Performance Evaluation of a LEO Mobile Satellite System Integrated with Intelligent-Transportation-System Networks

by

Tianning Liang

Thesis submitted to the

Faculty of Graduate and Postdoctoral Studies

In partial fulfillment of the requirements

For the MASc. degree in

Electrical and Computer Engineering

School of Electrical Engineering and Computer Science

Faculty of Engineering

University of Ottawa

Abstract

In Intelligent Transport Systems (ITS), the unavailable Road Side Unit (RSU) becomes an increasing serious safety-related problem because of its important role in ITS. However, there is no existing method to solve this problem effectively and stably nowadays. To solve the unavailable RSU problem, a novel 2-tier integrated communication system is proposed in this thesis to address the issue of unavailable RSU in ITS. Compared to some other solutions proposed in the previous research works, which mostly focus on improving the system performance by adjusting parameters of vehicular ad-hoc network among vehicles, the proposed 2-tier communication network, called ITS-LEO Integrated System (ILIS), is composed of conventional ITS system and Low Earth Orbit (LEO) mobile satellite system (MSS), where the LEO MSS is utilized as the complementary network when the RSU is unavailable. Since the LEO MSS primary message will get affected when overflowing messages from ITS to LEO MSS, we prioritize LEO MSS primary message over the overflowed message to minimize the effect, which is based on that the emergency message (EMsg) is given higher priority over routine message (RMsg) to get access to the channel in ITS. To optimize the utility of network resource, two different overflowing mechanisms are proposed in ILIS to improve system efficiency under different traffic density. Furthermore, we propose a bandwidth reservation protection mechanism for ILIS to increase the ITS network performance. A real-time simulation program in C++ is developed to evaluate the performance of ILIS in terms of Packet Loss Rate (PLR) and Delay, and simulation results show that adding LEO MSS as a complementary network to ITS is an effective way to solve the problem of an unavailable RSU.

Acknowledgement

I would like to express my deepest appreciation to my supervisor Prof. Hussein T. Mouftah of his kindness, generosity, and patience. During the process of finishing my research project, I have received a lot of guidance and advice from him, and he is always willing to offer help whenever needed.

Also, I would like to thank Dr. Zhipeng Wang for his creative ideas and his outstanding professional work to help me modify my paper and thesis.

In addition, I would like to express my gratitude to the Innovation WiSense Annual Workshop 2014 that offer me a great chance to examine my work and I really appreciate the poster examiners' suggestions.

Finally, I acknowledge that this work was carried out with the support of Innovation WiSense project and NSERC Strategic Network DIVA project, and the financial support from ORF-RE 02-009 Ontario Ministry of Research is greatly acknowledged.

Dedication

I dedicate this thesis to my father Cong Liang who has always given me his solid support to pursue my Master degree.

To my mother Liyun Lu, who has been always behind me in any circumstances.

I also dedicate this to my boyfriend Melquisidec Mamucod for his full support and encouragement.

Content

List of Figures

List of Tables

List of Acronyms

AC	Access Categories
ACK	Acknowledgement
AIFS	Arbitration Inter-Frame Space
AP	Access Point
ASTM	American Society for Testing Material
BA	Blind Area
CCH	Control Channel
CD	Contention Window
CDMA	Code Division Multiple Access
CR-LDP	Constraint-Routing Label Distribution Protocol
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DCA	Dynamical Channel Allocation
DIFS	DCF Inter-Frame Space
DSRC	Dedicated Short Range Communication
EDCA	Enhanced Distributed Channel Access
EMsg	Emergency Message
ES	Earth Segments
FCA	Fixed Channel Allocation
GEO	Geosynchronous Earth Orbit
GPS	Global Position System
IEEE	Institute of Electrical and Electronic Engineers
IFS	Inter-Frame Space
ILIS	ITS - LEO Integrated System
ITS	Intelligent Transportation System
LEO	Low Earth Orbit
LLC	Logical Link Control
LTE	Long Term Evolution
MAC	Media Access Control

MANET	Mobile Ad-hoc Network
MEO	Medium Earth Orbit
MLME	MAC layer management entity
MSS	Mobile Satellite Service
NAV	Network Allocation Vector
NPS	Non Priority Scheme
OBU	On-Board Units
OFDM	Orthogonal Frequency Division Multiplexing
PHY	Physical Layer
PIFS	PCF Inter-Frame Space
PLME	PHY layer management entity
PPS	Preemptive Priority Scheme
QPS	Queue Priority Scheme
RCS	Reserved Channel Scheme
RMsg	Routine Message
RSUe	Road-Side Units
RSVP	Resource Reservation Protocol
SAT	Satellite
SCH	Service Channel
SIFS	Short Inter-Frame Space
STA	Wireless Station
SS	Space Segments
TC	Traffic Categories
TDMA	Time Division Multiple Access
TXOPlimit	Transportation Opportunity Limit
VANET	Vehicular Ad-hoc Network
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
WAVE	Wireless Access for Vehicle Environment
WSMP	Wave Short Message Protocol

Chapter 1 Introduction

1.1 Thesis Background

With the increasing importance of traffic in our lives, more and more researchers are focusing on increasing traffic safety and improving the current traffic model. Due to high fatalities and serious effects of traffic accidents, how to better manage the vehicles running on the road becomes urgently needed. In such circumstances, an Intelligent Transportation System (ITS), a novel electrical traffic system, appears to be a good solution to ensure better communication between vehicles and a control center, in order to reduce traffic pressure and increase driving safety.

1.1.1 Intelligent Transportation System (ITS)

An Intelligent transportation system (ITS) is a real-time and highly efficient integrated management system, which applies the advanced telecommunication technique, wireless sensor technology and computer technology etc. in a complex integrated traffic management system.

Approved by the American Society for Testing Material (ASTM), 5.9GHz is applied to be the frequency bandwidth of Dedicated Short Range Communication (DSRC) E2213-02 and has become the standard. After that, the Institute of Electrical and Electronic Engineers (IEEE) imported the DSRC standard and adjusted it to the protocol suitable for vehicular environment, which is the foundation of protocol IEEE 802.11p. Nowadays, the most well-known protocol used for ITS is called Wireless Access for Vehicle Environment/Dedicated Short Range Communication (WAVE/DSRC), which applies the technique and agreement defined in protocol IEEE 802.11p and IEEE 1609 suites. Compared to other DSRC techniques, it has a shorter delay (0.0002s), a higher transport range (1000m) and a higher transmission rate (27Mbit/s). Because of environmental events happening very quickly and short driver response time, the requirements for communication environment between vehicles and transmit delay are highly strict.

As defined by WAVE/DSRC, the complete ITS is composed of vehicular on-board units (OBU) and roadside units (RSU) and the protocol defining communication among OBUs and communication between OBUs and RSUs. An OBU is the communication unit installed on the vehicle and is responsible for sending vehicle information and receiving control instruction, while a RSU works as the access point to collect data and send to the backbone network. There are two types of communication models in ITS: Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I). However, ITSs also have some limitations because of the protocol defined and the system structure design. So, an efficient complementary communication network is needed to provide service when an ITS is not able to work properly.

1.1.2 LEO Mobile Satellite Service (LEO MSS)

The following are the advantages of using LEO satellite to support ITS communication. On the one hand, the height of a LEO is relatively low, which can shorten the transmission delay; the path loss is also small, and multiple satellites can achieve global coverage with more efficient frequency multiplexing. On the other hand, cellular communication, multi-address, spot beam and frequency multiplex also provide the technique support for LEO communication. So, LEO systems are considered to be the newest and most promising satellite communication systems. In nowadays, there are two main LEO systems known to the public: Iridium and Globalstar.

1.1.2.1 Iridium

The Iridium system is a global satellite mobile communications system consisting of 66 low earth orbit satellites, which distribute on 6 polar orbits. The system name "Iridium" comes from the original system structure, which is composed of 77 satellites and connected with each other with the metallic element iridium. The Iridium system is composed of Space Segments (SS) and Earth Segments (ES). The ES includes a System Control Center, Gateway and User Terminal. There are Onboard Processors and Onboard Switches being equipped on Iridium satellite, adding the Inter-satellite Link (the most outstanding feature of Iridium system), so system performance is very advanced, complex and costly. Iridium opens a new global personal communication generation, which is considered to be a milestone of modern communication and allows people on the earth to communicate anywhere at all.

Iridium NEXT

Iridium NEXT is the second-generation global network of telecommunications satellites systems, which has an Iridium architecture of 66 satellites with 6 in-orbit spares and 9 on-ground spares. It is to be deployed between 2015 and 2017. Through replacing the old constellation and improving the earth system, Iridium NEXT gets a lot improvement on performance and new features. The biggest difference in Iridium NEXT is the expanded system capacity, higher data speed and the possibility of data transmission being available.

1.1.2.2 Globalstar

Globalstar system uses 48 low earth orbit satellites to provide worldwide users (excluding the north and south poles) gapless, cheap satellite mobile communication service, including voice, fax, data, messaging and locating etc. Adapting LEO communication technique and CDMA, Globalstar can ensure good voice quality and high security without any delay. Continuous multi-override and routing diversity allow Globalstar to provide nonstop service in an area where signals may be interrupted. Being a detour network, Globalstar is the extension to the current local, long distance, public and private telecommunication network, rather than being the competitor. Without the inter-satellite link and on-board processor, the cost of a Globalstar system is cheaper. However, simple design requires a lot of gateway in the system, and the number for Globalstar system is estimated at around 100 to 150 worldwide.

1.2 Thesis Motivation

Working as the bridge between the vehicles and backbone network and connecting the vehicles to the control center, the role of RSU is very important. In addition, RSU is in charge of allocating OBU channel and scheduling OBU to access transmission medium. However, RSU may be out of service due to various reasons (e.g. disaster, power outage, and accidents). When this happens, the area covered by the out-of-service RSU, called Blind Area (BA), becomes a potential hazard to vehicles because the control center cannot exchange safety-related messages with vehicles in this area. To solve this problem, some researchers propose to apply self-organized Ad-hoc network in ITS and communications among vehicles only rely on the neighboring vehicles only. According to the reported simulation results, the performance of decentralized ITS is affected by vehicle density significantly. So, a new method to solve the unavailable RSU problem efficiently and reliably is needed to study.

1.3 Thesis Objectives

The main objective of this thesis is to construct a new integrated communication system to ensure vehicle messages can be transmitted even if the RSU is not functioning properly. The new system needs to meet the requirement of the ITS on the number of messages sent successfully and the delay of messages transmitted as well as the requirement of LEO system.

Based on the main objective, there are some challenges appearing during the development of the new system:

1. The packet loss rate of ITS is not stable because the available bandwidth of LEO network is not fixed, especially under heavy traffic;

2. When reserving satellite bandwidth for ITS, the communication of satellite primary customer will be affected and increasing number of packets will be dropped;

3. Delay will increase when packets are overflowing in the satellite network, which cannot satisfy the requirement of ITS.

So, the objective for this thesis is not only building the new integrated system, but also solving all problems coming out during new system development.

1.4 Thesis Contributions

The main contribution of this thesis is to creatively rebuild the existing technique and network system by constructing a novel communication network and solving safety related problems. Compared to developing a brand new technique, reconstructing existing technology can solve the problem with lower cost, and it's also more acceptable for industry to apply in real life. The work has been done in this thesis is summarized briefly as follows:

1. Proposed a novel 2-tier communication network system called ITS - LEO Integrated System (ILIS) to solve the unavailable RSU problem and evaluate the performance based on important network parameters.
    - Analyze the ILIS system theory structure in detail from Channel Access, Message Prioritize, and Handover problem etc;
    - Construct the simulation model in C++ to evaluate the performance of new system ILIS: Packet Loss Rate and Delay;
    - Collect the simulation real-time data and use MATLAB to draw the change curves and analyze the figures;
2. Proposed a Bandwidth Reservation protection mechanism to make the best use of wireless resource between ITS and LEO networks for ILIS.
    - Reserve a certain amount of satellite bandwidth for ITS emergency message can have higher possibility to get access to the channel;
    - Through comparing different reservation amount, explore the relationship among ITS and LEO MSS system communication quantity with the bandwidth reservation amount that can achieve optimized system performance.

3. Built a real-time simulation model in C++ to observe data change in real-time.

4. Summarized the research problems that can be improved in the next step and listed the possible related research direction for the future work.

1.5 Thesis Outline

In this thesis, Chapter 1 gives the introduction of research, which is stated as Theory Background, Motivation, Contribution and Objectives. Chapter 2 presents the detailed technique illustration and related work of other researchers in ITS, LEO MSS and integrated system. I also do the comparison with my work and describe how I refer other works in my model. In Chapter 3, a detailed network system model is explained with the technique used in Physical Layer, MAC Layer, Network Layer and Transportation Layer, as well as two proposed overflow mechanisms. To evaluate the performance of proposed integrated network system, a real-time simulation is built in C++ and the simulation model design and implementation are introduced in Chapter 4 with Structure Chart, Flow Chart, State Chart and Pseudo Code. The simulation result is presented and analyzed in Chapter 5, and Chapter 6 concludes all the work has been done and provide the possible related future work after.

Chapter 2 Intelligent Transportation System and Low Earth Orbit Mobile Satellite Service Survey

2.1 Introduction

In Chapter 2, a detailed survey and related background research will be provided, and the feasibility of the proposed network system will be discussed through comparing with the existed integrated system.

The survey is introduced by five main parts: Firstly, I illustrate the currently used ITS protocol and techniques in detail as well as the related improvements other researchers have done. As the research basis of the ILIS, EDCA and Multiple Access techniques in IEEE 802.11p/1609 protocol suite are discussed particularly, which can help to understand the techniques of the newly proposed system. Secondly, an Ad-Hoc network is introduced, which is used by some researchers to solve the unavailable RSU problem, and I will give a more detailed simulation of ILIS in Chapters 4 & 5. As ILIS is composed of ITS and LEO satellite mobile network, a basic survey on LEO communication system technique and LEO wireless resource allocation technique is studied. In addition, according to the analysis of current satellite system applied in ITS and sampled integrated system structure of satellite with LTE, the possibility and advantage of ILIS is studied.

2.2 ITS Protocols & Techniques

2.2.1 WAVE Protocol

The most well-known protocol used for ITS is called Wireless Access for Vehicle Environment/Dedicated Short Range Communication(WAVE/DSRC), which consists of IEEE 802.11p and IEEE 1609 suites. Compared to other DSRC techniques, it has lower delay (0.0002s), higher transport range (1000m) and higher transmission rate (27Mbit/s). Because of environmental events happening very quickly and short driver response time, the requirements for communication environment between vehicles and transmit delay are especially strict.

In WAVE/DSRC, the ITS component includes vehicular on-board units (OBU) and roadside units (RSU). An OBU is the communication unit installed on the vehicle, which is responsible for sending vehicle information and receiving control instruction, while a RSU works as the access point to collect data and send to the backbone network. There are two types of communication models in ITS: Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I)[MSA10]. The authors of [LIN10] have given a detailed illustration about different transmission models in ITS, and the proposed field testing flow is considered to be a good base for real road test in the future.

WAVE/DSRC applies IEEE 802.1p as the underlying protocol and IEEE 1609 suite as the upper layer protocol. As shown in Figure 2.1, corresponding to the OSI Reference Model, IEEE 802.11p defines the communication agreement of Physical layer (PHY) and Media Access Control layer (MAC) [HAN12], while the Multi-Channel Operation in MAC layer to Application layer communication rules are defined by IEEE 1609 suite.

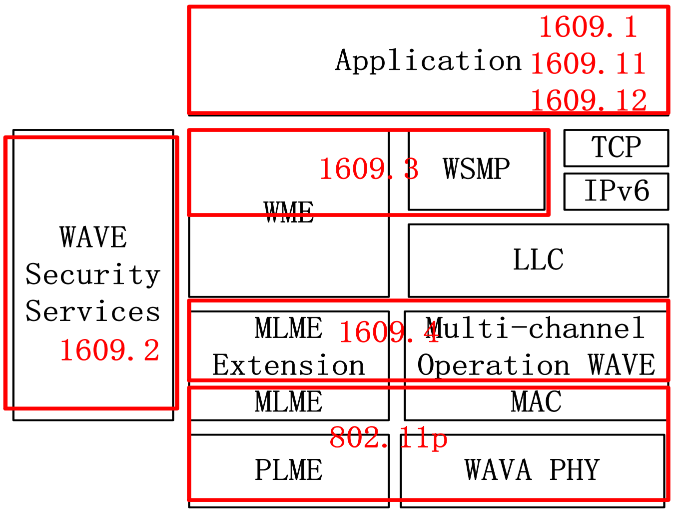


Figure 2.1 WAVE/DSRC Protocol Structure for ITS

According to the IEEE 802.11p, there are 75MHz bandwidth in the band (5.850～5.925GHz) FCC defines for ITS, and is divided into 7 channels with 10MHz each. One is the Control Channel and the other 6 are Service Channels, as shown in Figure 2.2. Using IEEE 802.11a as the Physical Layer technique, the relevant applications of IEEE 802.11p enhances vehicle driving safety, including collision warning and road situation warning etc. In [SON13] and [MUR08], the performance of IEEE 802.11p is estimated in detail through different simulation tools, and results show that 802.11p has strong advantages in reliable short distance message transmission.

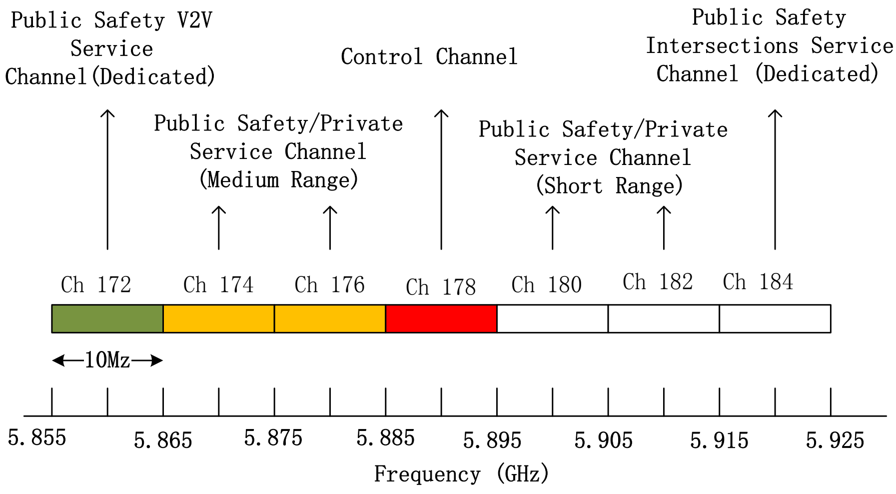


Figure 2.2 Channel Frequency Spectrum in IEEE 1609.4

In WAVE, 1609.3 works for network service, which is considered as the Layer 3 and Layer 4 for OSI system. The purpose is to provide the WAVE address and routing service, so as to connect the application service and low layer communication protocols. 1609.4 is the Multi-Channel Operation, including the operation of Control Channel (CCH) and Service Channel (SCH), Priority Buffering, Channel Switching and Routing Management Service. 1609.2 provides Security Encryption for corresponding application and management message. As a hot research point in communication, Channel Switching and allocation in ITS appears to be an increasing popular research direction and attracts a lot of experts to do the related studies. [WAN10], [AKB12], [GUO12] all work on proposing a new improved channel mechanism for IEEE 1609.4, which can dynamically switch between CCH and SCH. But in [WAN10] and [GUO12], the authors modify the current protocol definition, while [AKB12] gives the current MAC layer a new extension.

Based on the IEEE 802.11p/1609 protocol family, some key techniques applied in ITS protocol will be discussed in details as follows.

2.2.1.1 Enhanced Distributed Channel Access (EDCA)

EDCA introduces the Traffic Category, which differentiates messages types by assigning different priorities. In EDCA, there are eight Traffic Categories (TC) and four Access Categories (AC), and these 8 TC all belong to the defined 4 AC. For Access Category, each one has a unique sending queue, so there are 4 sending queues in each QoS supported station at the same time, which map to the 8 TCs. In other words, messages with a different priority will wait in the corresponding AC to be sent out, and each AC can get access to the channel with specific EDCA parameter. As discussed in [HAN12], the authors proposed an analytical model based on the current EDCA mechanism by modifying contention windows (CW) and arbitration inter-frame space (AIFS) for each access category (AC).

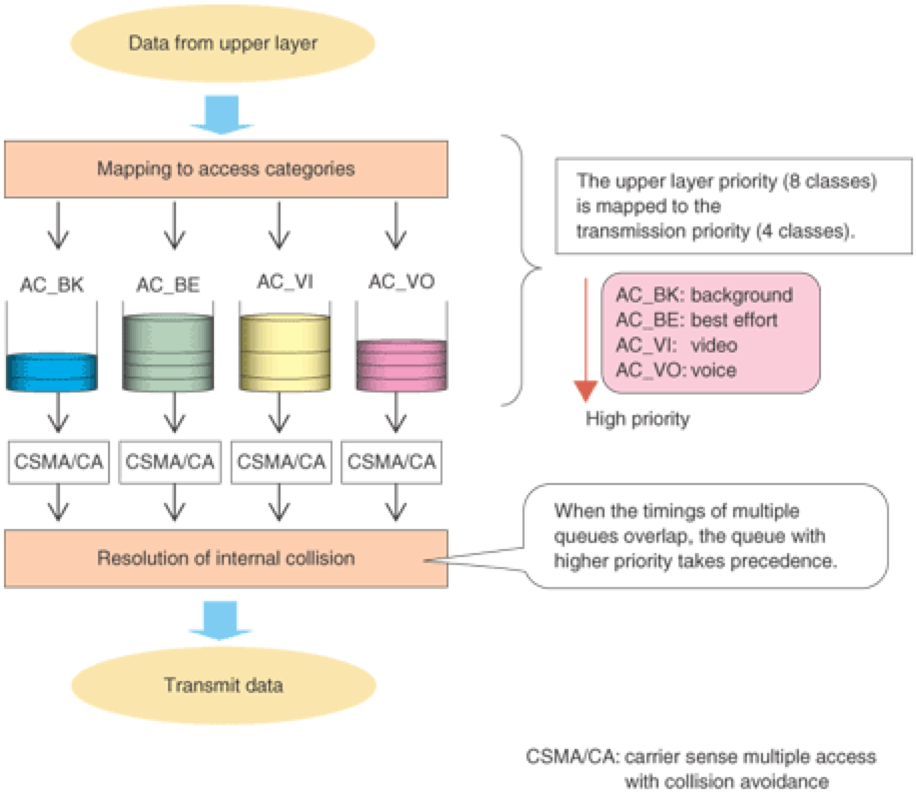


Figure 2.3 Enhanced Distributed Channel Access Structure [WEB01]

TABLE 2-1. Message Classification in EDCA

Priority	UP (Same as 802.1D user priority)	802.1D designation	AC	Designation
Lower	1	BK	AC_BK	Background
	2	-	AC_BK	Background
to	0	BE	AC_BE	Best Effort
	3	EE	AC_BE	Best Effort
Higher	4	CL	AC_VI	Video
	5	VI	AC_VI	Video
	6	VO	AC_VO	Voice
	7	NC	AC_VO	Voice

EDCA parameter: [PPT12]

1. Replace DIFS with AIFS: using different Inter-Frame Space for different

AC data frame. The waiting inter-frame space before sending data is called Arbitration IFS (AIFS), and the new added AIFS won't be fixed as the DIFS defined in DCF, which means the value of AIFS varies with service type. The AIFS value of low priority service (background, normal data) is higher than the one of high priority (video, voice).

$$AIFS[AC] = AIFSN[AC] \times aSlotTime + aSIFSTime \tag{2.1}$$

QSTA of Non-AP_AISFN >= 2， AP_AISFN >= 1

2. Change of Maximum/Minimum Contention Window: After waiting for an AIFS, the timer is set to be any value within [1, CW+1] for each Backoff, which is different to the range [0, CW] in DCF. The minimum contention window CWmin and maximum contention window CWmax are also related to AC: smaller value of CWmin and CWmax means higher possibility to get access to the channel, and the corresponding priority is higher.

3. Transport Opportunity Limit (TXOPlimit): this is the max lasting time value of TXOP. Once the station gets the TXOP, it can continually send multiple frames without re-contending for channels within the TXOPlimit. As inter-frame waiting time is only SIFS, it's very helpful to increase the channel use ratio. Also, the TXOPlimit varies with different ACs, and value being 0 means that station can only send one frame per time.

TABLE 2-2. Window Size and Interval in EDCA

AC	CWmin	CWmax	AIFSN	TXOPlimit		
				For PHY: defined in Clause 15 and Clause 18	For PHY: defined in Clause 17 and Clause 19	Other PHYs
AC_BK	aCWmin	aCWmax	7	0	0	0
AC_BE	aCWmin	aCWmax	3	0	0	0
AC_VI	(aCWmin+1)/2-1	aCWmin	2	6.016ms	3.008ms	0
AC_VO	(aCWmin+1)/4-1	(aCWmin+1)/2-1	2	3.264ms	1.504ms	0

Usually, the AC in each STA can be classified as one of the above four types to contend to get access to the channel. When some AC detects the medium is in an idle period of AIFS, it will start the backoff timer, and only the STA with the timer being 0 first has the right to send the frame. When more than one AC count to 0 at the same time, the AC with higher priority can get the TXOP to send data frame. It is worth noticing that, when different ACs in the same station need to send data at the same time, the station will apply Internal Conflict Resolution mechanism and only the winner AC can get access to the channel to contend with other stations.

So, it's better to set AIFS, CWmin and CWmax together to guarantee that the data with the highest priority can get access to the channel. In addition, the sum of the AIFS and CWmax values for high priority data should bigger than the ones for low priority data. Thus, low priority data can be guaranteed not to be locked and lose the opportunity to send data frame. The importance of message prioritizing can affect the performance of an ITS on a large scale, which is discussed thoroughly in [MAR09] and [FEN10].

The Improvement of EDCA [RAW11][CHA12][LUI14]

1. EDCA defines four Access Categories based on IEEE 802.11, and uses eight Priorities to get access to channel to provide different service levels;

2. The waiting time for channel to be idle becomes AIFS rather than the fixed value as DIFS. AIFS is related to AC: when AC value is higher, the priority is higher and AIFS value is lower;

3. The initial backoff window size is different with different AC service flow. When AC value is higher, priority is higher and initial backoff window is smaller;

4. TXOPlimit is proposed in EDCA. Within the TXOPlimit period, multiple frames can be sent continually between two communication ends, and inter-frame is only SIFS.

2.2.1.2 Multiple Access

In WAVE/DSRC, the multiple access method is CSMA/CA, which applies

ACK signals to avoid collisions. In other words, the messages are delivered to destination only after confirming STA has received the ACK signal.

To avoid collision, 802.11 defines that after all STA finish frame transmission, a waiting interval, called Inter-Frame Space (IFS), is required before sending the next frame and the length of IFS is decided by the type of frame. The waiting time of frames with higher priority is shorter while the IFS of lower priority messages are longer. If other higher priority messages arrive before the low priority message being sent out, the medium will become busy and the low priority message has to wait again. As analyzed in [NGU13], the collision, in this way, can be reduced ideally. The common IFS types are as figure 2.4 shows and a comparison is given based on the study from [BIA03][AFR10].

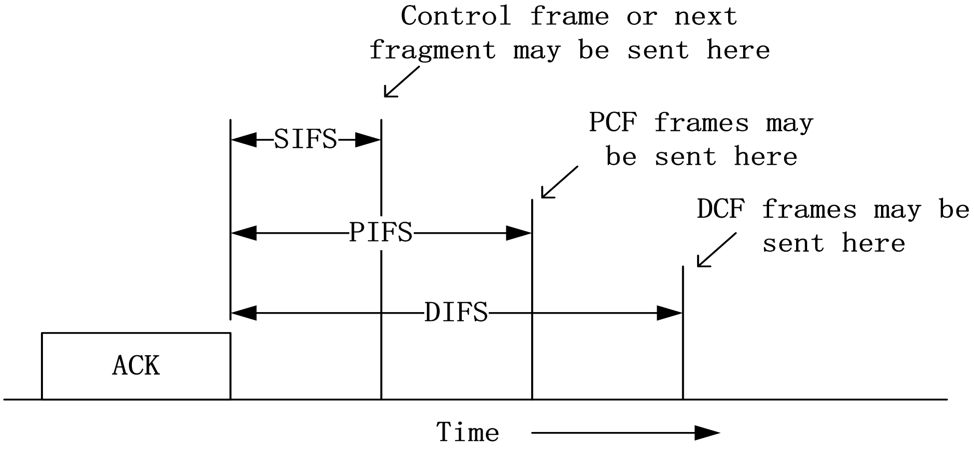


Figure 2.4 Inter-Frame Space in 802.11

Short Inter-Frame Space (SIFS). SIFS is the shortest IFS, which is used to separate frames in one session. During this period, STA can switch from sending mode to receiving mode. The messages using SIFS are: ACK frame, CTS frame, Fragmentation frame and all frames that are used to answer AP detection frame.

PCF Inter-Frame Space (PIFS). PIFS is used to get priority access on channels with PCF method. The length of PIFS is the length of SIFS adding a slot time, which is defined as: In a BSS, when a station get access to a channel at the beginning of a time slot, then other stations can detect it to be in a busy state in the next time slot.

DCF Inter-Frame Space (DIFS). DIFS is the longest IFS, whose length is the length of PIFS and another time slot. It is used when using DCF method to send data and management frames.

CSMA/CA Working Process is shown in Figure 2.5 [WEB05].

(1) Check if any STA is using the channel, then send the data frame after DIFS if there's a free channel.

(2) If destination STA can receive the frame successfully, then send the confirm ACK frame after SIFS.

(3) After resource STA receive the ACK frame, then there is a free period after DIFS, called Contention Window, indicating each STA contends for the channel.

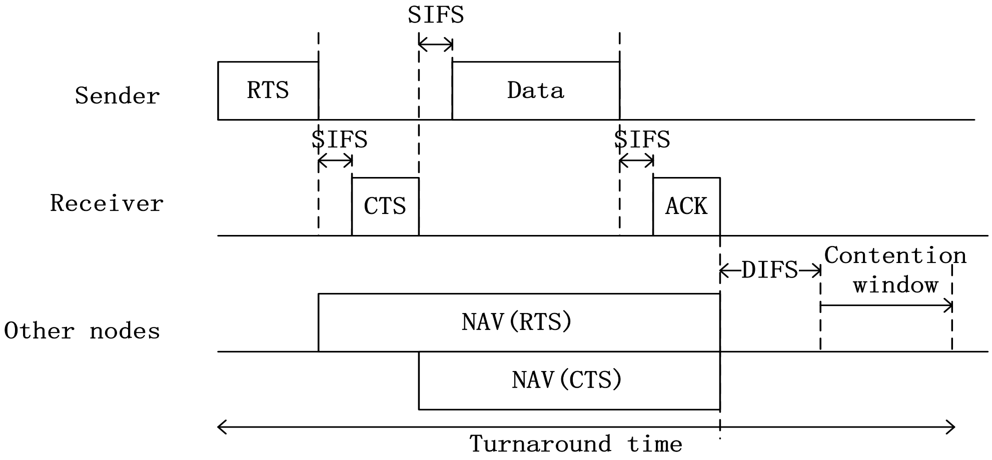


Figure 2.5 CSMA/CA process

If the channel is detected to be in use, STA will start the CSMA/CA backoff algorithm. This starts backoff when a channel is free and when it counts to 0, STA will send the frame to the channel and wait for the ACK. If ACK is not received, the data frame needs to be resent.

To solve the hidden nodes problem, the RTS/CTS is added to CSMA/CA, as discussed in [DHO12] and [MAD12]. When a free channel is detected and waits for a DIFS, STA sends RTS rather than data frame to destination STA, and destination STA will reply a CTS back. As shown in Figure 2.6 [DHO12], through RTS/CTS, hidden nodes can be effectively avoided.

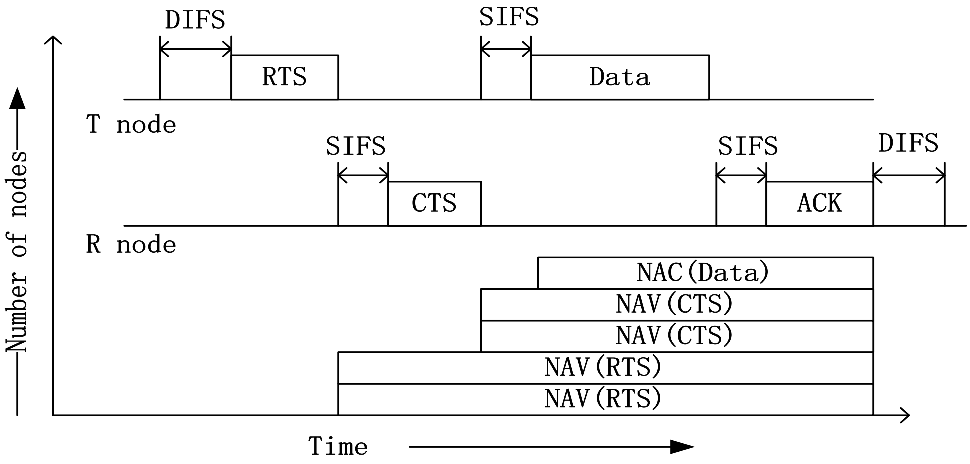


Figure 2.6 The RTS-CST-DATA-ACK for T (transmitter), R (receiver), DIFS(Distributed Inter-Frame Space), SIFS (Short Inter-Frame Space), NAV (Network Allocation Vector), ACK (Acknowledgement)

Compared to the current protocol, a lot of research papers have proven TDMA works better than CSMA in an ITS environment. Although the CSMA/CA applied in IEEE 802.11p can achieve a good performance in collision avoidance, but it also brings some inherent problems, especially when more than one vehicle backs off to 0 at the same time, delay will increase greatly. So, many researchers chose to use TDMA in VANET for ITS. [SJO11] and [ZHA14] evaluate the performance of both TDMA and CSMA to compare and analyze the difference, and the simulation shows that TDMA can shorten the transmission delay ideally over CSMA. Authors of [XIE12] [HAD14] [FAN07] proposed their own TDMA based MAC protocol to explain the advantages of TDMA. However, the deployment of a complete network system based on TDMA needs the access point to allocate the timeslot, which is called the RSU in ITS. To decrease the dependence of RSU, some researchers are seeking to use the self-organized network structure, like Ad-hoc, to replace the role of RSU in ITS, which is adopted in [GUO12] and [GAO13]. Nevertheless, self-organized network is proved to be unreliable and less secure than the centralized network structure. The integrated system proposed in this paper can solve this problem more effectively and reliably.

2.2.2 Vehicular Ad-Hoc Network (VANET)

VANET is the new application of traditional Mobile Ad-hoc Network (MANET) on traffic, and it is a special mobile self-organized network. Based on the current research [LUO10] [ZHU13], VANET has some problems different from other self-organized networks. Firstly, VANET owns all characteristics that a mobile self-organized network has, like autonomy, multi-hop routing, network topology dynamically changing, and limited network capacity etc. However, in special situations like on a narrow road, high density distribution of nodes moving at high speed can affect the message transmission ability directly, which can cause more packet loss and longer delays.

Recently, researchers have done a lot of research on VANET transmission problems, and some valuable ideas are helpful for VANET designs. However, since a VANET is a special case, its transmission control protocol is more challenging and unique. In VANET, geographic information, channel quality and routing status can all achieved by some certain methods, and they are significant for designing highly efficient and reliable transmission control protocols. At the same time, small communication channels, high-speed moving nodes and high density node distribution can bring more difficulties.

According to the relevant research on VANET [LUO10][ZHU13][LIU13], its characteristics can be summarized as follows:

- Wireless channel quality is unstable, and affected by roadside buildings, road environment, vehicle type and vehicle relative velocity easily.
- Network topology changes fast, and the link lifetime is short.
- Limited network capacity. The distribution of nodes in VANET is limited by the load, and its network capacity is more limited through network capacity algorithm [PIN10].

- Network payload varies with the traffic density, so nodes are required to adapt to such fast change.

However, as all nodes in VANET are vehicles and roadside infrastructures, this allows it to have some special advantages [WEB04]:

- Vehicle nodes can get enough energy support, and vehicular space allows wireless communication better performance as well as the strong computing and storage ability. Also, the road side unit can get enough energy support, better communication performance and storage ability.
- With the wide application of GPS and GIS, nodes in VANET can get more outside assistance information, including location, road environment etc.

Based on the above analysis, the pure Ad-hoc network, which is composed only of moving vehicles to replace the RSU [FAN07][GUO12], is not applicable for VANET because of low reliability and high delay. A new network system needs to be developed to solve the problem of relying only RSUs.

2.3 Satellite Communication System and Techniques

2.3.1 Satellite Communication System

Satellite communication system is a system that uses satellites to transmit signal globally. Classified as the orbit height, there are three main satellite communication systems: Low Earth Orbit (LEO), Medium Earth Orbit (MEO) and Geosynchronous earth orbit (GEO). Since LEO is the closest satellite communication system, it is usually used for the service with low latency tolerance and high security level requirements.

2.3.1.1 Low Earth Orbit (LEO) mobile satellite communication system

Low Earth Orbit (LEO) mobile satellite communication system is composed of Satellite, Ground Station, System Control Center, Network Control Center and

User Unit. All these devices constitute the main components of satellite communication system [WEB03][SIY11]:

1. Communications system unit, including the antennas and transponders that are responsible for receiving and retransmitting signals;
2. Power system unit, which includes the solar panels to provide power;
3. Command and Control subsystem unit, which maintains the connection with ground control stations.

As shown in Figure 2.7, the end user device can send signals to the satellite rather than the traditional base station. Multiple satellites are deployed on certain orbits and connected between different orbits by communication links, which work together to build cellular service structures on earth. The users are covered by at least one satellite and able to get access to system anytime.

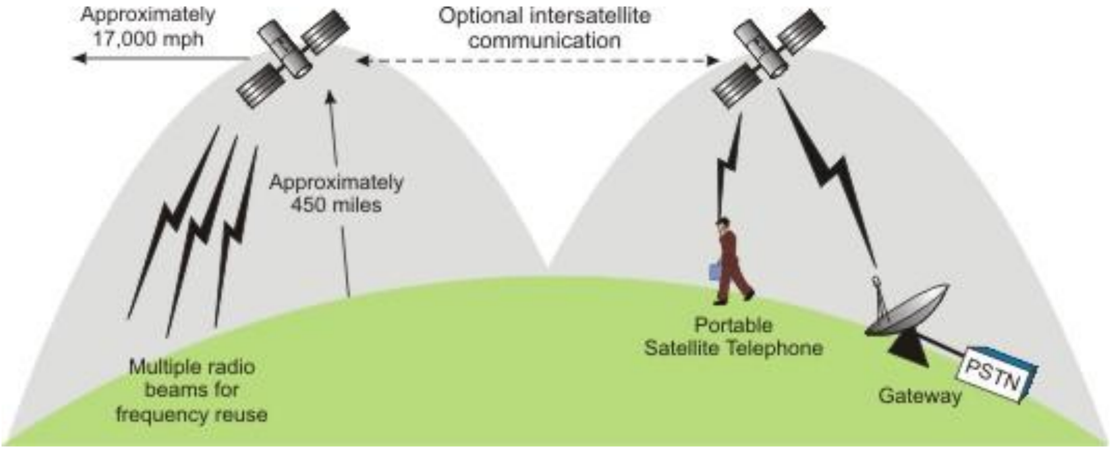


Figure 2.7 Low Earth Orbit satellite communication system. [WEB02]

2.3.1.2 LEO Wireless Resource

Wireless Resource Management happens when establishing a phone call. It needs to decide the appropriate satellite and spot beam for the user, assign a channel in the spot beam and decide the frequency that customer used to send the signal. Since a channel means a quantity of wireless resource and user uplink wireless resource is the bottle-neck, how to use the wireless resource efficiently in Wireless Resource

Management is an important problem.

The most significant technique in Wireless Resource Management is Channel Allocation, which is also the key problem in this thesis. Because the fast movement of satellites can lead the terrestrial user to stay in one spot beam for a short time, and the switch between spot beams happens frequently in LEO system, all kinds of optimized channel allocation policies are proposed to increase the channel access rate, especially for the switch between two neighbor cells. When the user needs to call or send message or switch from a range covered by one spot to the one covered by another spot, they need to get access to the channel covered by the satellite spot beam. [BIS14]

Channel allocation policies can be divided into two classes: Channel allocation between cells and Channel allocation within cell. For different cells, common channel allocation policies are: 1. Fixed Channel Allocation (FCA), which assigns each satellite spot beam a fixed number of channels in advance; 2. Dynamical Channel Allocation (DCA), which collects all wireless resources and allocates channel by system unified; 3. Hybrid Channel Allocation, which combines FCA and DCA to allocate channels in different way based on the service type. Within one cell, common channel allocation policies are [WEB02] Non Priority Scheme (NPS), Reserved Channel Scheme (RCS), Queue Priority Scheme (QPS) and preemptive priority Scheme (PPS) .

2.3.2 Satellite Communication Applied in ITS

Modern satellite technology has been used in ITS for research, like Global Position System (GPS), Automatic Toll Collection System and Road Construction Survey in ITS etc. and they will be discussed in detail in this sub chapter to show how satellite communication techniques are applied in ITS.

2.3.2.1 Global Position System (GPS) in ITS

With the fast development of electronic technique and network technology, building a low cost and high efficient GPS integrated service system becomes possible. ITSs are a new traffic revolution to increase traffic safety level, road network capacity and the vehicle transportation productivity. Effective communication technique, computer and network technology, vehicle position technique and e-maps are all possible electronic techniques which can be applied in ITS [AMI14]. As discussed in Chapter 2-1, ITS is composed of Advanced Traffic Management System, Advanced Traveler Information Systems, Commercial Vehicle Operation System, Electronic Toll Collection System and Public Transportation Operation System. So, the vehicle monitoring dispatching, security assistance service and navigation service in above systems all rely on GPS [MAK09][XIE14]. In addition, GPS is a useful tool in automatic charging like for tolls and in road or bridge planning and construction [MAK09].

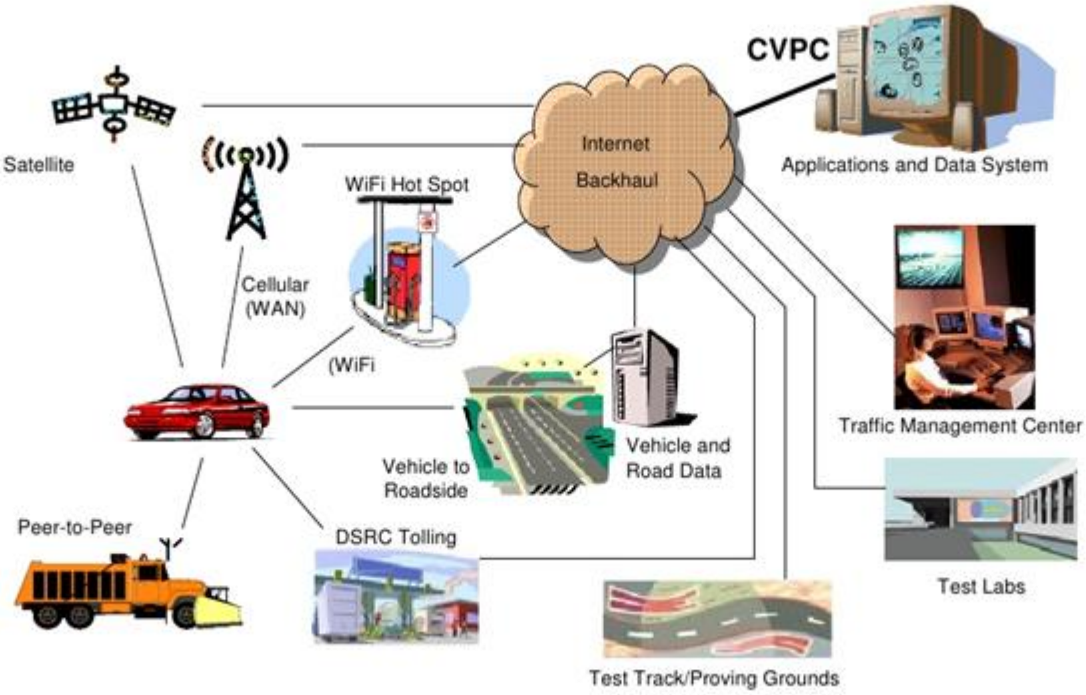


Figure 2.8 Satellite system applied in ITS [MAK09]

In traffic management, GPS navigation systems work with GIS e-maps, wireless communication networks and computer vehicle management systems together (as shown in Figure 2.8) and can implement multiple functions, like vehicle tracking, travel route planning and navigation, information inquiry and emergency assistance etc. Cars equipped with GPS to provide vehicle position for dispatching management can achieve better performance without increasing resource. Also, GPS e-maps can allow drivers to drive through unfamiliar areas quickly, which can shorten driving time. For commercial transportation, mobile data are sent by electric devices rather than paper when it works with the service application software, in which way to decrease work quantity and submit response data on time.

2.3.2.2 Electronic Toll Collection System based on Satellite Position

Based on the GPS and mobile communication technique, building communication with vehicle and management system achieves toll collecting without stopping the car [TOL10]. This new toll collection system of ITS is called Pay-per-use Road Use Charging (RUC).

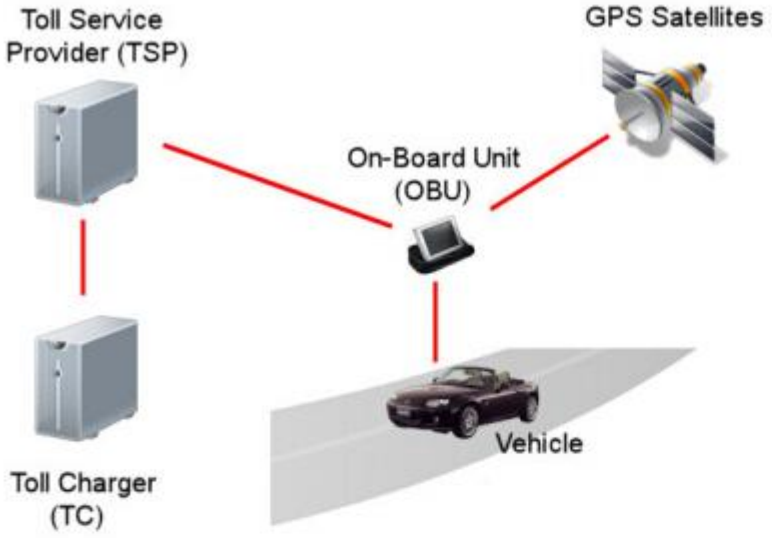


Figure 2.9 Electronic Toll Collection System based on Satellite Position. [BAL10]

Compared to the traditional Electronic Toll Collection (ETC) System, RUCs don't have road-side devices, which can decrease construction and maintenance costs. As shown in Figure 2.9, RUSs use OBUs to record drivers' routes and charge accurately as driving mileage can increase the efficiency. For passing efficiency, traditional ETC vehicle need to slow down and accelerate to pass the toll station, but there is no toll station in RUS so RUS vehicles don't need to stop for toll collecting. In addition, the RUS technique has a flexible payment method and drivers can pay on-line, which is more convenient for users. So, whether in terms of economic, social or environment benefits, RUSs appear to be higher efficient and low cost toll collection technology, as discussed in [TOL10] and [CHE12].

Based on the above analysis, we can see satellite systems have been widely used in ITS, especially for vehicle location and related services. As satellites have global coverage and high security characteristics, we design a novel 2-tier integrated network system of satellites and ITS to combine and make better use of two network resources and solve new problems. As discussed in Chapter 1, ITSs are facing a serious problem because of heavy reliance on RSUs and no complementary network system to provide service when the RSU is not available. So, extending the use of satellite in ITSs to provide complementary network service when RSUs cannot work properly is possible and reasonable.

2.4 Integrated System of Satellite and Terrestrial Communication system

As discussed in Chapter 2.1.4, satellites have been widely used in ITS, which provides the research base for working as the complementary network system for ITS in this thesis. In other words, the integrated system proposed in this thesis, ILIS (Integrated System of ITS with LEO), is the combination of two different kinds of communication networks - satellite network and ITS network. According to the survey, the integrated network system is proved to be able to improve throughput performance with least affect to the fairness and QoS [AIY14].

The term “Integrated System” refers to a system consisting of a Satellite Based Network with a Ground Component network that re-uses the same frequency spectrum and communicates with each other [DES10]. In recent research, integrated systems have been widely used in all kinds of communication areas to combine satellite systems with terrestrial communication systems, like the combination of satellite and LTE network [ARA13][AIY14][AMA11], combination of satellite and CDMA network [SHA10][KIM06][SIY11] and combination of satellite and 3G network [FAN08][RAV11]. Based on the simulation results, integrated systems are proven to be able to make better use of wireless resource and get more advanced performance.

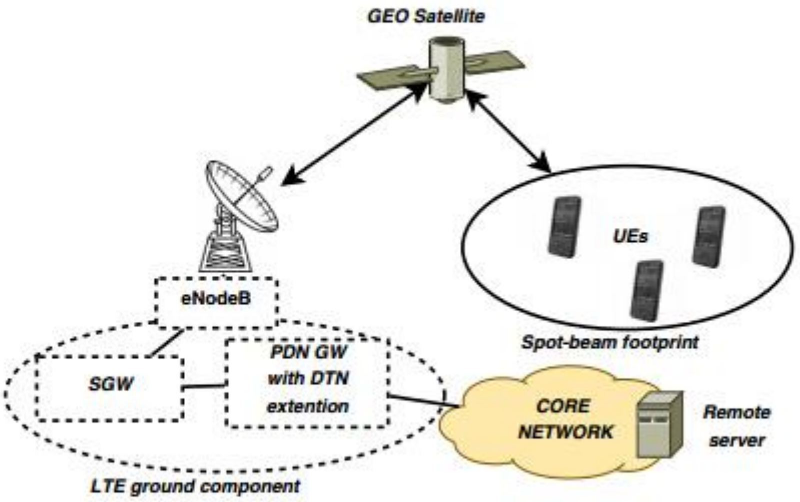


Figure 2.10 Satellite-LTE reference scenario. [AIY14]

Authors of [AIY14] have provided a typical integrated network system structure for reference, which is shown in Figure 2.10. As introduced in Chapter 2.1.3, a satellite communication system is composed of Satellite, Ground Station, System Control Center, Network Control Center and User Unit. All Radio Access Network mechanisms are deployed on earth. All these devices and control centers are combined to LTE components: The Gateway station is considered as the eNodeB, which makes sure the radio interface uses the LTE transmission protocols and sends the mobile terminals all the necessary parameters through the radio interface being linked with the eNodeB, SGW and the PDN GW work to provide delay tolerant services. When UEs want to communicate with remote servers, the data will need to flow through two different regions: the satellite and the terrestrial one. The authors in [AIY14] evaluate this integrated system using network parameters and it can be concluded that the satellite network is a suitable complement for terrestrial communication networks, especially to provide video streaming services.

However, there is no research applying satellite system into ITS for system performance research. Inspired by the previous work, the LEO MSS is integrated in ITS in this paper to work as the complementary network when RSU is not available. The above structure is meaningful to ILIS, because it shows the superiority of integrated systems when satellites work as the complement for terrestrial communication networks. Learned from but different to the related work, ILIS has its own characteristics which are more suitable for vehicular short distance communication in ITS, and the detailed ITS technique will be presented in Chapter 3.

Chapter 3 ITS - LEO Integrated System (ILIS)

3.1 Introduction

In this Chapter, a detailed description and analysis of the proposed system will be presented.

First of all, the reason for choosing Iridium Next to be the complementary network is presented through comparing and analyzing different LEO MSS systems. Then, the second part will illustrate all related techniques of ITS – LEO Integrated System (ILIS) in Open System Interconnection (OSI): Physical Layer – physical transmission parameters and encoding method; MAC layer – channel access and switch mechanism; Transmission Layer – bandwidth reservation method; and Network Layer – connection building process. In addition, the two overflow mechanisms proposed for ILIS will be introduced in Chapter 3 as well.

3.2 ITS - LEO Integrated System

3.2.1 LEO System Selection

Being a significant part of ILIS, the choice of the right complementary system is very important. As introduced in Chapter 1, with global coverage, low delay and non-gap connection with earth communication network, LEO satellite mobile communication systems are an ideal choice. Nowadays, there are two most well-known LEO communication systems: Iridium and Globalstar, and I will give a detailed comparison between these two systems in this subchapter.

TABLE 3-1. Comparison between Iridium and Globalstar

		Iridium	GlobalStar
System Structure	Height	485 miles 765 km	876 miles1414 km
	Global coverage	Yes	No
	Satellite	66	48
	Orbits	6	8
	Channel	3480/satellite	268800/satellite
	Beam Spot	48	16
	Access Method	TDMA/FDMA	CDMA
Cost	Annual Fee	$ 599.50	$ 300.00
	Out-of-bundle calls	$ 1.29/min	$ 1.99/min
	In-Network calls	$ 0.85/min	$ 1.99/min
Data Transfer	Circuit-switched Data Transfer Rate	2.4 kbps	7.2 kbps
	Frequency Band	1621.35 ~ 1626.5 MHz (Uplink) 1616 ~ 1626.5 MHz (Downlink)	N/A
	Communication Delay	< 210 ms	Varies significantly

From TABLE 3-1, we can see the differences between Iridium and Globalstar. For system structure, the distance between the satellite and earth is shorter for Iridium than for Globalstar, which means the delay of Iridium is lower in general. In addition, the Medium Access method for Globalstar is CDMA, so applying Globalstar as the complementary system of ITS, the air interface will be very complicated because ITS uses TDMA/FDMA to access the medium and the technical costs will be higher.

In terms of cost, although the annual fee of Iridium is higher than Globalstar, the cost per call of Iridium is lower for both Out-of-bundle and In-Network calls. When considering which should be the complementary system of ITS, unit price is more important because the main network is still ITS, and LEO satellite system only applies when the RSU is unavailable or the ITS cannot work properly. Also, there is no big difference in the annual fee between both systems. So the Iridium system is suited better to be the complementary network system of ITS when considering the costs.

For Data Transfer, we can clearly see that the internet speeds for these mobile terminals are suitable only for light data requiring applications. Since Globalstar applies CDMA as the medium access method, the voice data transfer rate can reach to 7.2 kbps and data transfer rate can be even higher. In comparison, Iridium doesn't show a competitive feature in data transfer rate, and sending a one megabyte file as attachment via email needs over one hour. This is not acceptable for modern high-speed mobile communication in this generation. Especially for ITS, which relies on the short range communication protocol and data transfer rates can reach as high as 6 Mbps, such a low data transfer rate like that of Iridium cannot meet the requirements of ITS.

Based on the above analysis, Iridium is considered to be a better complementary ITS system than Globalstar with only a serious problem - Low transmission rate. However, the next generation of Iridium, which is called Iridium Next, gives a chance to apply the Iridium system to work with an ITS. TABLE 3-2 gives the detailed comparison between both Iridium systems and shows the improved data transmission of Iridium Next. [WEB04][WEB05]

TABLE 3-2. Comparison between Iridium and Iridium Next on Data Transmission

	Iridium	Iridium Next
Voice	2.4 kbps	2.4 kbps
Circuit Switched Data	2.4 kbps	9.6 - 64 kbps
Short Burst Data	Low	Bandwidth On Demand
Iridium OpenPort	132 kbps	128 - 512 kbps
Iridium OpenPort Aero	132 kbps	128 - 512 kbps
L Band High Speed	N/A	Up to 512 kbps up / 1.5 mbs down
Broadcast	N/A	64 kbps

From the above table we can find out that Iridium Next has a great improvement on data transmission rate with some new techniques. In other words, Iridium Next remedies the most serious defect of Iridium by being a complement to the ITS system- Low Transmission Rate. In ILIS, Iridium Next is chosen to be the complementary network to work with ITS and provide services when the ITS cannot work properly.

3.2.2 ILIS Physical Layer Techniques

The transmission of signals relies on transmission media, and interface is required at the end of transmission media to send and receive signal. Working as the lowest of Open System Interconnection (OSI), the physical layer stipulates all kinds of transmission media/interface and the characteristics about transmitted signal. So, as the two-tier networks in ILIS are still isolated and each has its own transmission characteristics, the key physical layer techniques are analyzed separately here to illustrate how ILIS transmit signal physically under different situation.

3.2.2.1 ITS Physical Layer Technique Analysis

As introduced in Chapter 2, IEEE 802.11p applies Orthogonal Frequency Division Multiplexing (OFDM) in the physical layer, which is used in the frequency spectrum 5.9 GHz (5.850 ~ 5.925 GHz) with bandwidth 10MHz. In addition, 802.11p also adjusts correlation parameters, like carrier wave, to decrease the negative effect of multi-path attenuation.

To decrease the negative effect of multi-path attenuation, 802.11p decrease the bandwidth from 20MHz in 802.11a to 10MHz, which means all parameters are double of the one of 802.11a, as showed in TABLE 3-3.

TABLE 3-3. PHY Parameters Comparison between 802.11q and 802.11p

Parameters	IEEE 802.11a	IEEE 802.11p
Data rate (Mb/s)	6,9,12,18,24,36,48,54	3,4.5, 6,9,12,18,24,27
Modulation	BPSK,QPSK,16QAM, 64QAM	BPSK,QPSK,16QAM, 64QAM
OFDM Symbol Length	4us	8us
Guard Interval	800ns	1600ns
Sub-carrier Interval	312.5kHz	156.25kHz
Bandwidth	20MHz	10MHz
Error-correcting Code	Convolutional code K=7	Convolutional code K=7

From the comparison, we can find out the biggest different parameter is the Guard Interval (GI) 1600ns, which allows 802.11p can endure bigger root mean square (RMS) delay, and it can be used for the outside high-speed vehicular environment to satisfy the wireless network requirement in ITS. Based on the extended GI, other parameters have relevant change. To decrease the power of GI to 1dB, OFDM symbol length is defined to be 8us. So, the valid length is 6.4us after removing the GI, and the sub-carrier interval is 1/6.4 us, which is the half value of 802.11a. In another word, 802.11p is more sensitive about frequency offset than

802.11a.

IEEE 802.11p channel coding method is the Convolutional Encoding with constraint length 7 and code efficiency 1/2, and then do the Puncturing to get Convolutional encoding with code rate 2/3 and 3/4. All of these channel coding method work with BPSK, QPSK, 16QAM and 64QAM modulation methods to get encoding data rate 3~27Mbps.

3.2.2.2 LEO Physical Layer Technique Analysis

The terrestrial launch in Iridium is done by an earth station sender, which multiplexes the multipath signal to baseband signal firstly, and then encodes the baseband signal, modulates the intermediate-frequency wave and transforms to be the radio frequency (RF) signal through up-converter. Finally, the RF needs to be amplified by power amplifier and be able to send to the satellite by antenna.

The channel coding for error control is forward error correction (FEC) in Irridium NEXT, which can use the minimum coding redundancy to achieve the excellent error control performance. And the Convolutional Encoding is applied for channel coding here. In specific, Irridium system uses R=1/2，K=7 convolutional encoding method for gateway and R=3/4，K=7 convolutional encoding method for end user.

In Iridium, the modulation of both gateway and user end is QPSK, which is proposed based on the BPSK. QPSK has high anti-interference, good error robustness and high frequency utilization. As all carried information is on the phase, no matter how serious the amplitude attenuation and interference are, the information won't be lost as long as the modulated signal doesn't have error on phase. So, QPSK modulation can help satellite channel decrease attenuation and noise.

Based on the above analysis, it's not difficult to find that ITS and Iridium systems both have characteristics that allow signal transmission to satisfy the network requirement physically. To see the key technique and parameters in more details, I have summarized in TABLE 3-4.

TABLE 3-4. PHY Layer Parameter of ILIS

Parameters	ITS	Iridium
Data rate	3,4.5, 6,9,12,18,24,27(Mbps)	512 Kbps - 1.5 Mbps
Modulation	BPSK,QPSK,16QAM, 64QAM	QPSK, BPSK
OFDM Symbol Length	8us	N/A
Guard Interval	1600ns	0.22ms
Sub-carrier Interval	156.25kHz	333kHz
Bandwidth	5.85 -5.925 GHz	1616 - 1626.5 MHz
Channel	10MHz	41.67KHz
Error-correcting Code	Convolutional code K=7	Convolutional code K=7

3.2.3 ILIS Media Access Control (MAC) Layer Techniques

3.2.3.1 Channel Switch Mechanism

In ILIS, every time OBU generates a message, it needs to build connection with RSU and get allocated channel to send the safety-related packets in CCH and reserve the channel in SCH for non-safety-related packets. If it cannot build connection with RSU, which means the RSU isn't working properly, it will send the communication set up request to the satellite network in its current CCH Interval. Different from the fixed length of CCH/SCH in traditional ITS protocol, ILIS applies a dynamically channel switching method to reduce the waste of network resource.

There are two different cases of channel switching, corresponding to when the vehicle detects the unavailability of next RSU.

1. As showed in Figure 3.1, if RSU failure happens when the vehicle OBU is in the CCH interval, which means it cannot reserve SCH for infotainment service in the current Sync Interval, it will dynamically adjust the length of CCH and use the rest SCH to send safety-related message in the mean time. If the OBU still cannot detect the RSU by the end of the current Sync Interval, the non-safety-related message

won't get opportunity to send. But if the OBU can detect the RSU before the end of current Sync Interval (extremely small probability event because of the short Sync Interval length), the OBU will still be able to reserve the rest SCH for non-safety-related service.

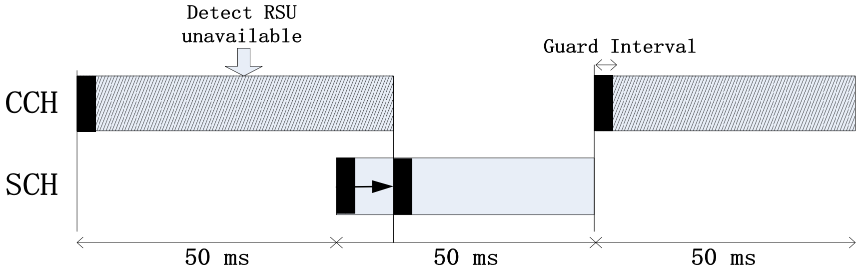


Figure 3.1 CCH/SCH dynamically switching mechanism when RSU failure happens in CCH

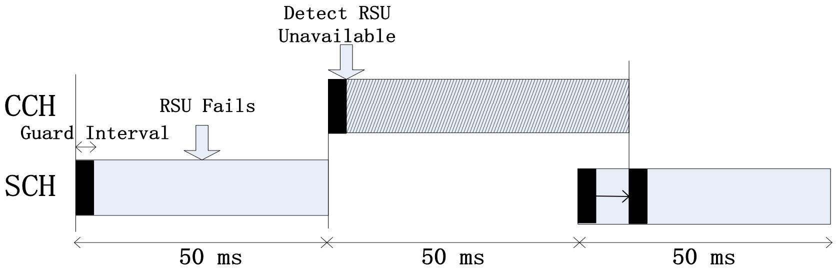


Figure 3.2 CCH/SCH dynamically switching mechanism when RSU failure happens in SCH

2. If RSU failure happens when the vehicle OBU is in SCH interval as showed in Figure 3.2, which means OBU detects problem at the beginning of the coming CCH. In this situation, it will send connection set-up message to satellite in the coming CCH and adjust the length of SCH as needed.

3.2.3.2 Message Type and Priority

In the existing integrated system, frequency reuse is applied when the message is sent via another network's wireless resource to avoid contention, where the interference will significantly affect system performance. So, based on the frequency reuse, we give messages different priorities to make effective use of network resources and avoid interference.

As defined in IEEE 1609.4, there are two different types of safety-related messages that vehicles produce: Routine Message (RMsg) and Emergency Message (EMsg). RMsg is generated periodically to indicate the vehicle's information, including position, direction, speed, etc., while EMsg is only produced when emergency event happens, which is called event-driven message. In the ITS environment, emergency message has higher priority than the routine message. In this study, LEO MSS treats the traffic generated by its own users with higher priority over the overflowed ITS traffic so as to reduce the impact of the overflowed ITS traffic on the service quality it provides to its own users.

TABLE 3-5. ILIS Message Priority

	ITS	LEO
SAT message	N/A	X
ITS overflowed Routine message	1	X1
ITS overflowed Emergency message	2	X2

As TABLE 3-5 shows, the message with the smaller number owns higher priority and only satellite system can read priority X. So, when a message transmitted in an ITS environment, an emergency message has higher priority than a routine message, while in LEO environment, the satellite message has the highest priority and overflowed messages can only get the channel that the message with the highest priority doesn't occupy. Through prioritizing different messages, the ILIS system can clearly differentiate the messages and ensure the satellite user won't be affected when the satellite works as the complementary network system for the ITS.

In ILIS, each vehicle is equipped with a buffer to store the packet when a channel is not available. If EMsg and RMsg are produced at the same time, EMsg has higher priority to access the channel while RMsg will be put in the buffer to wait for available channel. However, if the RMsg still cannot be sent after a new RMsg is produced, the old RMsg will be dropped and replaced by the new RMsg. By prioritizing different messages, ILIS system differentiates the messages and ensures the impact on the LEO MSS users is controlled to be limited within acceptable range when satellite works as the complementary network system for ITS.

3.2.4 ILIS Network Layer Techniques

Bandwidth Reservation

Two Overflow Mechanisms have already been discussed in Chapter 3.2.4, and the difference is clear. Since the available bandwidth resource that can be used for ITS is highly reliant on the communication quantity of satellite system, the unstable problem may affect the ITS system, especially Mechanism I. As Mechanism I overflows both Routine messages and Emergency messages to the upper network, the overflowed communication quantity is relatively high. In such a situation, the ITS may not be able to get any allocated wireless resource during the peak period of the satellite system. As mentioned before, the purpose of this integrated system is to provide a complementary network for ITS when RSU cannot work properly, but the unstable problem will affect the normal work of this integrated system when there is high satellite communication.

A Bandwidth Reservation mechanism is applied in ILIS to solve this problem. In this mechanism, a fixed bandwidth of LEO satellite system is reserved for the ITS to guarantee that it will be able to get access to the channel and transmit its messages. For LEO satellite messages, they cannot use the reserved bandwidth, which may cause a higher packet loss in the upper layer network. So, the reserved bandwidth quantity should adapt to the traffic density of both ITS and LEO satellite systems. These days, there are three main bandwidth reservation protocol and algorithm: Resource Reservation Protocol (RSVP), Constraint-Routing Label Distribution Protocol (CR-LDP) and Top-nodes algorithm.

3.2.4.1 Resource Reservation Protocol

RSVP is a signaling protocol used to reserve resources for flow along its path to satisfy the QoS requirement. The resource reservation process starts from the resource node sending a Path message, which the flow will follow to the destination node, and build the Path State along the way. When the destination node receives the Path message, it will send a Resc message back and build the reservation state along the way. The resource reservation is considered to be successful if the resource node receives the Resv message.

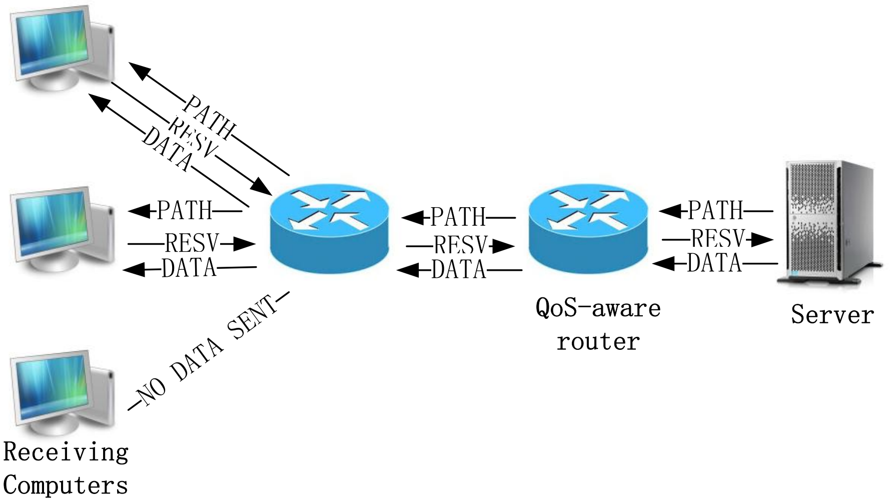


Figure 3.3 RSVP working flow

Being a signaling protocol on IP, RSVP allows any end system or host computer in the routing network to build bandwidth reservation paths from one computer to the other. It is important for services that require ensured bandwidth and no delay, like video transmission and audio conference.

In RSVP, the resource reservation is launched by receiver and it is one-way. For example, if the resource reservation is for the data flow from host A to host B, it doesn't work for the flow from host B to host A. That's because the dual-way routing isn't symmetrical, the routing path from A to B is not always the opposite routing path from B to A; also, data from different ends have different characteristics and different resource reservations.

RSVP provides two reservation methods:

- Distinct Reservation: the resource reservation only works for one sender. A different sender in one session occupies a different reserved resource.
- Shared Reservation: the resource reservation works for one or more than one sender. Multiple senders in one session share the reserved resource.

3.2.4.2 Constraint-Routing Label Distribution Protocol

CR-LDP is an extended LDP which strengthens traffic engineering. Traffic Engineering is the rational use of network resources and guaranteed QoS. CR-LDP uses a simple hard state control method and message distribution way, and applies UDP to find neighbor nodes while applying TCP for session, broadcast and transmit LDP messages, as Figure 3.4 shows. In the label request message, each node's address on the constraint routing is included, and this message will follow the path defined by constraint routing to the destination. The design of CR-LDP is Diff2serv, which can support the QoS level specified by the network and ensure transparency of the MPLS to other protocols through FEC mechanism, thus supporting multiple protocols.

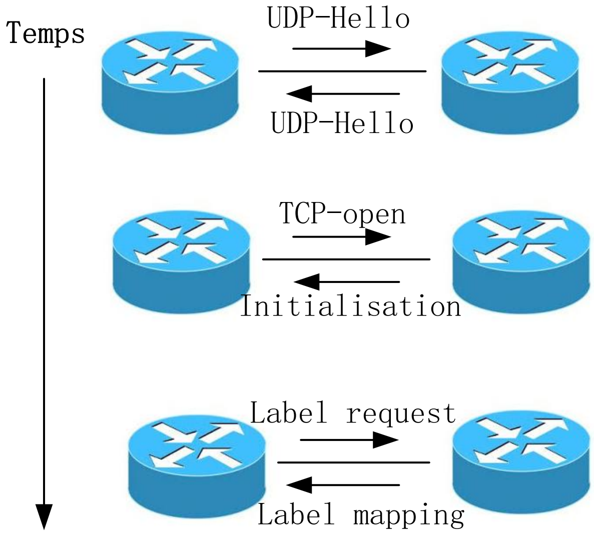


Figure 3.4 CR-LDP Message exchange

Based on but different to LDP, the building of CR-LDP not only follows the routing table and management system but also considers the limits of network service, like bandwidth, delay etc., while the LSP built in LDP only relies on the routing table information and management system information. Another big difference is that the LSR used to build the LSP in LDP is calculated from the distributed computing of network nodes, while the LSR of CR-LDP can be gotten from any network edge node or network management system deployment.

3.2.4.3 Top-nodes Algorithm

The top-nodes algorithm is an algorithm that can manage the resource reservation calendar when a resource is shared by multiple users. As Figure 3.5 shows, the resource reservation calendar is conceived as a binary tree and each leaf is the time period.

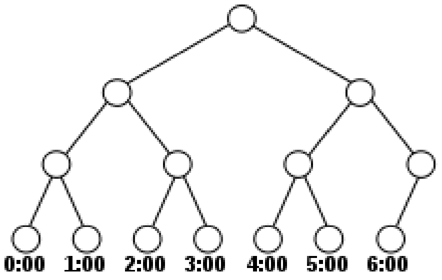


Figure 3.5 Node binary-tree structure

When a certain time period needs to be reserved for a resource, the "top-node" is selected. The conditions to become a "top-node" are:

1. All its sub-nodes are within the reservation time period;

2. It is a root node, or at least one sub-node is outside of the reservation time period.

So, for Figure 3.5, if a period from 1:00 to 5:59 is reserved, the "top-node" should be the blue node in Figure 3.6.

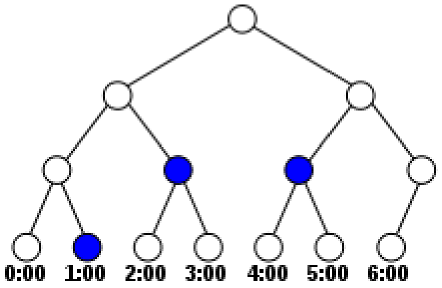


Figure 3.6 Reserved time period

The relationship between the number of all node (N) in the calendar and the number of "top-node" ($\mathrm{N}_{\mathrm{top-node}}$) is:

$$\mathrm{N}_{\mathrm{top-node}} = 2.\log\mathrm{N} \tag{3.1}$$

Based on formula (1), the information about reserved time can be obtained, like checking if a resource is available during a specific period of time, reserving resource for a specific time etc.

In ILIS, RSVP is applied to cause bandwidth reservation. As all channel allocation is implemented in the satellite when using the complementary network, so it can reserve the bandwidth after receiving the request from the vehicle and reply the route with bandwidth reserved to send a message. However, the bandwidth reservation ratio is not random, and it should be proportional to vehicle density and inversely proportional to satellite communication density, so when vehicular density increases, ILIS can reserve more bandwidth for the ITS, while decreasing the reservation quantity when satellite communication density increases to decrease the effect on the satellite. In this way, ILIS can achieve optimized usage of wireless resources with different traffic densities.

To decrease the cost and effect on the original satellite communication flow, ILIS only reserves a certain value of LEO satellite network bandwidth for ITS. If the amount of upstream flow is over the limit of reserved bandwidth, it may cause increasing packet loss rate and delay of original satellite communication. With the certain bandwidth value, we only overflow the EMsg to satellite when RSU is not available. As the RSU coverage range is 1km in ITS, it only take around 20s to drive through the blind area on highway. So, we only use LEO in urgent cases, which are safety-related to prevent terrible outcomes.

3.2.5 ILIS Transmission Layer Techniques

Since ILIS is a safety-related integrated network system, the transmission layer protocol is connection-oriented TCP, which applies the Three times handshake to build a connection. As showed in Figure 3.7, the message exchange between the

OBU and RSU of connection building process starts from the Connection Request of the OBU. When the RSU receives the request, it will allocate the channel for the OBU which launches the request and replies the approval message with the allocated channel that the OBU can use. After receiving approval messages, the OBU will send an ACK message to the RSU and start using the allocated channel to send data packets.

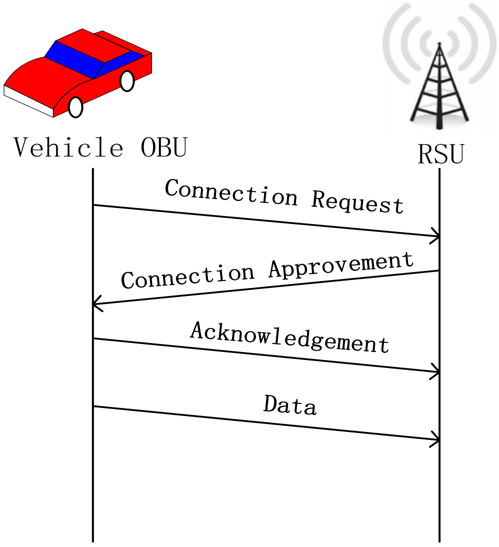


Figure 3.7 Connecting with RSU

In order to release the channel that the OBU is being allocated, it needs to close a connection after finishing sending the message, and the process is showed in Figure 3.8. If the OBU has finished sending messages and doesn't need the allocated channel any more, it will send RSU a FIN message to indicate there are no more packets to be sent to the RSU. However, the RSU may still have packets to send when it receives the FIN message from the OBU, so it will reply an ACK message to indicate it has received close requirement but it can keep sending messages. When the RSU finishes its sending, it will send a FIN message to the OBU and the OBU replies with ACK, which means both connection sides have finished sending and the connection will close.

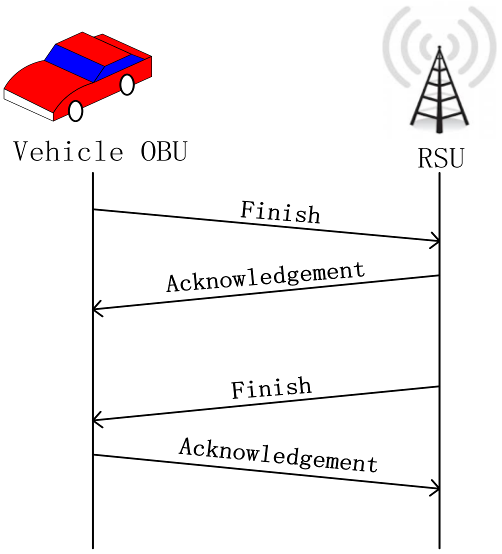


Figure 3.8 Disconnecting with RSU

Based on the above message exchange technique, the connection becomes a little complex in ILIS when connected from the RSU to SAT, and the process of building a connection is showed in Figure 3.8.

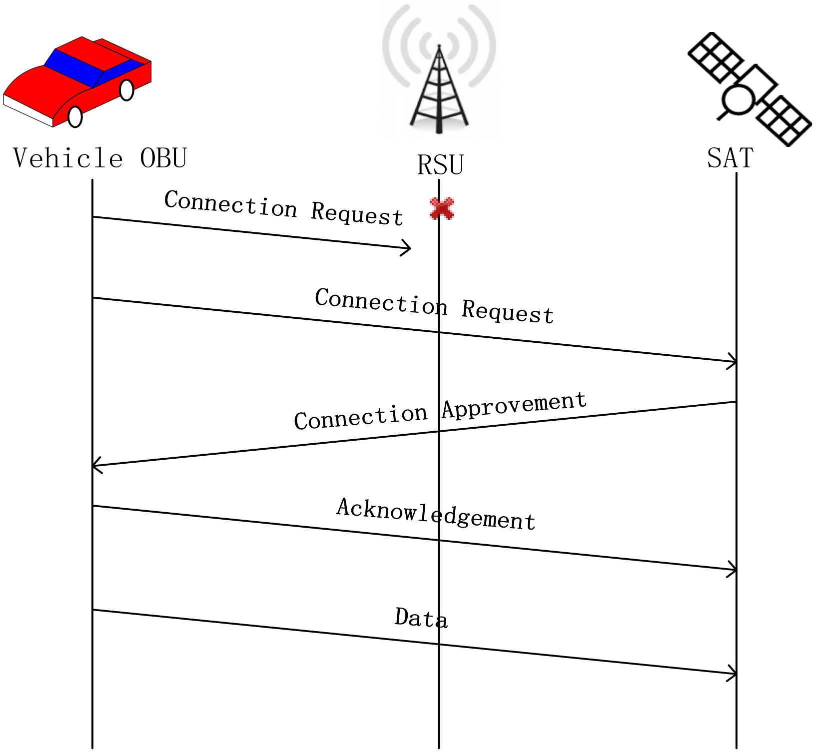


Figure 3.9 Connection Building with SAT

According to Figure 3.9, when the RSU doesn't work properly, the OBU cannot get an acknowledgement message after it has a sent connection request to RSU. In such case, the OBU will send the connection request to the LEO satellite to ask for channel allocation after waiting for a fixed period. Similar to the connection with RSU, SAT will reply the approval message with the allocated channel information to OBU, and OBU will use the allocated channel to start message sending. Also, the disconnection with satellite is the same process as with the RSU, which needs both sides to confirm closing before disconnection to ensure safety.

3.3 ILIS Overflow Mechanism

3.3.1 Overflow Illustration

To make better use of network wireless resources, there are two overflow mechanisms in ILIS. These two mechanisms can be activated dynamically as the traffic density varies.

Mechanism I

Overflow both Routine messages and Emergency messages to the satellite network when RSU is not available.

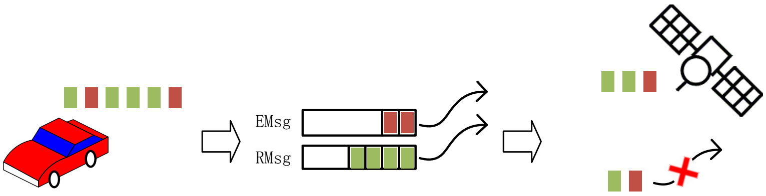


Figure 3.10 Mechanism I Packet Overflow

Mechanism II

Only overflow the Emergency messages to the satellite network when RSU is not available.

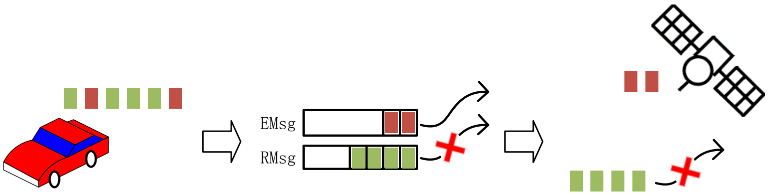


Figure 3.11 Mechanism II Packet Overflow

These two mechanisms have their own advantages and disadvantages and the advanced point of ILIS is that it can dynamically switch between Mechanism I and Mechanism II adjusting to the environmental conditions to make the best use of network wireless resources.

3.3.2 Comparison between Mechanism I and Mechanism II

The comparison of the two mechanisms has been summarized in TABLE 3-6.

TABLE 3-6. Comparison between Mechanism I &Mechanism II

	Mechanism I	**Mechanism II**
Advantage	More messages delivered	Higher delivery rate of Emergency messages
Disadvantage	Emergency messages have higher loss rate	All routine messages are dropped

Comparing these two mechanisms, obviously, Mechanism I can deliver more ITS messages over the network in general with possible consequence of unacceptable loss rate of EMsg. On the other hand, Mechanism II is able to provide more reliable transmission of EMsg by dropping all bandwidth competing RMsg. LEO MSS provides a complementary way to enable the ITS message transmission when RSU is not available, or just deliver emergency ITS messages when there is no sufficient bandwidth for satisfying the requirements of both types of messages. For Mechanism I, overflowing both RMsg and EMsg can maximize the use of network wireless resource. However, more message overflowed demands more bandwidth and results in more contentions. Mechanism II provides a method to make more efficient use of network resource when the available bandwidth cannot satisfy both overflowed RMsg and EMsg. ILIS should use either Mechanism I or Mechanism II according to actual traffic conditions for getting satisfying performance. For example, ILIS can start with Mechanism I, which maximizes the number of ITS messages delivered over the network. Once the packet loss rate of emergency message exceeds the required service quality threshold, ILIS will switch to Mechanism II for increasing the successful delivery of EMsg.

Chapter 4 Simulation Model

4.1 Introduction

Chapter 4 explains the detailed simulation design and development process.

The simulation model is a real-time system developed in C++ from scratch, which allows user to observe the data change real-timely, hence to understand better about the system running phase. I will illustrate the ILIS simulation model from following aspects: Flow Chart, Status Chart, Structure Chart and Pseudo Code (Appendix B). In addition, I will illustrate the detail process how I get the parameters: Packet Loss Rate and Delay.

4.2 Simulation Model

4.2.1 Highway Model

We build a 10km 2-lane and 2-way highway model with exit at both ends of the road. 11 RSUs are distributed every 1km. As Figure 4.1 shows, the last AP only cover the half coverage area because of the limit of highway length. Highway is chose because it is the typical road that can reflect the traffic data quickly and directly. What's more, the safety requirement is higher on highway because of its higher speed.

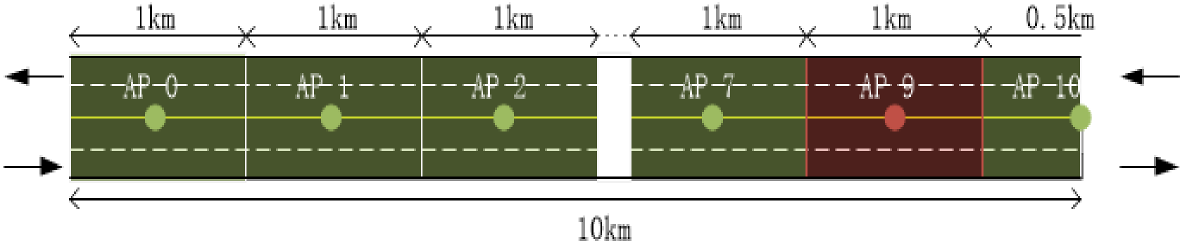


Figure 4.1 Simulated highway model

As showed in Figure 4.1, the 9th RSU doesn't work properly in the simulation and the red area - covered by the unavailable RSU is the blind area, where vehicle cannot send/receive any message. The vehicle arrival event is a Poisson event, which means the arrival interval time of each vehicle follows the exponential distribution. To increase the reliability of the simulation, we set the traffic density variable through changing the vehicle arrival interval (1s, 3s and 5s), and more bandwidth is required when the density is higher. Vehicles on the road generates routine message as frequency 10Hz and generate emergency message with probability 0.1, and both routine and emergency message has the same packet size in the simulation - 128 bytes.

4.2.2 LEO Satellite Simulation Model

In our simulation, Iridium NEXT communication system is adopted as the complementary satellite network. Iridium NEXT communication system is the second generation of Iridium satellite communication systems, which is composed of 66 LEO satellites at a height of approximately 765km from the earth. For simplicity, each satellite can be viewed as a special AP with satellite parameters. As the ground tracking speed of LEO satellite is as fast as 27000km/h, and the satellite primary customer is covered by at least one satellite at any time, we assume a customer only communicates with one satellite in Iridium system and the message handover between satellites is not considered here. Satellite system allocates channels to each communication packet when requested. The satellite customer traffic is generated as Poisson flow with mean packet generation rate of 700 packets per second and the data transmission rate is 1Mbps.

4.2.3 Simulation Result Parameters

For both ITS and LEO MSS, the packet loss happens in two situations: 1. the packet cannot get channel while the buffer size is full; 2. the packet exceeds the specified bandwidth capacity. The delay is affected by two factors:1. packet generation density; 2. overflow packet to satellite network.

Delay

Each vehicle is equipped with a buffer, which stores the packet waiting for the available channel. When a packet is push into the buffer, OBU can get the waiting time Tw through counting the packet number in front of it. Total delay consists of waiting delay Tw and transmission delay Tx.

$$\text{Total delay} = Tw + Tx \tag{4.1}$$

As the simulation is in an ideal environment, the transmit rate is relatively high compared to the little change of transmit distance within 1km, Tx is set to be a constant value 0.1ms for ITS and 1ms for LEO MSS to decrease the complexity and interference.

Packet Loss Rate

As mentioned before, every vehicle has a buffer, when the buffer is full, the old packet will be dropped. So,

$$\text{Packet loss rate } = \frac{\text{lost packet number in current cycle}}{(\text{processed packet number} + \text{lost packet number})} \tag{4.2}$$

Since the simulation is under a ideal environment and on a integrated system level, some assumptions are proposed in the simulation:

- If a packet is able to access the available channel, it's considered to be sent successfully without packet loss during the transmission.
- The downstream data from RSU to vehicle is not considered in this simulation, because the data is too small.
- The overlap area between every two RSU are ignored but handover process is considered in simulation.

4.3 Simulation Model Structure

4.3.1 ILIS Overall Module

The ILIS simulation model structure is showed in Figure 4.2, which composed two main parts: ITS and SAT (LEO MSS). The input of the whole ILIS module is the vehicle and primary communication flow, and the output is the system network parameter which will be used to evaluate this integrated system. The detailed module illustration is as follows.

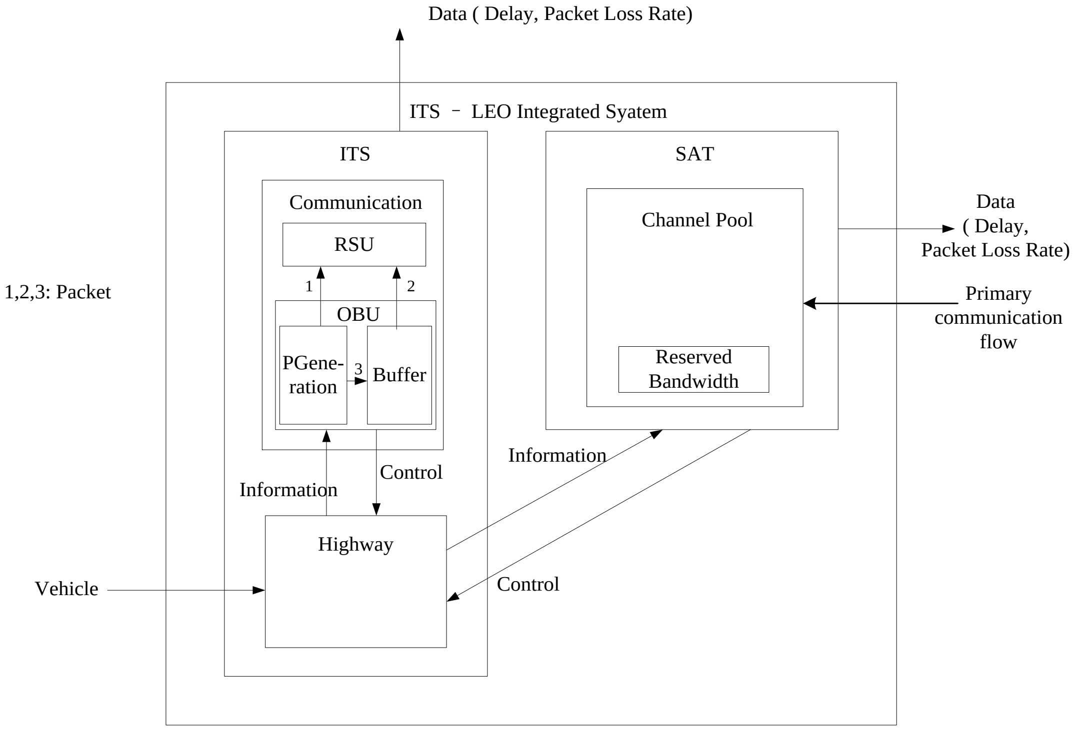


Figure 4.2 ILIS Simulation Module Structure

4.3.2 ITS Module

As Figure 4.3 shows, the ITS module is composed of a highway movement module and a communication module. For the highway module, there are three inputs and two outputs:

1. when a vehicle enters the highway with interval time as Poisson distribution, that is the input of the highway module;

2. when the vehicle generates packets and needs to send it, the vehicle will output the information to the communication module. As the information can go out to either the ITS communication module or the LEO MSS communication module, there are two information outputs here;

3. when the communication module has control information for the vehicle, it is the input of the Highway module. Same as the output to the communication module, the control input can be from the ITS communication module or the LEO MSS communication module.

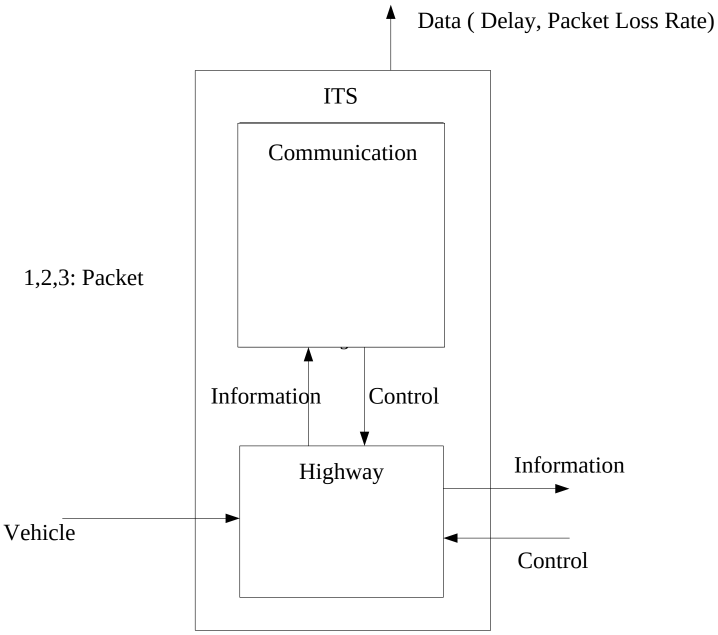


Figure 4.3 ITS Simulation Module Structure

For the ITS communication module, it only interconnects with the highway module. It has only one input from the ITS highway module and one output to the ITS highway module, and the detailed interior module structure is showed in Figure 4.4.

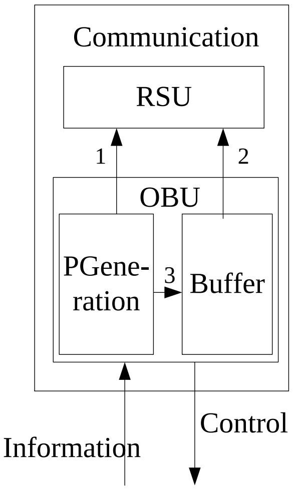


Figure 4.4 ITS Communication Simulation Module Structure

As shown in the above figure, the communication module is composed of an OBU and a RSU, and the OBU consists of a Packet Generation module and a Buffer module. When the vehicle on the highway sends information to the communication module, the OBU will generate a packet in the Packet Generation module, the packet can be outputted to RSU or to Buffer and outputted from Buffer module to RSU module. When the communication module has a message to send to vehicle, it will output control messages from the OBU to the vehicle.

4.3.3 SAT Module

As shown in Figure 4.5, besides the input and output to the Highway module, SAT communication has another input and output. As the movement and packet generation of LEO MSS levels are not the research objects, they are simplified to a Primary communication flow input to the SAT communication module, and the output is the satellite network performance parameter.

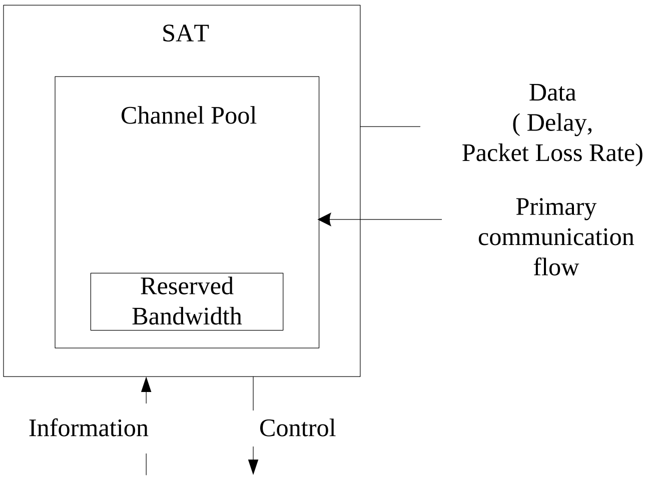


Figure 4.5 SAT Communication Simulation Module Structure

In the simulation, the satellite bandwidth is simplified to be the channel pool module, which is equipped with a Reserved Bandwidth module for implementing the bandwidth reservation protection mechanism. Since the primary communication gets access to the channel pool for channel allocation directly, it is considered to be the input of SAT Channel pool module. Based on the channel pool situation, satellite will output control message to vehicle to realize the channel allocation for ITS.

4.4 Simulation Message Process Procedure

4.4.1 ISIL Message Process (ITS part)

As shown in Figure 4.6, when the RSU is detected to be unavailable, the ITS message will overflow to the complimentary satellite network. If the RSU works properly, the packet generated by OBU will try to get access to the channel, i.e., the specific timeslot on a specific frequency spectrum. When it obtains the available channel, the packet will be sent out successfully, otherwise it will be put in the buffer waiting to access the channel again. If the RSU is not detected when vehicle requests connection to the next RSU, the packet will be overflowed to the satellite network. As discussed in section C, two overflow mechanisms are proposed for ILIS to make better use of wireless network resource under different traffic conditions.

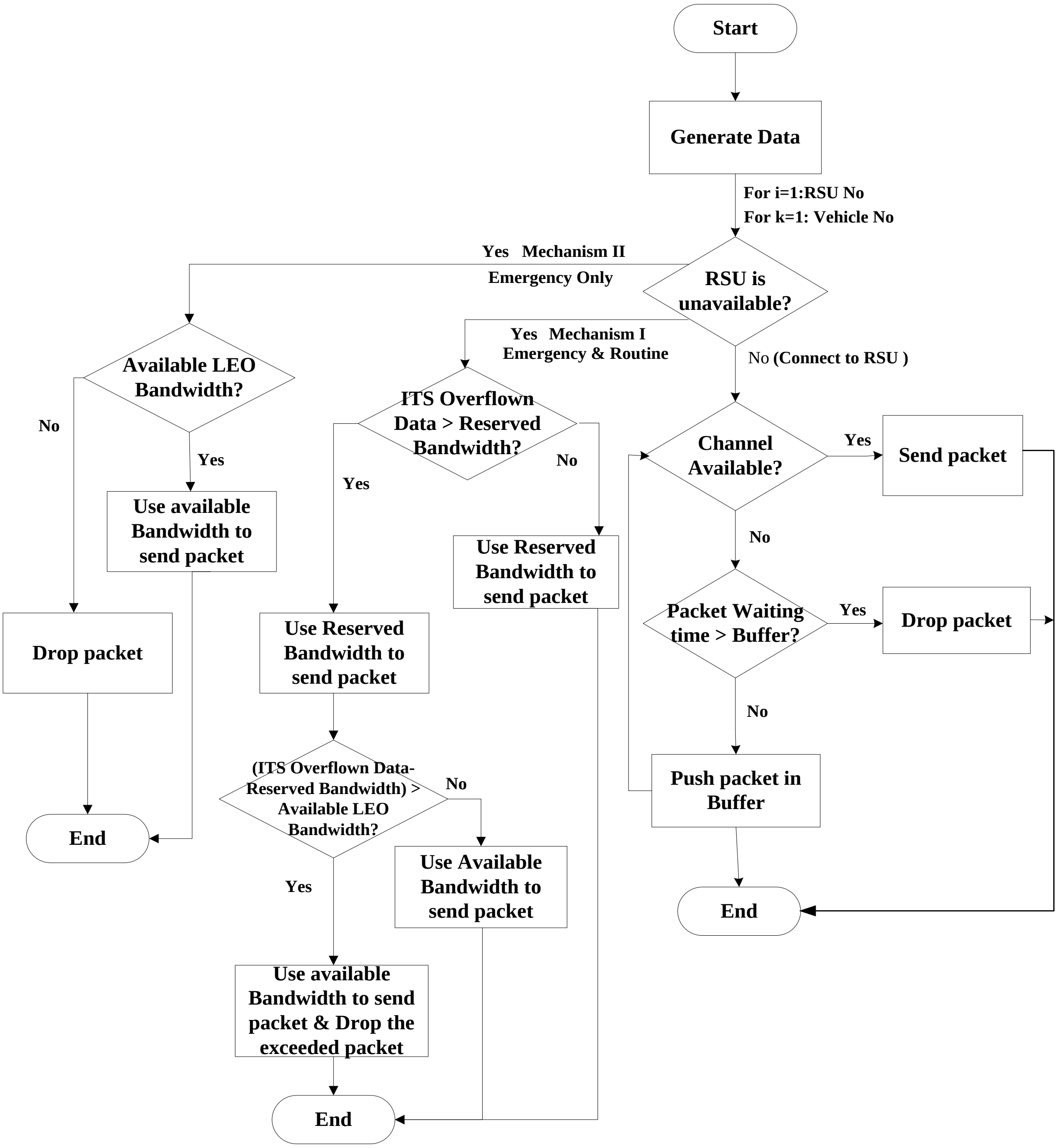


Figure 4.6 ISIL Procedure Structure

Since ILIS gives the satellite customer's message highest priority to decrease the effect of overflowed data flow, which means the available bandwidth that the ITS message can use, to a large extent, relies on the satellite customer's data quantity at that time. When the LEO MSS is in off-peak hours, the ITS can get enough wireless network resources to finish data transmission, But when LEO MSS is in peak hours and a large number of satellite customers are launching communication during that period, the LEO MSS cannot work properly as the complementary network for the ITS. To solve this problem, ILIS has a bandwidth reservation mechanism to reserve certain amounts of bandwidth in LEO MSS for the overflowed ITS traffic.

As the complementary network system, LEO needs to prioritize the traffic generated by its own customers and control the impact of the overflowed ITS traffic when it provides ITS service in emergency situations. When a vehicle leaves the blind area, which means the next RSU is available for use, the OBU will send the connection request to the RSU and stop using the satellite resource after the connection with RSU is established. Therefore, ILIS is able to provide safety-related network service in the blind area and adjust the usage of wireless resource dynamically with both ITS traffic density and satellite customer communication density.

4.4.2 ISIL Message Process (Satellite part)

For the satellite part, we consider it to be a special access point to simplify the simulation process. As Figure 4.7 shows, the satellite data flow is generated as Poisson flow. Since satellite packets have the highest priority over overflowed packets, which can ensure that at the minimum the LEO satellite mobile communication system will complement the ITS, the contention between satellite message and ITS overflowed message is limited. Without the ITS overflowing messages, the packet loss and delay of the satellite’s communication flow are mainly from contending for the channel. It's worth noticing that the effect on transmission of satellite data flow is different for different overflow mechanisms.

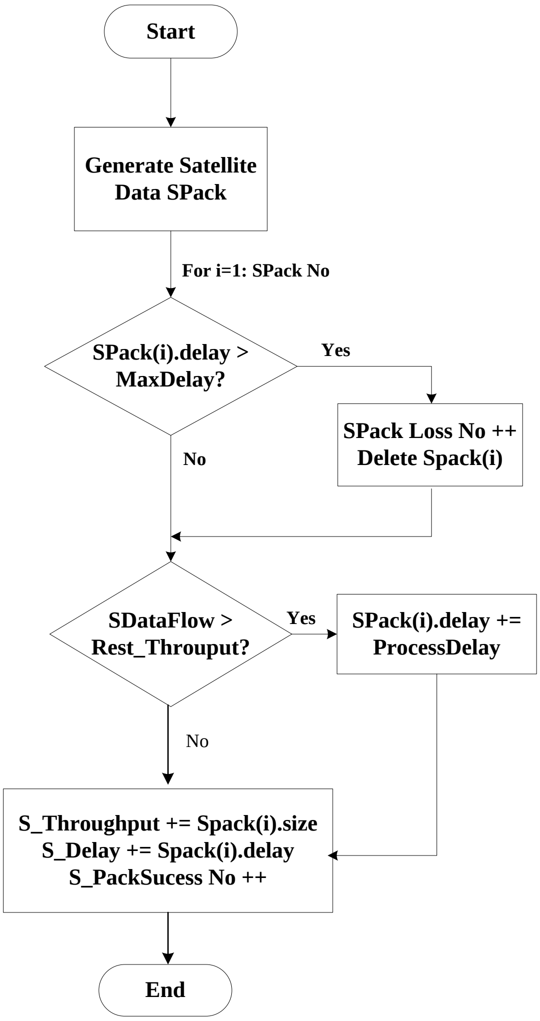


Figure 4.7 LEO Message Process

Effect of Mechanism I

As Mechanism I overflows both Routine messages and Emergency messages to Iridium NEXT system, the overflowed data quantity is relatively big, which may cause serious contention between satellite and overflowed messages in traditional integrated systems. However, ISIL induces the Message Priority mechanism, which prioritizes the message by assigning different Inter-Frame Spaces, therefore to make sure the effect of contention can be controlled to a minimum. So, the ITS overflowed message can only use the bandwidth that hasn't been occupied by satellite messages, and the effect of ITS overflowed messages to satellite messages is reduced.

Although satellite message has the highest priority, but corresponded packet loss will happen when applying Bandwidth Reservation mechanism.

Effect of Mechanism II

In Mechanism II, the overflowed data flow is smaller than Mechanism I because it only overflows emergency messages to satellite rather than both routine and emergency messages. Emergency messages are event-driven messages generated with probability 0.1 in my simulation. So, the effect of Mechanism II to the satellite system is considered to be lighter than the effect of Mechanism I. Meanwhile, the bandwidth reservation protection mechanism for Mechanism II does not work as well as Mechanism I.

4.5 Simulation Model State Cycle

In ILIS, the message processing based on priority is the key research point. As showed in Figure 4.8, there are 7 states during the process of message getting access to channel, and they can only be triggered by a certain condition to move to next state, otherwise they will stay at the same state.

IDLE

The default state, can be triggered by state *Sending Packet*, *Dropping Packet* and *Sending Packet (SAT)*, and trigger state *Accessing RSU* and *Accessing SAT*. If a vehicle is in *IDLE* state, that means it doesn't generate any packets at that time, and the vehicle will leave *IDLE* state once it has packets to send. From Figure 4.8 we can see that the next state for the vehicle can be *Accessing RSU* with trigger condition. Only one condition can trigger the *Accessing RSU* state: Generate Packet. For more details, two kinds of messages can be generated here: 1. Safety-related messages about the vehicle's information; 2.Control messages that are used to build connection with the RSU, and both of them need to get access to the channel allocated by the RSU.

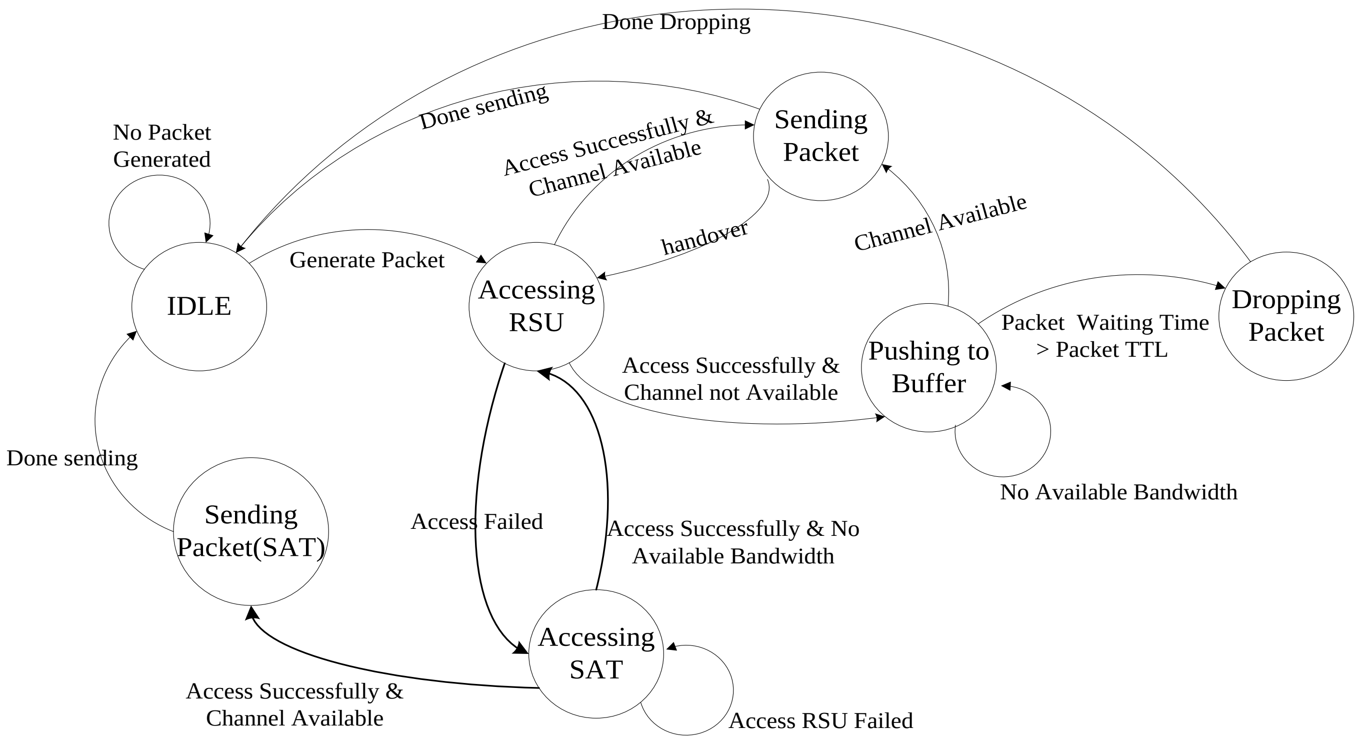


Figure 4.8 State Chart of ILIS

Accessing RSU

When a vehicle generates a packet and needs to send the packet, it will leave the *IDLE* state and change to the *Accessing RSU* state. There are three triggering conditions to leave this state:

1. If the vehicle connects to the RSU successfully and get an allocated channel from RSU, it will move to the *Sending Packet* state;

2. If the vehicle connect to RSU successfully but cannot get allocated channel from RSU, it will move to the *Pushing to Buffer* state;

3. If the vehicle cannot connect to RSU, it will move to the Accessing SAT state, which means it needs to overflow the packets to the satellite network. So, the condition that vehicle uses satellite complementary network is it cannot build a connection with RSU or RSU is not available for it any more.

Accessing SAT

The *Accessing SAT* state can only be triggered by the *Accessing RSU* state with condition Access Failed, which means vehicle can only launch the connection with satellite network when it cannot connect to the RSU, hence to control the overflowed message quantity to decrease the cost. Similar to the Accessing RSU state, there are three different conditions to move to the next state:

1. If the vehicle can get access to the satellite channel successfully, it will move to the Sending Packet (SAT) state;

2. If the vehicle can only connect to the satellite but cannot get available channel, it will go back to *Accessing RSU* again and try to connect to RSU;

3. If the vehicle cannot connect to the satellite, it will stay in *Accessing SAT* state until any other condition happens to trigger it to leave this state.

Sending Packet

This state can only be triggered by the condition that vehicle connect to the RSU successfully and allocate a channel successfully. After the vehicle finishes sending the packet, it will go back to the initial *Idle* state to get ready to generate a new packet. However, it's worth noticing that there is another condition that can trigger leaving this state, which is vehicle needs to handover to next RSU while sending the packet, then it will go back to *Accessing RSU* state to launch connection with the next RSU.

Pushing to Buffer

The *Pushing to Buffer* state can be triggered by the *Accessing RSU* state with condition Access Successfully but No Available Channel, which means when the vehicle connects to the RSU but no channel is allocated for it, it can put the packet in the buffer and wait for the next available channel. It will move to the Sending Packet state immediately once there is an available channel. However, if the time that packet stays in the buffer exceeds its Time to Live (TTL), it will move to the *Dropping Packet* state and that packet will be dropped.

Dropping Packet

As introduced in the last state, the *Dropping Packet* state is triggered by the *Pushing to Buffer* state with condition Packet Waiting Time exceeds Packet TTL. As the packet cannot stay in buffer for a long time if no channel is available, once the waiting time reaches the packet TTL, it will be dropped and buffer will be released for new packet. After finishing the packet dropping, it will move to the IDLE state and get ready for new packet generating.

Sending Packet (SAT)

As Figure 4.8 shows, the Sending Packet (SAT) state is triggered by the Accessing SAT state if the packet can get access to a satellite channel successfully. When it finishes sending packet, it will trigger the IDLE state and wait for generating new packet.

4.6 Pseudo Code

As showed in Appendix B, pseudo code has listed the general simulation flow. The simulation pseudo code has three main parts: 1. Vehicle Movement & Packet Generation, 2. RSU processing packet procedure, 3. SAT processing packet procedure.

Vehicle Movement & Packet Generation

The vehicle position is decided by the vehicle speed and vehicle running way, and the position decides which RSU the vehicle should build the connection with. Also, packet generation is divided into emergency message and routine message.

RSU processing packet procedure

This part shows how to count the packet loss rate and delay of the message transmission connecting to RSU.

SAT processing packet procedure

This part shows how to count the packet loss rate and delay of the message transmission connecting to satellite.

Chapter 5 Simulation Result Discussion

5.1 Introduction

I evaluated the system using two important parameters: Packet Loss Rate (PLR) and Delay, and the figures below are gotten by collecting large numbers of data through running simulation of a real-time system for a certain time.

Through analyzing the network parameters: packer loss rate, I assessed the integrated network system from different sides. First of all, I evaluated the improvement of two mechanisms of ILIS to ITS when the RSU cannot work properly. Then, I evaluated the performance of emergency messages and routine messages of mechanism I and mechanism II respectively. In addition, I evaluated the impact on the PLR and delay performance of both mechanisms as well as the PLR of LEO MSS when implementing the bandwidth reservation mechanism in LEO MSS.

5.2 Improvement of ITS when applying ILIS

5.2.1 Packet Loss Rate without applying ILIS

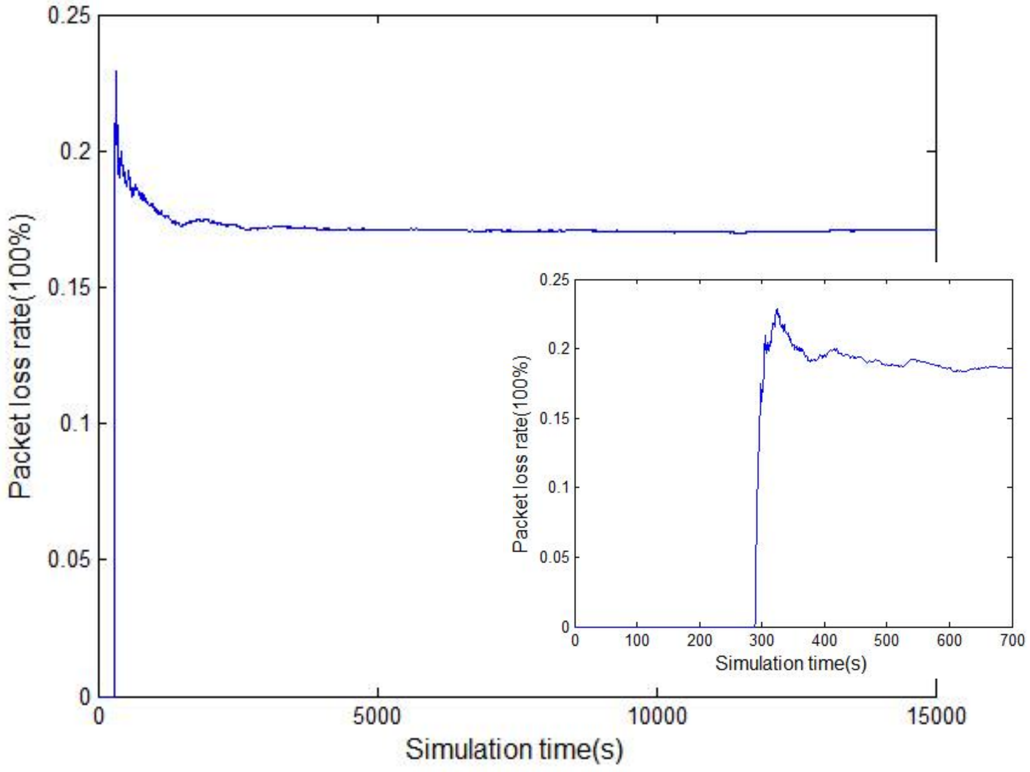


Figure 5.1 Packet Loss Rate without overflowing to satellite

Figure 5.1 shows the packet loss rate of the message transmission on this 10 km long highway. In general, the curve starts from 0 and stays steady at 17.13%, and there are four phases we can see from the enlarged figure in detail: Zero Phase, Initial Phase, Vibration Phase and Stable Phase.

Zero Phase

Zero Phase happens when vehicles enter the monitoring system, there is no packet lost because the number of packets hasn't reach the capacity limit of the RSU. This period lasts around 290ms, which can be verified according to the simulation model defined in the last chapter. Vehicles enter the system from the left end side and are follow the Ontario Highway rules, which is

$$v_{car} \in (90 \sim 110)\text{km/h}; \quad (5.1)$$

and we can estimate Zero Phase length t_{zero} range should be:

$$t_{zero} = \frac{L_{zero}}{v_{car}} = \frac{8km}{(90\sim110)} = (261.8\sim320)s \tag{5.2}$$

where L_{zero} represent the highway length with the available RSU according to the Figure 4.1. Since all vehicles enter from the left end at the beginning, when they exit from the right end, they are considered to enter from right end again, hence to realize two-way in this simulation. So, only the vehicles entering from the left are in the Zero Phase. The value of my simulation model is around 290s from the enlarged figure Considering that the specific value is affected by car speed and message generation methods, the simulation is completely within the estimation range.

$$t_{zero} \in (261.8\sim320)s \tag{5.3}$$

Initial Phase

The packets loss rate starts growing with the increasing number of vehicles entering the blind area. According to Figure 5.1, the Packet loss rate steadily climbs from 0% to 23% within 60s, which we called increasing period. The factor causing the loss of packet here is RSU not available in this area and the vehicle cannot send any packet when entering the Blind Area (BA) - the area covered by an unavailable RSU.

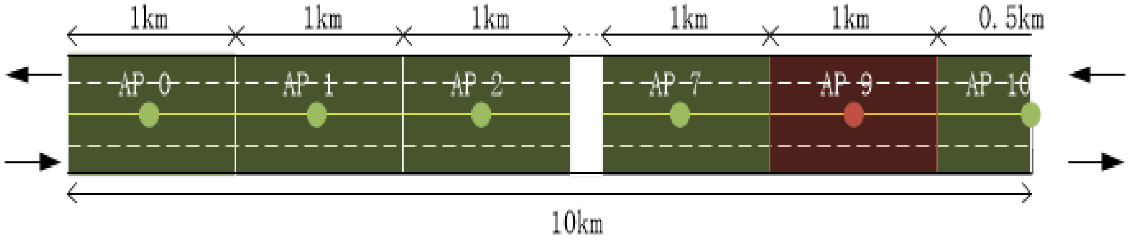


Figure 4.1 Simulation Highway Model (Recall)

It is worth noting that after the increasing phase, the curve goes down a little before it increases again. The reason is when the vehicles leave the BA, the next RSU is available for the vehicles and the packets can be processed by this RSU (the RSU 10 in above figure). As showed in Figure 4.1, the car will leave the monitored highway and re-enter from the opposite way (from right to left) according to the simulation model. So, the vehicle leaves the first half highway (from left to right) at

$$\mathrm{t}_{\mathrm{car\_1}} = \frac{\mathrm{L}_1}{\mathrm{v}_{\mathrm{car}}} = \frac{10\mathrm{km}}{(90\sim110)\mathrm{km/h}} \approx (327\sim400)s \tag{5.4}$$

From Figure 5.1, we see the value of my simulation is around 380s - the lowest point after a continual decrease, which is also within the estimation range. After this point, the vehicles from the opposite way (from right to left) start entering the system, so the Packet Loss Rate is caused by these two factors:

1. Unavailable RSU;
2. Packet Collision.

When the vehicle enters the BA from the other way, PLR increases but not as sharply as the first time because the number of vehicle in the green zone increases too. According to the calculation, the Initial Phase should finish at around 500s, and start entering the Vibration Phase.

Vibration Phase

In the Vibration Phase, the data is a little unstable because of the effect of the Zero Phase and Initial Phase. In other words, the correct value we use for research should be recorded after this period. However, the data base of this simulation is big enough (15000s) to ignore the effect of the beginning data, so even adding the beginning data, it won't affect the value’s accuracy, which we will discuss in the Stable Phase. In addition, the affecting factors in this phase also include the vehicle density in the blind area and the number of packets sent by the car.

So, the movement of vehicles and unstable data before both affect the stability of the curve in Vibration Phase. As time goes by, data quantity will grow until it is large enough to cover the unstable factors, then, it enters the Stable Phase.

Stable Phase

From Figure 5.1, we can see the system tends to be stable from 3000ms, and the PLR maintains at 17.13%. In other words, there are 17.13% packets are lost when 1 out of 10 RSUs shuts down on this 10km length highway. Although the vehicles still enter and leave the system as Poison flow, the curve can stay at the 17.13% because the large data base can remove the interference factors.

5.2.2 Packet Loss Rate when Applying ILIS Two Mechanism

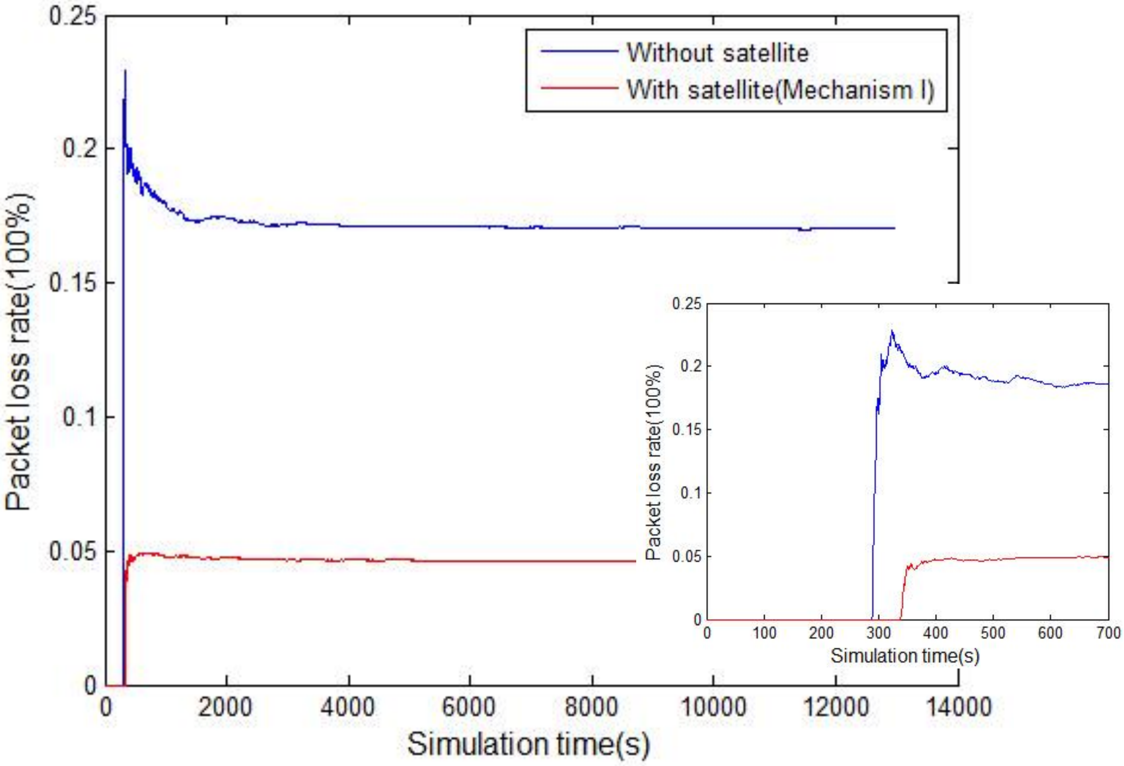


Figure 5.2 Packet Loss Rate of system with/without satellite network (Mechanism I)

The red curve in Figure 5.2 is the PLR when applying the satellite as the complementary network with both RMsg and EMsg being overflowed. Compared to the blue curve, the PLR drops sharply from 17.13% to 4.90% when using satellite network to replace the unavailable RSU. Although the packets generated within BA fail to access the channel, which are supposed to be dropped in ITS, they can still be processed by the satellite network. However, these packets can only use the rest of the satellite bandwidth besides its primary communication quantity, which means they may not have enough network resource to finish all transmission. That's where 4.90%

packets lost come from.

Different from the Mechanism I, overflowing both RMsg and EMsg to the satellite network, the Mechanism II only allows EMsg being overflowed to the upper layer. As showed in Figure 5.3, the black curve is the PLR of Mechanism II, and the value stabilizes at 15.53%. Using ρ to represent the packet loss rate, then we have $\rho_{\text{total}} = 0.1713$, $\rho_{\text{aff}} = 0.045$ and $\rho_{\text{RMsg}} = 0.1553$.

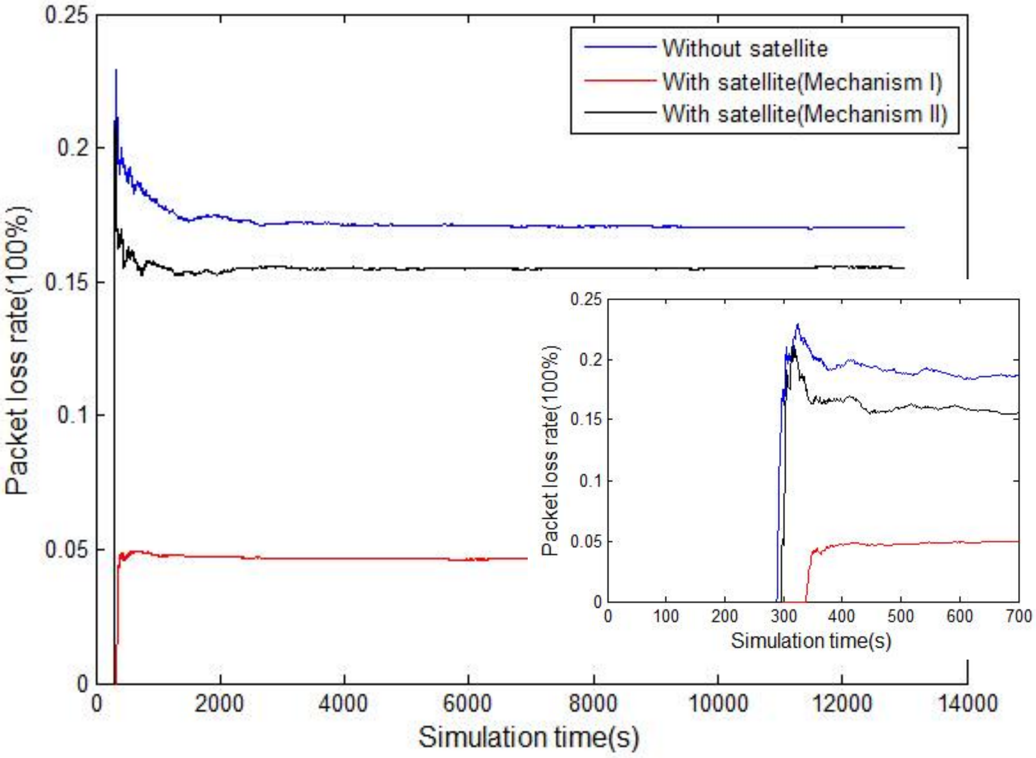


Figure 5.3 Packet Loss Rate of system with/without satellite network

(Mechanism I & Mechanism II)

The PLR of ITS without LEO MSS and with LEO MSS, including both Mechanism I and Mechanism II, are compared and displayed in Figure 5.3. As it shows, the PLR drops from 17.13% to 4.90% when using satellite network to complement the unavailable RSU, which appears to be a good improvement on data delivery. The high PLR of ITS, when there is no LEO complementary network added, is because of the unavailable RSU, and the packets of the vehicle in the area covered by that unavailable RSU are all dropped. In theory, if the communication environment is ideal, which means there is no external disturbance ($\rho_{\mathrm{aff}} = 0$) and only considering the packets in the same time period (total packet number is fixed), we have formula (5.5).

$$\rho_{\mathrm{EMsg}} = \rho_{\mathrm{total}} - \rho_{\mathrm{RMsg}} \tag{5.5}$$

Because when the total packet number ($\mathrm{N}_{\mathrm{total}} = \mathrm{N}_{\mathrm{EMsg}} + \mathrm{N}_{\mathrm{RMsg}}$) is fixed, where $\mathrm{N}_{\mathrm{EMsg}}$ represent the EMsg total number and $\mathrm{N}_{\mathrm{RMsg}}$ represent the RMsg total number. And we define $\mathrm{N}_{\mathrm{lost}}$ means the loss packet number, $\mathrm{N}_{\mathrm{suc}}$ means the successfully packet number, so we have:

$$\rho = \frac{\mathrm{N}_{\mathrm{lost}}}{\mathrm{N}_{\mathrm{lost}} + \mathrm{N}_{\mathrm{suc}}} * 100\% \tag{5.6}$$

According to formula (5.6), we have:

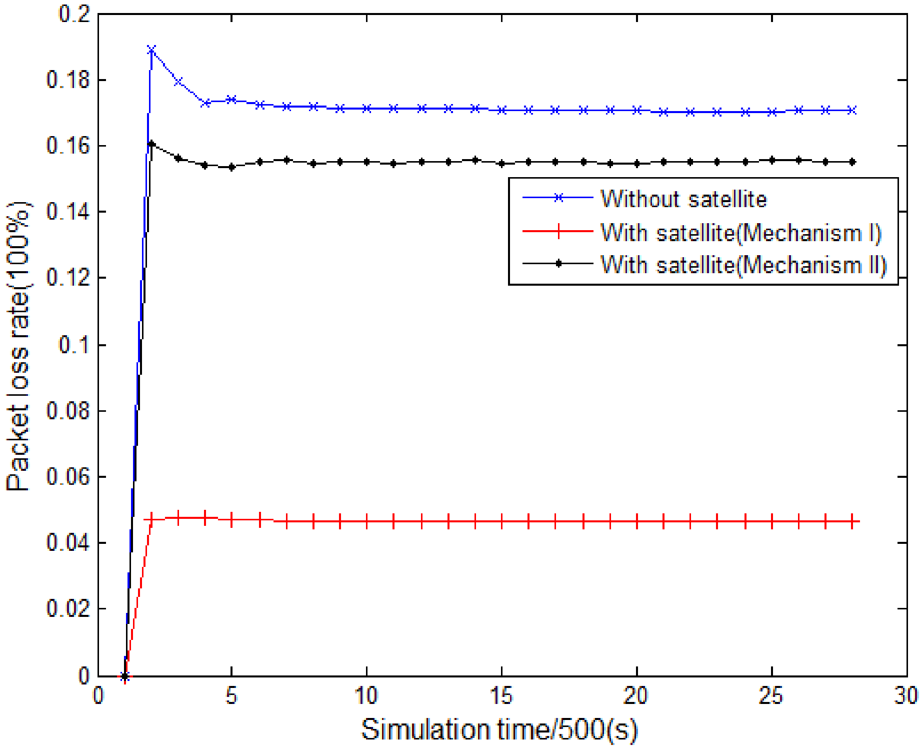
$$\rho_{\mathrm{total}} = \frac{\mathrm{N}_{\mathrm{lost\_RMsg}} + \mathrm{N}_{\mathrm{lost\_EMsg}}}{\mathrm{N}_{\mathrm{total}}} * 100\% \tag{5.7}$$

where $\mathrm{N}_{\mathrm{lost\_RMsg}}$ means RMsg packet loss number and $\mathrm{N}_{\mathrm{lost\_EMsg}}$ represent the EMsg packet loss number.

$$\rho_{\mathrm{EMsg}} = \frac{\mathrm{N}_{\mathrm{lost\_EMsg}}}{\mathrm{N}_{\mathrm{total}}} * 100\% \tag{5.8}$$

$$\rho_{\mathrm{RMsg}} = \frac{\mathrm{N}_{\mathrm{lost\_RMsg}}}{\mathrm{N}_{\mathrm{total}}} * 100\% \tag{5.9}$$

Formula (5.7) is the sum of the formula (5.8) and formula (5.9), which verifies the conclusion of formula (5.5).



Confidence Interval

PLR_ITS = 0.17118 ∓ 0.00015

PLR_Mec1 = 0.04658 ∓ 0.000106

PLR_Mec2 = 0.15506 ∓ 0.000891

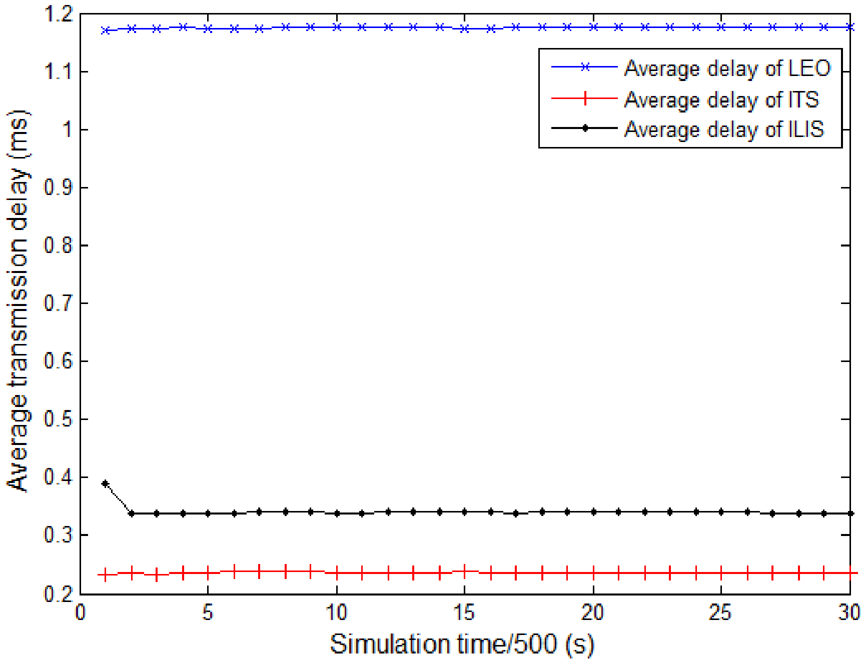
Figure 5.4 Packet Loss Rate of ILIS system with 500 sampled time

Comparing the characters of these three curves, we can get a more detailed difference between two mechanisms. The horizontal time axis will be sampled every 500s from this subchapter to observe the data results more directly. According to Figure 5.4, mechanism II (black curve) has almost the same zeros phase as the original one without using the satellite (blue curve), this is because mechanism II only overflows the emergency message to the upper layer, which is only the small part of packets generated and the effect to the overall PLR is relatively low at the beginning. So also the same thing happens in the Initial Phase and Stable Phase. Specifically speaking, the Initial Phase of Mechanism II shows similar characteristics as the PLR without satellite: Rapidly Increasing - Moderately Decreasing - Small Increasing - Vibratory Decreasing to Steady. However, the Mechanism I doesn't show similar characteristics as Mechanism II, which doesn't have sharp decrease and dramatic fluctuations. In general, Mechanism I's Initial Phase is more moderate than the other two.

For data value, we can see from Figure 5.4, the Zero Phase of Mechanism I ends at 340ms while the Mechanism II ends at 298ms, and the curve without satellite ends at 290ms. Similarly, the Stable Phase of Mechanism I starts at 600ms and Mechanism II starts from 2800ms, which is much closer to the value without satellite - 3000ms.

5.2.3 Average Delay when Applying ILIS

When overflowing message to the satellite network, the transmission delay through the integrated system becomes another problem because satellite owns higher delay. According to the survey, the delay of LEO MSS is around 10ms, which cannot cause any noticeable waiting time when applied in real life. So, the LEO satellite delay won't be the problem that influence it works as the complementary network system for ITS negatively. The specific result as showed in Figure 5.5.



Confidence Interval

Delay_ITS = 2.35921 ∓ 0.00679

Delay_LEO = 11.74593 ∓ 0.06375

Delay_ILIS =3.39588 ∓ 0.033427

Figure 5.5 Average Delay Comparison of ILIS

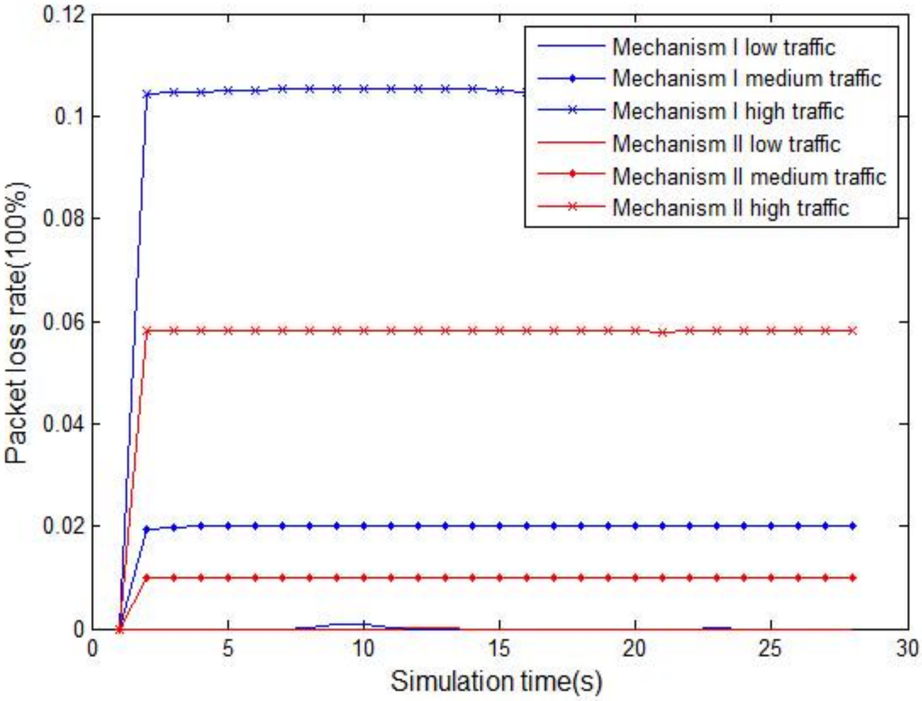
Figure 5.5 shows the average delay of ILIS compared with ITS and LEO MSS. As in the simulation assumption, the normal transmission delay of ITS and LEO MSS are 0.1ms and 1ms respectively. But from the Figure 5.5 we can find out the stable value of these two system are around 1.17ms and 0.23ms, this is because both LEO and ITS buffer size are set to be 3, the waiting time in the buffer is considered in the total average delay. The second curve is the ISIL average delay on this 10km highway, where transmission delay is 1ms in blind area and 0.1ms in other available RSU parts, the value stabilizes at 0.34ms. Even though the delay of LEO MSS is higher than ITS , but the ms level difference in real life is still not noticeable for message transmission.

When adding LEO MSS as the complementary network, the PLR gets good improvement because LEO satellite works as a replacement RSU and packets in blind area are able to use the LEO satellite network resource. However, these packets can only use the leftover bandwidth of the LEO MSS besides those carrying the satellite system's own traffic. There may not be enough network resources to accommodate the transmission of all the overflowed packets because the available satellite bandwidth is not fixed and ITS cannot always get enough bandwidth to overflow both emergency and routine messages. If the satellite has a large quantity communication flow at some point, which has already used all the satellite bandwidth, the ITS cannot send any packets to the satellite at that time. Conversely, if the satellite communication flow is very low, the ITS will overflow all the packets that cannot get access to the RSU channel to the satellite, which will lead the extremely high cost and lower the cost performance of the network resources. Therefore, certain portion of the overflowed packets was dropped and in our simulation, a 4.90% packet loss is observed. For Mechanism II, the PLR is 15.53% because all routine messages generated in the blind area were dropped. It is clear from the above figure that ILIS can reduce packet loss rate effectively.

5.3 Effects of Traffic Density

It is observed in Figure 5.3 that Mechanism II can improve PLR performance limitedly because it doesn't consider routine messages, which accounts for a large portion of the messages a vehicle generates. However, Figure 5.6 clearly demonstrates that Mechanism II works better than Mechanism I in delivering emergency messages under heavy ITS traffic conditions. After finishing the analysis of curve characteristics in Chapter 5.1.

In our simulation, when average vehicle arrival interval is 5s (Low traffic density), both Mechanism I and Mechanism II achieved a nearly 0% PLR for EMsg. When the inter-arrival time decreases to 3s (Normal traffic density), Mechanism I loses 2% emergency messages while Mechanism II only loses 1% emergency messages. When the interval reaches 1s (High traffic density), which means there is one new vehicle entering the simulated system every second on average, the PLR values of Mechanism I and II increase to 10.5% and 5.8%, respectively. The higher the traffic density, the bigger Mechanism II's improvement in delivering EMsg over Mechanism I.



Confidence Interval
PLR_Mec1_low= 0.0000228 ∓ 7.480592e-6
PLR_Mec1_med= 0.0201379 ∓ 0.000366
PLR_Mec1_hig= 0.1053064 ∓ 0.001937
PLR_Mec2_low= 0.0000739 ∓ 5.414502e-4
PLR_Mec2_med= 0.010079 ∓ 0.000572
PLR_Mec2_hig= 0.0582433 ∓ 0.0000398

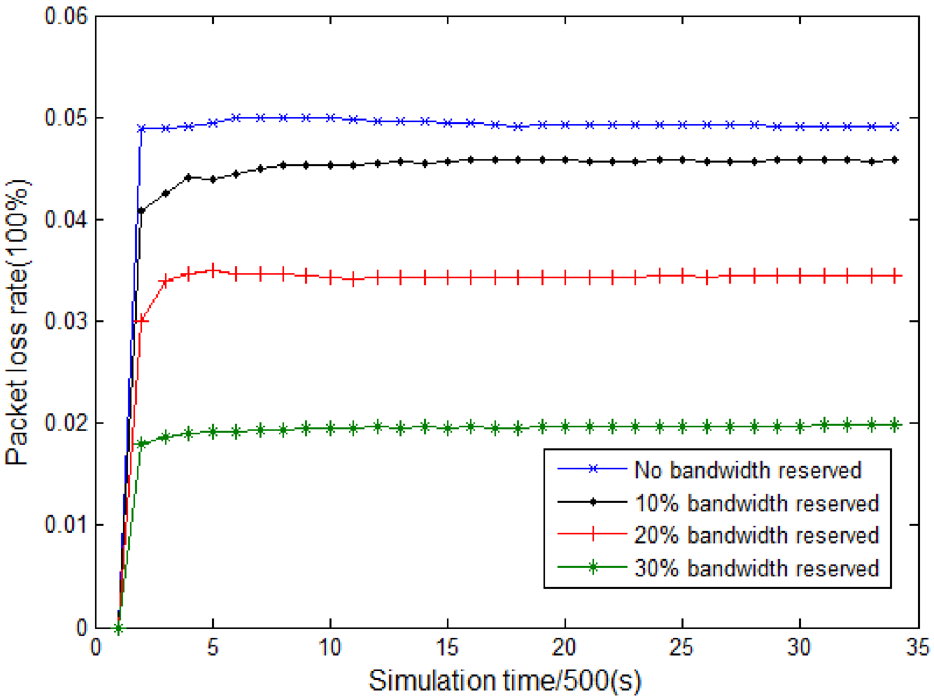
Figure 5.6 PLR Comparison of emergency message under different traffic density

Based on the above discussion, Mechanism II has the advantage for allowing more emergency messages delivered under high traffic density, while Mechanism I is able to deliver more messages. However, LEO MSS communication flow has more effect on Mechanism I compared to Mechanism II because Mechanism I needs to send more data than Mechanism II under the same available bandwidth. To solve this problem, we reserve different amounts of satellite bandwidth for ITS and evaluate the performance of both ITS and LEO MSS.

5.4 Effect of Bandwidth Reservation Protection Mechanism

5.4.1 Performance of ITS

As introduced before, a bandwidth reservation mechanism is proposed in ILIS to solve the problem of unstable available network resource for ITS. However, the LEO MSS performance will be affected as the usable network resource becomes less. In this section, we study the effect of reserving different amounts of bandwidth on the PLR performance of both ITS and LEO MSS.

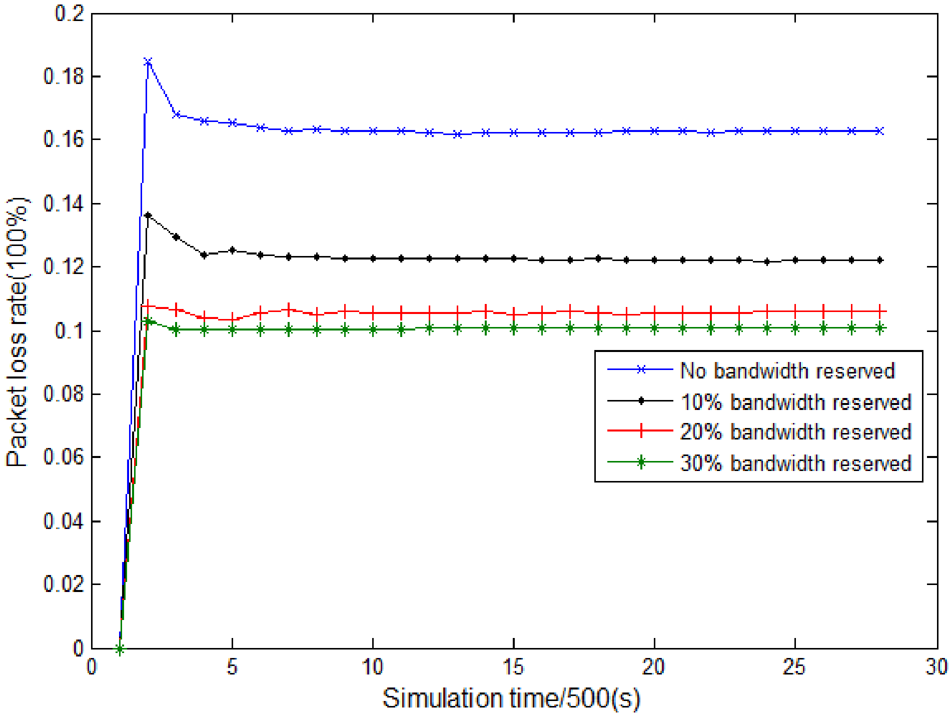


Confidence Interval
PLR_Mec1_noB= 0.049803 ∓ 0.000637
PLR_Mec1_10B= 0.0454403 ∓ 0.000063
PLR_Mec1_20B= 0.0342706 ∓ 0.000298
PLR_Mec1_30B= 0.0194065 ∓ 0.000415

Figure 5.7 Packet Loss Rate of monitoring system with different reserved satellite bandwidth (Mechanism I)

Figure 5.7 shows the PLR performance of mechanism I when reserving different amount of satellite bandwidth. It's easy to see that higher percentage of bandwidth reservation leads to lower PLR of ITS because ITS can get more available bandwidth to transmit messages. When reserving a certain amount of bandwidth to ITS, the effect of LEO MSS traffic will decrease. Once the reservation amount is over the overflowed message amount, the available bandwidth for ITS won't get affected by the satellite communication. However, excessive reservation can result in a waste of network resources and poor LEO MSS performance on data transmission, which is shown in Figure 5.9.

It is worth noticing that when reserving more bandwidth, the Stable Phase comes earlier: 10% reservation is 4000ms, 20% reservation is 3000ms and 10% reservation is 2000ms. In other words, higher bandwidth reservation can allow the system reach the steady status earlier.



Confidence Interval

PLR_Mec2_noB= 0.162998 ∓ 0.00412

PLR_Mec2_10B= 0.122778 ∓ 0.000831

PLR_Mec2_20B= 0.105328 ∓ 0.000511

PLR_Mec2_30B= 0.010027 ∓ 0.000736

Figure 5.8 Packet Loss Rate of monitoring system with different reserved satellite bandwidth (Mechanism II)

Figure 5.8 is the PLR result of mechanism II. Similar to mechanism I, the PLR of 30% bandwidth reserved is the lowest, followed by reserving 20% and 10%, while the worst is no bandwidth reserved. Specifically speaking, 10% reserved bandwidth can decrease PLR from 16.25% to 12.27%, 20% reserved bandwidth can drop to 10.54% and 30% reservation can reach 10.21%. So, for both mechanism I and mechanism II, we can get same conclusion. In terms of PLR value, 30% bandwidth reservation method is the best; in terms of improved degree, 20% reservation and 30% reservation can both get relatively ideal results - around 10%. Also, just like the curves in Figure 5.6, Figure 5.8 has a common characteristic: reserving more bandwidth from satellite network, the PLR can reach Stable status earlier..

In addition, there is a very important point showed in Figure 5.8, that is the performance of the system applying Mechanism II with bandwidth reservation protection mechanism is almost the same when reserving 20% and 30%, which doesn't follow the rule of Mechanism I: higher bandwidth can get stronger decrease of PLR. Comparing the essential characteristics of Mechanism I and Mechanism II, it's not hard to find that bandwidth reservation mechanism doesn't work well for Mechanism II is because Mechanism II only overflows EMsg to satellite, which means no matter how much bandwidth is provided, all RMsg are still dropped. So, when EMsg gets enough bandwidth to transmit, more bandwidth provided cannot decrease the message PLR value further.

5.4.2 Performance of LEO MSS

Although we have proved that using satellite network to be the complimentary network can decrease the packets loss problem very well, especially the mechanism I, we still need to study the effect of bandwidth reservation to satellite's communication of its own, because bandwidth reservation protection mechanism aims at saving cost as well as maximizing the network resource usage.

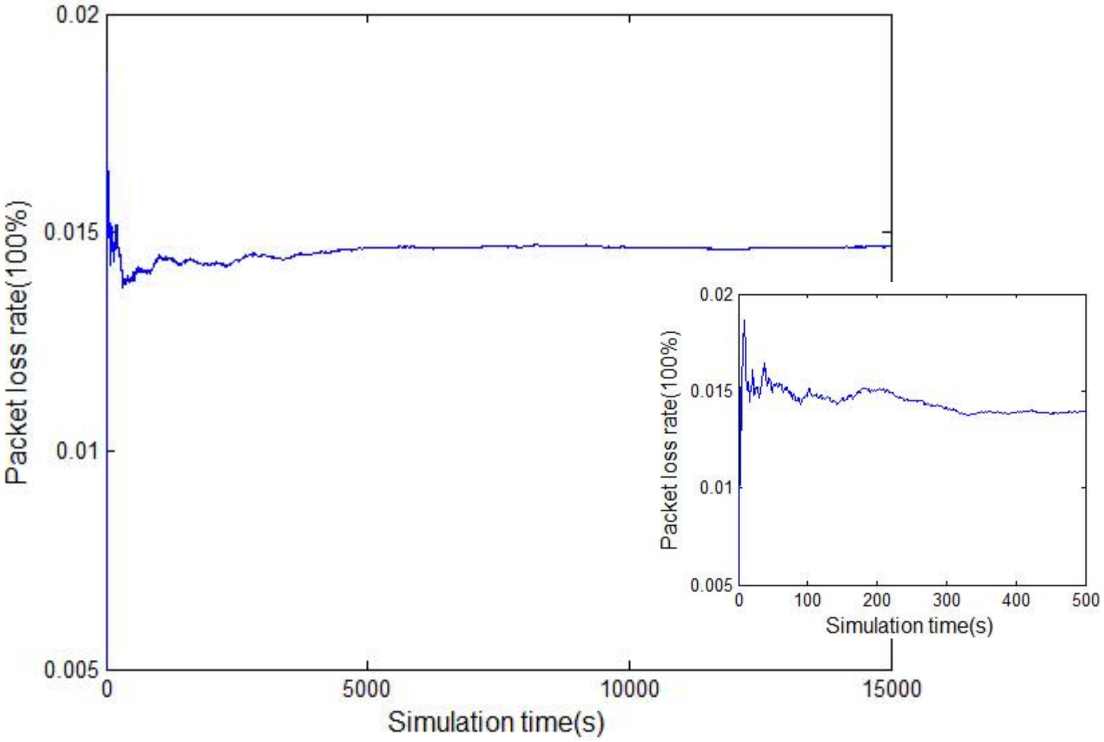


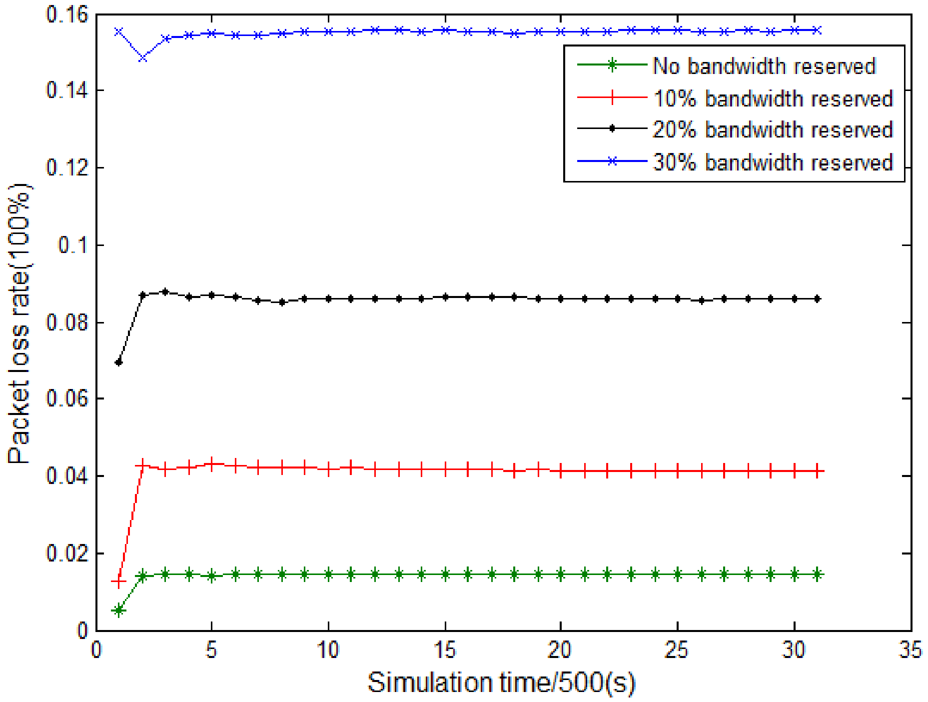
Figure 5.9 Packet Loss Rate of Satellite network with 30% bandwidth reservation

To observe the characteristics of satellite network PLR clearly, I took the PLR of satellite network with no bandwidth reservation (as showed in Figure 5.7) as the example to analyze. From the above figure, we see that the biggest difference to PLR of ITS is: PLR of SAT doesn't start from 0. That's because I set the satellite connection points arrival as Poisson process in my simulation, wh2ich means the event arrive interval T_n as formula (5.11).

$$P\left[\left(N(t+\tau)-N(t)\right)=k\right]=\frac{e^{-\lambda\tau}(\lambda\tau)^k}{k!}\qquad k=0,1,\cdots \tag{5.10}$$

$$F_{T_{n}(t)}=P\{T_n\leq t\}=\begin{cases}1-e^{\lambda t}, t\geq 0,\\ 0, t<0,\end{cases} \tag{5.11}$$

Hence, the satellite network has its own communication at the beginning and it doesn't have Zero Phase and Initial Phase. The vibration we observed here is because the effect of initial values, and as time length grows, the data will become steady.



Confidence Interval

PLR_Sat_noB= 0.0145348 ∓ 0.000279

PLR_Sat_10B= 0.0421121 ∓ 0.001948

PLR_Sat_20B= 0.0814636 ∓ 0.000275

PLR_Sat_30B= 0.15548597 ∓ 0.000692

Figure 5.10 Packet Loss Rate of Satellite network with different bandwidth reservation

Corresponding to different percentages of reserved bandwidth in LEO MSS, the PLR results of the LEO MSS are shown in Figure 5.10. When no bandwidth is reserved for ITS, only 1.47% packets are lost during the transmission. With the increase of bandwidth reservation from 10% to 30%, the PLR value of satellite network grows from 4.14% (10% reservation) to 8.59% (20% reservation), and then to 15.56% (30% reservation). It can be concluded that bandwidth reservation needs to consider traffic density of both ITS and LEO MSS in ILIS because the effect of reserving bandwidth is opposite on these two systems.

5.4.3 Trade-off between ITS and LEO MSS

According to the above analysis, bandwidth reservation protection can effectively decrease the PLR when ILIS applies Mechanism I, but doesn't make a big difference when ILIS applies Mechanism II. As showed in Figure 5.7, Figure 5.8 and Figure 5.10, the comparison of the PLR value of ITS when applying Mechanism I and LEO MSS is presented to show the trade-off of these two systems.

From comparison we can see the effect of bandwidth reservation protection mechanism is opposite on ITS and on LEO MSS, where reserving more bandwidth can decrease ITS PLR value while increasing the LEO MSS PLR value correspondingly. The result has been summarized in TABLE 5-1.

TABLE 5-1. Result Comparison between ITS and LEO MSS

	ITS	LEO MSS
No bandwidth reserved	4.91%	1.47%
10% bandwidth reserved	4.58%	4.15%
20% bandwidth reserved	3.45%	8.61%
30% bandwidth reserved	1.97%	15.53%

The data showed in the above table only reflects the situation of my modulation. As the performance of bandwidth reservation protection mechanism varies with both the vehicle communication quantity and satellite primary communication quantity, the best trade-off point should be considered with vehicle density and satellite primary customer density.

Chapter 6 Conclusion and Future Work

6.1 Conclusion

This thesis focuses on the message transmission in Intelligent Transport Systems and in Low Earth Orbit Mobile Satellite Service. To solve the problem of the unavailable RSU, a novel ITS - LEO Integrated System (ILIS) is proposed in this paper. In ILIS, LEO mobile satellite system is used as a complementary system for terrestrial ITS and offers wireless network resource to transmit packets generated by vehicles when there is no RSU available. Two overflow mechanisms are proposed for ILIS. Mechanism I overflows both routine messages and emergency messages to LEO satellite system while Mechanism II only overflows emergency messages. And these two mechanisms should cooperate to make better use of network resources.

Through analyzing the network parameters: packer loss rate, I evaluate the integrated network system from different sides: First of all, I evaluate the improvement of two mechanisms of ILIS to ITS when the RSU cannot work properly. Then, I evaluate the performance of emergency message and routine message of mechanism I and mechanism II respectively. In addition, I evaluated the impacts on the PLR and delay performance of both mechanisms as well as the PLR of LEO MSS when implementing the bandwidth reservation mechanism in LEO MSS.

A real-time simulation application is developed in C++ to observe and record the results over time. The simulation results show that Mechanism I has an overall lower PLR for ITS. However, emergency messages could have higher PLR, especially when the traffic is getting heavier. Mechanism II achieves higher delivery rate of emergency messages at the cost of dropping all routine messages. Lastly, reserving satellite bandwidth for overflowed ITS traffic can further improve the performance of ITS.

6.2 Future Work

In the future, ITS-LEO Integrated System can be studied in many directions to improve its performance and advantages.

1. It is meaningful to study the optimization of bandwidth reservation in LEO MSS under different traffic densities of both ITS and LEO MSS. Since the optimized trade-off point is related to the communication of both ITS and LEO MSS, we can do the research on the specific interior connection between them.

2. It would be interesting to study the Throughput of ILIS because how does message transmitted in the backbone network hasn't been studied, and we don't know how many message can be received successfully at the receiver side. So, if considering throughput in performance evaluation, it will be more reliably.

3. Also, the complete message transmission delay of ILIS can be studied, including the uplink connection delay, the delivery delay and the router queuing delay. Because the complete delay is more reliable when testing a system's performance and it's more accurate to check the effect of satellite delay on ILIS.

3. In addition, the integrate network system can be extended to other application area, like large data flow, best effort data flow etc. Through comparing different message types for ILIS, it's convinced to see which message is more suitable to use ILIS and how to adjust ILIS for other types of message.

In summary, as ILIS is still a new proposed integrated system, there are a lot of research points can be found to improve its performance, and I will also continue to study this new system after.

Reference

[AFR10] H. Afrancheh, S. Afrancheh and M. Mahdavi, "Providing a solution for negative impact of corrupted frames on inter frame spaces in IEEE 802.11 protocol on Ad Hoc networks", IEEE 3rd International Conference on Computer Science and Information Technology (ICCSIT), Vol. 9, July 2010, pp. 797 - 801.

[AHM12] A. Ahmad, M. Doughan, I. Mougharbel and M. Marot, "A new adapted back-off scheme for broadcasting on IEEE 1609.4 control channel in VANET", IEEE IFIP 11th Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net), June 2012, pp. 9 - 15.

[AIY14] G. Aiyetoro and F. Takawira, "A Cross-layer Based Packet Scheduling Scheme for Multimedia Traffic in Satellite LTE Networks", IEEE 6th International Conference on New Technologies Mobility and Security (NTMS), March 2014, pp. 1-6.

[AKB12] A. Akbarifar, J. Bagherzadeh and S. Yousefi, "An extension to IEEE 1609.4 for dynamic multichannel interval adjustment in WAVE architecture", IEEE 2nd International eConference on Computer and Knowledge Engineering (ICCKE), October 2012, pp. 272 - 277.

[ALA10] W. Alasmary and W. Zhuang, "The Mobility Impact in IEEE 802.11p Infrastructureless Vehicular Networks", IEEE 72th Vehicular Technology Conference Fall (VTC), September 2010, pp.1 - 5.

[AMA11] M. Amadeo, G. Araniti, A. Iera and A. Molinaro, "A Satellite-LTE Network with Delay-Tolerant Capabilities: Design and Performance Evaluation", IEEE Vehicular Technology Conference (VTC Fall), September 2011, pp. 1-5.

[AMI14] A. Amini, R. Vaghefi, J. Garza and R. Buehrer, "Improving GPS-based vehicle positioning for Intelligent Transportation Systems", Proceedings IEEE Intelligent Vehicles Symposium, June 2014, pp. 1023 - 1029.

[ARA13] G. Araniti, M. Condoluci and A. Petrolino, "Efficient resource allocation for multicast transmissions in Satellite-LTE networks", IEEE Global Communications Conference (GLOBECOM), December 2013, pp. 3023 - 3028.

[BAL10] J. Balasch, A. Rial, C. Troncoso and C. Geuens, "PrETP: Privacy-preserving electronic toll pricing", USENIX 19th Security Symposium, August 2010, pp. 63-78.

[BIA03] G. Bianchi and I. Tinnirello, "Analysis of priority mechanisms based on differentiated inter frame spacing in CSMA-CA", IEEE 58th Vehicular Technology Conference (VTC), Vol. 3, October 2003, pp. 1401 - 1405.

[BIS14]I. Bisio, M. Marchese, "The concept of fairness: Definitions and use in bandwidth allocation applied to satellite environment", IEEE Aerospace and Electronic Systems Magazine, Vol. 29, Issue 3, March 2014.

[BUL14] N. Bulgakov, V. Alybin and A. Krivoshein,"Design features of the spacecraft vehicle onboard equipment of the command-measuring system to control it in the zone of its coverage from a ground station and outside it", IEEE 24th International Crimean Conference on Microwave & Telecommunication Technology (CriMiCo), September 2014 , pp. 6-9.

[CAM11] C. Campolo, A. Vinel, A. Molinaro and Y. Koucheryavy, "Modeling Broadcasting in IEEE 802.11p/WAVE Vehicular Networks", IEEE Communications Letters, Vol.15 , Issue 2, February 2011, pp.199 - 201.

[CHA12] S. Chang, J. Cha and S. Lee, "Adaptive EDCA mechanism for vehicular ad-hoc network", IEEE 6th International Conference on Information Networking (ICOIN), February 2012, pp. 379 - 383.

[CHA12] S. Chatterjee, S. Banerjee, A. Mondal and J. Saha, "A region based channel allocation scheme for LEO satellite communication", IEEE 9th International Conference on Wireless and Optical Communications Networks (WOCN), September 2012, pp.1-6.

[CHE12] X. Chen, G. Lenzini, S. Mauw and J. Pang, "A Group Signature Based Electronic Toll Pricing System", IEEE 7th International Conference on Availability, Reliability and Security (ARES), August 2012, pp. 85 - 93.

[DES10] V. Deslandes, J. Tronc and A. Beylot, "Analysis of interference issues in Integrated Satellite and Terrestrial Mobile Systems", IEEE 5th Advanced Satellite Multimedia Systems Conference and the 11th Signal Processing for Space Communications Workshop (ASMA/SPAC), September 2010, pp. 256 - 261.

[DHO12] M. Dholey and G. Biswas, "Node-blockage reduction and removal of hidden-terminal problem of CSMA/CA MAC protocol", IEEE 1st International Conference on Recent Advances in Information Technology (RAIT), March 2012, pp. 321 - 324.

[FAN04] R. Fantacci, T. Pecorella and I. Habib, "Proposal and performance evaluation of an efficient multiple-access protocol for LEO satellite packet networks", IEEE Journal on Selected Areas in Communications, Vol. 22, Issue 3, April 2004, pp. 538 - 545.

[FAN07] Y. Fan and S. Biswas, "Self-Configuring TDMA Protocols for Enhancing Vehicle Safety With DSRC Based Vehicle-to-Vehicle Communications", IEEE Journal on Selected Areas in Communications, Vol. 25, Issue 8, October 2007, pp. 1526-1537.

[FAN08] L. Fan, H. Du, U. Mudugamuwa and B. Evans, "A Cross-Layer Delay Differentiation Packet Scheduling Scheme for Multimedia Content Delivery in 3G Satellite Multimedia Systems", IEEE Transactions on Broadcasting, Vol. 54, Issue 4, March 2008, pp. 806 - 815.

[FEN10] Y. Feng, Y. Du, Z. Ren and Z. Wang, "Adaptive Beacon Rate Adjusting mechanism for safety communication in cooperative IEEE 802.11p-3G vehicle-infrastructure systems", IEEE on 16th Asia-Pacific Conference on Communications (APCC), October 2010, pp. 441 - 446.

[GAO13] Y. Gao, Q. Ou, Q. Zeng and X. Zhang, "Analysis of mutual interferences between two components in satellite-terrestrial integrated system", IEEE 3rd International Conference on Consumer Electronics Communications and Networks (CECNet), November 2013, pp.145 - 148.

[GUO12] J. Guo, Y. Huo, C. Hu and T. Liang, "An adaptive and reliable MAC mechanism for IEEE 1609.4 and 802.11p VANETs", IEEE 15th International Symposium on Wireless Personal Multimedia Communications (WPMC), September 2012, pp. 55 - 59.

[HAD14] M. Hadded, R. Zagrouba, A. Laouiti, P. Muhlethaler and L. A. Saïdane, "An Adaptive TDMA Slot Assignment Strategy in Vehicular Ad Hoc Networks", Journal of Machine to Machine Communications, Vol. 1, 2014, pp.175–194.

[HAH13] V. Hahanov, W. Gharibi, B. Abbas and S. Chumachenko, "Cloud traffic monitoring and control", IEEE 7th International Conference on Intelligent Data Acquisition and Advanced Computing Systems (IDAACS), Vol. 01, September 2013, pp. 244 - 248

[HAN12] C. Han, M. Dianati, R. Tafazolli and R. Kernchen, "Analytical Study of the IEEE 802.11p MAC Sublayer in Vehicular Networks", IEEE Transactions on Intelligent Transportation Systems, Vol. 13, Issue 2, June 2012, pp.873 - 886.

[HUJ12] J. Hu and T. Song, "A vehicle-mounted communication system integrating satellite and terrestrial networks", IEEE 7th International Conference on Computing and Convergence Technology (ICCCT), December 2012, pp. 767 - 771.

[KIM06] B.Kim, C. Kim and D. Ahn, "Performance Evaluation for A closed loop power control using An Efficient Channel Estimation in SAT-CDMA", IEEE 63rd Vehicular Technology Conference (VTC 2006-Spring), Vol. 6, May 2006, pp. 2625 - 2629.

[KON10] C. Kong , X. Fan, Z. Xu and H. Zheng, "Design and Simulation of Two-Channel DDC in Satellite Cellular Integrated System", IEEE 6th International Conference on Wireless Communications Networking and Mobile Computing (WiCOM), September 2010, pp.1-4.

[LIN09] Y. Lin, H. Yen and S. Lin, "Delay QoS and MAC Aware Energy-Efficient Data-Aggregation Routing in Wireless Sensor Networks", Article on Sensors (Basel), September 2009.

[LIN10] C. Lin, B. Chen and J. Lin, "Field Test and Performance Improvement in IEEE 802.11p V2R/R2V Environments", IEEE Workshop Paper on 9th International Conference on Communication (ICC), May 2010, pp. 1-5.

[LIU13] Q. Liu, Q. Wu and L. Yong, "A hierarchical security architecture of VANET", IEEE International Conference on Cyberspace Technology (CCT), November 2013, pp. 6-10.

[LUI14] U. Luis, V. Andres, T. Carolina and M. Igartua, "MAX-MIN based buffer allocation for VANETs", IEEE 6th International Symposium on Wireless Vehicular Communications (WiVeC), September 2014, pp. 1-5.

[LUO10] J. Luo, X. Gu, T. Zhao, W. Yan, "MI-VANET: A New Mobile Infrastructure

Based VANET Architecture for Urban Environment", IEEE 72nd Vehicular Technology Conference Fall (VTC 2010-Fall), September 2010, pp. 1-5.

[MAD12] R. Madan, A. Sampath and N. Khude, "Enhancing 802.11 carrier sense for high throughput and QoS in dense user settings", IEEE 23rd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), September 2012, pp. 253 - 259.

[MAK09] O. Maklouf, Y. El halwagy, M. Beumi and S. Hassan, "Cascade Kalman filter application in GPSINS integrated navigation for car like robot", IEEE National Radio Science Conference (NRSC), March 2009, pp. 1-15.

[MAN13] G. Mannocchi, M. Amici, M. Marro, D. Giuliomaria, "A L-Band Transmit/Receive module for satellite telecommunications", IEEE European Microwave Conference (EuMC), October 2013, pp.951-954.

[MAR09] F. Martinez, J. Cano, C. Calafate and P. Manzoni, "A performance evaluation of warning message dissemination in 802.11p based VANETs", IEEE 34th Local Computer Networks (LCN), October 2009, pp. 221 - 224.

[MSA10] I. Msadaa, P. Cataldi and F. Filali, "A Comparative Study between 802.11p and Mobile WiMAX-based V2I Communication Networks", IEEE 4th International Conference on Next Generation Mobile Apps Services and Technologies (NGMAST), July 2010, pp.186 - 191.

[MUR08] T. Murray, M. Cojocari and H. Fu, "Measuring the performance of IEEE 802.11p using ns-2 simulator for vehicular networks", IEEE 8th International Conference on Electro/Information Technology (EIT), May 2008, pp. 498 - 503.

[NGU13] T. Nguyen, F. Baccelli, K. Zhu and S. Subramanian, "A performance analysis of CSMA based broadcast protocol in VANETs", Proceedings IEEE 32nd Annual International Conference on Computer Communications (INFOCOM), April 2013, pp. 2805 - 2813.

[NIW09] W. Ni, W. Li and M. Alam, "Determination of optimal call admission control policy in wireless networks", IEEE Transactions on Wireless Communications, Vol. 8, Issue 2, February 2009, pp. 1038 - 1044.

[PIN10] C. Ping, D. Edwards and C. Soung, "Scaling Capacity by Two Channels in

IEEE 802.11 Ad Hoc Networks With an SIR Comparison Algorithm", IEEE Transactions on Vehicular Technology, Vol. 59, Issue 4, January 2010, pp. 2071 - 2079.

[PPT12] A. Jafarian, S. Merlin, A. Asterjadhi, "EDCA Parameters", PPT, doc: IEEE 802.11-12/861r0, July 2012.

[RAV11] C. Ravishankar, A. Morris, C. Barnett and A. Noerpel, "Design and performance of a 3G mobile satellite system", IEEE Military Communications Conference (MILCOM), November 2011, pp. 1946 - 1951.

[RAW11] D. Rawat, D. Popescu, G. Yan and S. Olariu, "Enhancing VANET Performance by Joint Adaptation of Transmission Power and Contention Window Size", IEEE Transactions on Parallel and Distributed Systems, Vol. 22, Issue 9, January 2011, pp. 1528 - 1535.

[SHA10] K. Shanmugan, "Analysis of power control in satellite-based WCDMA Links", IEEE International Conference on Advanced Technologies for Communications (ATC), October 2010, pp. 231 - 236.

[SIY11] Y. Si, X. Luan, S. Ren and J. Wu, "An interleaver scheme for TD-SCDMA compatible GEO satellite communication system", IEEE International Conference on Information Science and Technology (ICIST), March 2011, pp. 627 - 630.

[SJO11] K. Sjoberg, E. Uhlemann and E. Strom, "Delay and interference comparison of CSMA and self-organizing TDMA when used in VANETs", IEEE 7th International Wireless Communications and Mobile Computing Conference (IWCMC), July 2011, pp. 1488 - 1493.

[SON13] H. Song and H. Lee, "An overview of analytic models of the IEEE 802.11p MAC protocol for vehicle-to-vehicle safety communications and their technical issues", IEEE on 4th International Conference on ICT Convergence (ICTC), October 2013, pp. 612 - 613.

[TOL10] R. Toledo, B. Ubeda, J. Santa and M. Zamora, "An analysis of positioning and map-matching issues for GNSS-based road user charging", IEEE 13th International Conference on Intelligent Transportation Systems (ITSC), September 2010, pp. 1486 - 1491.

[WAN10] Q. Wang, S. Leng, H. Fu and Y. Zhang, "An Enhanced Multi-Channel MAC for the IEEE 1609.4 Based Vehicular Ad Hoc Networks", INFOCOM IEEE Conference on Computer Communications Workshops, March 2010, pp.1-2.

[WEB01] NTT Technique Review
https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr200711sf6.html
Last access date: 2014-12-18

[WEB02] ALTHOS,
http://www.wirelessdictionary.com/Wireless-Dictionary-Low-Earth-Orbit-LEO-Definition.html
Last access date: 2014-12-18

[WEB03] Satellite communication,
http://www.britannica.com/EBchecked/topic/524891/satellite-communication/288217/How-satellites-work
Last access date: 2014-12-18

[WEB04] Iridium NEXT (Hosting Payloads on a Communications Constellation),
https://directory.eoportal.org/web/eoportal/satellite-missions/i/iridium-next
Last access date: 2014-12-18

[WEB05] IRIDIUM, http://www.decodesystems.com/iridium.html
Last access date: 2014-12-18

[XIE12] X. Xie, W. Fu, C. Liu and Q. Ye, "A TDMA Scheme for Emergency Forecasting in Dynamic Vehicular Networks", IEEE 8th International Conference on Wireless Communications Networking and Mobile Computing (WiCOM), September 2012, pp.1-4.

[XIE14] F. Xie, J. Liu, R. Li and Y. Hang, "Adaptive robust ultra-tightly coupled global navigation satellite system/inertial navigation system based on global positioning system/BeiDou vector tracking loops", IET Journal on Radar, Sonar & Navigation, Vol. 8, Issue 7, August 2014, pp. 815 - 827.

[ZHA14] R. Zhang, X. Cheng and L. Yang, "A Novel Centralized TDMA-Based Scheduling Protocol for Vehicular Networks", IEEE Transactions on Intelligent Transportation Systems, Vol. PP, Issue 99, August 2014, pp.1 - 6.

[ZHU13] W. Zhu, Q. Zhang and A. Fong, "Performance Analysis of a Hierarchical Structured VANET", IEEE 4th International Conference on Green Computing and Communications (GreenCom), IEEE 6th International Conference on Internet of Things (iThings), IEEE 5th International Conference on Cyber, Physical and Social Computing (iThings/CPSCom), August 2013, pp. 1352 - 1356.

Appendix A_ Confidence Interval

Confidence Interval is used to provide a random interval allow the probability of estimated parameter can satisfy the requirement. When θ is the parameter needed to be estimated, α is a given value ($0 < \alpha < 1$). If T_1 and T_2 that satisfy:

$$P(T_1 < \theta < T_2) = 1 - \alpha \qquad (9)$$

then $[T_1, T_2]$ is the confidence interval of θ, and the confidence level is $1 - \alpha$. T_1 is called Confidence upper limit and T_2 is called Confidence lower limit.

To calculate the Confidence Interval of the result in this thesis, we first need to understand its characteristics:

1. The Confidence Interval length $T_2 - T_1$ reflect the estimation precision, where precision is higher when the length $T_2 - T_1$ is smaller.

2. α reflects the estimation reliability, where more reliable with smallerα. When α is smaller, $1 - \alpha$ is bigger and estimation reliability is higher. However, the Confidence Interval length $T_2 - T_1$ is usually increase correspondingly, which means the estimation precision is lower.

3. When α is decided, the Confidence Interval selection method is not unique, and usually the smallest one will be chosen.

When giving sample function $g(X_x, X_2, \ldots, X_n, \theta)$, where $X \sim N(\mu, \sigma^2)$, the Confidence Interval is

$$\left(X' - t_{\frac{\alpha}{2}}(n-1)\frac{S}{\sqrt{n}}, X' + t_{\frac{\alpha}{2}}(n-1)\frac{S}{\sqrt{n}}\right)v \qquad (10)$$

For this thesis, Confidence Interval of all results are calculating as follows. The confidence level is 0.95, and all results are selected randomly with size 6. Take the Packet Loss Rate of ITS as example.

PLR_ITS = [0.17101, 0.17115, 0.17122, 0.17116, 0.17128, 0.17126]

According to the Confidence Interval limit formula:

$$T = \frac{X' - \mu}{S/\sqrt{6}} \sim t(5)$$

where $t_{0.025}(5)$ =2.5706, and x'= 0.17118;

So, $s^2 = \frac{1}{5}\left(\sum_{i=1}^{6} {x_i}^2 - 6{x'}^2\right) = \frac{1}{5}\left(\sum_{i=1}^{6} {x_i}^2 - 0.1758155\right)$

$=\frac{1}{5}(0.1758156-0.758155)=0.00000002$

s=0.0001414

According formula (10), the Confidence Interval of Packet Loss Rate of ITS is

$$(X' - t_{\frac{\alpha}{2}}(n-1)\frac{S}{\sqrt{n}}, X' + t_{\frac{\alpha}{2}}(n-1)\frac{S}{\sqrt{n}})v$$

$$= \ (x' - t_{0.025}(5)\frac{S}{\sqrt{6}}, x' + t_{0.025}(5)\frac{S}{\sqrt{6}})v$$

= 0.17118+-0.00015

Calculating other results in this way:

PLR_Mec1=[0.04657, 0.04653, 0.04663, 0.04654, 0.04663, 0.04660]

PLR_Mec2=[0.15476, 0.15499, 0.15493, 0.15506, 0.15532, 0.15531]

So, in Figure 5.4, the Confidence Interval of all results are

PLR_ITS = 0.17118 ∓ 0.00015

PLR_Mec1 = 0.04658 ∓ 0.000106

PLR_Mec2 = 0.15506 ∓ 0.000891

In Figure 5.5, the results are

Delay_ITS = [2.35897, 2.35769, 2.35822, 2.36014, 2.36009, 2.36017]

Delay_LEO=[11.73992, 11.75003, 11.74548, 11.74735, 11.74272, 11.75011]

Delay_ILIS=[3.38926, 3.38580, 3.40039, 3.40117, 3.40093, 3.39774]

the Confidence Interval of all results are

Delay_ITS = 2.35921 ∓ 0.00679

Delay_LEO = 11.74593 ∓ 0.06375

Delay_ILIS =3.39588 ∓ 0.033427

In Figure 5.6, the Confidence Interval of all results are

PLR_Mec1_low= [0, 0, 0, 0, 0.0002095, 0.001073]

PLR_Mec1_med=[0.0201385, 0.0200790, 0.0201032, 0.0201509, 0.0201633, 0.0201927]

PLR_Mec1_hig=[0.1049998, 0.1053317, 0.1053190, 0.1053577, 0.105501, 0.1053296]

PLR_Mec2_low= [0, 0, 0, 0, 0, 0.0001058]

PLR_Mec2_med= [0.0101387, 0.0100769, 0.0100825, 0.0100538, 0.0100794, 0.0100473]

PLR_Mec2_hig= [0.0582298, 0.0582759, 0.0582394, 0.0582117, 0.0582238, 0.0582792]

the Confidence Interval of all results are

PLR_Mec1_low= 0.0000228 ∓ 7.480592e-6

PLR_Mec1_med= 0.0201379 ∓ 0.000366

PLR_Mec1_hig= 0.1053064 ∓ 0.001937

PLR_Mec2_low= 0.0000739 ∓ 5.414502e-4

PLR_Mec2_med= 0.010079 ∓ 0.000572

PLR_Mec2_hig= 0.0582433 ∓ 0.0000398

In Figure 5.7, the Confidence Interval of all results are

PLR_Mec1_noB= [0.0498657, 0.0499675, 0.0499709, 0.0497487, 0.0496269, 0.0496378]

PLR_Mec1_10B=[0.0452941, 0.0452921, 0.0453805, 0.0455532, 0.0455849, 0.0455373]

PLR_Mec1_20B=[0.0343532, 0.0341644, 0.0342364 0.0342448 0.0343291, 0.0342944]

PLR_Mec1_30B=[0.0191799, 0.0192989, 0.0194088, 0.0195432, 0.0195132, 0.0194951]

the Confidence Interval of all results are

PLR_Mec1_noB= 0.049803 ∓ 0.000637

PLR_Mec1_10B= 0.0454403 ∓ 0.000063

PLR_Mec1_20B= 0.0342706 ∓ 0.000298

PLR_Mec1_30B= 0.0194065 ∓ 0.00041

In Figure 5.8, the results are

PLR_Mec2_noB= [0.1639265, 0.1627873, 0.1632508, 0.1627746, 0.1625189, 0.1627350]

PLR_Mec2_10B=[0.1232499, 0.1227027, 0.1226767, 0.1226776, 0.1226277, 0.1227338]

PLR_Mec2_20B=[0.1051398, 0.1058227, 0.1052872, 0.1052497, 0.1053957, 0.1053782]

PLR_Mec2_30B=[0.1003340, 0.1002888, 0.1003159, 0.1001869, 0.1001234, 0.1003807]

the Confidence Interval of all results are

PLR_Mec2_noB= 0.162998 ∓ 0.00412

PLR_Mec2_10B= 0.122778 ∓ 0.000831

PLR_Mec2_20B= 0.105328 ∓ 0.000511

PLR_Mec2_30B= 0.010027 ∓ 0.000736

In Figure 5.10, the results are

PLR_Sat_noB=[0.0144250, 0.0145195, 0.0146125, 0.0146337, 0.0146608, 0.0146578]

PLR_Sat_10B= [0.0430663, 0.0425512, 0.0421932, 0.0424576, 0.0421988, 0.0420055]

PLR_Sat_20B=[0.08655538, 0.0867823, 0.0865235, 0.0857292, 0.0853336, 0.0859558]

PLR_Sat_30B=[0.1552277, 0.1554044, 0.1556043, 0.15573183, 0.1553791, 0.1555685]

The Confidence Interval of all results are

PLR_Sat_noB= 0.0145348 ∓ 0.000279

PLR_Sat_10B= 0.0421121 ∓ 0.001948

PLR_Sat_20B= 0.0814636 ∓ 0.000275

PLR_Sat_30B= 0.15548597 ∓ 0.000692

Appendix B_ Pseudo Code

Vehicle Movement & Packet Generation

```
==============================================================
For i=1 to Vehicle_number
Begin:
Vehicle_i.m_nposition += Vehicle.Speed;
t =Vehicle_i.m_nPosition/1000;
    if(Vehicle_i.m_nPosition<=0)
        Delete Vehicle_i;
    if(Vehicle_i.m_nPosition>=20000)
        Delete Vehicle_i;
    if(Vehicle_i.m_nPosition%1000>500)
        m_ulAp = t+1;
    else
        m_ulAp = t;
    if(m_ulAp != m_ulPreap)//ap handover
    {
        m_ulAp = INVALID_AP;
        m_nApDelayCounts++;
        if(m_nApDelayCounts>SWITCH_DELAY)//reached handover time, access next ap
        {
            m_ulAp = t;
            m_ulPreap = t;
            m_nApDelayCounts = 0;
        }
    }
    PACKAGE pack;
    pack.uAddress = m_ulID;
    pack.nPosition = Vehicle_i.m_nPosition;
    pack.nInfo = 0;
    if(Drand()<0.1)
        if(m_qSendE.size()>=VEHICLES_PACKAGE_COUNTS)
            g_dwDischarged++;
        else
            m_qSendE.push(pack);
    else
        if(m_qSend.size()>=VEHICLES_PACKAGE_COUNTS)
            g_dwDischarged++;
        else
            m_qSend.push(pack);
End For
==============================================================
```

RSU processing packet procedure

```
================================================================
FOR i = 1 to rsu_number
Begin:
        counts = 0;
        For k= 1 to Vehicle_number
        Begin：
                If Vehicle_k.ap == rsu
                {
                        Throughput += Vehicle_k.packet_size;
                        Delay += Vehicle_k.packet.waitingtime;
                        Delete Vehicle_k.packet from waiting queue;
                       Counts++;
                }
                If counts > rsu_ConnectionNumber
                Break;
        End for
End for
================================================================
```

SAT processing packet procedure

```
==============================================================
For k= 1 to Vehicle_number
Begin：
        If Vehicle_k.ap == Satellite
        {
                Throuput += Vehicle_k.packet_size;
                Delay += Vehicle_k.packet.waitingtime;
                Delete Vehicle_k.packet from waiting queue;
               Counts++;
        }
        If counts* Vehicle_k.packet_size > Satellite_reservedBw
        Break;
End for
Poisson flow generates Satellite packet sPack;
For i= 1 to packet_number
If (sPack(i).delay> max_Delay)
{
        Satellite_PacketLossRate ++;
        Delete sPack(i);
        Continue;
}
```

```
If(Satellite_Throuput > Satellite_restBw)
{
        sPack(i).delay += Satellite_Delay;
}
Else
{
        Satellite_Throuput += sPack(i).size;
        Satellite_Delay += sPack(i).delay;
        Satellite_PacketSucessNo + 1;
}
=====================================================================
```