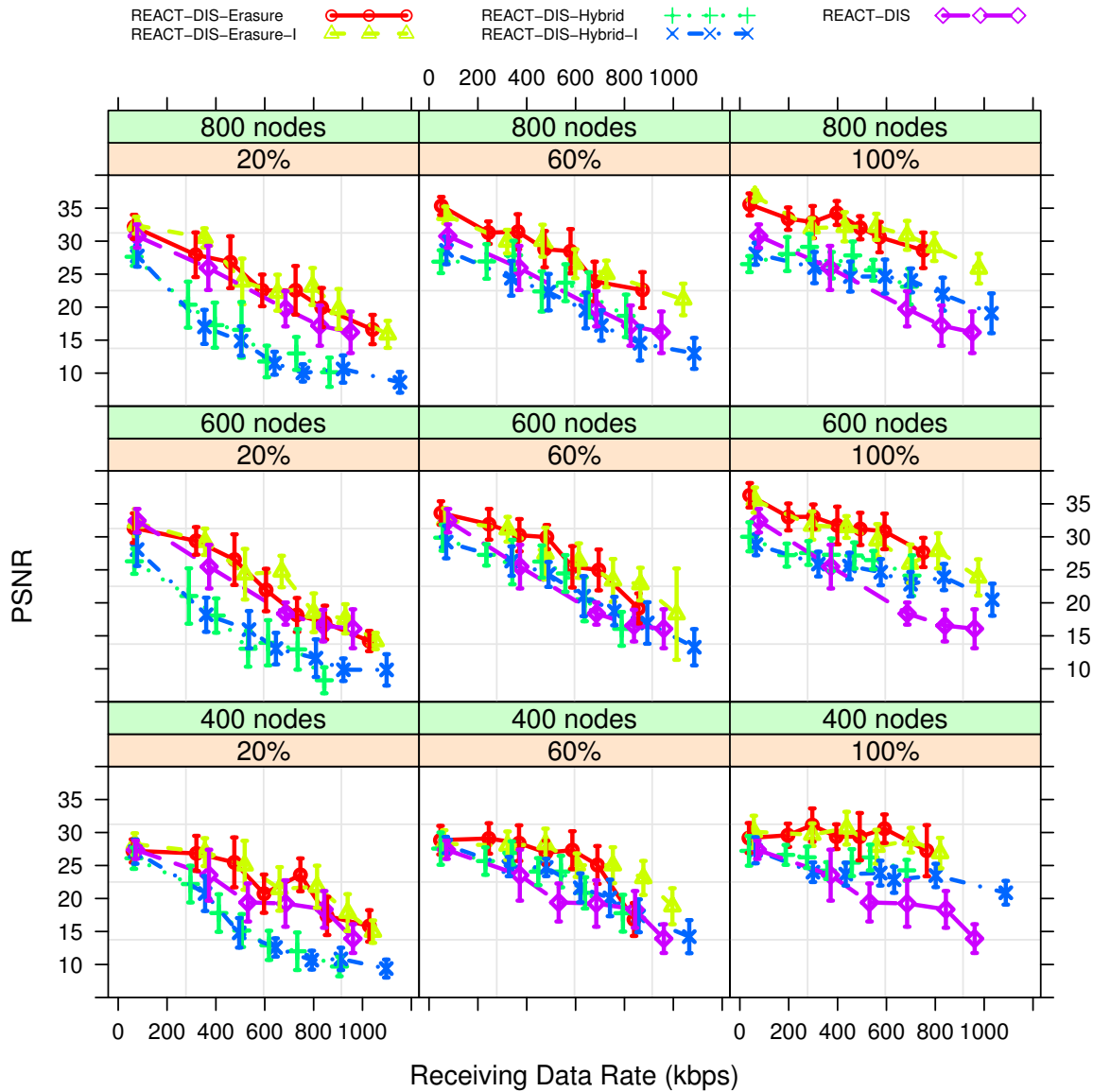


Figure 6.13: Video Dissemination - PSNR

tions when higher delivery ratios are observed.

For video unicast (Figure 6.14, the improvements by the selective solution VIRTUS-Erasure-I are more pronounced in terms of SSIM. The reception of a higher percentage of I-frames leads to higher quality videos while maintaining higher receiving rates. The use of redundancy in all frames by VIRTUS-Erasure incurs in higher SSIM, however, receiving rates are stronger deteriorated which limits the ability of displaying videos at

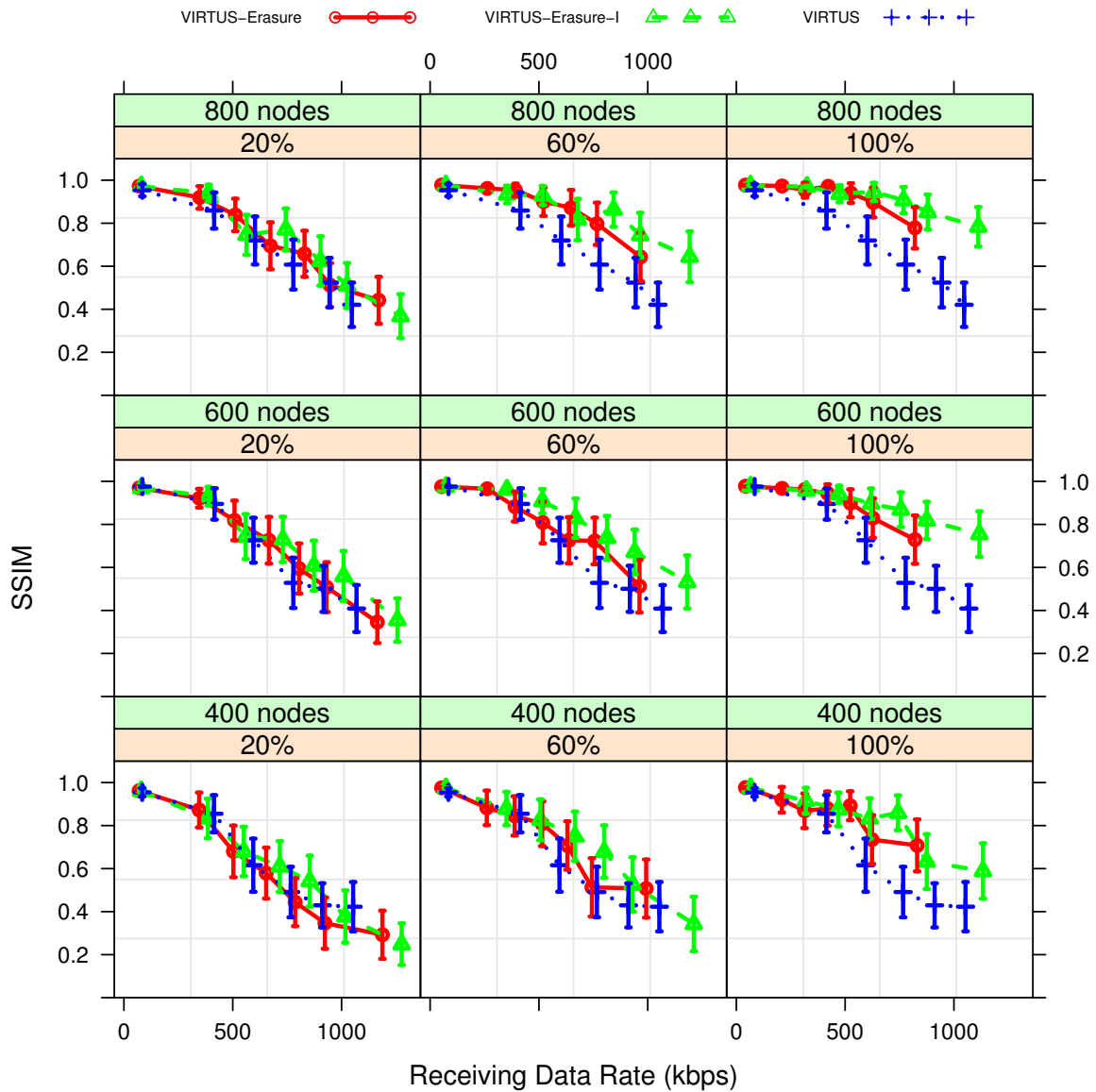


Figure 6.14: Unicast Video Streaming - SSIM

high bit rates at end-users.

In video dissemination (Figure 6.15), the improvements in SSIM are significantly higher for the selective solution REDEC-Erasure-I when compared with the others. The advantages in terms of video quality by using selective Erasure Coding over selective Hybrid Coding, both non-selective solutions and original REDEC is clear when considering structural distortion.

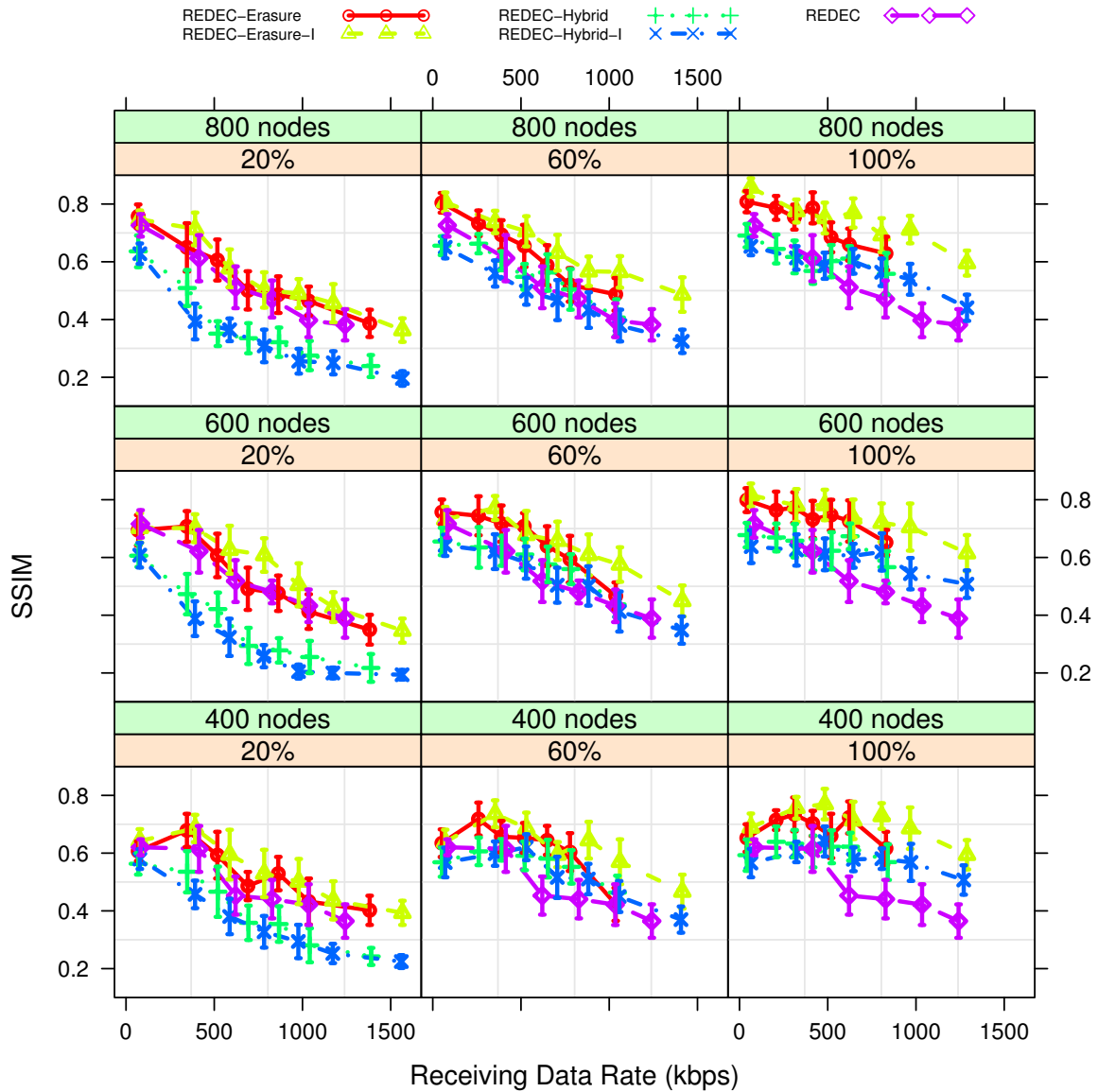


Figure 6.15: Video Dissemination - SSIM

6.3.2.6 Delay

Figures 6.16 and 6.17 depict the average end-to-end delay obtained through the use of each solution. The delay is plotted in a logarithmic scale due to different scales of results observed at low transmitting rates by the Hybrid solutions that use NC.

It can be observed that for solutions with no redundancy and for those that use EC have offered the same level of delay (only in a few cases did the solution with EC

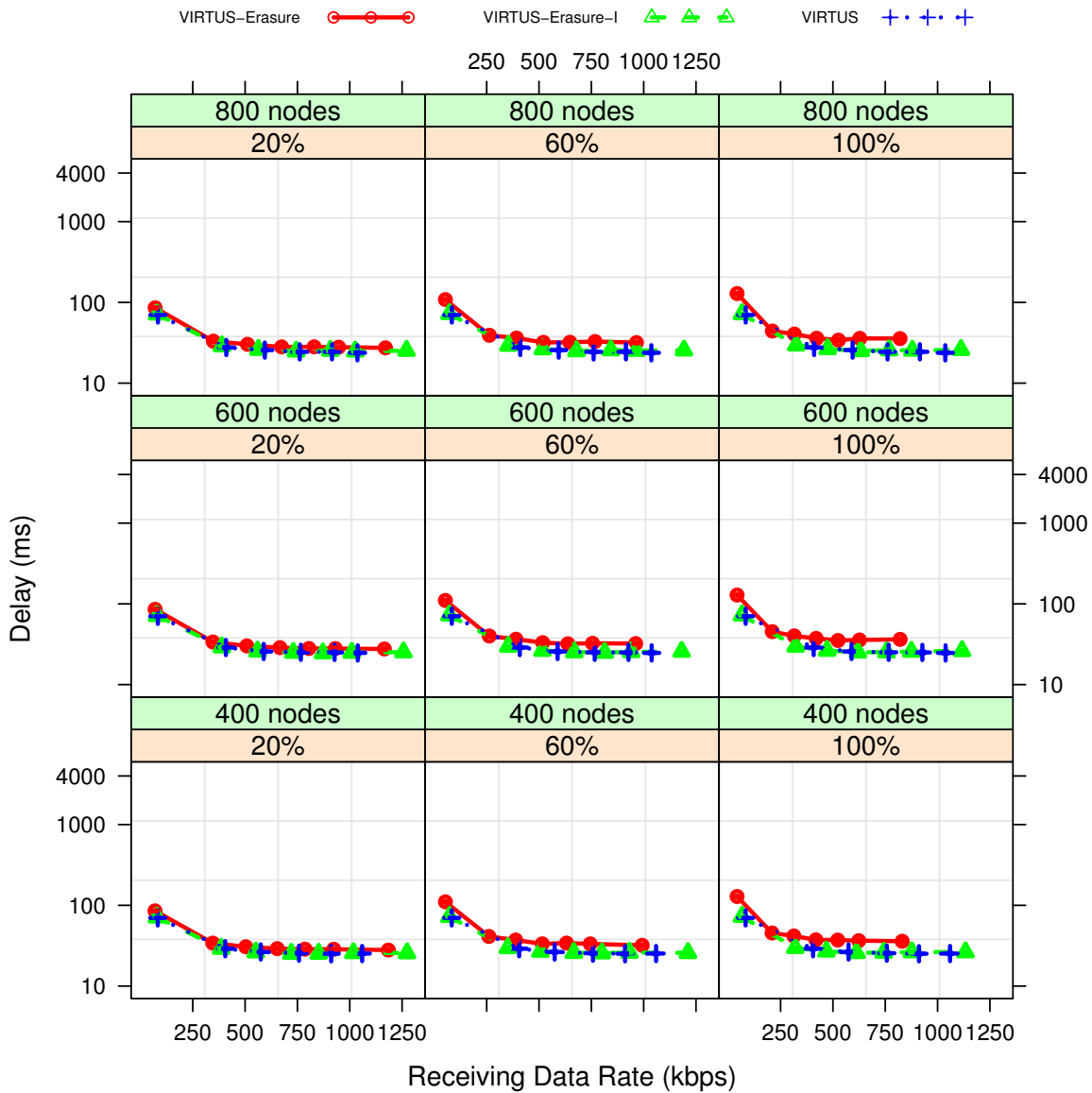


Figure 6.16: Unicast Video Streaming - Delay

for all packets have a slightly longer delay when the transmitting data rate was 100 kbps). These delays were always under 200 milliseconds which is certainly acceptable for video streaming purposes. The solutions using our Hybrid approach offered substantially longer delays (up to 4 seconds) due to the need for intermediary nodes to wait for the reception of a whole block prior to further forwarding of any new packet. The delay was reduced with increases on the transmission rates (higher receiving rates are reached with

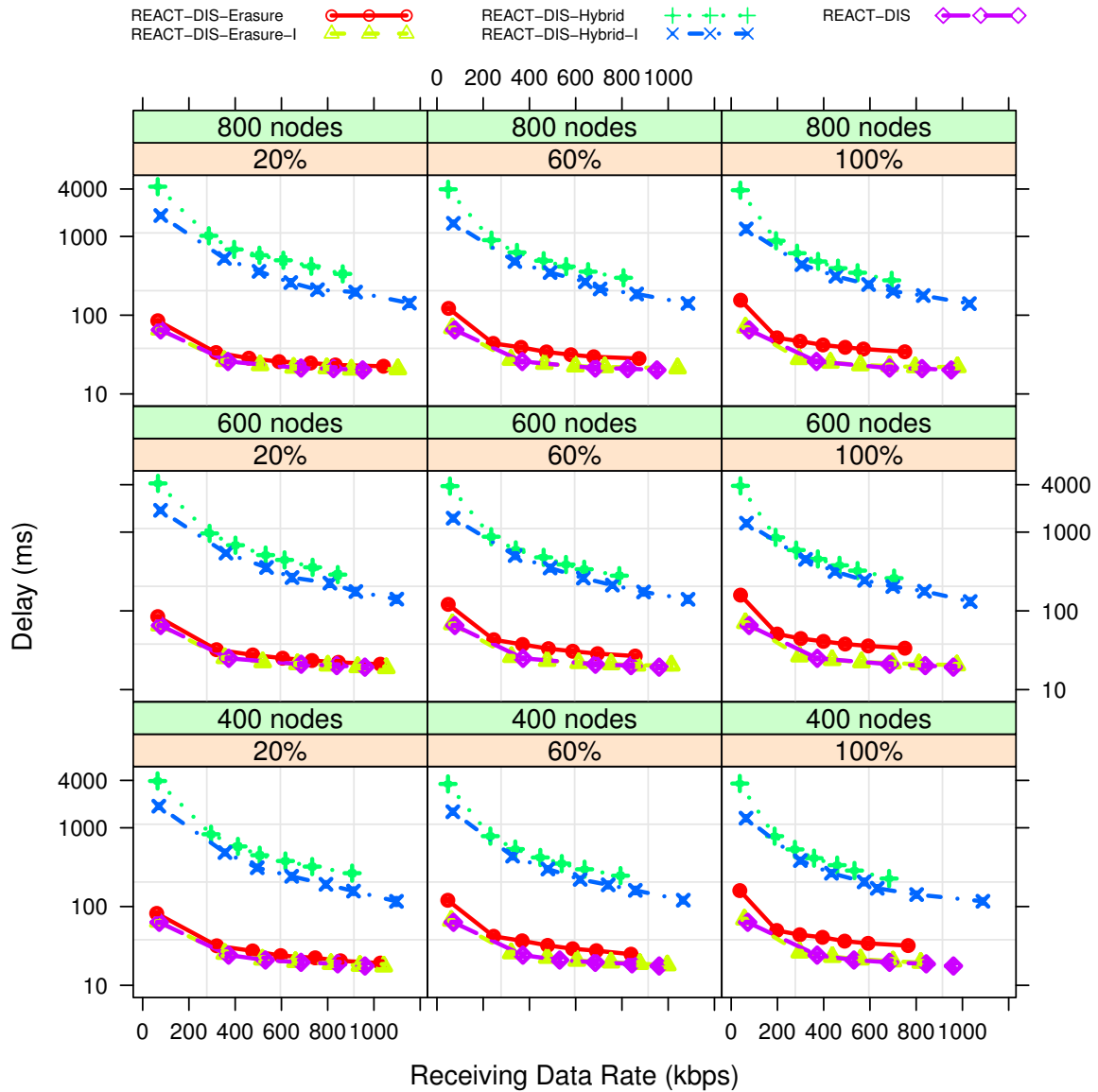


Figure 6.17: Video Dissemination - Delay

increasing transmission rates), because the time to transmit and receive a whole block was reduced. At high transmission rates, the observed delay converges to values close to 200 milliseconds. Therefore, the longer delay experienced with NC is only an issue at very low transmission rates.

6.3.2.7 Number of Transmissions

The use of resources by each solution is evaluated as the number of transmissions of packets carrying video content³. Figures 6.18 and 6.19 show the number of transmissions used by each solution.

The results regarding video unicast in Figure 6.18 show that additional redundancy significantly increases the number of transmissions; the increases are slightly higher than the amount of additional redundancy (e.g. 65%-70% when 60% is used, 110%-130% when 100% is used). However, the solution that focuses only on I-frames has a much lower increase; around a third of the amount of additional redundancy (e.g. 30%-40% when 100% is used). It is interesting to observe that further increases on transmission rates (shown by increases in receiving rates) lead to a lower number of transmissions. This happens because the loss of packets occur in hops close to the source node and further relays of packets, sent by the source, are not performed.

Figure 6.18 shows the number of transmissions in the scenario of video dissemination. The EC solutions performed similarly to the EC solutions in unicast. The Hybrid solution showed a higher number of transmissions but it was indifferent to increases in the percentage of additional redundancy. This is due to the fact that the EC part of the Hybrid solution occurs only for the first hop of communication. REDEC-Erasure-I was the solution that exhibited the smallest increase in the number of transmissions when compared to the solution with no additional redundancy at all.

As mentioned before, it is clear that the solutions that focus the additional redundancy only to the most important data (I-frames) is able to achieve the benefits in video quality (Section 6.3.2.4) while limiting the impact in overhead.

6.3.3 Flexibility of amount of additional redundancy

The results in the previous section show a strong correlation between the amount of forced additional redundancy and the performance observed. Increases on extra redundancy are expected to result in increases in delivery ratio and consequently in video quality. An undesirable expected collateral effect is in the substantial increase on bandwidth consumption. Furthermore, for the specific case of video streaming, additional redundancy incurs in reduced rates by which unique video content is received at end-users.

³All packets carrying video content have a payload of 1,000 bytes and the solutions that use NC only need one integer in the header that is used as a seed for a pseudo random number generator to define the used random coefficients.

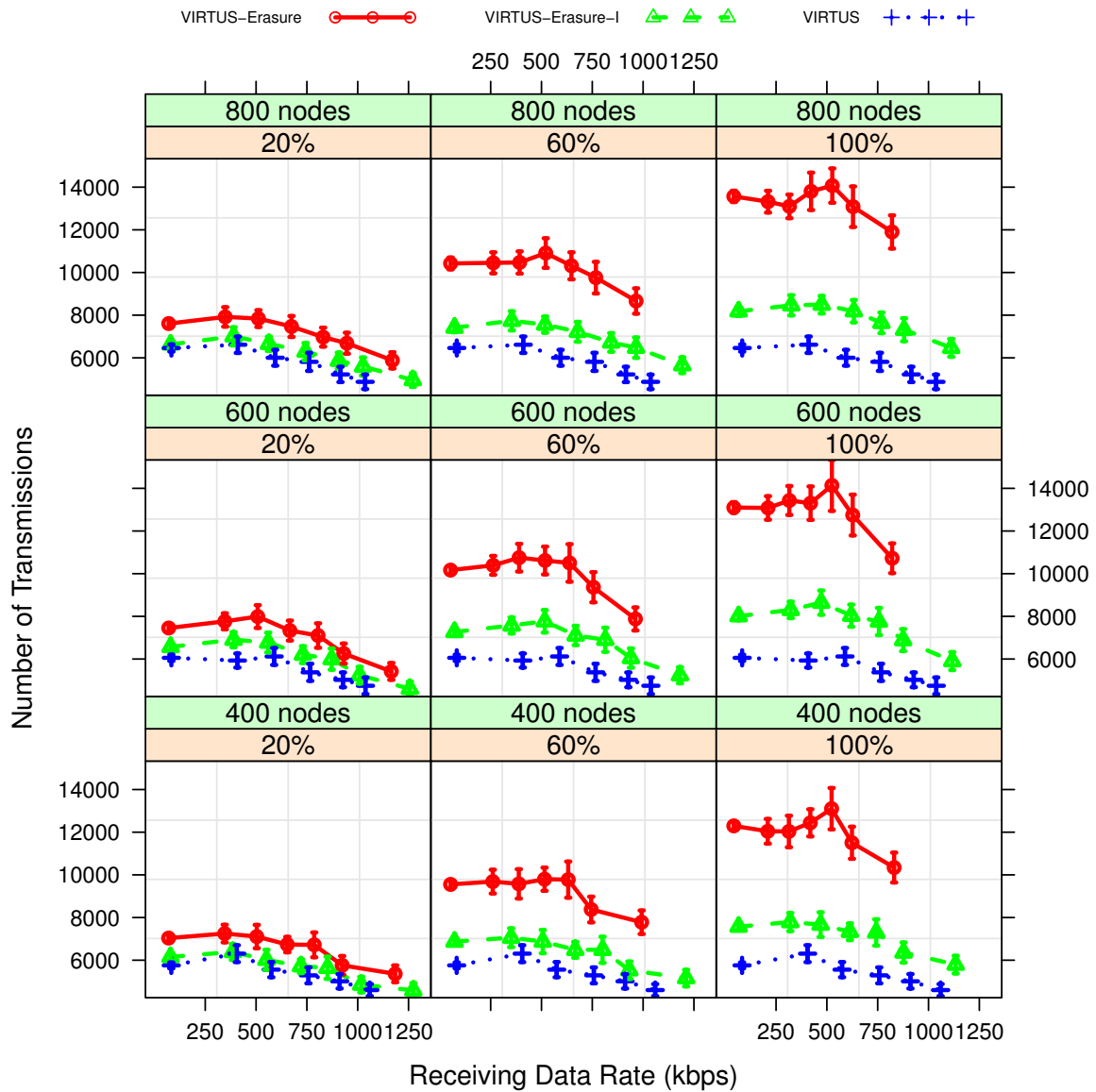


Figure 6.18: Unicast Video Streaming - Number of Transmissions

Therefore, it is fundamental to understand specific applications requirements as well as network properties and constrains in order to define the amount of additional redundancy used. If the underlying rates of packet loss in the network are not very pronounced, lower amounts of additional redundancy may be sufficient for high delivery rations and video quality while preventing substantial increases on bandwidth consumption. In the case of topologies that offer high losses, the use of large amounts of additional redun-

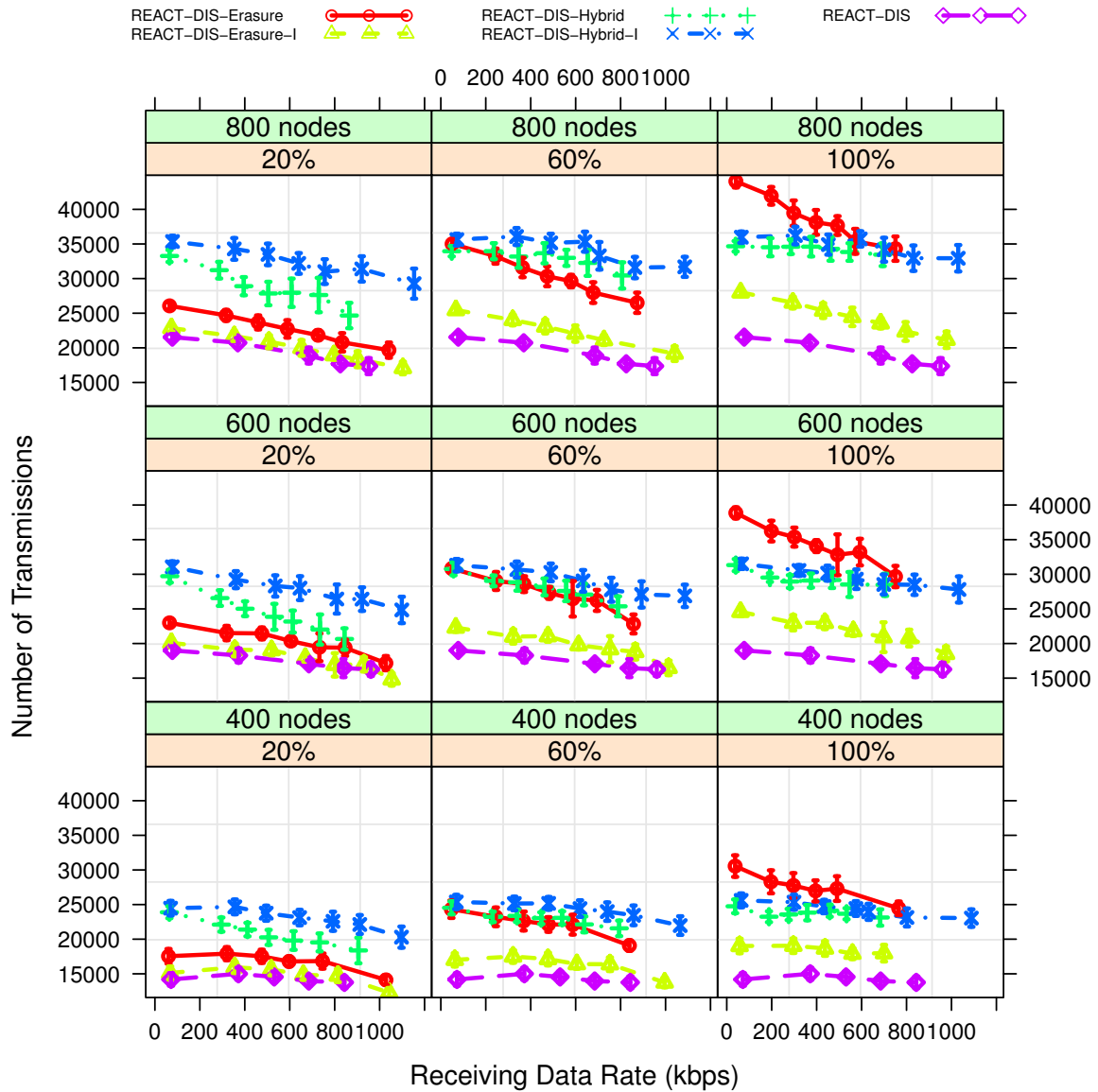


Figure 6.19: Video Dissemination - Number of Transmissions

dancy is necessary for high video quality as long as the service priority is sufficient to justify the increases in bandwidth consumption.

6.3.4 Summary

The use of redundancy was evaluated in different ways in a highly realistic simulation for both video unicast and video dissemination. Besides the use of additional redundancy

for all packets, a novel approach has been proposed that focus the use of such technique solely on the crucial data of I-frames.

In video unicast, it could be seen that using redundancy for all packets obtained the best improvements in delivery ratio (up to 10 percentage points). Nevertheless, the selective solution in data regarding I-frames reached the same improvements in PSNR (up to 100%) and even slightly higher improvements in SSIM with the need of only a third of the overhead by the homogeneous solution. Therefore, our selective solution (VIRTUS-Erasure-I) is the best approach towards unicast video streaming.

Video dissemination offers the opportunity to take advantage of the redundancy inherent to dissemination. For this reason, it has been evaluated both an Erasure Coding approach as well as the Hybrid solution that uses Erasure Coding in the first hop of communication and Network Coding for the reminder of the network. It was shown that specially in terms of video quality (PSNR and SSIM), the Hybrid solution was outperformed by the ones that use only Erasure Coding (REDEC-Erasure and REDEC-Erasure-I). This is mainly due to issue of NC using RLC (necessary for diversity) does not support partial recovery of a block when not enough packets are received for a full decoding. For the EC solutions, it could be observed that the selective solution (REDEC-Erasure-I) outperforms the homogeneous approach (REDEC-Erasure) by providing the same improvements in PSNR and SSIM while incurring much less overhead.

In the following, we present a list with the main contributions from this evaluation:

- **Receiving Data Rate at Video Application Layer:** to the best of my knowledge, this work is the first to evaluate the issues and solutions for video streaming over VANETs from the perspective of the receiving rate of unique video content at the video application layer. This is fundamental to an understanding of how suitable solutions can support the streaming of videos of a higher quality. It was noticeable how transmission rates are not fully converted to receiving rates even when no additional redundancy is used. Furthermore, the use of additional redundancy leads to lower receiving rates and this has to be taken into consideration for a fair comparison.
- **Increases in Delivery Ratio, PSNR and SSIM with Additional Redundancy:** the use of additional redundancy was beneficial in both unicast video streaming and video streaming dissemination. We have observed that although lower receiving rates are achieved with our EC and Hybrid solutions, the improvements in delivery ratio, PSNR and SSIM were significant.

- **Selective Redundancy on I-frames:** the novel approach of using additional redundancy selectively on packets that carry data of I-frames was shown to offer the best results. Although the increases on delivery ratios by these solutions (VIRTUS-Erasure-I, REDEC-Erasure-I and REDEC-Hybrid-I) were not of statistical significance, the video quality measured by both PSNR and SSIM showed substantial improvements, especially when additional redundancy of 100% was used. Furthermore, the cases with EC only (VIRTUS-Erasure-I and REDEC-Erasure-I) offered increases on PSNR with no increases on delay and a limited increase on the number of transmissions (at least a third of the overhead of solutions with additional redundancy to all packets). These solutions have also achieved higher receiving rates for the same transmission rates when compared to the solutions that use additional redundancy for all packets.
- **Erasure Coding outperforms Network Coding:** it has been shown that the use of redundancy incurs in substantial increases in cost. In this thesis, the cost has been considered in terms of both bandwidth consumption (number of transmissions) and deterioration of receiving rates. Furthermore, Network Coding incurs in substantial increases on end-to-end delay. The improvements in delivery ratio and video quality in Network Coding were not sufficient to compensate this cost. However, the improvements observed by the use of Erasure Coding were significantly higher and with the lower costs in both bandwidth consumption and deterioration of receiving rates of the selective solution, it was shown that such technique can improve the performance of video streaming solutions over VANETs.
- **Thorough and Realistic Simulations:** an extensive set of simulations was conducted on the top of a highly realistic scenario. The wireless communication was modelled with high fidelity to reflect the expected communication between vehicles in accordance to the most current standards. More than 30 executions were conducted for each of the more than 400 combinations of scenarios and solutions. All this provided the necessary information to corroborate our conclusions.

6.4 Final Remarks

A thorough study on the use of redundancy for video streaming over VANETs was provided. We have investigated both EC and NC techniques. We have designed XOR-based Coding with a strategy concerning the degrees distribution and segment selection

suitable for the application of video streaming over VANETs. Furthermore, we have proposed the use of a Hybrid solution that uses EC for the first hop on video dissemination and NC for the remaining intermediary transmissions towards other receivers.

The novel selective approach was shown to be greatly beneficial. The use of additional redundancy focused solely on packets carrying the data of I-frames does not lead to increases in delivery ratio, however, the improvements on video quality were similar to those experienced when additional redundancy was forced on all packets. Furthermore, these same improvements in video quality required a significantly lower number of transmissions.

All solutions were evaluated in an exhaustive set of highly realistic simulations through the perspective of the receiving rate of unique video content at the application layer in the receivers. The receiving rates that each solution can offer are important for an understanding of the quality of videos that can be displayed to users. Solutions that use additional redundancy to overcome packet loss decrease the transmission rate of unique content for the same network transmission rates. Therefore, it is important to analyze the trade-off between the improvements in delivery ratio and the reduction on receiving rates. With this in mind, it was shown how the selective use of additional redundancy for only packets carrying the data of I-frames is a better strategy than using additional redundancy for all packets.

Chapter 7

Conclusions and Future Work

This thesis focus on providing feasible solutions to the stringent challenges of video streaming over Vehicular Ad Hoc Networks (VANETs). Several applications require or would benefit greatly with the support of video streaming capabilities. These applications range from an informative service of displaying videos captured in real-time of streets and roads in a way that drivers can assess better traffic conditions, to improvement in emergency response by streaming video from an accident simultaneously to paramedics in an incoming ambulance and physicians in a hospital.

However, the highly dynamic topology of VANETs imposes severe difficulties in the task of communication. The high degree of movement of vehicles is the main aggravating characteristic of VANETs that causes links between reachable vehicles to be constantly disrupted. Besides that, the wireless nature of the communication creates a scenario that the communication channel is shared among all nearby vehicles and it is fundamental to manage correctly its use. Video streaming stress to the maximum these challenges in VANETs due to video's demanding requirements of delivery ratio, latency and scalability.

Therefore, it is fundamental to develop new solutions to the challenging network model of a VANET in accordance with its peculiarities. Previous solutions to the more general model of Mobile Ad Hoc Networks (MANETs) are not suitable to VANETs because MANETs' topology is not as dynamic and nodes in VANETs do not suffer from the same hardware restrictions of computational power and energy source of MANETs' nodes.

Initially, we showed in this thesis my contributions in the solution of neighbor localization and neighbor prediction. These are relevant issues as many services require the use of the location of neighboring nodes; and the prediction of the availability of a future

new connection is extremely useful to handle eventual path breaks. Besides that, a deep investigation on the role of mobility on VANETs' connectivity was conducted through a perspective of VANETs as Complex Networks. Insightful information was observed in regards to the impact of mobility on the topology of VANETs. All this background work was fundamental to build a broad knowledge of the underlying aspects of Vehicular Ad Hoc Networks. This knowledge was extremely useful for the pursue of effective and efficient solutions for video streaming over VANETs.

We have designed, implemented and evaluated two novel solutions for video dissemination in VANETs: REACT-DIS and REDEC. These solutions are designed to handle VANETs' dynamic topology, its non uniform density and video streaming's latency requirement. They are both receiver-based solutions where the choice of which nodes participate in the relay of packets is taken at receivers instead of senders. Receiver based approaches usually lead to high end-to-end delays as the decision to relay packets rely on a waiting mechanism. This was solved by changing the perspective or relay selection from every single transmission to a time window within which no further waiting is necessary.

REACT-DIS uses a non-deterministic approach to handle density variation. Nodes decide to become relay nodes based on probabilities that varied according to the number of overheard retransmissions of the same packet. When a larger number of retransmissions is observed, a smaller probability a node has to become a relay node. The number of retransmissions observed is highly correlated to local density.

REDEC handles the non-uniform density of VANETs in a different way. The function used for every node to calculate its waiting time divides the region that the previous transmitter reaches into three sectors. In a dense region, it is highly likely that there are many potential relay nodes in the most suitable region and for that reason a steeper curve is used. The least suitable sector is used most likely in low density regions, therefore, the curve can be less steep as it is unlikely there is competition between many nodes.

REACT-DIS fulfilled all video streaming requirements for data rates up to 100 kilobits per second (kbps). At higher data rates, delay requirements were fulfilled but it has suffered from high packet loss rates. It was observed that the necessary cancellation process in receiver-based solutions is highly deteriorated at high data rates. For this reason, REDEC decouples the process of relay node selection from that of video transmission.

REDEC's modifications were shown to provide substantial improvements in delivery ratio and PSNR. Although it decreases REDEC's ability to react to topology changes, the frequency by which relay node selection is triggered is sufficient to overcome this. It was also shown that REDEC adapts well to changes in density as it provides high

receiving rates of video content at both low and high density scenarios.

We have also developed a unicast solution, namely VIRTUS, that is also reactive to topology changes, offers low end-to-end delay and it is scalable. VIRTUS employs the same receiver based approach used in REACT-DIS but it uses a more sophisticated way of defining nodes suitability to be relay nodes and the duration of the time window that they remain as such. In REACT-DIS, the duration of the time window is static and its value was empirically defined. VIRTUS decides the duration of this time window based on estimations on how long a receiving node continues within reach of the previous relay node. This prediction is performed at the receiver side in order to maintain the reactivity property of receiver based solutions. We have used a target tracking mechanism design by Ramos (see Appendix A) that uses a Bayesian model with a particle filter system to calculate the future positions of nodes based on gathered information of location, speed and direction. The waiting time of a node to relay a message is calculated in an equation that balances geographic advancement and stability (in this case, stability is related to the amount of time a node is predicted to remain within reach of another node).

VIRTUS is evaluated as two different modules where the second is extended by the use of a density-aware relay node selection decoupled from video transmission (DADV). The density-aware mechanism used requests nodes to observe the number of duplicates received and adapt the maximum waiting time used. The idea is that when many duplicates are perceived, it is beneficial to increase the maximum waiting time so receivers waiting time is spread wider decreasing the occurrence of multiple nodes with similar waiting times. This extension also exploits the benefits of using a relay node selection decoupled from video to transmission to avoid issues with cancellation at high data rates.

Both modules of VIRTUS (with and without DADV) have obtained low end-to-end delay that fulfills video streaming requirements. They have also improved in terms of delivery ratio and PSNR observed. VIRTUS with DADV was shown to be the solution with best results achieving very low end-to-end delay, high delivery ratios and PSNR and the best conversion of transmission rates to receiving rates of video content.

For REDEC and VIRTUS, the receiver-based paradigm was adapted to video streaming peculiarities by having the decision of becoming a relay node to be extended to a time window rather than for only a single transmission; and, by decoupling the relay selection process from that of video transmission. For this reason, these solutions were able to achieve higher delivery ratios at higher data rates. For video streaming, it is important to handle high transmissions rates as they are fundamental to offer high receiving rates

of video content at end users so videos of higher quality can be displayed.

REDEC and VIRTUS still suffered from packet loss, thus, it was necessary to study error correction mechanisms that deal properly with the observed packet loss. We have investigated the use of redundancy for this purpose as it does not require any interaction between source and destination(s). Redundancy could be implemented with the transmission of simple copies of the original data however this would not be an efficient manner of take advantage of the extra entropy.

We have investigated the different approaches to make use of inherent or additional redundancy. In terms of where data is encoded, Network Coding and Erasure Coding strategies were considered. Furthermore, it was discussed the use of Random Linear Coding and a novel XOR-based Coding strategy was designed based on the desired characteristics to suit better video transmission over VANETs issues. The combinations of these strategies were studied for both video dissemination and video unicast.

The process of dissemination already leads to an inherent redundancy since the task of reaching many nodes requires some overlap of transmissions. For the case of unicast, redundancy is strongly avoided as the goal is to obtain end-to-end paths with the minimum amount of relay nodes. Therefore, in this thesis, the use of inherent redundancy was considered only for video dissemination while the use of additional redundancy was studied for both unicast and dissemination.

The study of the Random Linear Coding and XOR-based Coding techniques was valuable to understand their details and impact on video streaming over VANETs. The performance of Random Linear Coding is greatly influenced by the size of the block by which the original content is divided. In scenarios where packet loss is higher, it is better to have blocks with smaller size so the value of the reception of a packet is maximized. In the case where packet loss is lower, it is more beneficial to have larger blocks as the value of eventual lost data is minimized. The size of a block did not affect the performance of XOR-based Coding, however, the packet degree that dictates how many segments of data are used for coding its content influences the benefit of its successful reception. The degree has to balance the trade-off between the probabilities of being decoded and decoded into content that has not been received yet. The experimental results have shown that smaller degrees are preferable over larger degrees.

The use of Network Coding is based on re-encoding by intermediary nodes that increase the diversity of transmitted data, thus, the reception of redundant transmission can be used to recover previously lost data. It was observed in this thesis, that the performance of Network Coding is highly afflicted by loss in the first hop of communication as

it propagates to a whole block and for the remaining of the network. For this reason, we have designed a novel hybrid solution that forces additional redundancy in the first hop while the remaining nodes continue with a Network Coding approach. A crucial aspect on the study of the use of redundancy for video streaming is the impact of receiving rates of unique video content. As mentioned before, these rates are related to the quality of video that can be displayed for end-users. When additional redundancy is forced at the source node, increases on the amount of redundancy reduce the rate of transmission of unique video content. Therefore, the improvements in delivery ratio have to be sufficient to compensate the reduction on the rate of reception of unique video content. The study on this thesis is the first (for the best of my knowledge) to consider this fundamental perspective.

The extensive experiments conducted have shown that Erasure Coding, which forces additional redundancy from the source, have obtained the best gains in delivery ratio and video quality. The use of 100% of additional redundancy lead to the best results as it overcomes the high packet loss rates at high transmission rates. This improvement was independent of the worse ratios of conversion of data transmission rates to receiving rates of unique video content.

We have also proposed a selective use of redundancy depending on the relevance of the data transmitted to video quality. This novel solution limits the use of Erasure Coding and the Hybrid solution to packets carrying content of I-frames. By this manner, it could be seen that the content of the crucial information of I-frames had better delivery ratios without lead to steep decreases on receiving rates of unique video content. The results shown that although lower overall delivery ratios were obtained, the video quality was similar to that of the solutions that consider all packets in the same way. Besides, higher receiving rates were achieved with a significantly lower overhead in terms of number of transmissions.

In the following section, some future directions of research on Vehicular Ad Hoc Networks and on video streaming over VANETs are listed.

7.1 Future Work

As mentioned, this thesis has provided substantial advancements in a variety of research topics in Vehicular Networks and specially in the provision of video streaming support over Vehicular Ad Hoc Networks. Nevertheless, it has also brought up interesting challenges that were outside of the scope of this thesis. There are also some issues that have

not been mentioned in this thesis yet but that are topics that require further research.

Here follows a list of these topics that may guide further research in Vehicular Networks:

- Different works in this thesis have used models that estimate the position of vehicles in the near future. In Chapter 3, it was shown a solution that uses a naïve vectorial model based on gathering information location, speed and directions for this estimation. This model was used to predict the position of current neighbors in order to reduce the frequency of exchange of beacons necessary for an accurate location of neighbors. Besides that, this prediction was further used to anticipate the availability of a future link. A more complex model developed by Heitor Ramos (see Appendix A) based on a Bayesian system using particles filtering was used by VIRTUS to estimate the time that a node remains as a potential candidate to relay further an incoming message. These models achieve distinguishing accuracy depending on different scenarios and a comparison between them and other existing models would provide valuable information for designers to select the most suitable one. Once again, information of the location of real vehicles could be used to evaluate the performance of these solutions.
- The solution developed in Chapter 3 to predict imminent neighborhood between out of reach nodes is aimed to be used for sender based routing solutions. These solutions can use this information to overcome eventual path breaks. This would increase the reactivity of sender based solutions and potentially make it feasible the use of these solutions over VANETs. The use of neighborhood prediction should be evaluated modifying MANETs well-known solutions (such as AODV [92] and DSR [55]) as well as in the develop of new sender based solutions.
- The unicast solution VIRTUS presented in this thesis (see Chapter 5) aims at preventing multiple nodes to transmit at the same hop level. This limits the inherent redundancy of ad hoc networks. It could be interesting to investigate the trade-off between increasing delivery ratio and cost by permitting some more redundant transmissions. These redundant transmissions could benefit from a Network Coding strategy.
- The issue of video streaming over VANETs was tackled in this thesis through the network perspective. It would be worthy to study the same topic through the perspective of video codecs. For example, there are coding techniques (in this case

of video coding) design for environments with higher rates of packet loss. Most of these solutions divide the video content in different layers in a way that losing part of this data permits the continuity of video content but with some loss in quality. There are different layering approaches that distinguish themselves mostly in terms of the distribution of importance of the different layers. There has not been yet a thorough work that evaluates the suitability of these solutions to video streaming over VANETs.

- The unicast solution developed in this work attempts to form a single path between source and destination. A different paradigm is to use multiple paths for the delivery of content from one node to another. The advantages of this approach is in terms of both resilience and load balancing. It is possible to use different paths as a recovery option in case data transmitted in one does not reach the destination. Multiple paths could also be used to distribute the load of a single one; for example, instead of transmitting at a rate of 2,000 kbps in one single path, two paths transmitting at 1,000 kbps could offer the same rate at the receiver. The main challenge in multipath solutions over VANETs is how to find paths that do not interfere with each other without incurring in excessive increases on the number of hops between source and destination.
- One topic that has been mostly neglected by the research community in VANETs is the issue of communication holes in these networks. The transmission of a packet that transverses a block composed by dense buildings is unlikely to be successful. Even larger communication holes are common in urban environments with parks, lakes or rivers that extended longer than the transmission range of vehicles. Besides that, there are yet communication holes which occurrence is dynamic and are formed simply by the lack of vehicles at a certain period of time in some regions in a city. These communication holes poses as serious issues for persistent connectivity in VANETs. We suggest that extensive studies on this topic should be conducted towards feasible solutions for a successful deployment of VANETs in a near future.

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