Green Communication Protocols for Mobile Wireless Networks

by

Xiaoli Zhou

A dissertation submitted to the
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The undersigned hereby recommends to the
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Abstract

Wireless networks enter a new era in which various objects, such as mobile phones, computers, vehicles, watches, are automatically and intelligently connected to provide ubiquitous services. Green communication protocols are required to save energy consumption and improve transmission performance. MAC protocols can detect the signal status and energy consumptions of physical channels to adapt to the dynamic wireless conditions. They can also provide node-to-node transmissions for network layer protocols under green wireless networks.

The thesis presents three energy efficient communication solutions under different delay-tolerant networks scenarios to study the efficiency of MAC transmission protocols within wireless networks: CPMAC, AFLAS and TREE. CPMAC applies three energy-aware algorithms to transmit different quality requirements of data within one contact interval in sparsely connected sensor networks. Simulations and analysis shows CPMAC outperforms two other important MAC protocols in wireless sensor networks and vehicular ad-hoc networks in throughput, delay, energy consumption. AFLAS uses an adaptive frame length aggregation scheme for Vehicular Networks that is designed to improve transmission efficiency and increase data throughput. Suitable aggregation frame lengths are calculated according to the current wireless status, and applied in the MAC layer at the onset of data transmissions to save overhead and energy consumption. The simulations of AFLAS exhibit a significant improvement results in data throughput, retransmissions, overheads and transmission efficiency in comparison to non-adaptive aggregation schemes. TRaffic adaptive Energy Efficient MAC protocol (TREE) adapts its work modes: reservation and contention mode, to traffic density and adjusts its duty cycle to achieve energy efficiency. TREE demonstrates better performance in terms of energy efficiency and traffic adaptability than the schedule-based MAC protocol TDMA, the contention-based protocol CSMA and the traffic adaptive protocol TRAMA under mobile sensor network environments.

By studying and designing MAC protocols in wireless environments, the thesis shows the comprehensive knowledge and principles of communication protocol designs with latency relaxed. Future work is discussed for further designs and implementations of green communication protocols.

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I would also like to thank my family. Without their great tolerance and support, I cannot finish my PhD study.

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Publication

The following publications by the author are relevant to this thesis:

Journals:

- AFLAS: An Adaptive Frame Length Aggregation Scheme in Vehicular Networks, *IEEE Transactions on Vehicular Technology 2016 Pages:855-867*
- A MAC Transmission Strategy in Sparse Delay-Tolerant Sensor Networks, *Wireless networks, Springer Journals 2015 Pages:2237-2252*
- Traffic Adaptive Energy Efficient MAC Protocol for Mobile Delay-Tolerant Sensor Networks,(submitted)
- Delay-Tolerant Sensor Networks: A new challenge for MAC Transmission Protocols , Elsevier Computer Networks ,(submitted)

Conferences:

- Throughput and energy efficiency of MAC Protocols for Mobile Wireless Sensor Networks, *IEEE WCNC Conference 2017* (Accepted)
- An Adaptive Traffic Energy-Efficient MAC Protocol for Mobile Delay-Tolerant Sensor Networks, *IEEE GLOBECOM Conference 2016* (Accepted)
- Energy-Efficient MAC Schemes for Delay-Tolerant Sensor Networks, *IEEE ISCC Symposium 2016 Pages: 495-500*
- Adaptive Frame Length Aggregation Scheme in Vehicular Delay-Tolerant Networks, *IEEE GLOBECOM Conference 2015 Pages: 1-6*
- An adaptive energy-aware MAC frame size scheme in Wireless Delay-Tolerant Sensor Network, *IEEE WCNC Conference 2015 Pages: 849-854*

- An Efficient Adaptive MAC Frame Aggregation Scheme in Delay Tolerant Sensor Networks, *IEEE GLOBECOM Conference 2014 Pages: 277-282*
- An Efficient Transmission Strategy in 802.11 MAC in Wireless Delay-Tolerant Sensor Network, *IEEE ICC Conference 2014 Pages: 5497-5502*

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Glossary of Terms

802.11 DCF	802.11 Distributed coordination function
ACK	Acknowledgment
AFLAS	Adaptive frame length aggregation transmission scheme
A-MPDU	Aggregated multiple packet data units
A-MSDU	Aggregated multiple service data units
AODV	Ad-hoc On-Demand Distance Vector (AODV) Routing
ARQ	Automatic repeat request
BER	Bit error rate
CB-DTP	Cluster-based delay-tolerant protocol
CBR	Constant Bit Rate
CNR	Carrier Noise Ratio
CPMAC	Contact-Predicted MAC
CSL	Conflict Slot List
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access/Collision avoidance
CTS	Clear to send
CW	Contention Window
DTN	Delay-tolerant Networks
DTSN	Delay-tolerant Sensor Networks
FCS	Frame Check Sequence

FER	Frame error rate
FTS	Fault Tolerant Slot
GPSR	Greedy Perimeter Stateless Routing
IP	Internet protocol
LPT	Least Power Transmission Algorithm
M/M/1	A single server queue model, where arrivals are determined by a Poisson process and job service times have an exponential distribution
M/M/c	multi-server queueing model
MAC	Media Access Control
MACA	Multiple access Collision Avoidance
MACAW	MACA-Wireless
NAV	Network allocation Vector
N-DATA	Normal data frame
N-DATA-R	Remaining N-DATA
NTF	Notification packets
OCI	One Contact Interval
OFDMA	Orthogonal Frequency-Division Multiple Access
PTB	Power and throughput balanced algorithm
PTI	Power and throughput increased algorithm
QoS	Quality of Service
RBER	Residue Bit Error Rate

RFC	Request for comments
RSL	Receive Slot List
RTS	Request to send
S-MAC	Sensor MAC protocol
SNR	Signal Noise Ratio
TCP	Transport Control protocol
TDMA	Time Division Multiple Access
TRAMA	Traffic Adaptive Medium Access protocol
TREE	TRtraffic adaptive Energy efficient MAC protocol
TSL	Transmit Slot List
TwoRayGround	Propagation model
U-DATA	Urgent data frame
UMTS	Universal Mobile Telecommunications System
VANET	Vehicular ad-hoc networks
VDTSN	Vehicular DTSN
WBAN	Wireless Body Area Networks
WLAN	Wireless local area networks
WSN	Wireless sensor networks

Chapter 1

Introduction

1.1 Communication Protocols for Green Mobile Wireless Networks

Wireless networks enter a new era in which various objects, such as mobile phones, computers, vehicles, watches, are automatically and intelligently connected to provide ubiquitous services. For instance, sensors on home appliances and systems can make it easier to everyday monitor and control home appliances for smart home. Embedded body sensors and actuators can gather and analyze patients' body data and take actions for smart healthcare [1]. Agricultural activities have also been examined through various sensors measuring temperature, humidity, and toxins to determine the efficiency of pesticides and fertilisers [2], [3]. These wireless networks include wireless sensor networks(WSN), wireless personal area networks (WPAN), wireless body are networks(WBAN), home area networks(HAN),neighbourhood are networks(NAN), machine-to-machine(M2M), clouding computing(CC) and data center(DC). The information and communication technologies enable users to access, store, transmit, and manipulate a variety of information. Green technologies are required to efficiently utilize energy and support data communications. These technologies in wireless networks may turn off facilities that are not needed, send the only data that are needed, minimize the wireless transmission data path, trade off processing for communications and employ advanced communication techniques [4].

Green wireless network applications require data transmission protocols to improve transmission performance, such as energy conservation, efficiency and throughput improvements. There are several transmission approaches in the network layer and above for green wireless networks.

Most protocols are for use in the network or transmission layers, and cannot handle physical challenges in wireless networks. First, bundle protocols may not bring additional improvement in transmission performance, when sensor networks are almost homogeneous with no inconsistent processing delay. Second, physical connections in wireless channels are seldom considered in Bundle protocols, even though they are commonly applied in unstable and dynamic wireless environments. Within the sensor network scenarios, instability in wireless channels presents a severe challenge, and instigate particularly long and unpredictable delays. Last, energy conservation in sensor networks compromises channel status and transmission performance. In a green wireless networks, most sensors are tiny battery-powered chips, and energy conservation is essential for extending network longevity in far-reaching sensor monitoring areas. In addition, dying or sleeping sensors for energy conservation make it more challenging to perform data communications under intermittent connections with unpredictable delay. Furthermore, throughput, channel utilization and reliability are traded for energy conservation in green wireless networks. Therefore, new transmission strategies other than bundle protocols have been developed to face the challenges in green wireless networks.

Approaches in the MAC layer can efficiently resolve the challenges in green wireless networks. First, the MAC layer in a green wireless networks has direct access to physical channels and energy usage. The MAC layer has various tasks in different channel access methods, scheduling algorithms, energy detections, power control schemes, rate adaptability and error control schemes. Thus, the MAC layer can provide various approaches to improve energy conservation, throughput, channel utilization, and reliability to handle challenges in green wireless networks. Second, the MAC layer is the middle layer that supports network connections and higher layer requirements such as throughput, congestion control, latency, etc. The MAC transmission strategies can also work with bundle protocols under general wireless networks. Therefore, MAC transmission protocols have been researched to improve the transmission performance of green wireless networks.

1.2 Protocol Design Challenges in Green Wireless Networks

The characteristics of green wireless networks affect the designs and the schemes used in the MAC layer when we consider data transmissions among multiple sensors and different connections. In this section, the main characteristics of green wireless networks are introduced to indicate the application requirements and design challenges in green wireless networks MAC protocols.

1.2.1 Energy and resource constraints

Most sensors operate on a battery supply, equipped with less memory and fewer computation capabilities in order to reduce costs. Specific energy constraints are considered for certain applications, such as those in which static or mobile sensors are placed in distant areas and are intended to last 15-20 years, since the longevity of these sensor networks depend largely on the energy consumption of the sensors [5]. For example, the health monitoring sensors in local offices must be low-cost and resilient, so that sinks can harvest the required health data and send it to the data center. Other resource constraints, such as processors and memory, also exist in these tiny, cheap sensors, limiting their computation capability and buffer size.. These energy and resource constraints comprise the major challenges throughout the sensor networks.

1.2.2 Dynamic topology and traffic patterns

Most sensor networks contain numeric static or mobile sensors, which run similar transmission protocols on a large scale. The connections between sensors are dynamic and intermittent, and result in different perspectives to the network topology and traffic patterns. MAC transmissions are required to consider fixed or dynamic topologies and traffic scenarios for designing elegant schemes.

Topology

The topologies of sensor networks are mainly self-organized and can adapt to data transmission requirements. MAC protocols often treat these dynamic topologies, as peer-to-peer connected, star connected and mixed connected, according to the sensor's physical locations or logical connections between sensors (Fig. 1.1).

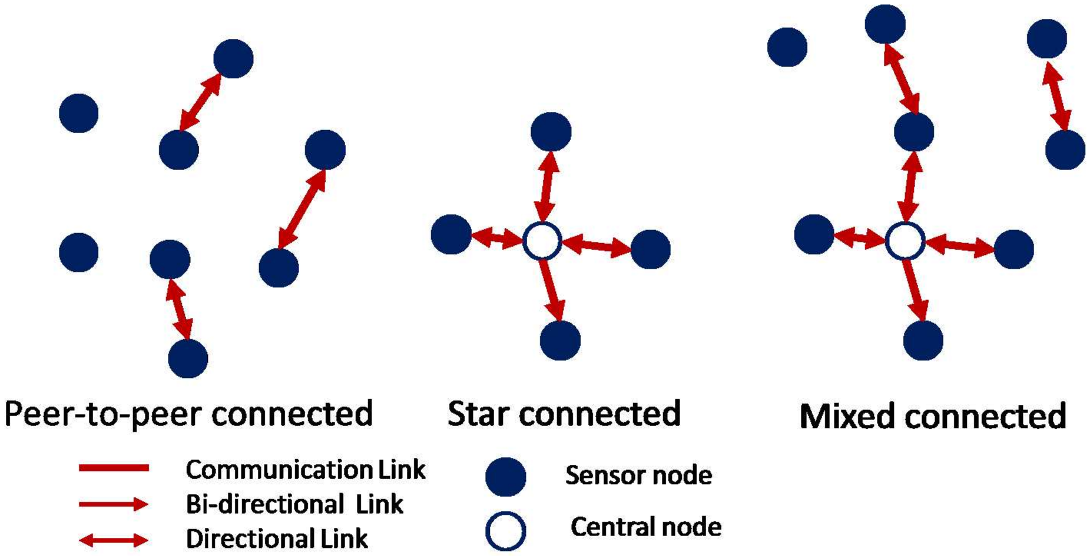

Figure 1.1: Topology and traffic in a green wireless networks

- *Peer-to-peer connected.* The sensors select the transmission counterparts and send data packets. They are casually connected, and may disconnect due to mobility or collisions. There is no scheduled or designated communication link between sensors. MAC protocols face problems in access contentions, hidden terminals, and collision resolutions during sensor communications. However, transmission protocols based on peer-to-peer topology can easily be extended on a large scale, and can be applied to mobile environments.

- *Star connected.* Sensors are grouped into clusters according to location or logical connections in star connected topology. The clusterheads may control and/or schedule other sensors' transmissions, and are also responsible for collecting all the data from the sensors in their clusters and transmitting to the data sinks. This topology may demonstrate good energy and throughput efficiency when the traffic load is high. However, the centralized topology may not scale well when the sensors spread into many clusters, and the data links between sinks to clusterhead and clusterhead to sensors are highly burdened. Tree-based topology is a multi-layer centralized network in which parents control and schedule data transmissions between parent nodes to child nodes. This topology forms the obvious connection links for improving transmission efficiency. However, since it relies on the logical connections between parent nodes and child nodes, tree-based topology is vulnerable to link changes and sensor mobility.

- *Mixed connected.* Mixed connected topology shows the sensor connections under complicated environments: some sensors can form the star connected data communication in dense areas, while other sensors may only find, at most, only one peer-to-peer connection after experiencing long searching times for communication links in sparse areas. MAC protocols should consider various topologies to design the media access strategies and MAC frame structure.

Traffic

Traffic within sensor networks is often dynamic, and traffic directions may vary due to different data collection requirements of the sensors. The traffic flows can be directional or bi-directional. For example, the sensors monitor the environment or traffic data, and send it periodically or via event-based reporting to the data center. This traffic is mainly targeted to the sinks or routers that are connected to the data center. In bi-directional traffic, data transmission and control messages can be delivered from data sinks to sensor nodes. Traffic patterns vary, and depend largely on the sensor's locations and the timing of sensing events. Sensor mobility also elicits changes in traffic patterns in green wireless networks.

1.2.3 Mobile sensors

Applications in sensor networks have begun using mobile sensors for changing and dynamic scenarios: road detection sensors in vehicles, body sensors in human bodies or in migrating birds and animals, or temporary sensors in disaster rescue objects. Mobility affects MAC design and implementation in the following aspects.

- *Topology changes.* Topology changes due to mobility will destroy existing connections, and require new connections to deliver data packets. MAC protocols are required to adapt to sensor mobility and maintain the data transmission performance with changes in topology. Departing sensors may destroy the quality of an established link, thus increasing the rate of packet retransmission. Incoming sensors may increase collision probabilities when unexpected terminals try to access the existing connections, thus extending connection setup procedures.

- *Synchronization and schedule changes.* In centralized networks, node mobility increases the complexity of the management process in the central node or sinks, as synchronizing nodes may vary according to nodes' positions and speed. The central nodes are required to identify the new arriving sensors, and recalculate the scheduled list and resource allocation in time.
- *Contention changes.* In ad-hoc networks, the possibilities of hidden terminals and contentions increase when the sensor nodes move. Collision avoidance schemes are expected, and retransmissions may occur more often in mobile environments.

MAC designers are required to consider the demanding mobility of application requirements for improving performance in the MAC layer. The duty cycle in the MAC layer may vary to accommodate more mobile nodes. Collisions and hidden terminal problems occur when the sensors' mobility is unexpected. MAC frame transmission schedules may experience continuous changes, thus introducing more overhead messages. Supporting mobility in green wireless networks is another challenge in MAC protocol designs.

1.2.4 Delay tolerance

Delay tolerance is a predominant characteristic in green wireless networks, and also presents a challenge in the design of MAC due to its other performance requirements, such as trading latency. MAC designers are required to examine delay causes and find the trade-off factors to enhance other performance in green wireless networks. The causes of delay during the process of MAC protocols can be divided in the MAC layer according to various reasons.

- *Processing delay.* Time required by nodes to identify and process the packet header. This is dependant on the node's processing unit.
- *Queueing delay.* Time spent by MAC packets in the buffer of sensor nodes.
- *Accessing delay.* Time spent by nodes to access the physical channels after the packet is processed and queued.

- *Transmission delay.* Time taken by nodes to push the MAC data packets onto the channels.

- *Propagation delay.* Time required for a wireless signal to reach its destination.

The significant delay in a green wireless networks is caused by fluctuating physical channels of sensor networks, which result in unpredictable queueing, access and transmission delays in the MAC layer. The processes also yield opportunities to improve efficiency in throughput, energy conservation and reliability. In some sensor networks propagation delay is the main cause of latency, and is predictable. When applications are not real-time and bear various unpredictable or predictable delays in data transmissions, agile MAC schemes can be designed to improve specific performance in green wireless networks.

Green wireless networks applications may experience energy constraints, dynamic topologies and traffic, and mobility requirements with several delay properties. With the considerations of these characteristics as main challenges, MAC designers can choose various performance metrics to design or optimize data transmissions and media access control.

1.3 MAC Performance Metrics for Green Wireless Networks

Performance metrics are design targets for MAC protocols, and function as evaluation tools to check the usability of the protocols in green wireless networks applications. When the delay requirement is relaxed in green wireless networks, energy consumption, mobility, throughput and reliability become the main performance metrics for designing and evaluating a MAC scheme.

1.3.1 Energy conservation

Energy conservation helps extend network longevity in battery-driven sensors, and is a major requirement for sensors in harsh and remote areas. MAC protocols should consider energy consumption during every stage of data transmission. Three major issues impact energy conservation in the MAC layer:

- *Collisions.* When two or more nodes transmit simultaneously within their transmission range, collisions may occur. Collided transmissions are terminated, and retransmissions should be scheduled. Both of these procedures are energy-consuming.

- *Overhearing and idle listening.* Sensors may wait and listen to the channels. Irrelevant packets are sometimes heard by sensors. This irrelevant hearing or unnecessary listening may drain sensors' energy.

- *Overhead.* Control messages are commonly used in the MAC to coordinate and schedule sensors during transmissions. Greater overhead used by MAC protocols results in higher energy consumption for a single transmission.

Energy conservation requirements have largely shaped MAC protocols in several ways. The duty cycle scheme is commonly employed in wireless sensor networks to conserve energy and extend network lifespan. A sensor working in the duty cycle may change status from working mode, such as the transmitting, listening, and receiving stages, to the sleeping mode, which consumes one tenth the energy of the transmission stage [5]. For some MAC protocols in sensor networks, designers trade network longevity for latency, throughput, reliability, fairness and scalability.

1.3.2 Throughput

Throughput is not always the first priority in green wireless networks. In the early stage of sensor networks, in which the sensors transmit only event data, sporadic data packets are required in a green wireless networks; thus, MAC approaches often sacrifice throughput or capacity in order to conserve energy. However, with the development of tracking or video monitoring applications in sensor networks, throughput has become a major requirement in green wireless networkss. For instance, video sensors in vehicular networks may detect road surfaces or track specific cars. In these scenarios, energy conservation and reliability can be traded by throughput to achieve the application requirements.

Improving throughput in a green wireless networks is challenging. Duty cycle, fault nodes and mobility deteriorate wireless channel status, and the capacity of physical channels is constrained. In order to better share wireless channels to multiple nodes, MAC protocols schedule the node transmissions and avoid collisions and retransmissions. Channel utility is also considered for maximizing capacity in the MAC layer. MAC protocols must meet high throughput requirements in many applications.

1.3.3 Mobility

Most MAC protocols are required to detect sensor location changes and accommodate the mobility to efficiently transmit MAC frames for multiple sensors. Sensor mobility can be classified through speed and patterns. Sensor's speed may range from 0-150 km per hour, making the data transmission contact interval between sensors very short. Moreover, continuously moving sensors dynamically change the topology of the current network, resulting in greater complexity in forming MAC protocols. MAC protocols also observe sensor mobility by patterns, which are the movement pattern of sensors in WSN. The mobility patterns can be classified by dimension, velocity, group directions, mobile predictability and limitations. There are three main mobility patterns commonly used in green wireless networks scenarios:

- *Random walk mobility pattern.* Sometimes, sensor nodes are attached to the body of an ambulatory animal or human. The sensors have limited speed and often move randomly or follow certain pedestrian routes.

- *High-speed mobility pattern.* Sensors on vehicles may move very quickly and follow specific two-dimensional paths or highway trajectories. Highway traffic conditions may contain group information for this mobility pattern.

- *Dynamic medium mobility pattern.* Sensors in wild environments may move along with their carriers, such as water, wind, birds and soil. The mobility patterns of these sensors largely depend on the nature of the carriers.

MAC designers can employ these typical speeds and patterns as application scenarios to design and evaluate transmission strategies in green wireless networks.

Three performance metrics, mobility, delay and throughput, affect one another in wireless networks. According to [6], the transmission delay for a single packet in a mobile network is inversely proportional to the velocity of the mobile nodes. The entire throughput of this network is independent of the velocity of the mobile nodes. According to [7], data throughput under relaxed delay constraints can be elevated for mobile environments while it has limited increasing room for stationary scenarios.

However, node mobility cannot continuously increase data throughput under certain delay requirement, which is called critical delay.

When we loosen the delay constraints which that are above critical delay, either throughput or mobility performance can be improved as long as we consider the mobility properties. The authors in [8] studied the critical delay and found the patterns and nature of sensor mobility impact the critical delay while the network setting cannot. Authors in [8] proposed a trade-off relationship between throughput and delay under the fixed and mobile ad-hoc networks, showing that optimal delay scales down with the hop counts, the transmission range, the velocity of the mobile nodes, and degree of mobility. [6] considered m random mobile nodes and n uniformly static nodes, and calculated the best achievable throughput $O(Wm/n)$ where W is the maximum available bandwidth. The maximum delay is $2dv$, where v is the velocity of nodes and d is the diameter of the network. Therefore, MAC protocols can trade latency for throughput and mobility support in green wireless networks.

1.3.4 Reliability

Applications in green wireless networks have various expectations for data transmission reliability. In certain applications, such as environmental monitoring scenarios, reliability can be as relaxed as latency. However, in some applications, such as car tracking and number identification scenarios, the collecting data must be accurate, and strong reliability is required for data transmission. In addition, when MAC protocols support strong reliability, retransmissions in the higher layers may be reduced, thus improving end-to-end transmission efficiency. Reliability in the MAC layer is achieved using different schemes.

- *Forward Error Control.* Data transmissions in the MAC layer consider noise and interference in fluctuating wireless channels. Error control is effective for improving transmission reliability and reducing retransmissions. Frame error control, such as framing check sequence (FCS), is an error control strategy used in the MAC frame transmission for checking and correcting the frame. Overhead is added in each frame for error control to improve reliability.

- *ARQ and retransmissions.* Automatic repeat request (ARQ) is another error control mechanism that employs acknowledgments and time-outs mechanisms to identify successful packet transmission. When a negative acknowledgment is received, extra retransmissions must be sent, thus increasing packet delay.

- *Redundant transmissions.* By using more than one channel, path, or different versions of MAC frames to transmit one data packet, the receiver combines the multiple replicas or versions and obtains the original with no retransmissions. The strategy trades multiple resources, such as channels or paths, for robust reliability and reduced latency.

MAC protocols balance the requirements of reliability, overhead spending and latency to achieve performance goals.

1.3.5 Delay trade-off

When delay is loosened in green wireless networks, several schemes can be considered in the MAC layer to approach performance goals.

- *Flexible resource allocation and scheduling.* The relaxed latency in green wireless networks allows flexible channel access methods to share the wireless channels. MAC protocols in green wireless networkss can use comparatively more resource allocation and scheduling algorithms than delay-sensitive scenarios.
- *Contention relief.* The contentions triggered by quick transmissions may be relieved in green wireless networks. Different strategies can be applied to avoid or handle the contentions.
- *Extra energy consumption.* With longer transmissions comes greater energy consumption There is a balanced point between energy and latency regrading throughput, efficiency and reliability.

MAC protocols in green wireless networks consider these schemes with relaxed latency requirements to improve throughput, energy conservation, mobility, and reliability performance.

In general, MAC transmission strategies in green wireless networks are diverse due to the complex characteristics and various performance matrices for sensor applications.

1.4 The Outline of The Thesis

This thesis presents three typical energy-efficient data transmission solutions under green wireless networks. These solutions demonstrate various approaches we could design to improve data transmission efficiency when latency can be compromised.

When the mobile sensor attempts to retrieve data from the other fixed or mobile sensors, contact time is very important for completing the transmission in green wireless networks. The fast-moving vehicles with sensors reduce the contact time. Since opportunities for the connections are very precious and contact intervals are very short, it is necessary for sensors to use an efficient data transmission strategy. On the other hand, energy consumption in a sensor network has long been an existing constraint in data delivery. Our first MAC design CPMAC is to seek an optimal solution for the transmission of MAC data in a short contact interval between two sensors in green wireless networks. We propose a strategy which considers data throughput and energy consumption during the interval in order to evaluate delivery efficiency. This strategy schedules three types of rate and power control algorithms, based on the estimated contact time between sensors, as well as the types of data and MAC buffer limitations during the transmission intervals. The purpose of the strategy is to efficiently transmit different types of services in MAC 802.11 DCF in a short contact interval, while balancing throughput and energy to extend the sensors' lifetime.

Our second MAC design AFLAS is to find an adaptive data aggregation technique, according to the channel status and the packet error rate, to improve transmission efficiency in green wireless networks. The transmission scheme can prioritize the upper layer packets and encapsulate the upper layer data, according to the QoS requirements to improve data throughput. In addition, the scheme considers sensor energy residue and buffer status as important factors for efficient transmission of the aggregated data. The adaptive aggregation frame size in the MAC layer can also be calculated through wireless channel status and collision possibility.

Energy consumption and throughput improvement are essential in the design of MAC for green wireless networks. However, when latency is relaxed in green wireless networks environments, traditional metrics such as throughput and energy consumption cannot express the transmission efficiency and energy consumption. Therefore, transmission strategies in green wireless networks can use data packets over energy as energy efficiency to demonstrate efficiency under the requirements of high data volumes and energy conservation. We examine and analyze the MAC parameters that impact energy efficiency with reservation-based and contention-based MAC approaches under green wireless networks environments. Simulation results from two typical MAC protocols also match the results of our analysis regarding energy efficiency in green wireless networks.

Green wireless networks require efficient MAC transmission strategies that include energy constraint, relaxed latency, mobility support and diverse traffic load. The third MAC scheme TREE examines reservation-based and contention-based MAC schemes with throughput and energy consumption, through the use of queue models. It also analyzes the MAC strategies with a prospective of energy efficiency under green wireless networks environments. From the analysis, we propose a TRaffic adaptive Energy Efficient MAC protocol (TREE) to achieve better data transmissions and as energy consumption, in order to satisfy the requirements in green wireless networks. In our protocol, reservation and contention modes are adjustable to adapt to the traffic load with a suitable duty cycle length for achieving energy efficiency. The simulation results of TREE demonstrate better performance in terms of energy efficiency and traffic adaptability than the schedule-based MAC protocol TDMA, the contention-based protocol CSMA and the traffic adaptive protocol TRAMA under mobile green wireless networks environments.

The thesis is organized as follows: Chapter 2 introduces the related green protocols and designs in wireless networks. Chapter 3-6 presents the three solutions in green wireless networks. Chapter 7 discusses future work and concludes the thesis.

Chapter 2

MAC Transmission Strategies in Wireless Sensor Networks

Wireless data transmissions often experience long delays in sensor networks due to harsh environments and limited resources. Many sensor applications allow transmission latency and require improved performance in energy conservation, throughput, reliability and mobility. The MAC layer is suitable for detecting unstable wireless channels and improve transmission performance in Delay-Tolerant Sensor Networks (DTSN). This chapter builds on various strategies on MAC designs in DTSN, and presents a comprehensive study on MAC protocols in unpredictable and predicted delays in sensor networks. We study MAC protocols, which trade long, unpredictable delays in data transmissions for energy conservation, mobility, throughput and/or reliability. We also present MAC protocols in DTSN which adapt their access control and transmission processes to the predictable delays. From the aspect of delay tolerance, the chapter examines these MAC protocols through the trade-off between delay and other performance metrics, and shows the effectiveness and limitations of these MAC designs. The purpose of the chapter is to present and analyze the current MAC techniques suitable for DTSNs and seek future research trends for developing new MAC protocols in DTSNs.

2.1 MAC Protocols for Sensor Networks

MAC protocols are designed to share common wireless channels between many sensor nodes, and manage communication in the MAC layer. In general, according to the methods of access to the medium, there are two major prototypes of MAC approaches: contention-based and reservation-based approaches [5]. In reservation-based approaches, some nodes periodically send synchronization and scheduling packets to inform neighboring nodes about the time cycle, address, frame length, scheduling list, etc. (Fig. 5.3). The neighboring nodes listen to the channel for synchronization packets, then follow the cycle to send, receive and sleep. From the synchronization and scheduling frames, the listener may find a transmission slot for a sender and a receiving slot from the coordinator.

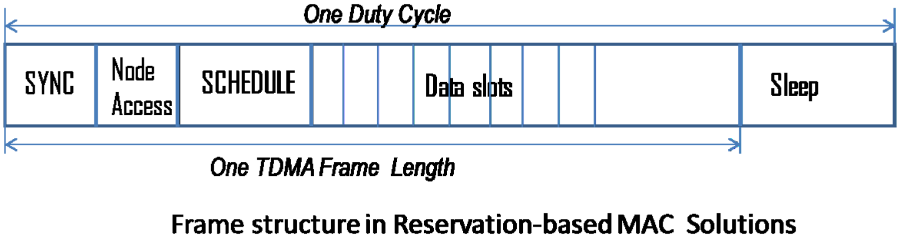

Figure 2.1: Frame structure in reservation-based MAC Solutions

The sender may transmit its data frame in a scheduled data transmission slot (shown in Fig. 5.5). The receiver can acknowledge the sender in a scheduled receiving slot. If the sender has more than one data frame to transmit, it should wait for another scheduled transmission slot in the following duty cycle. Due to the scheduling list, the channel access process is collision-free. Sensor nodes that are not coordinators conserve energy by decreasing control frames, and save data transmission latency by reducing the time for carrier sensing and collision avoidance. In high traffic areas, the central nodes can schedule multiple data transmissions between sensors and increase network throughput. However, the central nodes, or coordinators in clusters, spend extra energy when transmitting synchronous and scheduling frames and calculating scheduling algorithms. Thus, the central nodes may deplete their energy first, and affect the MAC data transmissions. This scenario is worsened when the data traffic is low. Moreover, the centralized topology may not scale well in large sensor networks.

In a contention-based approach without global synchronization (asynchronous approach shown in Fig. 5.6), sensor nodes compete the common shared wireless channels, and the first accessed node is allowed to access the channel and transmit. Carrier Sense Multiple Access (CSMA) is a representative scheme of contention-based MAC protocols. When a node has a transmission request, it listens to the wireless channel

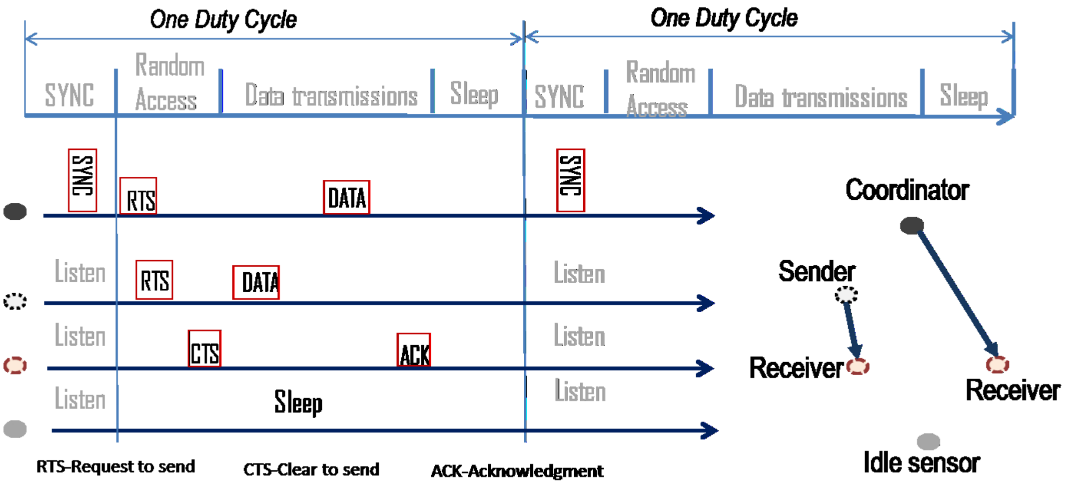

Figure 2.2: Transmission process in reservation-based MAC Solutions

and starts carrier-sensing procedure. If the channel is detected as busy, the node waits for a clear channel so that it can avoid collisions with the ongoing transmission. When the channel is detected not busy, the node initiates data transmissions after a selected random back-off time. This is a typical scenario for trading sensing and waiting times for collision avoidance to access the wireless channel. Contention-based MAC protocols scale well in large networks due to a lack of topology limitation.. The sensor nodes spend their energy according to their transmission request. This will save energy in low and medium traffic scenarios without affecting throughput. However, access collisions increase when the traffic is high with contention-based MAC protocols. Throughput and energy conservation performance also decrease due to additional control frames and retransmissions. Moreover, hidden terminal problems in contention-based MAC protocols will worsen the throughput and access performance.

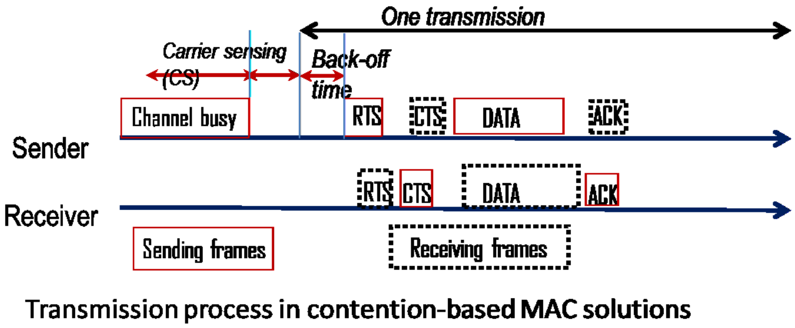

Figure 2.3: Transmission process in contention-based MAC solutions

With the DTSN environment, MAC parameters, processes and algorithms can be designed to improve certain performance indicators for sensor applications when the delay constraint is loosened. Many MAC protocols have been designed in delay-tolerant sensor networks for different perspectives of use. In DTSNs, some applications can loosen the delay constraints to trade better performance for throughput, mobility or reliability. However, some applications experience long propagation delays in specific scenarios involving MAC layer approaches. MAC protocols surveyed in this paper are classified according to the latency causes and the performance metrics in DTSNs, such as propagation delay MAC solutions (Section 2.2) and accessing and transmission delay MAC solutions. The latter is classified in the paper according to performance metrics such as energy-saving MAC protocols (Section 2.3), traffic-adaptive and throughput improvement MAC protocols (Section 2.4), mobility support solutions (Section 2.5)and reliable MAC protocols (Section 2.6). The following sections discuss these types of MAC protocols, and future trends of MAC protocols for DTSNs.

2.2 MAC Solutions for Propagation Delay

The propagation delay in the paper refers to the length of time required for wireless signals to travel to their destination. The propagation delay is much longer in long-distance transmission and underwater scenarios. Electromagnetic signals are normally used as transmission media, bearing data information in terrestrial environments. Since the speed of these signals through the air is almost the speed of light, the propagation delay is not significant compared to processing delay and queueing delay. However, when the distance between two nodes is very large, such as in satellite communications, the propagation delay may significantly affect the transmission schedule and the access control methods [9]. Another considerable propagation delay scenario occurs in underwater wireless environments. It takes five orders of magnitude longer time for a signal to transmit through underwater acoustic environments than terrestrial radio environments with same distance [9]. Regular media access control protocols experience lower performance in throughput, energy efficiency and channel utilization. Therefore, large amounts of research in the MAC layer have begun in recent years to adapt to or take advantage of propagation delay.

2.2.1 Strategy 1:improve channel utilization

The propagation delay is proportional to the distance travelled, thus it is predictable given the transmission distance. Therefore, the MAC scheduler can process extra data transmissions during the propagation waiting period [9] in the middle of one complete data transmission. The MAC layer may sequentially schedule the control frame and data frame transmission with the RTS-CTS-DATA-ACK procedure in order to improve data frame transmission efficiency. Considering the long propagation delay, the sender may transmit other frames between the time interval of sending and receiving frames, such as the time period after sending RTS (Request To Send) and waiting for CTS (Clear To Send). [9] adopted a scheme called the parallel algorithm of commands in the MAC layer, and stated that the capacity of the wireless channel improved with the use of parallel controlled MAC transmissions.

Similar channel utilization improvement strategies are also employed in underwater acoustic sensor networks (Fig. 5.2). [10] applied the broadcast nature of wireless environments and made use of long propagation delay in the underwater acoustic channel. In MAC strategy, one sensor node can communicate multiple sensor nodes using RTS/CTS exchange messages. It is based on MACA (Multiple Access Collision Avoidance) protocols in [11], and extends to underwater scenarios with multiple synchronous nodes. The sender listens for the busy signals of its neighbors, and predicts the propagation delays between them. It then transmits its control frames or data frames during selected periods when its neighbors are quiet. The strategy in [10] not only improved network performance and channel utilization, but also reduced the possibilities of contention due to hidden terminals and exposed terminals. [10] employed static underwater nodes, so that propagation delay could be predicted.

However, with the movement of the ocean, the prediction of the propagation delay may not be sufficient for scheduling a proper transmission.

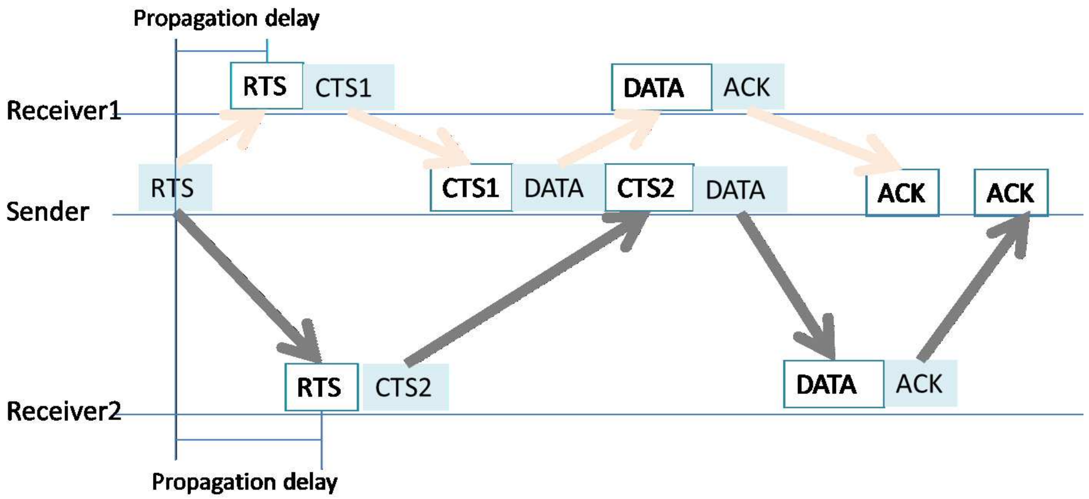

Figure 2.4: Propagation delay MAC solution in a DTSN

2.2.2 Strategy 2: collision-avoidance

Collision-avoidance approach in underwater environments focuses on collision-free access techniques and reliability in transmissions. Cluster-based delay-tolerant protocol (CBDTP) in [12] used a reservation-based MAC strategy, which selected a clusterhead as a central controller to schedule the data transmissions of every node in this cluster. The clusterhead set a collection round with a specific order for each node and broadcasts this information to all nodes in the cluster. In the collection round, each sensor sends its data to the head when needed, according to the schedule, or enters sleep mode to conserve energy. This strategy reduces the handshaking that occurs between nodes once the sensor has data to send, and improves transmission efficiency. However, the registration stage is required to initialize the networks, and the nodes are in a fixed position, so that clusters can detect the communication link status and propagation round trip delay. In addition, the clusterhead may first run out of energy, since it processes many calculations and buffer usage, thus affecting the entire cluster transmission.

By using the long propagation delay, the authors in [13] also applied the information obtained by a node to avoid collisions and improve throughput performance. [13]

is not a reservation-based MAC approach, but it does not require handshaking. In this approach, the sensor nodes overhear the sending and receiving frames of their neighbors and, with the propagation delay, form a local database indicating the busy durations of sensor nodes nearby. The sensor nodes may also send a small advance notification packet (NTF), allowing other nearby sensors to calculate the time of incoming data frames. This strategy could reduce collisions in slow-moving or static underwater sensor environments, with no additional synchronous requirements. It is a simple, low-cost protocol. The trade-off is that each sensor must calculate and store the local database in order to send and receive packets.

2.2.3 Strategy 3: energy conservation

Since path loss is proportional to the square of the frequency of the propagation signal, using low frequency band may help save energy. [14] introduced an energy-saving MAC strategy for underwater sensor networks that reduced the average transmission power in the physical layer instead of employing logical methods, such as sleep mode, handshaking frames between nodes, and transmission time scheduling. Sensor nodes are grouped according to their distance from the sink node detected by propagation delays; thus, the propagation delays are almost similar in one peculiar group. Then, a same frequency band is used within one group. This design employs the principle that a higher frequency band is allocated to the group closer to the sink node, and a lower frequency band to the farther group. This principle can conserve energy for farther group with the lower frequency band. According to this setting, the long propagation delays do not require special considerations in the same frequency band within one group. Therefore, when the central sink node allocates these frequencies as sub-channels to sensor nodes based on sensor propagation delays, the sink node broadcasts a sub-channel allocation message to all sensor nodes in this cluster. Then each node can transmit a data packet through an allocated sub-channel. Under the SNR requirements of an underwater environment, the sensor with this group channel assignment could save transmission power, and thus conserve sensors' energy.

2.2.4 Summary

The physical transmission media and the transmission distance between two nodes determine the propagation delay in wireless networks. Though the delay cannot be adjusted, it can be predicted in the MAC layer, given the transmission distance. During the predictable delay period, additional scheduling algorithms for duty cycle, channel access and resource allocation can be applied to these MAC protocols in order to improve channel utilization, reduce collisions and conserve energy (Table 2.1). The scenario column of Table 2.1 lists the environmental information, sensor distribution and speed, and network topologies. The strategy column of Table 2.1 lists the methods applied by these MAC protocols under the scenarios. All the tables in the chapter show the scenarios and strategies with the same intention. However, when the distance between these sensors varies due to significant mobility, the propagation delay cannot be predicted. Thus, these MAC protocols are limited to fixed sensor networks or little mobility scenarios.

Table 2.1: MAC Solutions for Propagation Delay

Protocols	**Scenario**	**Strategies**	**Performance improvement**
A. Markhasin et al. [9]	Satellite transmissions	Schedule another transmission during propagation intervals	Channel utilization improvement
Y. Zhong et al. [10]	Underwater acoustic sensor networks	Transmission frames during selected periods and collision avoidance	Channel utilization improvement
V. Bharghavan et al. [12]	Fixed underwater sensor networks	Central nodes schedule transmissions	Throughput improvement
Z. Zhang et al. [13]	Fixed underwater sensor networks	Reduce handshaking	Throughput improvement
N. Chirdchoo et al. [14]	Fixed underwater sensor networks	Schedule transmission according to propagation delay	Energy-saving

2.3 Energy-saving MAC Protocols

Energy conservation has been an important motivating factor for designing a MAC protocol in sensor networks, due to the considerations of network lifetime and connectivity performance when some sensors are powered off. Many MAC protocols in DTSNs focus on energy conservation to extend network longevity. The duty cycle is an energy-saving approach in which sensors' active and sleep modes change periodically, saving transmission and receiving power. Long delays during transmission may result in additional energy consumption. There is a significant trade-off between latency and power consumption in the MAC transmission process.

2.3.1 General energy conservation solutions

MAC layer can detect the energy consumption during access, transmission and receiving processes. Three main MAC solutions are often used in recent sensor networks to reduce sensors' energy consumption [5] [15].

- *Reducing collisions* Collisions waste data transmissions and consume energy. Agile MAC approaches can avoid or reduce collisions, thus saving energy. Reservation-based MAC protocols set collision-free channels by synchronizing the sensors and scheduling time slots for each sensor to transmit or receive. The trade-off for collision-free channels are synchronization and scheduling processes. Contention-based MAC protocols, such as CSMA/CA and MACA [16], negotiate communication channels among sensors by applying the exchange of small control packets, such as RTS and CTS, before data transmission. These approaches also add a random back-off time before the RTS packet transmissions to reduce the possibilities of multiple collisions resulting from synchronized neighbors. Transmissions often occur between two nodes, and hidden terminals may become involved during transmissions, leading to collisions. Collisions increase according to node density in these scenarios. There are some protocols in the middle with no rigid time synchronization requirements, such as S-MAC and T-MAC. These protocols schedule time slots between local neighbors as virtual clusters, and therefore the collision probability in these protocols is lower than CSMA or MACA approaches.

- *Reducing overhead* A great deal of research focuses on reducing different control information in packets: the synchronization of interactive messages, preambles, scheduling packets, acknowledgment packets, etc. For instance, reservation-based MAC protocols, such as FlexiMAC [17], make use of the tree topology or position-based information to reduce synchronization overhead. Since the short preamble requires less energy than the full-length preamble, preambles are divided into smaller packets, and are sent with intervals between these small packets in some protocols, which use techniques derived from BMAC [18]. Data aggregation strategies could also be used to reduce the RTS/CTS and header transmissions during asynchronous MAC transmissions [19].

- *Reducing overhearing and idle listening* Elegant scheduling strategies reduce unnecessary overhearing and idle listening, thus conserving energy. For instance, the address information in the preambles prevents non-addressed receivers from listening to the incoming packets [20]. The transmission time indicated in the frame header prohibits the unrelated receivers from idle listening. Scheduled slots only awaken the possible receivers in reservation-based approaches. However, asynchronous request messages may wake up several potential senders and receivers, thus wasting energy. The timing information in RTS/CTS informs other listeners of the transmission period to avoid idle listening and overhearing. For instance, 802.11 [21] used network allocation vector (NAV) to indicate MAC frame transmission duration for listeners, which could sleep until the time was up.

Most MAC protocols in DTSNs use mixed strategies to save energy. Synchronous and asynchronous MAC protocols have different strategies for conserving energy in DTSNs. In the following sections, four different strategies in the MAC layer are presented to conserve energy in DTSN environments.

2.3.2 Synchronous transmissions

Synchronous MAC protocols use global or local clock from the center nodes to synchronous surrounding sensors and data transmissions. With synchronous frame from the center nodes, data transmissions can be scheduled with different time slots, thus collisions during the access period can be minimized. Table 2.2 lists the selected synchronous MAC protocols with various performance goals.

Crankshaft [22] is a TDMA synchronous MAC protocol designed for the dense traffic environments of WSN. Sensor nodes in Crankshaft wake up at a specific offset of the duty cycle to listen to their messages. This protocol divides the MAC frame into broadcast slots and unicast slots. Each node is synchronized so that it can listen to one of the unicast slots to receive its packets, as well as listen to broadcast slots for general information in each frame. The sender nodes contend with packet transmissions in their receivers' listening slots. The average message latency under dense traffic scenarios increases because a node must wait for another duty cycle for resending once it is not selected in this duty cycle by center nodes or fails to receive an acknowledgment from its receiver. Compared to contention-based MAC protocols, Crankshaft saves overhead for setting up communication links between senders and receivers. However, the TDMA-based strategy constrains the scalability and mobility of the networks. Similar approaches can be found in O-MAC [23] and PMAC [24].

S-MAC [25] is a loosely synchronous MAC protocol that can extend its scalability and lack of central nodes as its advantage. Each S-MAC sensor may receive and follow its neighbor's schedule SYNC while entering the network. When an incoming sensor listens for a time period and does not hear a SYNC frame from other nodes, it can broadcast its schedule through the SYNC packet. This allows S-MAC a looser synchronization among surrounding nodes compared with TDMA schemes. While TDMA requires specified short length synchronizing, scheduling, transmitting and receiving time slots, S-MAC sets a time period for SYNC and random access. Thus, extra delays are introduced to compromise the synchronization process. Each node has the flexibility to choose its listen and sleep schedules. After receiving or transmitting the SYNC packets, sensor nodes require additional overhead messages to access channels and avoid collisions and reliable transmission. If multiple nodes request data transmissions to one node, these nodes must compete the access through the sequence of the RTS messages and CTS from the receiver indicates the winning node. The process requires more time for ensuring the data transmissions between senders and receivers than TDMA. These loosely synchronous nodes also increase latency to build up the communication links. For instance, when a potential receiver does not hear any related information, it broadcasts its schedule and goes to sleep. The sender may miss its schedule, and waits for another cycle. The sender and receiver may finally meet after several cycles. This is the expense of latency for a lack of central synchronization. However, since there are no real clustering and central nodes in S-MAC, this scheme adapts quite easily to changes in topology. The trade-off is the longer listening and link scheduling period than those reservation-based MAC approaches.

T-MAC [26] alleviates the fixed duty cycle in S-MAC, and proposes an adaptive duty cycle according to traffic flow. All nodes periodically wake up according to duty cycles to listen their neighbors for potential transmitting. They may continue their energy-saving mode until this duty cycle ends. Meanwhile, new messages are queued in the nodes. The active period of each duty cycle varies in order to handle the current packets in the queue. In an active period a node listens and may receive and transmit data frames, if the center node schedules data transmissions for the queue. When no transmission occurs for a specified time period. This active period ends. Thus the duty cycle varies in T-MAC solution. This strategy can improve the highest expected traffic load by dynamically determining an optimal active period under variable load. It also extends the wait time for the nodes to transmit and join the network.

LTM-MAC [27] is a single-hop, location-based TDMA MAC protocol for mobile to fixed node's transmission in underwater sensor networks. Mobile nodes have higher priority for data transmissions than fixed nodes. The fixed sensors must listen for a long period until no mobile node has potential transmissions. This design allows urgent data transmissions from the mobile nodes to static sensors to be sent within a short contact interval. Considering data throughput and energy consumption, LTM-MAC improves performance in energy efficiency during urgent data transmissions in short contact intervals.

Table 2.2: Energy Saving MAC Solutions 1: synchronous transmissions

Protocols	**Scenario**	**Strategies**	**Performance improvement**
Crankshaft [22], O-MAC [24], PMAC [23]	Static nodes, centralized topology, and dense traffic	Central controlled data transmission to save overhead	Save energy by reducing contentions and overhead
S-MAC [25]	Static or mobile, local centralized, and low or medium	Local synchronous MAC with fixed duty cycle	Reduce overhead by local control; Increase scalability
T-MAC [26]	Static or mobile, local centralized, and variable traffic load	Local synchronous MAC with adjustable duty cycle	Reduce overhead by local control; Heavy traffic load
LTM-MAC [27]	Static with mode nodes, centralized network with low urgent traffic	Fixed nodes transmit in pre-defined sequence, but mobile nodes have higher priority to insert data transmissions	Improve throughput and energy efficiency

2.3.3 Asynchronous transmissions

Asynchronous MAC protocols aim to build up direct communication between senders and receivers, without a synchronization process. The senders use preamble sampling and low power listening presented in BMAC [18] to wake up the receivers. Preamble sampling requires to transmit a preamble first and then transmit data frames. The surrounded nodes may detect the preamble and then receive the following data frames after the preamble.

In asynchronous MAC protocols with preamble sampling, the preamble may contain non-data, address, time and/or data, at the cost of increasing preamble length. The preamble is also designed to be easy to decode. However, long preambles require long periods of listening from receivers and consume extra energy. Therefore, MAC designers divide a long preamble into several small preambles in order to save listening time. For instance, Enhanced BMAC [28] sets the time information so that the receivers can go back to energy-saving state after it decodes the information from the preambles. The receivers then wake up according to the time information to receive the data. Many protocols such as MFP [29], B-MAC+ [30], SpeckMAC [31], DPS-MAC [32], and SyncWUF [33] use similar schemes. The receivers can listen to the broadcast time information from the preambles, and they save energy to sleep state until the time is up to receive data frames. Similar preamble design can be found in CSMA-MPS [34], TICER [35], X-MAC [36] and MHMAC [37].

Actual data packets can also be used as preambles to repeat the data packets in some protocols, such as SpeckMAC-D [31] and MX-MAC [38]. The receivers can receive the data packets directly without listening at least preambles and data frames. This strategy may save energy consumption during preamble detection. However, the receivers must decode these data packet preambles to understand the target receivers from the destination address. Thus, the channel sampling duration increases and energy consumption also increase. The trade-off between the data packets as preambles requires delicate length and timing designs to save energy.

AS-MAC [39] uses duty cycle to avoid idle listening, and also applies Low-Power-Listening to minimize the periodic wakeup time in a mesh network. The sensor nodes gather the wakeup schedules from their neighbors. Thus, the nodes do not overhear any packets, because each receiver has its own unique wakeup offset. This allows the senders to acquire the channel at the receivers wakeup time. Therefore, AS-MAC saves energy and has fewer collisions and overhearing time than traditional asynchronous MAC. However, the design of wakeup offset can only apply to stationary sensors with no dynamic position changes. Therefore, AS-MAC cannot support mobility and dynamic change scenarios in DTSN.

Most asynchronous designs are suitable for low traffic load scenarios. The preambles and channel avoidance solutions work well under these scenarios since the overhead messages for channel detections are not significant compared to synchronous and scheduling overhead in synchronous MAC solutions. However, when the traffic load is high, the channel detections and collision occurrences may last for a long period and prohibit data transmissions. Table 2.3 shows the asynchronous transmission solution list of energy-saving MAC protocols.

Table 2.3: Energy Saving MAC Solutions 2: asynchronous transmissions

Protocols	**Scenario**	**Strategies**	**Performance improvement**
TICER [35] CSMA-MPS [34] X-MAC [36] MHMAC [37]	Static or mobile, ad-hoc network with low to medium traffic	Preamble with time information to extend sleeping time	Energy-saving by extending long sleep period
Enhanced BMAC [28] MFP [29] BMAC+ [30] DPS-MAC [32] SyncWUF [33]	Static or mobile, ad-hoc network with low to medium traffic	Slotted preamble to reduce idle listening	Energy-saving by reducing transmission length
SpeckMAC [31] MX-MAC [38]	Static or mobile, ad-hoc network with low to medium traffic	Repeat data as preamble to reduce idle listening	Energy-saving and decoding data quickly
AS-MAC [39]	Static, mesh network, low to medium traffic	Wakeup offset and wake up schedule to identify receivers to reduce collision and overhearing	Energy-saving in fixed networks

2.3.4 Strategy 3: cross-layer designs

Diverse approaches in cross-layer designs are developed for energy efficiency, since cross -ayer designs can reduce control messages between layers in DTSN.

NCCARQ-MAC [40] combines network coding in the network layer and ARQ messages in the MAC layer, and forms a cooperative ARQ MAC in wireless networks. The protocol uses neighboring nodes between the source and destination stations to help relay the incorrectly received packets to the destination. Network coding is applied in the helper nodes through redundant transmissions between source and destination. The energy is saved through decreased control packets and the contention process for one transmission. NCCARQ-MAC shows 80 percent energy efficiency compared to simple ARQ MAC, through analysis and simulations.

Cuomo et al. [41] presented an energy-efficient, cross-layer design for ZigBee sensor networks. This approach presented a central coordinator election strategy in self-organized ZigBee environments, though knowledge of the topology. Energy conservation is achieved through minimizing the averages of hops between sensor nodes to the coordinator.

Luca Catarinucci [42] proposed another cross-layer approach to minimize the energy consumption in sensor networks. The approach introduces a wakeup radio to detect higher layer data transmissions with low energy consumption. The duty cycle can be adjusted to save more energy for the sensor nodes with the wakeup radios.

Table 2.4 shows cross-layer MAC design list of energy-saving protocols.

Table 2.4: Energy Saving MAC Solutions 3: cross layer designs

Protocols	**Scenario**	**Strategies**	**Performance improvement**
NCCARQ-MAC [40]	Static or mobile, ad-hoc, low or medium	Asynchronous MAC	Using network coding to reduce retransmission and contentions
Cuomo et al. [41]	Static centralized PAN, low or medium	Synchronous MAC	Select central nodes through hop counts
Luca Catarinucci [42]	Mobile, ad-hoc with various traffic load	Asynchronous MAC	Wakeup radios to detection transmissions

2.3.5 Summary

Synchronous MAC protocols conserve energy by reducing control messages and collisions in the MAC layer. Additional control messages, such as broadcast transmissions for synchronization and scheduling, are required to allocate transmission slots and avoid contention. The amount of energy saved is significant in high traffic loads, where these control messages are shared by many transmissions. However, when traffic is low to medium, these overhead messages consume more energy than those in asynchronous schemes. In addition, for the applications that require large scales, synchronous protocols may find additional control and resource allocation problems when the number of sensor nodes is large.

Without paying the price for synchronization, asynchronous MAC protocols use low duty cycle and establish communication between senders and receivers. Sensor nodes can work long time under a low-power sleep mode, and wake up periodically to detect packet transmission with its destination. Asynchronous MAC protocols significantly decrease energy consumption, at the cost of longer link setup times, compared with synchronous approaches and locally scheduled approaches. In addition, low duty cycle keeps the asynchronous MAC applications away from dense traffic scenarios, which may experience a high probability of collisions, re-transmissions and wait times in low duty cycles.

Recent research shows a trend indicating that throughput and energy conservation should be considered together to improve energy efficiency, as in LTM-MAC. Since improving energy conservation sometimes brings compromised throughput, energy efficiency can present the effectiveness of MAC protocols to improve combined throughput and energy performance.

Cross-layer designs can reduce control messages and improve energy efficiency in the MAC layer. Since different layers have various requirements and approaches, cross-layer MAC protocols can be specific and related to the requirements of research for energy-efficient applications.

2.4 MAC Solutions for Traffic-Adaptive and Throughput Improvement

For scenarios in which the capacity of the physical channels is limited in a DTSN, traffic adaptation is an alternative to fulfilling the throughput requirement in certain areas. Traffic adaptability can assign available resources to nodes in high demand, thus improving effective throughput in sensor networks. Since dense traffic areas require more transmissions, the scheduling process in the MAC layer may allocate channel resources to the nodes in these areas, improving network efficacy. Nodes in low traffic areas may experience longer wait times for data transmissions. MAC protocols can adapt throughput to traffic patterns. Various MAC protocols have been developed in recent years within sensor networks to work under different traffic loads.

2.4.1 Strategy 1: dynamic resource allocation

TRaffic-Adaptive Medium Access (TRAMA) [43] protocol is a pioneering MAC strategy that provides traffic-adaptive schemes to save energy in sensor networks. TRAMA uses a scheduling-based, collision-free access approach, similar to S-MAC, with local synchronization. An election scheme is employed to select receivers according to the broadcast schedules and traffic loads as follows: Each sensor gathers its neighborhood information and transmission schedules. This information specifies the potential receivers of its traffic. Then the local center node can assign time slots for these neighbor nodes to transmit or receive packets. This allows some nodes to go to energy-saving mode to conserve energy when the schedule is broadcast in this cycle. Since the schedule is based on current data transmission requests, all the nodes can adapt to dynamic traffic patterns. However, the traffic adaptability only applies to a certain range in which the traffic is relatively high. Local synchronizing and scheduling exhausts local center nodes in TRAMA, and consumes a great deal of energy if the traffic is very low. This has resulted in more efforts for MAC protocols in diverse traffic environments.

TaMAC [44] protocol is a MAC scheme developed for a star topology of Wireless Body Area Networks (WBAN), in which a central coordinator controls the scheduling and synchronizing network operations. TaMAC protocol has two channel access mechanisms for normal and urgent traffic requests. Wakeup radio mechanism works for urgent and on-demand communication request, where the resource allocation has higher priority. Traffic-based wakeup mechanism is used for non-urgent, common traffic request and the coordinator schedules and assigns channel resources to the surrounded nodes from their traffic patterns. Since the scheme separates different priorities of current traffic from channel access process, it can conserve low power consumption and achieve certain Quality of Service for various traffic using the TDMA concept.

PMAC (Pattern MAC) [24] is another traffic-adaptive TDMA-based protocol that uses neighborhood traffic information, similar to TRAMA. However, in a different manner than TRAMA, PAMAC forms wakeup and sleep patterns for sensors according to neighborhood traffic. By following these patterns, a sensor node may sleep over some MAC Synchronization or broadcast frames to conserve energy when no traffic is active in the network. Sensors exchange their patterns at the end of each frame, and a node pattern is updated using these patterns, indicating local traffic information. The pattern information is presented through multiplicatively or additively increasing or decreasing the wakeup and sleep time. The acute (multiplicative) or slow (additive) increase of sleep time depends on the application's scenario. Although PMAC is developed to achieve greater energy-savings under lower traffic loads, and higher data throughput in dense traffic loads, it cannot reduce idle listening during consecutive active slots. In addition, using a fixed time slot for the wakeup period may result in high collision possibilities when traffic is high. Moreover, traffic patterns in PMAC are formed through the static nodes' information and negatively impacted by node mobility.

ATLAS [45] employs IEEE 802.15.4 superframe structure which includes three parts of periods for contention, designated, and sleeping. The length of contention, designated, and sleep period can be adjusted according to traffic loads. For high traffic scenarios, ATLAS can extend contention period and designated period to accommodate more data transmissions. For low traffic period, it extends the length of sleeping period to save energy. ATLAS considers the network capacity as the major indicator for adjusting traffic load status in order to improve energy efficiency and channel utilization. Another approach, PLA-MAC [46], also uses the similar superframe structure according to traffic load, and conserve power consumption. The limitation of the WPAN topology for IEEE802.15.4 constrains ATLAS and PLA-MAC to general applications in DTSNs.

Table 2.5 shows a dynamic resource allocation strategy list for traffic-adaptive and throughput improvement in MAC protocols.

2.4.2 Strategy 2: hybrid access

Some MAC protocols present hybrid models for the MAC layer of wireless sensor networks in order to take advantage of both reservation-based MAC and contention-based MAC protocols, and to adapt to different traffic patterns and loads (Fig. 5.1). Contention-based MAC protocols, such as the slotted CSMA/CA, exhibit low energy consumption and efficiency in low-density traffic areas, and also cause lower network throughputs due to the large overhead and collisions due to multiple transmission requests in short contention period under heavy traffic areas. Reservation-based MAC

Table 2.5: Traffic adaptive MAC solutions 1: dynamic resource allocation

Protocols	**Scenario**	**Strategies**	**Performance improvement**
TRAMA [43]	Static and slow mobile, local centralized networks with low to medium traffic	Assign nodes to sleep according to traffic patterns, select receivers according to traffic load	Energy-efficient in medium traffic loads and high energy cost in low traffic load.
TaMAC [44]	Static, centralized network with low to medium traffic	Two channel access, central node allocates resource according to traffic patterns, wakeup radio used for emergency traffic	Energy-efficient and improved Quality of Service.
PMAC [24]	Static, centralized, adaptive traffic	Neighborhood traffic helps form nodes' wakeup patterns	Energy conservation for no traffic period.
ATLAS [45] PLA-MAC [46]	Static and slow mobility Local centralized, WPAN Low to medium, adaptive	Adjust MAC 802.15.4 superframe according to traffic load	Save energy and improve throughput.

protocols such as TDMA offer good throughput in heavy traffic load scenarios, exhaust central coordinating nodes, and consume high energy in synchronization and scheduling processes when the traffic is low. Therefore, the hybrid of these two schemes fosters diverse traffic adaptability in the MAC layer.

Gilani et al. [47] introduced a hybrid TDMA-based and CSMA-based MAC protocol based on IEEE 802.15.4 standard. Data frame reserved bits are used to acquire the queue state information from the network nodes in this scheme. The central coordinator collects the data queue status from surrounding nodes and detects collisions of the current network. It then forms the current traffic load status. Based on this information, the coordinator divides the contention access period (CAP) for CSMA/CA and TDMA uses. The heavy traffic load results in short CAP for TDMA to reduce collisions and access overhead. The light traffic load indicates long CAP for contention as CSMA/CA to save scheduling and synchronizing process. Therefore, this hybrid protocol can reduce energy consumption and improve data throughput.

iQueue-MAC [48] is another MAC approach that uses in CSMA in low loads, and TDMA in heavy loads. iQueue-MAC uses the queue length of senders as an indicator to allocate time slots for the senders during synchronous mode in heavy traffic load scenarios. During light traffic periods, queue-MAC works as a CSMA MAC with low duty-cycle to conserve power. However, sensor mobility is not considered when implementing the protocol.

Z-MAC [49] basically used the CSMA MAC scheme, but it also employed a schedule as a TDMA method for improving collision resolution performance. Similar to TDMA, Z-MAC allocates slots for each node through a scalable channel scheduling algorithm DRAND during deployment stage. Even through this process costs energy and overhead messages, it assigns higher priority for these slots to the predefined users than other randomly access nodes. Similar to CSMA, each slot can be randomly accessed through carrier sensing and data transmission. However, the predefined user has higher priority than other users by setting initial contention window. This design reduces collisions within slot access process, thus conserve energy and increase throughput. Funneling MAC [50] is another CSMA and TDMA hybrid MAC protocol. It treats WSN multi-layer data collecting process to sinks as a funnel-shaped problem. The close-to-sink sensors have dense-traffic and may apply a TDMA scheme, while the remote-to-sink sensors have low traffic load and should use a CSMA scheme. MH-MAC [37] is another protocol similar to Funneling MAC. It allows nodes to change modes between asynchronous mode and synchronous mode based on traffic density. These three hybrid MAC protocols perform better in fixed-sensor nodes to adapt to various traffic. However, when mobile nodes come in and trigger frequent topology changes and re-calculations of the assignment process, extra energy consumption and overhead messages become an issue for these protocols.

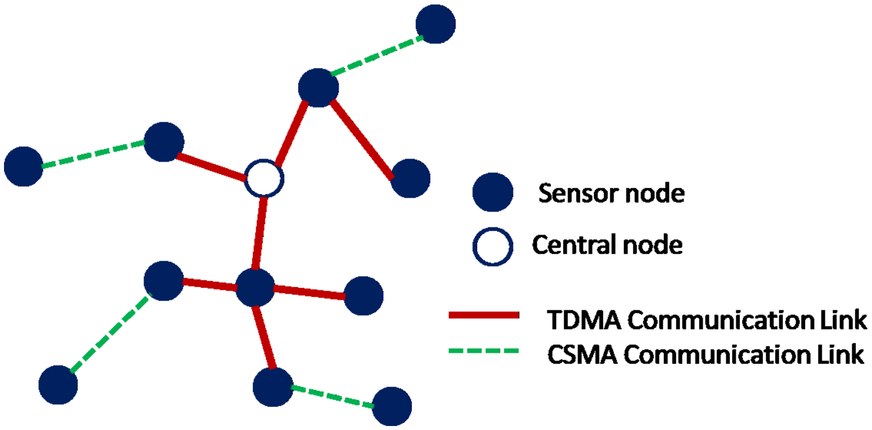

Figure 2.5: Hybrid Access Methods

Table 2.6 shows hybrid access strategy list for traffic-adaptive and throughput improvement MAC protocols.

Table 2.6: Traffic adaptive MAC solutions 2: hybrid access methods

Protocols	Scenario	Strategies	Performance improvement
Hybrid CSMA/TDMA [47]	Static and slow mobile Local centralized, WPAN Low to medium, adaptive	CSMA and TDMA combined, resource reserved according to queue state information	Improve throughput and conserve energy.
iQueue-MAC [48]	Static Local centralized Low to medium, adaptive	CSMA and TDMA combined, resource reserved according to buffer queue length	Improve throughput and conserve energy.
Z-MAC [49], MH-MAC [37], Funneling MAC [51]	Static Ad-hoc Low to medium, adaptive	Switch TDMA and CSMA according to traffic conditions	Improve throughput and conserve energy.

2.4.3 Strategy 3: block and aggregated transmission

Burst transmissions [52] introduce an auto-adaptive algorithm in body sensor networks. The algorithm employs various length of sampling period and preamble according to different traffic patterns in order to accommodate burst transmissions. The protocol also establishes energy-efficient communication path to the sink node. Since this mechanism dynamically adapts to the current network traffic, it is very energy-efficient during burst transmissions.

AFLAS [19] is an adaptive aggregation scheme for MAC 802.11 for wireless delay-tolerant environments. Fig. 5.7 shows one aggregated frame which contains several small MAC sub-frames in AFLAS. AFLAS aggregates multiple small MAC frames into large aggregated MAC frames. The length of the aggregated frame can be adjusted according to the upper layer requirements and wireless channel status. This scheme reduces the number of transmissions, and decreases transmission overhead. Therefore, AFLAS improves transmission throughput and energy efficiency under dynamic channel status.

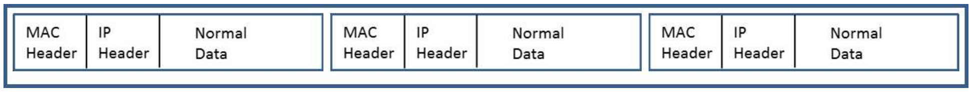

Figure 2.6: Aggregation frames in MAC protocols

Table 2.7 shows a block and aggregated transmission strategy list for traffic-adaptive and throughput improvement in MAC protocols.

Table 2.7: Traffic adaptive MAC solutions 3: block and aggregated transmission

Protocols	**Scenario**	**Strategies**	**Performance improvement**
Burst transmissions [52]	Static or low mobile, Ad-hoc, Low to medium, adaptive traffic	Adjust sampling period and preamble length according to traffic patterns	Improve throughput and energy efficiency.
AFLAS [19]	Mobile, Ad-hoc, Low to high traffic	Aggregate some MAC frames into larger one according to traffic load and wireless channels	Reducing overhead and improve throughput.

2.4.4 Duty cycle adjustment

Duty cycle is widely used in sensor networks to save energy and improve throughput. An adjustable duty cycle can provide throughput improvement and energy conservation in DTSNs. Self-Adaptive Duty Cycle MAC (SEA-MAC) [53] is another duty cycle adjustable scheme. SEA-MAC extends the nodes' active duration in heavy traffic loads and shortens the active period in low traffic loads. This strategy is designed to schedule more data transmissions in bursty and high traffic loads, and assign nodes into sleep mode in a timely manner under the light traffic load to save energy.

2.4.5 Summary

When the physical connections or channel bandwidth are limited in DTSNs, traffic adaptation is a direct method of improving throughput in high traffic and connected areas. MAC traffic adaptive schemes can employ dynamic resource allocation methods in a fixed, TDMA-based, centralized network to achieve traffic-adaptive and throughput improvement: TRAMA allows some nodes to sleep or wake up according to traffic patterns. TaMAC uses an additional wakeup radio for urgent traffic to accommodate the additional traffic loads. PMAC adjusts sensors' wakeup and sleep patterns to facilitate low or heavy traffic loads in the following duty cycle. ATLAS and PLA-MAC design a long superframe for the heavy traffic loads to improve capacity and energy efficiency. However, these MAC protocols are limited to their centralized network topology, and cannot perform well on a large scale. Faulty central nodes may ruin the data connectivity around the clusters. In addition, these protocols cannot support high mobility, where the traffic patterns change dynamically.

CSMA and TDMA hybrid access methods can also improve throughput and energy efficiency in dynamic traffic scenarios. These hybrid protocols take advantage of TDMA for heavy traffic loads in multiple data transmissions and CDMA for light traffic loads in less synchronous transmission scenarios with scheduling overhead. However, these protocols are limited to the centralized topology used for TDMA, and cannot scale well in large networks. Mobility support is also a big issue in these protocols, for the mobile sensors bring occasional connection setup and breakdown, and increase the complexity of channel allocation.

Block or aggregated transmissions can adjust data transmission bits during one transmission according to traffic load. These protocols save control frames in the MAC layer, thus improving throughput and energy conservation. They are not limited to topology, and can scale well in large networks. However, the traffic pattern prediction determines the effectiveness of the performance in these protocols.

Duty cycle adjustment can fit in low and heavy traffic loads by longer active time in heavy traffic scenarios. However, the duty cycle of multiple sensors may cause additional problems such as collisions and data slot allocations. The coordination between sensors and duty cycle synchronization also brings challenges in traffic-adaptive MAC protocols.

The strategies in traffic-adaptive solutions can apply in different scenarios for various application requirements in DTSNs.

2.5 Mobility Support MAC Protocols

Mobility brings topology and traffic changes in sensor networks. These changes impact MAC designs in access control, collision avoidance and link connections. Cluster-based MAC solutions and ad-hoc connected MAC solutions have different approaches for addressing incoming mobile sensors for connection setup and outgoing mobile sensors for resource allocation. Hybrid approaches and cross-layer designs consider traffic density to improve energy conservation and throughput.

2.5.1 Cluster-based MAC approaches

M-TDMA MAC protocol [50] is a mobile-aware TDMA-based MAC protocol that splits a given cycle of MAC superframe into a control part and a data part. The control part, which is used to manage mobility, contains head transmission cluster information in the first slot, access information for new nodes in the second slot, and broadcast information for new nodes in the third slot. The data part contains a data slot for node transmission, and free slots reserved for new nodes. Each cluster has its own clusterhead, which is responsible for scheduling and assigning a unique slot to each node. To manage mobility, extra slots are kept as shared slots across clusters, and free slots for future allocation. These extra slots are the time expense for obtaining mobility in this TDMA-based protocol. When a clusterhead receives access information in the control part of the MAC frame from an incoming sensor, it verifies unassigned slots in the data part and allocates available slots for this node. If collisions occur during the access period in the control part of the TDMA superframe, randomly back-off timer is used for new arriving nodes to retransmit the access requests. The protocol considers the access contentions due to mobility and flexible slots for resource allocation. However, the slots occupied by outgoing sensors are not rearranged in a timely manner so as to save energy. In addition, this protocol can only be applied to low-speed mobility scenarios, in which clusterhead can synchronize the neighboring sensors and reserve slots for these nodes during the time that the sensor is in motion.

2.5.2 Ad-hoc connected MAC approaches

MS-MAC [54] supports mobility by extending S-MAC protocols. Similar to S-MAC, a node in MS-MAC first listens SYNC messages with existing schedules for a certain period of time. If the node does not hear any SYNC packets, it will choose its own duty cycle and broadcast this information as SYNC before it goes to sleep. When a node receives more than one SYNC messages, it will wake up on both schedules. The SYNC message in MS-MAC contains the scheduling information for the senders, mobility information for the neighbors, and estimated speed for these sensors. According to the mobility information and estimated speed of neighbors, the temporary center node can identify an active zone nearby and schedule data transmissions. It can also prepare to setup new connections for incoming mobile nodes and reschedule when mobile nodes move to other clusters. When a node is moving at a relatively high speed, neither the SYNC information from other neighbors, nor its broadcast schedule can be heard. MS-MAC adjusts the frequencies of the synchronization period, according to the nodes' speed, so that the SYNC information either from other neighbors or by itself may be heard. This adjustable duty cycle allows nodes to set up connections timely with new neighbors and save energy when mobile nodes are not active.

MMAC (Mobility adaptive MAC) [55] considers the physical connection changes of nodes due to their mobility and topological variation, and estimates mobility patterns according to the physical location of the sensors. MMAC separates the network into clusters, and estimates traffic flow and mobility patterns in order to form a collision-free schedule. According to this information, the clusterhead broadcasts the predicated mobility states of its location and potential two-hop neighbors. It dynamically assigns data transmissions for these potential sensors and forms flexible superframe length for these transmissions. The protocol can improve energy efficiency as well as throughput with mobility scenarios. However, the positional knowledge of sensors has been often inaccessible in most sensor networks, and limits the applications of this protocol.

2.5.3 Hybrid MAC approaches

FlexiMAC (Flexible MAC) [17] is a synchronized, TDMA-based MAC protocol with flexible slot structure to allow network dynamics and node mobility. The sinks gathers neighbor exchange packets during a contention period in order to form a data-gathering tree. FlexiMAC defines two major slot structures: data-gathering slots and multi-functional slots. The sinks can collect uplink traffic through data-gathering slots based on the created tree. Downlink traffic and synchronization is transmitted through multi-functional slots. Incoming new mobile nodes can send their transmission request through Fault Tolerant Slot (FTS) as the contention period to add new nodes to the existing data-gathering tree. Most of the tree structures in MAC protocols work for fixed sensor networks since building tree requires channel resource and energy. Tree reconstruction due to link failure or mobility may consume large amounts of energy. In addition, parent-child and child-parent communications in tree structure may not always be optimal communication channels for efficiency transmission protocols.

2.5.4 Cross-layer designs for mobile sensors

MobiSense [56] provides a collision-free, multi-channel MAC and network protocol with high data throughput, fast hand-off, and energy-efficient transmission scheduling. It uses a hybrid architecture combining stationary and mobile nodes, and organizes nodes into a cluster-tree topology. The stationary nodes working as clusterheads provide a reliable, high throughput backbone, while mobile nodes move between stationary nodes using multi-channel communications and fast hand-off between clusters. According to the topology information and access requests from the network layer and the MAC layer, the contention window can be adjusted to minimize collisions. By using multi-channel in the MAC layer, high throughput is achieved in MobiSense. Although the cross-layer design brings high throughput and mobility support, MobiSense is constrained with specific mixed static and mobile sensor scenarios in scalability and fixed topology. When large numbers of mobile nodes moved to this network, the scheduling and hand-off procedure may not be efficiently completed, and transmissions may be compromised.

2.5.5 Summary

Mobility support in reservation-based MAC protocols are achieved through reserving extra time slots for incoming sensors, and recycling unused time slots for outgoing sensors. The scheduling and synchronizing process is rendered more complex, with dynamic numbers of sensor and access requests. Collisions or hidden terminal problems caused by moving sensors can be relaxed through synchronizing and scheduling algorithms. Latency is traded to obtain extra time slots. Contention-based MAC protocols face the the problem of exaggerated collisions and hidden terminals with mobile sensors. The speed and mobility patterns of moving sensors can help identify the probability of collisions. The length of data frame transmissions and the duty cycle of data transmissions can be extended to relax collisions in asynchronous MAC protocols. Hybrid MAC schemes can utilize the tree topology as the backbone transmission path, and connect mobile sensors as leaves by using CSMA access to avoid destroying the constructed transmission path. The cross-layer MAC design can obtain topology and mobility information of the networks in order to optimize access to mobile sensors (see Table 2.8).

Table 2.8: MAC protocols for mobility

Protocols	**Scenario**	**Strategies**	**Performance improvement**
M-TDMA [50]	Static and mobile mixed Centralized Dense traffic	Allocate free slots for incoming moving sensors	Trade delay for mobility
MS-MAC [54]	Static and mobile mixed Centralized Low to medium traffic	Estimate node's moving speed according to SYNC, allocate slots for moving sensors	Energy-saving and mobility support
MMAC [55]	Low to medium mobility Centralized Low to medium traffic	Adjust frame length for transmission of potential nodes	Energy conservation and mobility support, location-based
FlexiMAC [17]	Static and mobile mixed Centralized Low to high traffic	Build data-gathering to add incoming mobile sensors	Energy-saving and mobility support
MobiSense [56]	Static and mobile mixed Centralized tree Low to high traffic	Access control according to network information, multi-channel MAC	Improve throughput, energy-efficiency and fast hand-off.

2.6 MAC Protocols for Reliability

MAC protocols achieve strong reliability through two strategies: retransmission and redundant packets. When redundant solutions often introduce high resource consumption in sensor networks, retransmission solutions trade latency and energy to improve reliability.

2.6.1 Redundant-based solutions

Transmitting packet replicas is a technique for enhancing reliability. The packet replica can be transmitted through multiple radios, channels, links or paths. The receiver may recover the original packets from these corrupted packets through negotiated methods. Frequency channel shifting forms different channels against channel fading and interference. These wireless channels can be used to transmit packet replicas to enhance reliability in Alert [57], [58], [59]. Due to the resource constraints in channels, paths, and as radios, redundant-based MAC solutions are blocked by the energy-efficient approach.

Random Backoff MAC [60] makes use of the broadcasting nature of data transmissions in wireless networks as multiple channels to multiple receivers, thus using redundant transmissions without extra energy consumption. The protocol is designed to ensure that at least one multicast receiver forwards the correctly received broadcast message to the next node until the packet arrives at the destination. Random Back off protocol employs the PFR protocol as a characteristic multipath disseminating scheme, which helps choose paths favoring probability without flooding entire networks as broadcast messages. The step ensures that at least one receiver can correctly obtain the packets. As more than one receiver can forward the message, three collision avoidance strategies are also presented to reduce interference and energy consumption. Simple random backoff protocol (SRBP) uses a random uniformly distributed backoff timer to control the forwarding time for the receivers. The range of this random backoff timer depends on the latency and energy requirements of the applications. Adaptive Random Backoff Protocol (ARBP) introduces the traffic and density of the current networks as parameters to adjust the time range. The Range Adaptive Random Backoff Protocol (RARBP) is based on ARBP and the distance of the message transmission path to adjust the timer. The Random Backoff MAC actually trades latency to avoid collisions between multiple forwarding receivers in multipath transmission networks to obtain higher reliability. However, the multipath strategy of Backoff MAC can only be applied in one-way traffic or low-density traffic networks. When the high transmission request arises, message explosion may occur, thus destroying the data communications.

2.6.2 Retransmission-based solutions

In data communication networks, retransmission is often used to achieve data transmission reliability. When a packet is not correctly received with a NACK message or ACK time-out, the sender triggers retransmission of this packet until the maximum retransmission limit is reached. Retransmission is widely considered in sensor networks when energy and memory resources are constrained for recovering the lost data. RMAC [61] is a multi-hop CSMA/CA MAC approach that employs explicit automatic repeat request (ARQ) message as an error control mechanism to acknowledge the sender. Intermediate sensor nodes may relay data packets to the next hop, without waiting for the back-off period after a packet reception. The sender overhears the forwarding message as an implicit acknowledgment, which infers successful transmission to the intermediate nodes. Reliability is enforced by using both implicit and explicit acknowledgments in RMAC. RMAC also increases node-to-node reliability by adjusting the maximum retransmission attempts, based on packet error rate. This retransmission strategy can also be found in other reliable MAC protocols such as E2RMAC [62] (see table 2.9).

2.6.3 Summary

Reliability is improved through retransmission-based and redundant-based MAC approaches in DTSNs (Table 2.9). Considering the energy and resource constraints in sensor networks, retransmission-based MAC solutions are the main trend for improving reliability in DTSNs. However, when the traffic is low or the traffic direction is specified, the broadcast nature of wireless networks can gain multiple path transmissions and improve reliability.

Table 2.9: MAC protocols for reliability

Protocols	**Scenario**	**Strategies**	**Performance improvement**
Random Backoff MAC [60]	Fixed or mobile Ad-hoc Low density	Broadcast messages and receivers, forwarding only one replica	Improve reliability and energy conservation
Alert [57] [58] and [59]	Static Ad-hoc Low	Multiple frequency channels or multi-radios	Increase reliability and energy consumption
RMAC [61]	Static Ad-hoc Dense	Multi-hop CSMA/CA with explicit ACK and overhearing ACK	Improve reliability and energy efficiency.

2.7 Summary

This chapter studies various techniques and designs applied to MAC protocols in green wireless sensor networks. After examining the characteristics and performance metrics of DTSNs, five directions of MAC protocol designs in DTSNs are shown in this paper: propagation delay, energy efficiency, mobility support, throughput improvement and reliability solutions. The chapter analyzes the trade-off between latency and other performance metrics in these MAC protocols to obtain the application requirements, and indicates that the parameters of MAC designs can impact specific

MAC performance. The chapter also indicates possible future research directions in MAC protocol designs for DTSNs.

Chapter 3

MAC Transmission Strategy in Sparse Vehicular Networks

3.1 Introduction

Wireless Sensor networks have been in development for over twenty years and applied research approaches have investigated nearly every area applicable. The network collects data from tiny, low cost sensors that are static (or mobile) and which gather the required information according to target applications. Since the data collection is periodic or random, the services supported by the network are often delay-tolerant; this means the data center is not always in urgent need of a real-time response from sensors. Therefore Delay-Tolerant Sensor Networks (DTSN) [63] are used for many sensor-based applications. Moreover, due to the interests of automotive companies and Intelligent Transportation System (ITS) designers, mobile sensors on the vehicles have become integrated in many DTSN based applications. This has led to the development of Vehicular Delay-Tolerant Sensor Network (VDTSN) [64], [65]. For instance, sensors on vehicles detect road surface deterioration and report the data to the monitoring system in under-developed or rural areas [66]. Cars can also monitor road congestion and traffic-related pollution in urban areas [67] [68]. In the remote communities of developing nations lacking telecommunication infrastructures, automotive sensors can harvest local health and environmental data, which is stored in affordable specific stations to help prevent diseases [69], [70]. In post-disaster environments where communication services are not accessible, vehicular sensors play an important role; these sensors report the data of the first scene in order to rescue human lives [71], [72].

The sparsely connected vehicular delay-tolerant sensor networks not only have connectivity issues, but also have to consider energy constraints of ordinary sensors, transmission efficiency, and different packet requirements in urgent scenarios [5]. One of the popular research topics in delay-tolerant sensor networks is energy and computation constraints which still exist in VDTSN remote sensors. Sensors on vehicles can easily be powered and maintained. However, ordinary mobile or fixed sensors are supposed to be used for 10 to 20 years without battery changes and maintenance in remote communities. These sensors try to send their collected data to vehicular sinks to spare the buffer and to transmit data using as little energy as possible in order to save the battery. Moreover, periodic changing modes of sensors intending to save energy degrade connectivity: sleeping nodes cannot act as relay nodes to assist with data communication. The balance between energy consumption and data transmission efficiency becomes a serious topic [73]. Therefore, in VDTSN mobile sensors are intermittently connected, thus reinforcing the need to make the utmost use of the temporarily available communication links [74] [75].

In sparsely connected VDTSN, building connections in the transportation layer or developing routing information in the IP layer can provide accessible communication to the upper layer; however, this is very costly due to the continuously changing topology and the short contact interval. The build-up connections and the routing table may become out-of-date immediately while the sensors are moving with high-speed vehicles [76] [77]. Most routing protocols use the store-carry-forward rule which is suitable in delay-tolerant networks. However, when the network topology is highly volatile and the contact opportunity is rare in VDTSN, these protocols cannot perform well [5], [78], [79]. As a result, the MAC layer becomes involved in the data communication in VDTSN.

The MAC layer can be considered to be the glue needed to solve data throughput efficiency, energy conservation and the different service issues in VDTSN for several reasons. In VDTSN, fluctuating wireless channels, dynamically changing connections and rare and short contact intervals are the major difficulties for sensor applications. The MAC layer has direct access to the physical layer status and can choose the most suitable transmission opportunity and data rate to complete the data transmission. Meanwhile, the MAC layer can coordinate the multi-user access and retransmission procedures required for the data transmission through a common wireless medium; it also considers energy consumption processes such as overhearing, idle listening, synchronising etc. Moreover, the MAC layer can acquire packet priorities from the upper levels, such as IP packets or DTN bundles, and schedule data frame transmissions according to the available wireless channels. Therefore, the MAC layer acts as a suitable inter-medium layer to satisfy the data throughput efficiency as well as QoS priorities.

The contributions of the solution are as follows: We introduce a novel MAC layer strategy designed for sparse VDTSN that considers quality of service and energy consumption. This strategy (Contact-Predicted MAC as CPMAC) provides three transmission algorithms, using an adaptive rate and power control method to adapt to the unstable wireless status in estimated transmission intervals. Using experimental and analytical data, the MAC transmission strategy demonstrates better performance than other MAC schemes in VDTSN regarding different service requirements, throughput,and buffer and energy constraints.

The rest of the chapter is organized as follows: Section 2 introduces the related work. The transmission strategy scenarios, calculation methods and algorithms are presented in Sections 3, 4, 5. Sections 6 and 7 show the strategy performance through simulation results and analysis. Finally, Section 8 concludes the chapter.

3.2 Related Work

The MAC layer plays an essential role in data transmissions with energy and complexity constraints in wireless sensor networks. It controls multi-user access through common wireless channels, and provides relative transparent data transmission services to upper layers without indicating the physical network status [80], [81], [82], [78], [79]. MAC approaches must balance network longevity, reliability, fairness, scalability and latency [83] [84].

In sparse Vehicular Delay-Tolerant Sensor Networks, where the traffic load is irregular, the contact interval is rare and short, and wireless connections are not always available, hybrid approaches with the random-access method are often used as the solution for achieving better performance in data throughput and the energy efficiency [85], [25], [26], [86], [87], [88], [89], [90], [91]. Our scheme in this solution adopts the commonly used RTS/CTS/DATA/ACK mode and applies new features for unstable and irregular traffic sensor networks. We have also employed the data rate adaptivity and power control scheme to improve transmission efficiency and conserve energy.

3.2.1 Wireless Channel Status Indication Selection

In a wireless network, the wireless channels fluctuate dynamically in time and frequency domain because of fading, interference, high mobility etc. The MAC layer can obtain the channel conditions by SNR (Signal to noise ratio) [92], BER (Bit error rate) [93], FLR (Frame loss rate) [94] etc. from both sender and receiver sides through the MAC message interactions.

SNR is the ratio of the current signal strength to the system background noise. The sender can measure the SNR from a received data frame or other frames and select the appropriate data rate at the given SNR. The receiver can also measure the SNR from RTS [92] and can inform the sender of the suitable data rate through CTS messages. Normally, the average of multiple measurements results in a better channel estimation than the data from just a few measurements. In a delay-tolerant scenario, accumulation of multiple measurements is not realistic when connections can hardly be found and the time duration of connections is relatively short. The channel estimation must rely on the current SNR measurements in DTSN. This solution uses the SNR from the RTS on the receiver side and uses consecutively positive ACKs on the sender side as measurements used to adjust the data rate.

BER measurements use predefined symbols and send them from the sender to the receiver. The receiver can detect the exact bits by comparing the received and the predefined symbols. This is superior to SNR, which cannot separate the interferences from the signals. According to the BER, channel conditions can be estimated for the suitable data rate transmission [93]. Because predefined symbols can be simultaneously transmitted with data, the channel estimation may not require extra delay. This is suitable in DTSN, where quick estimation is very important during very short contact intervals. However, predefined symbols also bring extra overhead and decrease the delivery ratio.

FLR calculates the frame loss probabilities occurring during the evaluation of channel conditions [94], [95]. Since it requires a relatively longer measurement cycle than SNR or BER based on multiple data frame transmission times, FLR is not suitable for short contact transmissions in a delay-tolerant scenario.

3.2.2 Energy Efficiency

In order to extend the lifetime of sensors and to conserve their energy, energy consumption must be minimized. In typical sensor applications, energy consumption is dominated by node radio consumption. Sensor radios generally have four working modes: transmitting, receiving, idling and sleeping [96]. Transmitting uses much more energy than receiving, and both modes conserve more energy than idling and sleeping modes. It has also been proven that it is more energy-efficient to schedule sensors in idling and sleeping modes than in transmitting and receiving modes. However, this schedule strategy degrades connection opportunities and decreases system delivery probability in delay-tolerant networks. Therefore, transmission power control is widely used in wireless networks to conserve energy and to reduce interference which is particularly important in wireless systems. In conditions where fully decoded data is received, less transmission power indicates a superior method of energy conservation. This solution uses transmission power control to save the energy of sensors.

Rate adaptivity is one of the most frequently employed methods for improving MAC data throughput [92], [93], [94], [97]. Recent work considers a combination of rate control and power conservation to achieve data delivery efficiency [73], [98], [99], [100]. The interaction between rate adaptivity and power control is shown in [99], where a PCRA MAC scheme was designed to balance data rate, energy consumption, SNR, and the BER. A mapping table of power and data rate is used in [98] to maintain a highly efficient energy transmission. In the short contact delivery duration which this solution presents, the maximum levels of throughput and energy conservation are both important. Therefore, transmission control, overall energy consideration, and transmission data rates are applied in three different algorithms to fulfil different types of services. In this solution, the measurements of data throughput and energy saving are the most important in the evaluation of the transmission strategy. In addition, the MAC buffer and data types also affect the selection of algorithms during one contact interval.

3.2.3 Different Services Supported in MAC Layer

The MAC layer has begun supporting different services in recent years. These approaches often use quality of service (QoS) features to schedule transmission and resource allocation procedures. For instance, SD-MAC [101] differentiates packets into four service classes by examining the upper layer packet types embedded in the packet header. A MAC layer resource allocation approach is provided in [102] in mesh network with QoS assurance and service differentiation. A MAC protocol is proposed in [103] for a distributed cognitive radio network; this addresses quality of service (QoS) requirements for delay-sensitive applications by defining different priorities during channel reservation. In delay-tolerant networks in which different application requirements may be applied, our scheme proposes the MAC transmission strategy to prioritize the MAC frames with less complex quality of service (QoS) support.

3.3 Scheme Overview

Let us suppose there is one moving vehicular sink traveling through the middle of the sparsely connected mobile or fixed sensors in the VDTSN environment (Fig. 3.1). The sink travels at 20-120 km per hour and tries to harvest the data provided by ordinary sensors sparsely covering the roadside, or by other vehicular sensors. Similar scenarios can be found in [71], [66], [69], [67], [70], [104], [105]. Since the sink has no energy and no storage constraints, it can store the collected data until it finds the data center or moves to the next stop to offload its data. When the sink travels, it may wake up the sensors in a certain range with specific messages while the sensors in the roadside periodically listen to the wake-up message. The awake sensors send the collected data through the contention-based mechanism to access the wireless channel.

During this One Contact Interval (OCI), it is preferable to use less power to send more data, conserving energy in order to conduct an efficient transmission. This can be expressed by the received data throughput over power consumption. Therefore, the sensor can send the required data to the sink using a higher data rate with relatively less power when the sensor and sink are close and the wireless channel is good. Conversely, the sensor sends data using a lower rate with considerably higher power when both elements are not close enough.

The vehicular sink must periodically send out the wake-up messages and prepare to receive the data from other sensors. The length of the wake-up message and the waiting period is set by the protocol. After the transmission period, the wake-up cycle is reset and continues.

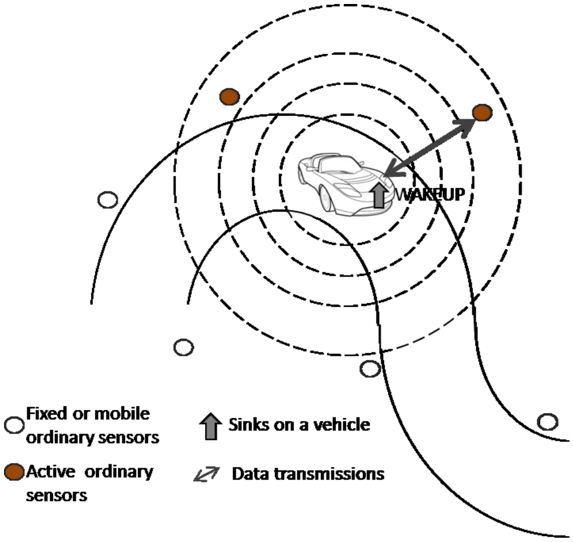

Figure 3.1: Sparse VDTSN scenario

The strategy must address appropriate timing for sending out the data in order to save energy. We know that in one contact interval, wireless conditions usually improve when the sensors become close and the conditions worsen when sensors are further apart. If we can schedule the higher data transmission in the middle of the interval while the communicating sensors should be closer and the channel SNR is good, we may save transmission power. This can enable us to reduce transmission and retransmission times, thus conserving sensor energy.

Therefore, the aim of this strategy is to achieve the following: In the specific time of the contact interval, transmission algorithms can be selected in order to efficiently send out prioritized data to the sink without depleting the sensors' battery power and buffers.

3.3.1 Strategy Overview

The sink in a vehicle periodically sends WAKEUP messages which last for the duration of P_{WAKEUP} using ordinary power. The listening sensors periodically change their radio modes from sleeping to listening to catch the probable WAKEUP message. The time period of sleeping and listening can be expressed as P_{sleep} and P_{listen}. Therefore, the time of the WAKEUP message should be longer than $P_{sleep} + P_{listen}$ so that the WAKEUP message can be heard by the sensors.

$P_{WAKEUP} \geq P_{sleep} + P_{listen}$;

The interval between two WAKEUP messages can be represented by the integral multiple n of P_{WAKEUP} depending on the system requirements. The maximum waiting time required for the sensors to hear the WAKEUP message is $n * P_{WAKEUP} + P_{sleep}$(see Fig. 3.2). The minimum waiting time is 0.

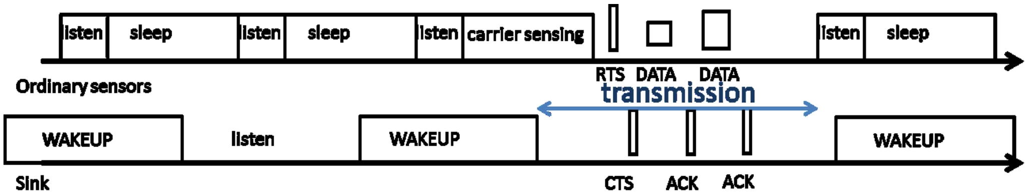

Figure 3.2: WAKEUP period

After the sensor receives the WAKEUP message, it enters active mode in which it senses the carrier and prepares to send out data. The sensor waits for inter-frame space (similar to DCF inter-frame space DIFS) and begins its back-off timer. When the timer expires and no other carrier is sensed, the RTS/CTS/DATA/ACK procedure begins. If another carrier is sensed before the back-off timer expires, the sensor must wait for a transmission from another sensor, reset the back-off timer, and send its own data after the other transmission has finished if the sink can still be reached.

In order to improve data throughput, the first RTS/CTS is used to avoid hidden or explicit terminals. The data frame is then sent out continuously without RTS/CTS, and the ACK message is received to confirm that each DATA frame has been correctly received (see Fig. 3.3). The transmissions of DATA and ACK frames between sinks and ordinary sensors cannot wake up other ordinary sensors, thus inhibiting collisions from other sensors during the one contact interval. The procedure saves time and energy for sensors in short and dynamic intervals. However, the fair handling of each sensor is strongly challenged in this scenario, whereas other sensors must wait for longer periods of time to send their own data. In sparsely connected VDTSN where other nodes have a rare probability of being present, this approach uses the precious contact opportunity for the lucky respective sensor to connect with the sink all the times until it has finished data transmission or the wireless channel has expired.

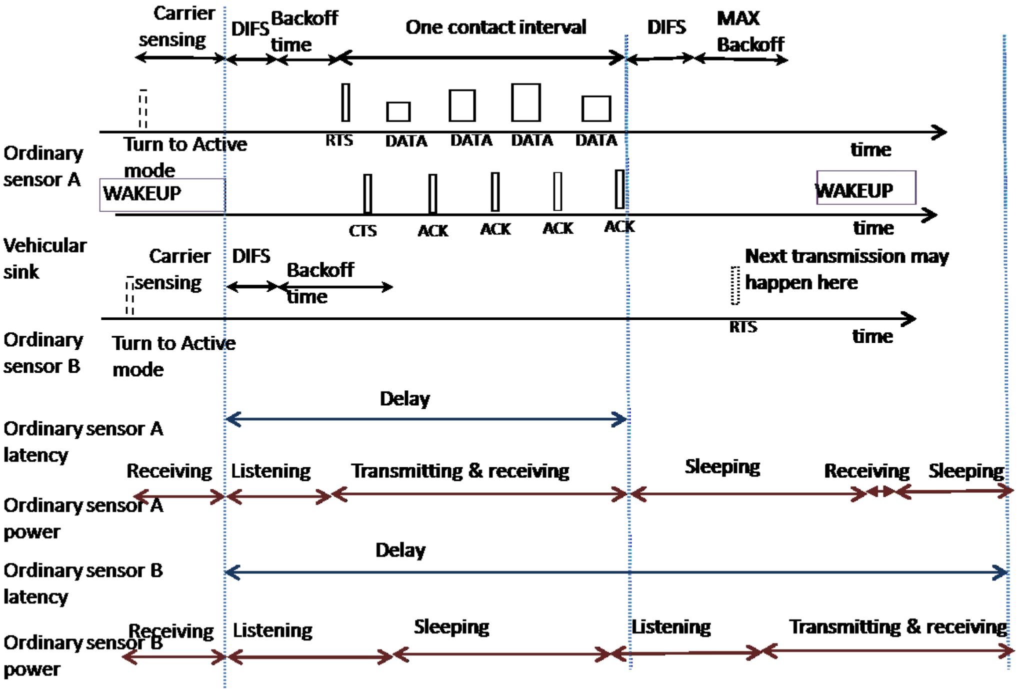

Figure 3.3: Strategy overview

3.3.2 Data Priority and Buffer Status

Before transmitting data in the MAC layer, the sensors examine the data buffer and prioritize the data according to the upper layer requirements and the self-detection of the sensor's buffer status. We only send out data with the highest priority if the contact interval is very short. In our strategy, the sender node prioritizes the data according to the upper layer requests and classifies data into two groups: urgent (U-DATA) and normal (N-DATA). Urgent data has a high priority and will be transmitted immediately when the available link exists. Normal data transmissions depend on the buffer size of the sender node. The storage buffer is set to a threshold (for example 50 percent), so that the data over the threshold has the second priority (N-DATA). The remaining data in the buffer N-DATA-R has the lowest priority in this contact interval (Table 4.1).

Table 3.1: Data priority

Data types	Buffer status	Priority
U-DATA	limited	1
U-DATA	unlimited	1
N-DATA	limited	2
N-DATA-R	unlimited	3

3.3.3 Estimated One Contact Interval

The one contact interval for sensor transmission can be estimated through historical records, round trip delays and other techniques. We cannot use the propagation time and the propagation speed at this time in the MAC layer because it lacks accuracy without precise position application assistance (such as GPS). In this scheme, under very short and unstable sparse area conditions, the estimated contact interval is calculated through the first RTS/CTS interactions. Theoretically, using the free space path loss equation, we can deduct the estimated distance between the two sensors with the received RTS/CTS signal strength.

Free space path loss may be understood as the loss of signal strength of an electromagnetic wave that would result from an unobstructed line of sight path through free space. The received power with distance d, from a radiated transmitting antenna is given as

$$P_r(d) = P_t G_t G_r \lambda^2 / ((4\pi)^2 d^2 L) \tag{3.1}$$

where: P_t is the transmission power;

P_r is the received power;

G_t is transmission antenna gain;

G_r is received antenna gain;

L is the loss factor not related to propagation;

λ is the signal wavelength.

The path loss for the free space model in dB is :

$$P(dB) = 10log(P_t/P_r) = -10log(G_t Gr \lambda^2 / ((4\pi)^2 d^2) \tag{3.2}$$

We can use Transmitted RTS power as P_t and Received RTS (RTS threshold) as P_r. We can then calculate the distance d.

According to the mobility speed V_s of the sending nodes, we can deduct the estimated one contact interval by using the following equations:

$$T_{Estimated} = 2 \times d/V_s \tag{3.3}$$

When interference or fast fading occurs during RTS transmission, the estimated contact interval may not represent the real contact interval. We must set up a backup estimation when interference occurs. Since the vehicles in our scenarios often visit the same sensors periodically in sparsely connected areas in order to collect the data, we could record the historic estimated contact intervals in vehicular sinks which do not have memory constraints. Each time we obtain the estimated contact interval $T_{Estimated}$ from the current signal strength, we compare it with the average value of historic records. The real contact intervals between the sink and sensors are recorded by the sink, and the last three are retained to form an average value. If the difference between the average record and $T_{Estimated}$ is larger than 20 percent, we will discard $T_{Estimated}$ and use the average value of historic records.

3.3.4 The Relationship Between Power Data Rate and SNR

We use the power control and the adaptive data rate during the one contact interval to improve data throughput and to decrease the number of transmission times, if it is possible to reduce energy consumption. According to Shannon's communication theory, the rate R for any source of bandwidth W_B is bounded by:

$$W_B \times (log(Pe/N)) \leq R \leq W \times (log(P/N)) \tag{3.4}$$

Where P is the average power of the source, P_e is its entropy power and N is the allowed mean square error. Therefore, we can find the minimum and maximum power P_{iMin} and P_{iMax} for a certain data rate $R_i$with bandwidth determined.

The Shannon-Hartley theorem [106] indicates that the upper boundary of channel capacity or the data rate R_i (bit per second) has a relationship with the SNR and the bandwidth used for this transmission.

$$R_i = W_B \times log(1 + SNR) \tag{3.5}$$

Therefore, in certain wireless environments with specific SNR requirements and bandwidth, we can obtain the maximum data rate to transmit data. We have formed a table (Table 4.2) in this way:

Table 3.2: Mapping table of the data rate, power and SNR

SNR (dBm)	Data Rate (Mbps)	Max Power (dBm)	Min Power (dBm)
SNR_i	R_i	P_{Min}	P_{Max}

We used six data rate levels ranging from R_1 to R_6 and six power levels ranging from P_1 to P_6 where the R_1 and P_1 are the basic rate R_{basic} and power P_{basic}:

$$R_i = i \times R_1 \qquad (For i = 2, 3...6)$$

$$P_i = (P_{Min} + P_{Max})/2 \qquad (For i = 2, 3...6)$$

3.4 Transmission Strategy

After introducing the basic scenarios, we will present the scheduling transmission strategy in this section.

3.4.1 Scheduling the Data Transmission

The objective of the transmission strategy is to schedule the important or Urgent data (U-DATA) transmission in the best wireless condition; these conditions are supposed to exist in the middle of the contact intervals, or in the closest distance between two nodes, in order to avoid retransmission and to save power. The data rate in the middle contact interval can be higher with less energy consumption than in the other time position. Accordingly, the normal data (N-DATA) is transmitted in the second middle contact interval. If the connection still exists between the sink and the nodes, the extra data (N-DATA-R) can be scheduled with the lowest priority.

First, the sender examines the buffer data and sets the data priorities. The amount of U-DATA packets (D_{udata}) and N-DATA packets (D_{ndata}) is collected as well as the buffer threshold of the sensor D_{Thres}. We can calculate the average of one data frame transmission time similar to the 802.11 DCF MAC T_p:

$$\begin{aligned} T_p =& DIFS + 3 \times SIFS + (CW_{min}/2) \times T_{slot} \\ &+ T_{RTS} + T_{CTS} + T_{Data} + T_{ACK} \end{aligned} \tag{3.6}$$

Where $DIFS$ is the DCF Inter-frame Space; $SIFS$ is the Short Inter-frame Space; CW_{min} is the minimum for the contention window. T_{slot} is the basic unit of time for the protocol. $T_{RTS}, T_{CTS}, T_{Data}$ and T_{ACK} are the transmission time of RTS, CTS, Data, and ACK.

We use the $T_{Estimated}$ as the one contact interval which is calculated before data transmission. The average U-DATA transmission time is obtained using the average data rate R_{Avg1} is $(T_p \times R_{Avg1} \times D_{udata})$. If the estimated contact interval is short when $T_e < (T_p \times R_{Avg1} \times D_{udata})$, only U-DATA can be transmitted using the maximum data rate and the transmission power during the contact interval. We did not change the rate or power in order to send as much U-DATA as possible. If the contact interval is longer when $T_{Estimated} \geq (T_p \times R_{Avg} \times D_{udata})$, the U-DATA can be sent as well as the N-DATA. There will also be an optimal method for scheduling each type of data transmission in such a way that considerations of throughput and energy conservation are balanced. Intuitively, the U-DATA should first be sent, followed by the N-DATA. However, in our strategy, when the contact time is enough for both U-DATA and N-DATA transmissions, the U-DATA will be sent in the middle of the contact interval where lower level power or higher data rates are easier to achieve. In addition, the N-DATA will be sent at the beginning and the end of the transmission to save energy where the higher power level or lower data rate must be applied. We also found a better throughput and power-saving performance in our simulation results. The schedule process is shown in Fig. 3.4.

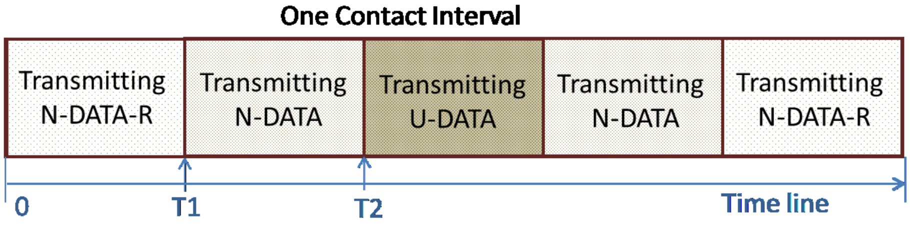

Figure 3.4: Scheduled timeline

We must calculate the T_1 and T_2 to schedule the U-DATA and N-DATA transmission. The estimated time for transmitting U-DATA T_{udata} can be calculated as shown below:

$$T_{udata} = Min(T_{Estimated}, T_p \times D_{udata} \times R_{Avg1}) \tag{3.7}$$

Where $R_{Avg1} = (R_{MAX} + R_1)/2$.

We will schedule the U-DATA transmission at T_1 after the data transmission starts during the contact interval.

$$T_1 = \frac{T_{Estimated} - T_{udata}}{2} \tag{3.8}$$

The amount of N-DATA above the buffer threshold D_2 is $(D_{ndata} - D_{Thres})$. We can calculate the estimated average data rate R_{Avg2} and the highest data rate R_{high} to transmit D_2. We set the highest data rate R_{high} when transmitting N-DATA D_2 to balance the energy consumption and data throughput. The estimated time needed to transmit D_2 N-DATA T_{ndata2} can be calculated as shown below:

$$\begin{aligned} R_{Avg2} =& T_p \times D_{Thres}/T_{ndata} \\ R_{high} =& 2 \times R_i - R_{basic} \qquad (3.9) \\ T_{ndata2} =& Min((T_e - T_{udata}), (T_p \times D_2 \times R_{Avg2})) \qquad (3.10) \end{aligned}$$

We will schedule the N-DATA D_2 transmission at T_2 after the data transmission starts during the contact interval.

$$T_2 = (T_{Estimated} - T_{udata} - T_{ndata2})/2 \tag{3.11}$$

3.4.2 Adapting to Real Channel Conditions Using ACK

The scheme sends data at the scheduled time assuming the estimated contact interval is correct and has no fast fading problems. In real wireless networks, the wireless channel conditions may change rapidly due to various factors. We have to consider these rapid changes during the contact interval as well as the transmission efficiency. The detected SNR can be the first element to adapt to the rapid wireless changes before transmission begins. In addition, the ACK messages sent from the receiver to verify the adaptive data rate and power are well suited to the current wireless status. The accumulated positive ACK rate represents the efficiency of the adaptive algorithms. The accumulated NACK may require faster adjustments to algorithms.. Compared to SNR, the accumulated ACK messages take a longer time to outlook the problem; thus, we do not count on ACK to adjust the data rate and power. Instead, we use it to adjust the adaptive level (Algorithms 4, 2).

3.4.3 Three Proposed Algorithms

If the inter-contact time is long enough for U-DATA and N-DATA to transmit, there will be an optimal schedule that involves the use of the three algorithms in a balanced way that considers throughput and energy conservation. In this solution, we schedule the higher data rate transmission in the medium level of the inter-contact interval to save transmission power, given that the distance between the sensors is closer and the wireless channels are better than at the beginning and the end of the inter-contact interval. The inter-contact time can be estimated $T_{Estimated}$ when the sender has U-DATA packets (D_{udata}) and N-DATA packets (D_{ndata})in its buffer. The buffer threshold of the sensor is D_{Thres} and the average of one data packet transmission time in MAC is calculated in T_p. The framing procedure is described as Fig. 3.5.

In Section III, we introduce three types of data which have three priority levels (see Table 4.1). We use three transmission algorithms to control the data rate and power corresponding to three types of data:

Power and Throughput Increased (PTI): Maximizing data throughput by increasing data rate and power;

Power and Throughput Balanced (PTB): Adaptive data rate and power control based on SNR and ACK during the estimated inter-contact interval;

Least Power Transmission (LPT): Energy saving mode. Uses the basic power to transmit data.

3.5 Transmission Algorithms

There are three algorithms used for controling the data rate and power in order to provide three types of services.

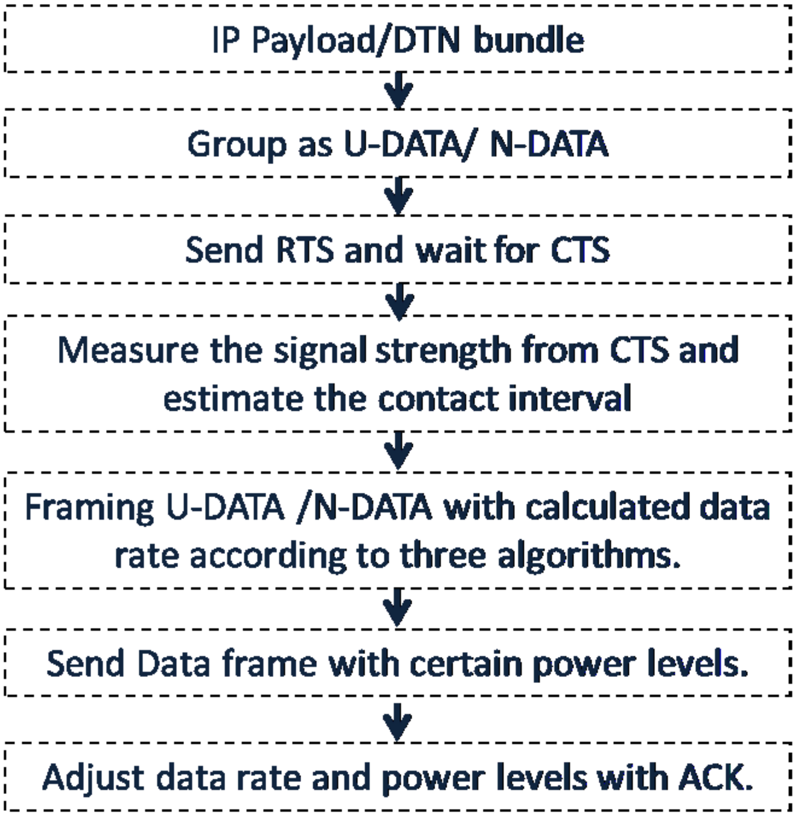

Figure 3.5: MAC framing using three algorithms

3.5.1 Power and Throughput Increased

This algorithm is used for U-DATA transmission. It uses the highest possible rate to transmit data and adjusts the data rate frequently according to channel conditions. The sender node sends RTS using the basic power P_1 and waits for CTS. The receiver node calculates the received signal noise ratio (SNR) of RTS. According to Table 4.2, the receiver node selects the data rate for this transmission and sends CTS back with the selected data rate R_i in the CTS message. The sender receives the CTS and checks the same Table 4.2 to find the maximum power P_{max} related to this data rate R_i, and the sender sends the first data packet with the data rate R_i and power P_i. The sender then awaits the ACK in the predefined period of time. The sender transmits the remaining data packets without RTS/CTS messages. If the ACKs are received consecutively several times and the data rate is not the highest, the data rate will increase to R_{i+1}. If the data rate is already at the maximum rate of the system, the power will decrease to the lower level according to the Table. However, if the ACK is not correctly received (NACK), the data will be retransmitted using the same rate R_i with an increased power level P_{i+1} if the power level has not reached the system maximum, or at the lower rate R_{i-1} and with the highest power if the power has already reached the maximum level. If three consecutive ACK messages are not correctly received, the sender re-transmits the data packet at the basic data rate and power (Algorithm 4).

3.5.2 Power and Throughput Balanced

This algorithm is used for normal data transmission when the MAC buffer reaches the storage threshold prior to the inter-contact interval. We set the highest data rate of the algorithm as R_{high} (derived from the Equation 3.10) so that the N-DATA transmission can be bounded by the rate and the correspondent power. The details are shown in Algorithm 2.

3.5.3 Least Power Transmission

This is an energy saving transmission algorithm to be used when there is no urgent data or buffer crisis. The sender uses the minimum power P_{basic} during the transmission. The data is sent first at the basic data rate and corresponding power. If positive ACKs are consecutively received with the same data rate, the data rate may increase to the higher level with no change in power level. If two negative ACKs are consecutively received with the same data rate, the data rate may also decrease to the lower level and trigger the re-transmission. If ten negative ACKs are consecutively received at the same data rate, the data transmission stops.

3.6 Performance Evaluation

To evaluate and compare the schedule strategy and the three algorithms, we prepared two sets of simulations in NS2. The first one simulates the efficiency of the transmission strategy and three algorithms during one contact interval. The second compares the SMAC and 802.11 with energy and data throughput.

The simulations include 20 mobile sensors set in the NS2 system randomly and specifically. We used the TwoRayGround fading model. The optimum data rate

Algorithm 1: Power and Throughput Increased

```
$Rate = R_1$; $Power = P_1$;
if $U\text{-}DATA \neq NULL$ then
    Sender:
    send first RTS using $R_1$ and $P_1$ /*basic rate and power*/;
    Receiver:
    $P_d = P_r / P_{threshold}$;
    $i = log(P_d)$;
    send first CTS with $i$;
    Sender:
    send data using $Rate$ and $Power$;
    $Rate = R_i$ ;$Power = P_i$;
while $U\text{-}DATA \neq NULL$ do
    Receiver:
    if correctly received data then
        send positive ACK;
    else
        send negative ACK;
    Sender:
    if No ACK or negative ACK then
        if consecutiveNACK $\leq 3$ then
            if $Power \neq MAX$ then
                $Power = P_{i+1}$;
            else if $Rate \neq MIN$ then
                $Rate = R_{i-1}$;
            Retransmission data using $Rate$ and $Power$;
        else
            $Rate = R_1$; $Power = P_1$;
    else
        if consecutivePACK $\geq 10$ and $Rate < MAX$ then
            $Rate = R_{i+1}$;
```

Algorithm 2: Power and Throughput Balanced

```
set $R_{high}$; $Rate = R_1$; $Power = P_1$;
if N-DATA $\neq$ NULL and Buffer $>$ Theshold then
    Sender:
    send RTS using $R_1$ and $P_1$;
    Receiver:
    $P_d = P_r/P_{threshold}$;
    $i = log(P_d)$;
    send CTS with $i$ ;
while N-DATA $\neq$ NULL and Buffer $>$ Theshold do
    Sender:
    send data using Rate and Power;
    $Rate = R_i$ ;$Power = P_i$;
    Receiver:
    if correctly received data then
        send positive ACK;
    else
        send negative ACK;
    Sender:
    if No ACK or negative ACK then
        if consecutiveNACK $\leq$ 10 then
            if $Power \neq MAX$ then
                $Power = P_{i+1}$;
            else
                $Rate = R_{i-1}$;
            Retransmitted data using Rate and Power;
        else
            Abort transmission;
    else
        if consecutivePACK $\geq$ 100 then
            if Rate reached $R_{high}$ and Power ¿ $P_1$ then
                $Power = P_{i-1}$;
            else
                if Rate never reach $R_{high}$ and Power ¡ MAX then
                    $Power = P_{i+1}$;
```

and power for a given SNR was selected according to [98]. The ad-hoc on-demand distance vector (AODV) was used as the routing protocol.

During one contact interval, we first conducted the simulation separately with all N-DATA at 500 bytes using PTB and LPT and all U-DATA at 500 bytes using PTI. We then used the schedule strategy, with half the U-DATA and half the N-DATA transmitting in one estimated contact interval, and compared this to the transmission without scheduler. The mobile sensor transmits the U-DATA and N-DATA while passing through the fixed sensors at the constant speed of 10, 15, 20m/s within the estimated inter-contact time. The initial distance between the sensors was 500 metres and the closest distance between the sensors has been set to 100m, 150m and 200m. Each of the simulations was run for 250s (See Table 4.3).

Table 3.3: Simulation parameters

Propagation model	TwoRayGround
MAC Layer	SMAC, 802.11, this scheme
Routing	AODV
Radio Range	500m
Mobile Speed	10,15,20 m/s
Number of nodes	21
Simulation Time	250s

3.6.1 Simulation Results - Data Throughput

The data throughput was significantly improved by using PTI, PTB and LPT (see Fig. 3.6). Since the data rate and power level changes during the inter-contact time, the data throughput of the three algorithms is better than those belonging to the conventional 802.11 MAC, which has no power and rate control. PTI obtains the greatest throughput due to its high data rate strategy, without considering energy conservation. LPT uses basic unchanged power and rate control and gets a better data throughput than conventional 802.11 MAC. However, PTI can transmit more frames than LPT during the same length of intervals because of the higher power in PTI. The closest distance between the sensors greatly affects the data throughput

(100m, 150m, 200m). The slopes of the curve show that the highest data rates are achieved in the middle of contact when two sensors are the closest.

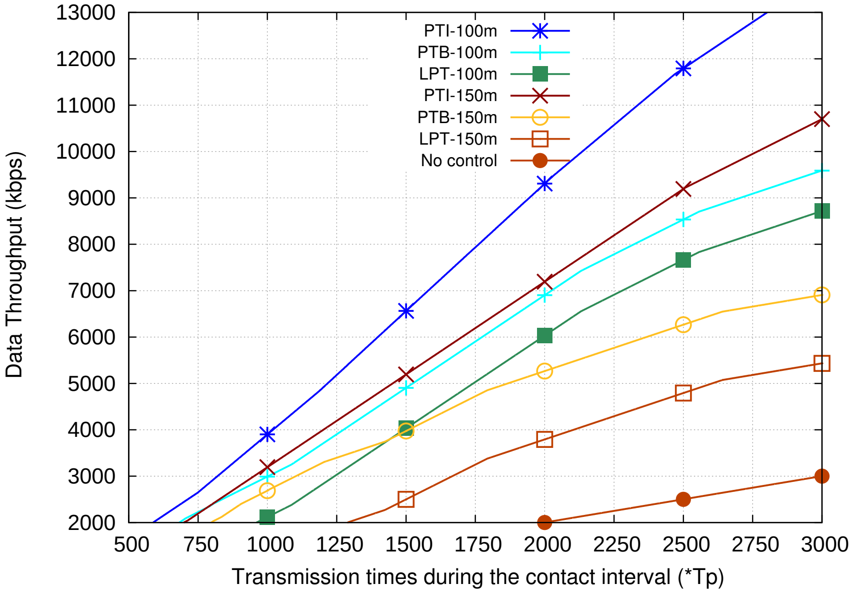

Figure 3.6: Data throughput during one contact interval

3.6.2 Simulation Results - Power Consumption

As seen in Fig. 3.7, LPT consumes the same amount of power as the conventional 802.11 MAC because no data rate was added during the transmission. However, PTI consumes much more power than PTB and LPT. This is because the higher data rate transmits with higher power levels in order to satisfy the SNR requirements. The highest power consumption occurs near the end of the inter-contact interval, where the sensor must boost the power to transmit data against the long wireless channel conditions.

3.6.3 Simulation Results - Throughput vs. Power

At the beginning of the inter-contact, LPT algorithm demonstrates greater efficiency (with the ratio of throughput to power) than PTB and PTI (see Fig. 3.8). This indicates it is energy efficient to use the basic power to transmit data if the two sensors are not close enough to one another. After a while, the PTB algorithm shows

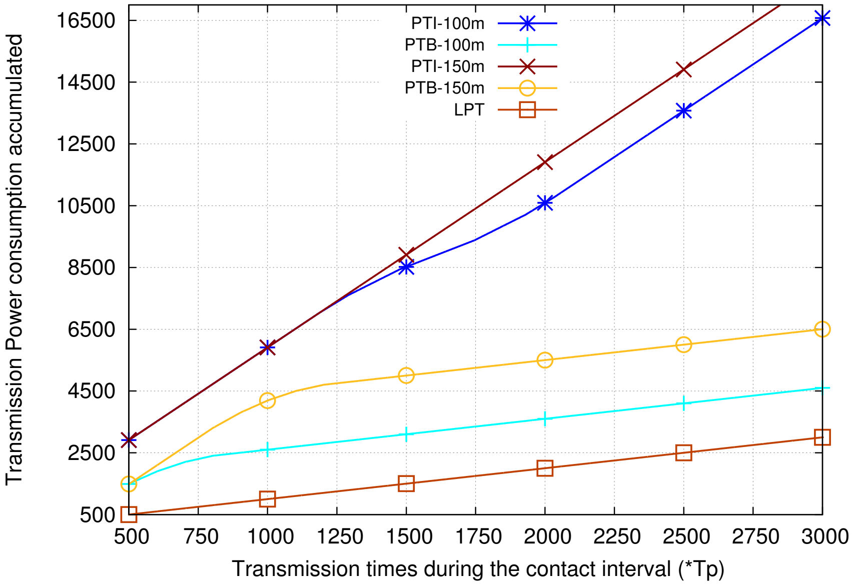

Figure 3.7: Transmission power consumption during one contact interval

better efficiency than PTI and LPT until the middle of the inter-contact interval. Rate and power control actually improve the throughput energy efficiency at this point of the interval. After the middle of the inter-contact interval, LPT and PTB show the same level of efficiency. If a higher data rate is required to transmit, as in the case of N-DATA at the buffer, PTB can be used. When we can transmit all the buffer data in this interval, the use of PTB is better than PTI due to fewer transmission attempts. That is why we can schedule the algorithms based on estimating the time interval and data buffer.

3.6.4 Scheduled and Unscheduled

We sent 3500 packets of N-DATA and 3500 packets of U-DATA using the scheduled and unscheduled strategies shown in Fig. 3.9. The transmission power consumption of the scheduled strategy is less than the unscheduled one in condition of 100m and 150m. Only PTI algorithm is used in the 200m closest inter-contact interval, and only 2200 packets of U-DATA can be transmitted during the interval.

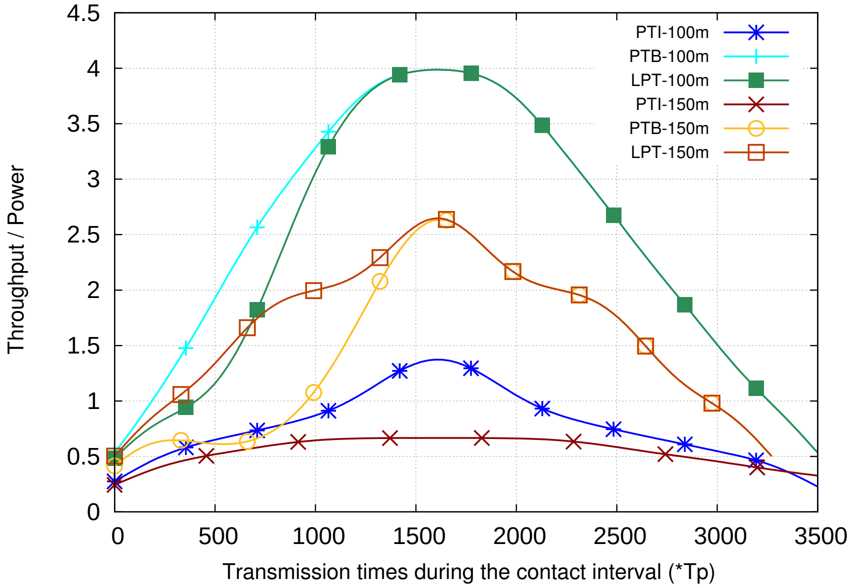

Figure 3.8: Data throughput and Power consumption ratio

3.7 Protocol Analysis

This MAC protocol aims to improve data transmission efficiency in sparsely connected vehicular delay-tolerant networks. The characteristic similarities of traditional sensor networks, VANETs and VDTSNs, combine different MAC requirements and solving methods. SMAC is one of the prominent pioneering studies on MAC protocols in WSNs; and 802.11 DCF is the basic and dominant MAC protocol widely used for vehicular networking. We thus compare the proposed protocol to SMAC and 802.11 DCF through several aspects: throughput, latency, energy consumption, scalability, fairness and robustness.

3.7.1 Throughput Analysis

In 802.11 DCF, each vehicular node waits for a random period called the back-off timer; it ranges from zero to a maximum value, called the Contention Window (CW), before transmitting. There are four messages during data transmission: Request-To-Send (RTS), Clear-To-Send (CTS), Data and Acknowledgment (ACK) in sequences during the transmission cycle (see Fig. 3.10). RTS/CTS handshaking method is employed to avoid hidden or exposed terminal problems and access collisions. Every data transmission attempt awaits an ACK to confirm successful transmission. In addition,

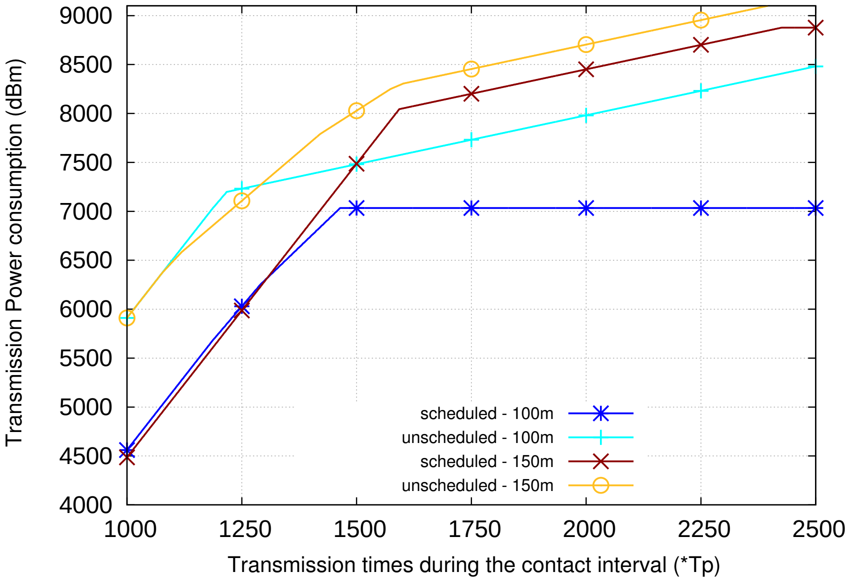

Figure 3.9: Scheduled and unscheduled strategy

each node maintains a network allocation vector (NAV), which is extracted from the RTS, CTS, data and ACK packets. NAV acts as a virtual carrier sense by predicting when the medium will be busy. The widely used and standard IEEE 802.11p in the vehicular ad-hoc network adopts the basic 802.11 DCF; it does not contain authentication and association in the MAC and PHY layers due to the stringent timing requirements.

In One Contact Interval (OCI) T, the data transmission throughput can be described as the time used to transmit data when the data rate R is steady.

The duration of one data frame transmission can be calculated as follows:

$$\begin{aligned} T_{frame} =& DIFS + 3 \times SIFS + (CW_{min}/2) \times T_{slot} \\ &+ T_{RTS} + T_{CTS} + T_{ACK}) \end{aligned} \tag{3.12}$$

The number of frames that can be transmitted during one contact interval is:

$$T_{NoFrame} = T \mod T_{frame} \tag{3.13}$$

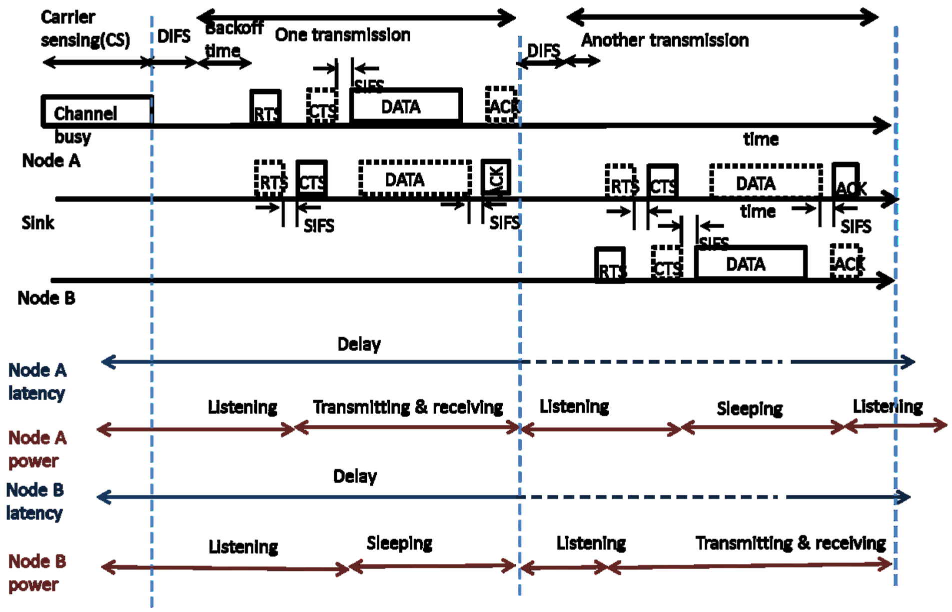

Figure 3.10: 802.11 DCF overview

The data transmission time can be expressed as:

$$\begin{aligned} T_{80211data} =& T_{No_{f}rame} - (DIFS + 3 \times SIFS \\ & + (CW_{min}/2) \times T_{slot} \\ & + T_{RTS} + T_{CTS} + T_{ACK}) \end{aligned} \tag{3.14}$$

The SMAC sensor has a fixed duty-cycle that is used to reduce idle listening overhead. Sensor nodes regularly broadcast SYNC packets. This includes a time stamp at the beginning of a slot, if they cannot receive SYNC packets from other sensors for a certain time, which allows other sensors to adjust their local clocks to compensate for drift (see Fig. 3.11). New nodes may join the schedule slot they have received; they may also adjust their own radio switch-on-off cycle based on the SYNC packets. These sensors form a so-called virtual cluster. If the sensors want to send data, they use RTS/CTS during the active period to avoid DATA access collision after the SYNC messages. After the active period, the sleep period is initiated to conserve energy. The active period in SMAC determines that short data messages are suitable for this design. The data transmission time can be calculated as:

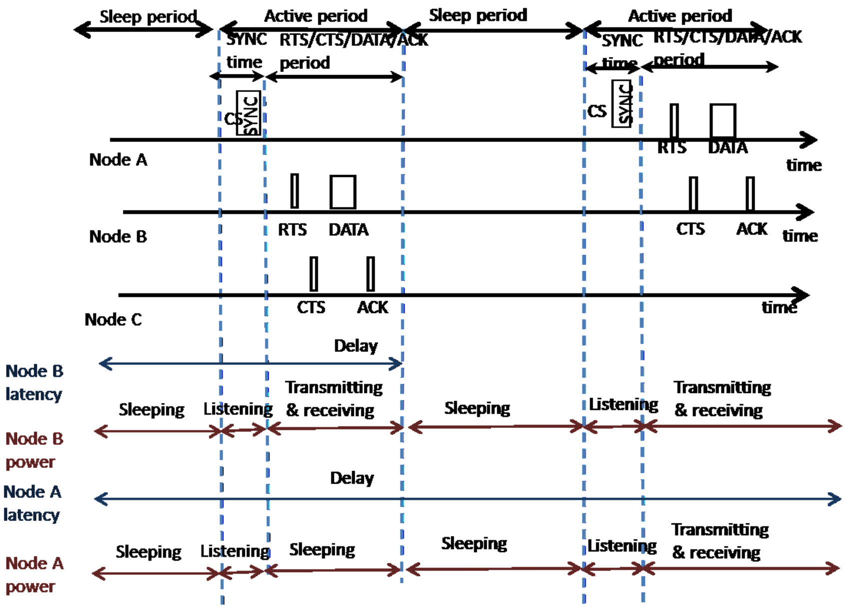

Figure 3.11: SMAC overview

$$\begin{aligned} T_{SMACdata} =& (T_{active} - T_{sync} - (DIFS + 3 \times SIFS \\ & + (CW_{min}/2) \times T_{slot} \\ & + T_{RTS} + T_{CTS} + T_{ACK})) \\ & \times (T \mod T_{active}) \end{aligned} \tag{3.15}$$

The data throughput can be expressed as:

$$\begin{aligned} D_{SMACthroughput} =& T_{SMACdata} \times R \\ D_{80211throughput} =& T_{80211data} \times R \end{aligned} \tag{3.16}$$

In our approach, as shown in Fig. 3.3, we can calculate the data transmission time and throughput in the manner below:

$$\begin{aligned} T_{data} =& T - DIFS - (CW_{min}/2) \times T_{slot} - SIFS \\ & - T_{RTS} - T_{CTS} - 2n \times SIFS + n \times T_{ACK}; \\ D_{throughput} =& T_{data} \times R_i; \end{aligned} \tag{3.17}$$

As seen from the equations above, the proposed approach has more time to transmit data than SMAC and 802.11 DCF during one contact interval, thus increasing the data throughput. If we add the adaptive data rate R_i, which is higher than the data rate in SMAC and 802.11, the data throughput increase is significant (Fig. 3.12). We simulated the three approaches with data throughput during one contact interval in the NS2 system and the results showed the same trend in data throughput.

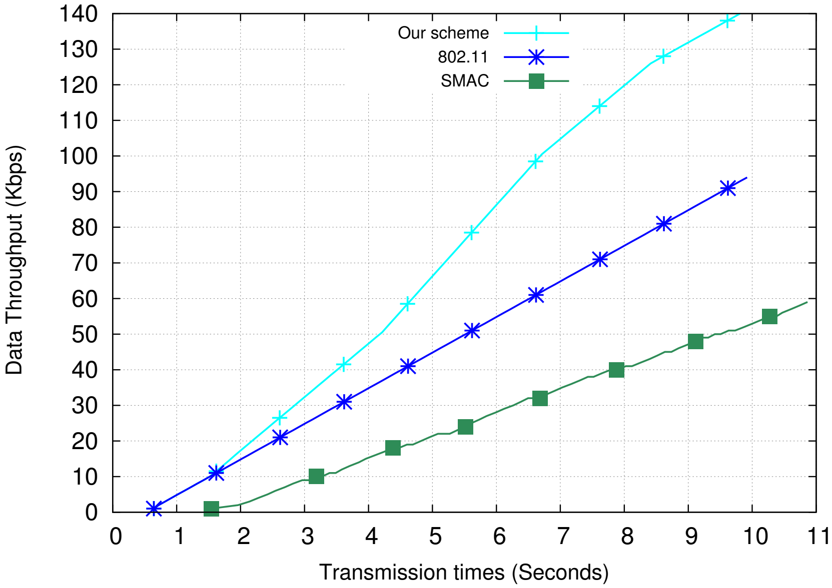

Figure 3.12: Data throughput comparison with SMAC and 802.11

3.7.2 Delay Analysis

In sparsely connected VDTSN, we can hardly identify the end-to-end delay from one sensor to the data center, since the end-to-end connection may not exist. Assuming that the vehicular sinks have connections to the data center, we can only calculate the data transmission delay from sensors to the sink in the MAC layer to describe the latency of each protocol. From the SMAC and 802.11 shown above (Fig. 3.10 and Fig. 3.11), we can deduct the maximum and minimum time to finish the data transmission for one sensor.

If the traffic takes the form of a small data packet and is periodic as SMAC assumes, one data frame is enough for one sensor to complete the transmission. However, the collected data may not be sent as one data frame in most sparse VDTSN and VANET scenarios where the sensors store information and wait for transmission opportunities. The delay of completing the transmission of data required for one sensor largely depends on the contention occurrences during the contact interval in SMAC or VANET approaches.

When no contention occurs, the SMAC duty cycle may result in greater delay than the other two. The delay in 802.11 DCF and our scheme is not significant. The difference in delay between 802.11 DCF and our scheme is that our scheme only uses RTS/CTS control messages once in order to save time and energy; 802.11 DCF, however, uses RTS/CTS for each data frame transmission for the fairness of the competing sensors.

When contention occurs during the transmission, our scheme performs better than the other two in terms of latency. In our proposed scheme, once the sensor has the opportunity for transmission, it occupies the channel all the time until the transmission finishes or until the wireless channel is broken. Therefore, the delay in our scheme is relatively small when contention occurs.

3.7.3 Energy Consumption Analysis

Compared with SMAC, our approach considers only the energy constraints in ordinary sensors and leaves sinks in vehicles aside. SMAC uses the duty cycles of sleeping and active modes to save power for each sensor. Our approach draws on the experience of SMAC and applies the periodic listening state to ordinary sensors with limited energy. These sensors do not listen to WAKEUP messages from sinks if they do not have enough data to send. When they collect enough data and hear the WAKEUP messages nearby, they seize the transmission opportunity through the contention-based mechanism (RTS/CTS) and transmit the entire data during this contact interval. During the transmissions, the sensors adjust the transmission power to gain higher data rates, provided that wireless conditions are good. Therefore, the energy consumption of sensors in our approach is higher than SMAC (see the simulation results in Fig. 3.13).

Our scheme saves more RTS/CTS transmissions than 802.11 DCF if data packets are larger than one frame. However, our adaptive rate control increases power consumption, thus using more power than 802.11 DCF.

If we calculate the transmission efficiency by the data throughput over energy consumption, our scheme performs better in terms of transmission efficiency than

SMAC and 802.11 DCF (see Fig.3.14).

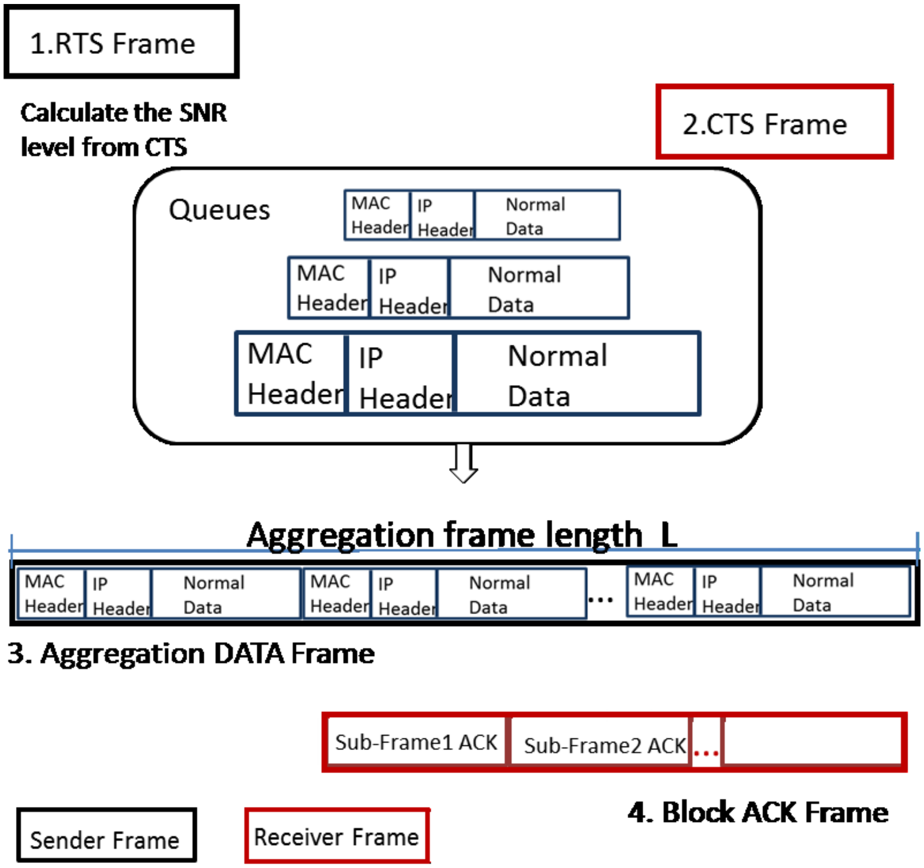

Figure 3.13: Energy consumption comparison with SMAC and 802.11

3.7.4 Scalability and Robustness Considerations

The proposed scheme does not use a central coordinator, nor does it casually synchronize other sensors as does SMAC. It applies similar sensor-to-sink contact methods as ad-hoc networks 802.11. Therefore, this scheme scales well like VANET and can be used in large sparse VDTSN.

If the contact sensors are out of order or transmission is blocked during the transmission, the strategy does not make any effort to repair them, since the effects of the block are only experienced locally by these sensors. This will not deteriorate the entire network. However, if the sink in the vehicle is damaged, the entire transmission procedure will be compromised. As a result, our MAC protocol is largely dependent

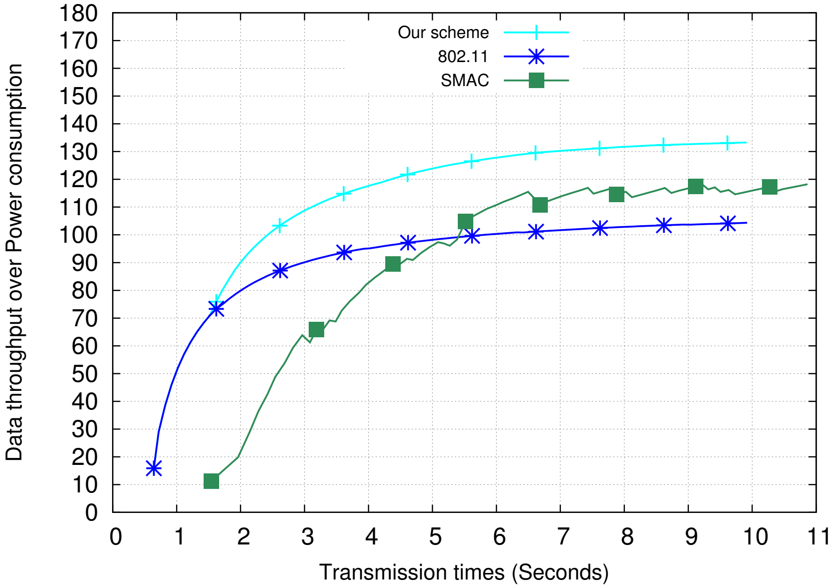

Figure 3.14: Transmission efficiency comparison with SMAC and 802.11

on the sink performance. Fortunately, engineers can easily change the damaged sinks in the vehicle in the sparse VDTSN.

3.8 Conclusion

This chapter proposes an efficient MAC approach CPMAC for sparsely connected Vehicular Delay-Tolerant Sensor Networks (VDTSN). The sink in the vehicle initiates the dispersive mobile or fixed sensors to prepare collected data transmissions. The awake sensor catches the precious transmission opportunity and prioritizes the MAC data into three different types according to buffer limit and data properties. With the prediction of the sensor-sink contact interval, the sensor uses three transmission algorithms to efficiently send out the collected data to the sink in a manner that balances data throughput and energy. From the simulation results and a comparison with two other classic MAC protocols, CPMAC presents better performance in terms of data throughput, one transmission delay and power-saving aspects than the two other MAC approaches in sparse VDTSNs.

Chapter 4

MAC Frame Aggregation for Vehicular Networks

4.1 Introduction

Vehicular Networks have begun to enable diverse automotive applications, including safe and efficient entertainment services, through vehicle-to-vehicle and vehicle-to-infrastructure communications. Vehicles in different locations or trajectories form data communication partitions or clusters when they travel [107] [108]. They can also act as commuters, connecting the data transmissions between the partitions or clusters. For instance, a public transportation system could install sensors on buses to collect information about road conditions or traffic data from roadside sensors [109]. In a disaster rescue scenario, vehicular networks could gather and apply immediate first scene information to save human lives [110]. In remote areas, where no infrastructure networks exist, a vehicular ad-hoc network could help gather information related to human health or environment to improve local living conditions. Data packets may accumulate in these commuters and wait for transmission opportunities. In these scenarios, data transmission opportunities largely depend on the unpredictable or periodic mobility of the vehicles.

Many protocols in the network layer have been developed for different mobility and traffic patterns and scenarios [111]. However, while high mobility and unexpected interactions among vehicles are common in Vehicular Networks, mathematical models of mobility and traffic patterns seldom help improve the transmission efficiency of the wireless channels. Transmission strategies are necessary to detect transmission opportunities and prioritize the data packets for sending, in order to best make use of the precious short connections between vehicles within the unstable vehicular networks.

The MAC layer can detect physical channel status and transmission opportunities, and is responsible for scheduling the data transmission layer over this volatile vehicular environment [112] and [113]. However, small data packets transmissions in the MAC layer bring significant overhead during one transmission opportunity under most current MAC strategies of vehicular networks. Throughput and transmission efficiency are compromised while transmitting small packets many times, which represent a major challenges for Vehicular Networks.

Vehicles can also store and carry data packets while they are waiting for transmission opportunities. When incoming data has accumulated in the vehicular nodes, the data buffer requires efficient queue management strategy in the MAC layer instead of commonly used strategies in the network layer [114]. As the vehicles move, new transmission opportunities can be detected, and the data buffer can be released according to wireless channels.

Data in queues can be aggregated to transmit in order to reduce overhead, thus improving transmission efficiency in the MAC layer. Unlike data packets in the network layer, acknowledgement messages for the aggregated data frames in the MAC layer can be provided during every hop of the data transmission. Adjustment and adaptive solutions can also be provided to improve the performance of MAC strategies.

This chapter proposes an adaptive frame length aggregation transmission scheme (AFLAS) in the MAC layer over the Vehicular Networks environment. The contributions of this chapter are described as follows:

- We calculate the relationship between Signal Noise Ratio (SNR) and the frame length of the MAC layer, and form the aggregated levels in the aggregation process. Frame length is impacted by current channel interference and noise as well as the probability of collision between users.

- The incoming data frames are queued in the MAC layer for aggregation purposes in the Vehicular Networks environment. We use a different queue management strategy in the aggregation process in order to improve transmission efficiency.

- We develop a novel aggregation scheme based on IEEE 802.11 in the MAC layer according to frame length and priority queues. The simulation results show that our scheme outperforms the non-adaptive frame length strategy regarding data throughput, retransmissions, and transmission efficiency.

The chapter is organized as follows: Section II introduces related work; Section III, IV, and V describe our adaptive frame length strategy and algorithms; Section VI shows the performance results and analysis; and finally, Section VII concludes the chapter.

4.2 Related Work

MAC layer strategies schedule access to the common wireless channel among different vehicle nodes. IEEE 802.11 standards are a group of typical MAC protocols for the casually connected ad-hoc nodes and 802.11p is an amendment for 802.11 standards for a vehicular communication system. 802.11p and 802.11 share the majority of media access strategy, except that 802.11p adds additional features for Intelligent Transportation Systems (ITS) applications [115].

In order to improve transmission efficiency in the Vehicular Networks environment, MAC strategies must consider several important techniques such as MAC frame length and scheduling scheme. Packets from upper layers may be of any size and can be aggregated in the MAC layer in order to reduce overhead messages during an interactive connection. The length of the aggregated frames varies, and can be adjusted to adapt to the wireless channel status.

4.2.1 MAC Aggregation under 802.11

MAC frame aggregation decreases the number of overhead messages by small packet transmissions, as well as the number of transmission times. Thus, recent simulations and empirical research have proven that aggregation in the MAC layer has better results in terms of throughput and transmission efficiency perspectives [116–120]. IEEE 802.11 is the commonly used physical and MAC layer standard in vehicular networks. It provides two types of MAC layer aggregation: A-MSDU and A-MPDU. A-MSDU combines several upper layer data units which have common MAC properties, such as identical destination addresses, the same type of services or same lifetime. A-MSDU accumulates these data units into one large aggregated data unit, and adds one common MAC header and Frame Check Sequence (FCS) [21]. On the other hand, A-MPDU only accumulates several small complete MAC protocol units, which include the respective MAC headers, data units and FCS, into one large MAC protocol unit without adding a common MAC header or tail. Therefore, in an ideal environment where every transmission is successful and without error, A-MSDU performs better than A-MPDU, with fewer overhead messages in aggregation frames. However, since A-MPDU keeps the original MAC header and FCS in the aggregation frame and allows the block ACK of each subframe in one aggregation frame, Ginzburg et al. [118] shows that A-MPDU aggregation outperforms A-MSDU aggregation, whose performance considerably degrades in high packet error rates and fluctuating wireless environments. In this MAC solution, we use these two aggregation methods as our basic aggregation MAC frame formats, and introduce adaptive length of the aggregated frames under unstable wireless conditions of vehicular environments.

4.2.2 Frame length in the MAC layer

Frame length is essential for improving the performance of data throughput and frame loss rate in communication networks. Long packets decrease the overhead ratio of the data transmission, and may thereby improve efficient data throughput (also known as goodput in [121] and [122]). However, large packet size may be easily impacted by channel collisions or signal level changes due to length of transmission time. This will lead to an increase in the number of retransmissions, which decreases transmission efficiency and results in longer delays. Short packets consume less transmission time and have less possibility of meeting collisions and signal level changes during transmissions, even though they contain more overhead messages than longer packets. In addition, the number of retransmissions may decrease when using shorter packets. Shorter packets have better latency performance; therefore, voice packets or packets used in a real-time system may be more effective when their size are reduced.

A great deal of research tends to specify optimal packet length for particular application requirements. For instance, considering the requirements of stringent delay and the packet loss rate of voice packets in the UMTS network, Poppe etal. [123] focuses on fixed-length voice packets. The Residue Bit Error Rate (RBER) is used to calculate packet loss rate, which can derive the optimal length of voice packets in the network. Sankarasubramaniam et al. [124] considers stable sensor network scenarios and uses a fixed Bit Error Rate (BER) for the wireless channel to calculate the fixed optimal frame size in the sensor network in order to save energy. Wang et al. [121] proposed another packet selection scheme for energy conservation in WLAN. In the paper [125], [126], and [127] provide cross-layer packet size selection schemes from TCP or IP to the MAC layer in order to achieve better transmission throughput (goodput) in complicated sensor networks. Zhang et al. [122] obtains the optimal packet size for improving goodput and energy consumption in IEEE 802.15.4 networks. Krishnan et al. [128] chooses the aggregation packet size to improve the throughput in the MAC layer. The optimal packet length is fixed throughout the data transmissions in these works. However, in vehicular communication networks where connections between vehicles are intermittent, there is no fixed optimal frame length in the MAC layer to improve the transmission performance. Therefore, we need to calculate the suitable frame size under current wireless channel conditions.

The frame size in the MAC layer is dominated by four main factors in wireless environments: the channel status, the possibility of collision, the overhead messages for transmissions and the requirements for the upper layer. Therefore, researchers have used various approaches to meet their performance requirements. In the approaches [122], [123], [124], [129], [130] and [131], Bit Error Rate or Packet Error Rate (PER) is used to deduce the Frame Error Rate (FER) to the optimal frame length. [125] and [126] use Carrier Noise Ratio (CNR) as the wireless channel indicator to select frame size.

In high mobility and volatile topology networks with unstable wireless channels, obtaining the PER calculation requires a significant amount of time, and may be out-of-date when a new packet size of transmission packets is required. Therefore, Carrier Noise Ratio or Signal Noise Ratio (SNR) can be applied in fluctuating channel status environments as the current channel status indicator to predict the optimal packet size. Therefore, the current detected SNR is selected as one of the indicators to the wireless channels in order to adjust packet size in this MAC solution.

Other researchers have considered contention occurrences, which lead to retransmissions and high frame error rate. Wang et al. [121] uses contention window, transmission collision probability, and channel conditions to calculate the transmission probability and to save energy in 802.11 DCF environments. Zhang et al. [122] considers the CSMA-CA contention, protocol overhead, and channel conditions, and derives optimal frame sizes to save energy in 802.15.4. Thus, collision possibility is also selected as another important indicator to adjust the frame length of the aggregated frame in vehicular networks.

Several researchers have focused on adaptive length packet size to fit specific environments. SPSA [131] is an adaptive packet size selection protocol that uses the BER calculation to predict the current packet size in WLAN, which may not apply to moving nodes. Dong et al. [132] describes another non-fixed optimal length scheme for sensor networks and link estimation methods are applied in order to select frame size for aggregation or fragmentation based on multi-hop sensor networks to save energy, and to incorporate upper layer requirements. Although link estimation adapts to obtain an optimal frame length, this method uses energy consumption to obtain adaptive frame length which may not apply to vehicular networks. ACK messages in the MAC layer can verify channel status, and can also be used as an indicator to set the length of the aggregated frames. Therefore, an adaptive packet size can be selected for aggregated MAC frames through multiple indicators in the unstable, dynamic wireless conditions of Vehicular Networks.

4.2.3 Queues in the MAC layer

Data packets may accumulate in the buffers of the MAC layer when communication connections are intermittent under volatile wireless environments. Some research analyzes channel access queues in IEEE 802.11 effects on the transmission delays under unsaturated and finite load conditions [133] [134]. Other research focuses on directing the queues in the MAC buffer in order to obtain traffic adaptivity or transmission efficiency. For instance, Queue-MAC [135] adds a queue indicator in a MAC frame to indicate and balance the traffic load in a hybrid CSMA/TDMA system. This protocol assumes the awareness of queue-length in the MAC layer and uses it to adapt to low and high traffic load. Nandiraju et al. [136] considers the hop counts in the MAC layer to affect the queue management in the transport layer and improve transmission efficiency. Limited research work has discussed queues in MAC aggregation process. In our MAC solution, we group data frames into different queues during aggregation process to prioritize and aggregate the data frames in order to save transmission overhead.

4.3 Approach Overview

Suppose the vehicular nodes on the road receive and relay the data packets to different destinations according to routing information. These nodes are required to store and carry these data packets until they find the next relay or the destination. These nodes may aggregate the small data packets into large data packets in order to make the transmission efficient and conserve the resources of wireless channel. Different small packets are received into separate queues according to the aggregation policy, then aggregated into larger packets when a transmission opportunity is detected. In the transmission process, aggregation packets size may be impacted by the wireless channel status such as signal strength and interference level, since retransmission is increased and transmission efficiency is degraded, particularly for aggregated packets.

Therefore, an adaptive MAC strategy must consider the following challenging issues: (*i*) How to connect the current wireless channel status with the MAC frame length in order to improve transmission performance under unstable Vehicular Networks; (*ii*) How to adjust the frame length in a timely manner to adapt to the changeable channels; and (*iii*) How to prepare the data packets to form long or short MAC data frames.

Three solutions are provided in our scheme to achieve an adaptive frame aggregation in Vehicular Networks.

4.3.1 Build relationship between length of aggregation frames and SNR

Data aggregation reduces the number of transmission times and overhead; thus, transmission efficiency is improved. However, when the signal strength is not strong enough between two vehicles, the aggregated data frame may incur higher frame error rates and more retransmissions than a normal data frame and thus, transmission efficiency is worsened. Intuitively, the aggregated frame length must be short when the physical channel is not good enough, and vice versa. Therefore we need to determine the relationship between the aggregation frame length and the wireless channel status so that initial aggregation level can be set under current detected SNR.

4.3.2 Using Block ACKs or ACKs as an adjustment indicator

When an aggregated frame is sent to the receiver node, the ACKs or Block ACKs may be returned from the receiver to show that the frame transmission is complete. These ACK messages may also indicate the state of the mapping between SNR and frame length and may thereby trigger an adjustment of the mapping level in our scheme. A timely adjustment with ACK messages will improve the adaptation of our scheme to current wireless channels. Block ACK messages indicate the acknowledgement of each separately received subframe in the A-MPDU scheme. Therefore, only incorrectly received subframes are retransmitted afterwards. However, when the A-MSDU aggregation scheme is used, ACK messages only indicate receipt of whole aggregated frames. Thus, each subframe in the A-MSDU must be retransmitted if A-MSDU is not correctly received.

4.3.3 Aggregate data frame with priorities

The upper layer data may have different priorities, which can be categorized into separate queues. For instance, urgent data may require instant transmission due to latency considerations. Some control messages or fragmented data may not be aggregated. Data frames with the same destination may be aggregated to save the overhead, and to also save packing and unpacking time in the other side nodes. In a high mobility and volatile topology environment, the data frames may be queued and stored in the transmission nodes, where they wait for a transmission opportunity. Queuing management in the upper layer is mostly focused on congestion control. In the MAC layer of Vehicular Networks, the queueing strategy can be combined with the aggregation policy, and thereby reduce the aggregation and de-aggregation times.

4.4 Aggregated Frame Length

The main purpose of aggregation is to increase good throughput of transmission without significantly increasing transmission frame errors. Thus, through aggregation, transmission efficiency is improved. In this section, a suitable frame length for the aggregation scheme to indicate the initial aggregation level is calculated under the current wireless channel status.

4.4.1 Transmission efficiency indicator

Overall transmission efficiency can be treated as correctly received data frames over all sending data frames. In the MAC layer, the control frames, headers of data, interframe slots and retransmission are considered as overhead for calculating transmission efficiency. RTS/CTS/DATA/ACK interactive frames are used in this scenario.

$$TE = \frac{D_L}{(D_{oh} + D_L)(1 + P_e)} \tag{4.1}$$

where D_L and D_{oh} are the bit number of data frames and overhead respectively; and P_e is the possibility of error transmission which leads to retransmission. We can express the data frames $D_{ReTrans}$ as follows:

$$D_{ReTrans} = (D_{oh} + D_L)P_e \tag{4.2}$$

The transmission time of data frames and control frames (including RTS, CTS, and ACK frames) can be expressed by the data rate and the data bit length. We assume that the data packets that are required to transmit in the MAC layer are fixed, and that the transmission rate of this layer is stable; therefore we can use the transmission time of each frame to indicate transmission efficiency.

$$T_{data} = D_L/R_{data} \tag{4.3}$$

$$T_{Control} = D_{control}/R_{Basic} \tag{4.4}$$

The overhead transmission time includes RTS, CTS and ACK frame transmission, the inter-frame space, and the retransmission time due to RTS collisions.

$$\begin{gathered} T_{oh} = T_{RTS} + T_{CTS} + T_h + T_{ACK} \\ +3 \times SIFS + (T_{RTS} + SIFS)(1 + P_c) \end{gathered} \tag{4.5}$$

Where P_c is the probability of collisions during transmissions. If we consider the DATA/ACK mode where RTS/CTS are not used to avoid collisions, the transmission efficiency can be computed using the basic rate as data rate as follows:

$$TE = \frac{T_{data}}{(T_{oh} + T_{data})(1 + P_e)(1 + P_c)} \tag{4.6}$$

4.4.2 Frame loss probability

Aggregation can improve data throughput only when the aggregation will not increase packet loss. Packet loss in wireless networks can be classified into two types: collisions, which are the result of unfavourable traffic conditions; and channel errors, which are the result of unfavourable channel conditions. A collision occurs when a nodes packet overlaps in time with that of another node that is close enough to the destination to interfere. A channel error occurs when the SNR of a received packet is low due to a large path loss or a deep multipath fade.

According to Bianchi [137], the conditional collision probability is calculated by:

$$P_c = 1 - (1 - \tau)^{n-1} \tag{4.7}$$

where τ is the transmission probability in a virtual slot, and n is the number of nodes which exist in this slot.

Interference and noise during the data or ACK transmissions result in frame errors. The longer the frame, the greater probability of error. In high mobility and volatile topology networks, signal strength can be detected during the transmission stage. Related to SNR, BER is another important physical parameter that represents the error rate of current packets or frames. Digital communication theory indicates that the bit error rate from the receiver node may be affected by a number of factors, including transmission channel noise and interference, wireless multipath fading, modulation and coding schemes, and bit synchronization problems. Transmission channel noise and interference and wireless multipath fading can be detected through SNR. For instance, BER may be improved by choosing a high signal strength or by increasing transmission power. Given certain modulation and synchronization schemes, as well as types of transceivers used, BER is determined by the current SNR level. We use three modulation rates (QPSK, 16QAM and 64QAM) with the Rayleigh fading model to calculate the BER, since QPSK is used for control frames such as RTS, CTS and ACK and headers of data frames. 16QAM and 64QAM can be applied to the payload of the data frames. According to the calculated BER, we can deduce the probability of channel errors with the data length D_L.

For a sequence of data D_L sent at a constant modulation rate R_{data} over a channel, the probability of channel error is given by:

$$P_e = 1 - (1 - BER_{16/64})^{D_L} \tag{4.8}$$

where $BER_{16/64}$ represents the BER value under the 16QAM or 64QAM modulation with the Rayleigh fading model [138]. Since a data frame consists of a preamble and header sent at a basic rate with QPSK modulation, and the payload of the data frame is possibly sent at a higher rate, the probability of channel error can be computed as follows:

$$P_e = 1 - (1 - BER_{16/64})^{D_L}(1 - BER_{QPSK})^{D_h} \tag{4.9}$$

where D_h is the length of header and preamble of this frame, and BER_{QPSK} represents the bit error rates of basic speed with QPSK modulation.

There are two different types of aggregation frames in 802.11: A-MPDU and A-MPDU. For A-MSDU, we could use the above transmission failure probability, since the A-MSDU contains a common MAC header for each of its subframes.

For the A-MPDU scheme, in which MAC headers can be found in each subframe, the probability of channel error can be calculated as follows:

$$P_e = 1 - \prod((1 - BER_{16/64})^{D_{Li}}(1 - BER_{QPSK})^{D_{hi}}) \tag{4.10}$$

where D_{Li} and D_{hi} are the payload and header part of subframe i in one A-MPDU aggregation frame.

4.4.3 Relationship among frame length, transmission efficiency, and SNR

According to the above equations, we calculate the relationship between SNR and transmission efficiency under different frame lengths. Fig. 5.1 and Fig. 5.2 show the relationship between transmission efficiency and SNR under different frame lengths. In this process, we consider three modulation schemes: 16QAM and 64QAM in payload transmissions, and QPSK in overhead transmissions with the Rayleigh fading model. A suitable length of aggregation frame can be chosen according to these equations under certain SNR levels. The relationship between BER and SNR can be described by equations (4.11) and (4.12).

$$BER = \frac{1}{2} erfc(\sqrt{E_b/N_0}) \tag{4.11}$$

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-t^2}\, \mathrm{d}t \tag{4.12}$$

For instance, in the case of the QPSK modulation and the AWGN channel, the BER as a function of the SNR (which is represented by Eb/N0) is given by:

$$BER' \simeq \frac{1}{4 \times E_b/N_0} \tag{4.13}$$

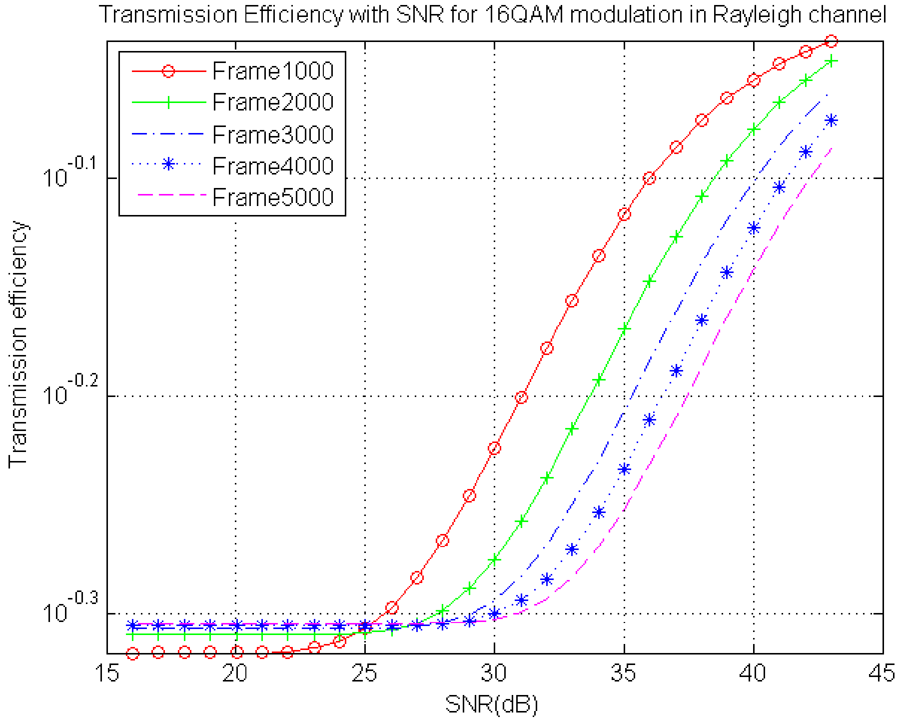

Figure 4.1: Transmission efficiency and SNR for 16QAM modulation in Rayleigh channel

By using the analytical frame length under certain SNR levels, aggregation levels can be set as described in Section V.

4.5 Aggregation Scheme

In the MAC layer, data frames are prioritized into groups and aggregated into larger frames in the process. Procedures and algorithms for this aggregation scheme are presented in this Section.

4.5.1 Data priority

The first stage of the aggregation scheme is to group the data frames before transmission. In this scheme, we consider data properties of the upper layer as well as routing information in order to form different groups of the MAC data. For instance, the quality of service (QoS) in the IP layer can be one criteria used to form the priority. In addition, there are frames which cannot be aggregated. The upper layer data is

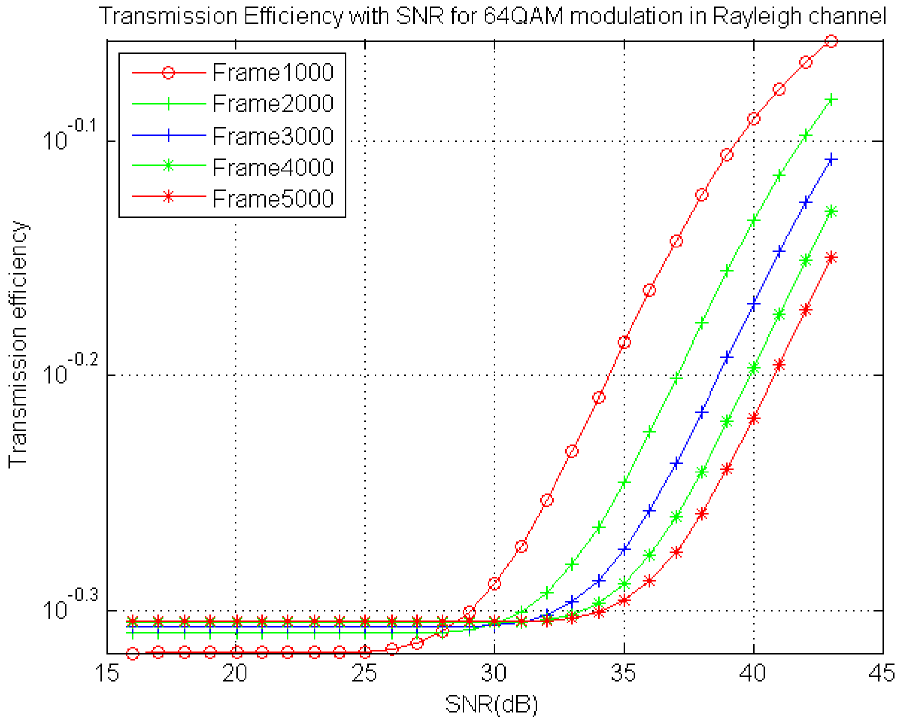

Figure 4.2: Transmission efficiency with SNR for 64QAM modulation in Rayleigh channel

separated into three types of queues in this scheme:

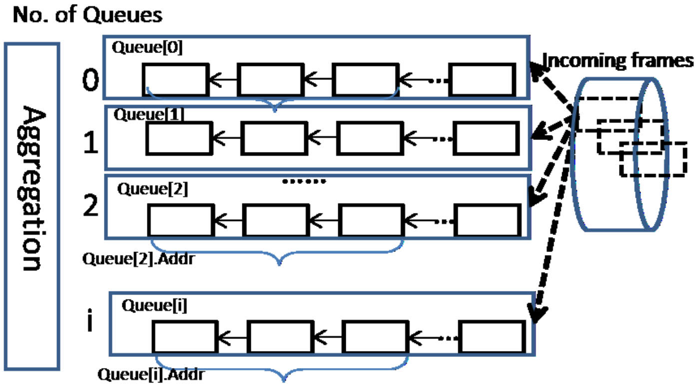

Figure 4.3: Data priorities and queuing

Urgent data queue

The data with the highest priority as urgent data will arrive at $Queue[0]$. When a transmission opportunity is detected, the urgent data is sent first with the aggregated frame, according to the SNR level. Once the frames in one of the other queues is transmitted, the $Queue[0]$ will be checked. If there are data frames waiting for transmission, we will deliver these data frames in $Queue[0]$ in order to reduce latency. Rather than waiting for enough frames, the aggregation process in $Queue[0]$ aggregates the current data frames in $Queue[0]$ under the current SNR status.

Data frames that cannot be aggregated

Data frames which cannot be aggregated, such as multicast data or the fragmented data, are placed into $Queue[1]$ to be transmitted without using the aggregation scheme.

Data frames that can be aggregated

These incoming frames can be grouped under the same address (RA field in 802.11). This RA address may be the multi-hop MAC destination or the one-hop destination. In this scheme, the incoming frames are grouped with the same destination IP address in order to reduce aggregation and de-aggregation time in each inter-medium node. Data frames in the same queue may be aggregated to form a larger frame to improve throughput and reduce overhead.

In the queuing management algorithm (as shown in Alg. 3), the $IncomingF$ is directed to different queues. When the frame has a destination address that differs from the address of exiting queues, a new queue is created for this frame. When the maximum number of queues is achieved, the algorithm returns to the start queue to avoid using extra buffer. Each time an incoming frame passes through this algorithm, it is in one of the specified queues.

4.5.2 Aggregation levels

From Section IV, we can identify the aggregation level according to the current SNR. First we check $Queue[0]$ to ensure that urgent data is sent without delay. Next we check each queue from $startqueue$ to $startqueue+i$ and $Queue[1]$ in turn to aggregate

Algorithm 3: Incoming frame enters a queue

```
if Incoming frame is urgent frame or control frame then
    put IncomingF into $Queue[0]$; return;
if Incoming frame fragmentation threshold < Threshold then
    put IncomingF into $Queue[1]$; return;
if Incoming frame is multicast frame then
    put IncomingF into $Queue[1]$; return;
i=start queue; Flag=True;
while $i <= NoOfQueues$ and $Flag$ do
    if $IncomingF.Addr == Queue[i].Addr$ then
        put IncomingF into $Queue[i]$;
        Flag = False;
    $i++$; if $i > maxqueue$ then
        i= start queue;
if $i > NoOfQueues$ then
    put IncomingF into $Queue[i]$;
    $Queue.Addr = IncomingF.Addr$;
    $NoOfQueues++$;
```

multiple frames into one super-frame. The aggregation procedure of A-MPDU is described in Fig. 6.2.

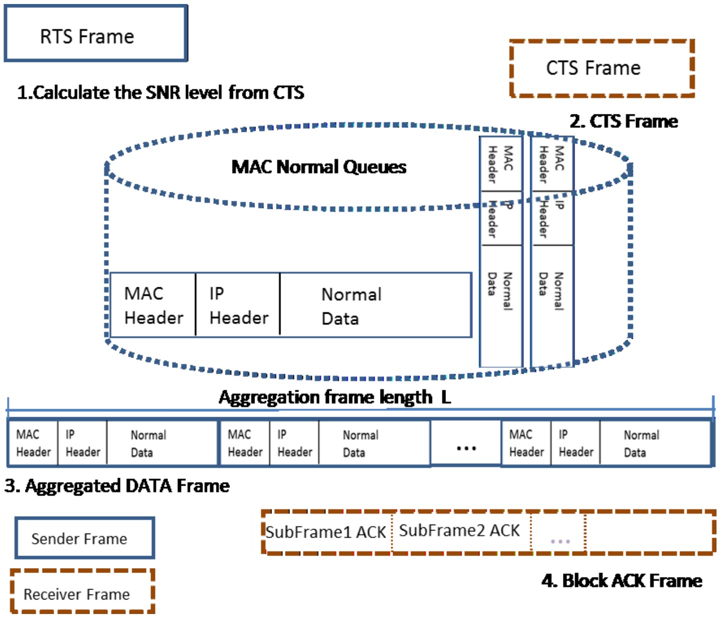

Figure 4.4: Aggregation procedure in queues (A-MPDU)

A suitable frame length is obtained under the current detected SNR according to the equations in Section IV. Therefore, the following tables (Table 4.1 and Table 4.2) can be formed under 802.11 A-MPDU and A-MSDU scenarios. The maximum length of A-MPDU is 65,535 octets, and each A-MPDU subframe is a multiple of 4 octets in length [21]. The maximum body length in A-MSDU is limited to 2324 octets. We set different aggregation levels in these two aggregation schemes.

Table 4.1: Aggregation level with A-MPDU:aggregation frame length and SNR

$A_{level} = I$	Conditions	SNR_{level}
0	No Aggregation	1
1	$Length[1] < 2000 octets$ OR $No.Subframe[1] < 5$	2
2	$Length[2] < 4000 octets$ OR $No.Subframe[2] < 5$	3
3	$Length[3] < 6000 octets$ OR $No.Subframe[3] < 10$	4
4	$Length[4] < 8000 octets$ OR $No.Subframe[4] < 10$	5
5	$Length[5] < 65535 octets$ OR $No.Subframe[5] < 64$	6

Table 4.2: Aggregation level with A-MSDU:aggregation frame length and SNR

$A_{level} = I$	Conditions	SNR_{level}
0	No Aggregation	1
1	$Length[1] < 500 octets$ OR $No.Subframe[1] < 5$	2
2	$Length[2] < 1000 octets$ OR $No.Subframe[2] < 5$	3
3	$Length[3] < 1500 octets$ OR $No.Subframe[3] < 10$	4
4	$Length[4] < 2324 octets$ OR $No.Subframe[4] < 10$	5

4.5.3 Aggregation level adjustment

Although we calculate the aggregation levels from the Rayleigh fading channel, we still cannot predict actual wireless channel status due to unexpected interference and fast fading. Therefore, ACK messages are needed to adjust the aggregation levels and compensate for the difference between current and theoretical wireless channel status. In this scheme, we do not simply adjust the frame length based on the ACK messages; these have already become obsolete due to the short transmission interval and the intermittently connected network. We use ACK as an indication to adjust the mapping levels.

The calculation method is described through the following example: If the ACK threshold is reached, 50 percent of the negative ACK (NACK) is received in one ACK block, the aggregation frame is not suitable, and the aggregation level will downgrade to the same SNR level. When a more consecutive NACK threshold in an ACK block is reached, the aggregation level returns to a non-aggregated level. The Block ACK in A-MPDU from the receiver node gives ACK messages for each sub-frame in one aggregated frame by using one ACK frame. An ACK message to a A-MSDU frame indicates the correctness of the aggregated frame, but not the correctness of each subframe. We use different thresholds of ACK to adjust aggregation levels in A-MPDU and A-MSDU.

4.5.4 Aggregation algorithm

When the vehicle detects a transmission opportunity, it checks the frame queues in the buffer and measures signal strength during the transmission of RTS/CTS interactive frames. The algorithm in the sender part first checks $Queue[0]$ once it finishes its last frame transmission to find its next transmission opportunity. According to the current SNR level, we can calculate the aggregation level, which indicates the admitted frame length and number of subframes in the aggregated frame. The algorithm adds one frame each to check if the maximum limit is reached, and then aggregates these frames into one aggregated frame. The RTS and DATA frames can be transmitted to the receiver part.

When $Queue[0]$ is empty, the algorithm checks $Queue[i]$ while the sender finds the transmission opportunity. Data frames in $Queue[1]$ cannot be aggregated and are transmitted immediately. Data frames in $Queue[i]$ can be aggregated according to the current SNR level. When the aggregation is finished, we change the current pointer of $Queue[i]$ to the next queue. When the sender receives the ACK or BlockACK messages from a receiver, retransmission may be triggered for NACK or Non-ACK messages. The number of times that ACK or NACK is not received during one transmission is recorded to adjust the aggregation level.

In what follows, we shall present the aggregation algorithm (Algorithm 4): first, the upper layer data packets are separated into different queues. The sender attempts to send out RTS message to initiate a transmission. When the receiver gets the RTS message, it sends back a CTS message to accept the request. According to the SNR_{level} of the CTS from the receiver, the sender calculates the SNR_{level} and checks the $Queue[0]$. If the queue is not empty, it aggregates the data frames in the queue in order to form an aggregation frame which has the frame length, and a number of sub-frames that corresponds to the SNR_{level} as shown in Table 4.1.

When $Queue[0]$ is empty, the sender turns to $Queue[i]$. The sender accumulates data frames in $Queue[i]$ and obtains an aggregation frame corresponding to the SNR_{level} of the CTS message. After that, the sender transmits the aggregated frame like an ordinary DATA frame belonging to the MAC layer, along with the newly calculated transmission durations in the frame header. When the receiver gets the DATA frame, it calculates the CRC part of each sub-frame, and sends back the Block ACK messages according to each sub-frame in the aggregated frame.

When the sender receives the ACK or Block ACK, it checks the error rate of the sub-frames in one large aggregated frame. If the error rate is above the ACK threshold, the sender adjusts the mapping step ($Queue[i]_{step}$) between the SNR_{level} and the $Queue[i]_{level}$ for each queue. A consecutively high error rate in Block ACK affects $Queue[i]_{step}$, which is then downgraded to 1. In addition, consecutively received high levels of negative ACKs result in A_{level} and A_{step} returning to initial value with no aggregation. However, when a low error rate in a Block ACK is received, the A_{step} will be upgraded to a higher level.

4.6 Performance Evaluation and Analysis

The simulations include 20 mobile nodes which are randomly set in the NS2 system. In our experiments, we choose to use the TwoRayGround fading model as well as AODV and GPSR routing protocols. These nodes transmit different packet data

Algorithm 4: Aggregation algorithm

```
SENDER:
if $SNR_{level} > 0$ and $No.Queue! = 0$ then
    if $Queue[0]! = Null$ then
        $Queue[0]_{level} = SNR_{level} - A_{step}$;
        $I = Queue[0]_{level}$;$A_{Flength} = 0$; $No.Subframe = 0$;
        Get one data frame from $Queue[0]$;
        while $A_{Flength} + Framelength < Length[I]$ and $No.Subframe + 1 < No.Subframe[I]$ and $Frag_{aggregated} == Yes$ do
            Add this frame in $Queue[0]$ into aggregation pool;
            $A_{Flength} = A_{Flength} + Framelength$;
            No.Subframe ++;
            Get another data frame from $Queue[0]$;
        if $A_{Flength}! = 0$ then
            Aggregate the data; Recalculate frame header;Transmit Aggregated Data;
        else
            Transmit current Data frame;
    else
        if $Queue[i]! = Null$ then
            if $i! = 1$ then
                $Queue[i]_{level} = SNR_{level} - A_{step}$;
                $I = Queue[i]_{level}$; $A_{Flength} = 0$; $No.Subframe = 0$;
                Get one data frame from $Queue[0]$;
                while $A_{Flength} + Framelength < Length[I]$ and $No.Subframe + 1 < No.Subframe[I]$ do
                    $A_{Flength} = A_{Flength} + datalength$;
                    No.Subframe ++;
                    Get another data frame from $Queue[0]$;
                Aggregate the data; Recalculate frame header;Transmit Aggregated Data; $i + +$;
                if $i > No.Queue$ then
                    $i = 1$;
            else
                Transmit one data frame in Queue[1];
RECEIVER:
Transmit CTS and send ACK/BlockACK;

SENDER:
if the NACK is larger than ACK threshold then
    $Queue[i]_{step} + +$;
    consecutively received NACK times ++;
    if consecutive NACK times is larger than ACK times threshold then
        $Queue[i]_{level} = 0$;
        $Queue[i]_{step} = 0$;
    else
        the consecutive NACK times =0;
        if $Queue[i]_{step}! = 0$ then
            $Queue[i]_{step} - -$;
```

of $n \times 200$ bytes per packet at a constant speed. We first simulate our adaptive frame length strategy using A-MPDU and A-MSDU respectively; we then compare this adaptive strategy with three different aggregation schemes. The simulations demonstrate several related results in data throughput, overhead and retransmissions, and transmission efficiency. Each simulation was run for 250s. Simulation parameters are listed in Table 4.3.

Table 4.3: Simulation parameters

Propagation Model	TwoRayGround
Routing Protocols	AODV/GPSR
Radio Range	<500m
Number of Nodes	21
Simulation Time	250s

4.6.1 Simulation results - Adaptive frame length strategy and non-adaptive strategy

Fig. 4.5 shows the data throughput comparison results using our frame length adaptive strategy. When the 802.11 A-MPDU aggregation scheme is applied, our adaptive frame length strategy shows higher good data throughput than the scheme that does not employ adaptive frame length. The reason behind this is due to the fact that the long A-MPDU frame may experience more error probability when the wireless channel is unstable. Our strategy considers the wireless channel SNR for adjusting our frame length, thereby improving the good data throughput during transmissions.

Fig. 4.6 and Fig. 4.7 respectively show the retransmission and overhead comparison results using our frame length adaptive strategy. Our adaptive scheme exhibits lower overhead and retransmissions in comparison to the non-adaptive scheme using A-MPDU aggregation. When both aggregation schemes save overhead messages, our scheme decreases retransmissions by adjusting our frame length, which adapts to

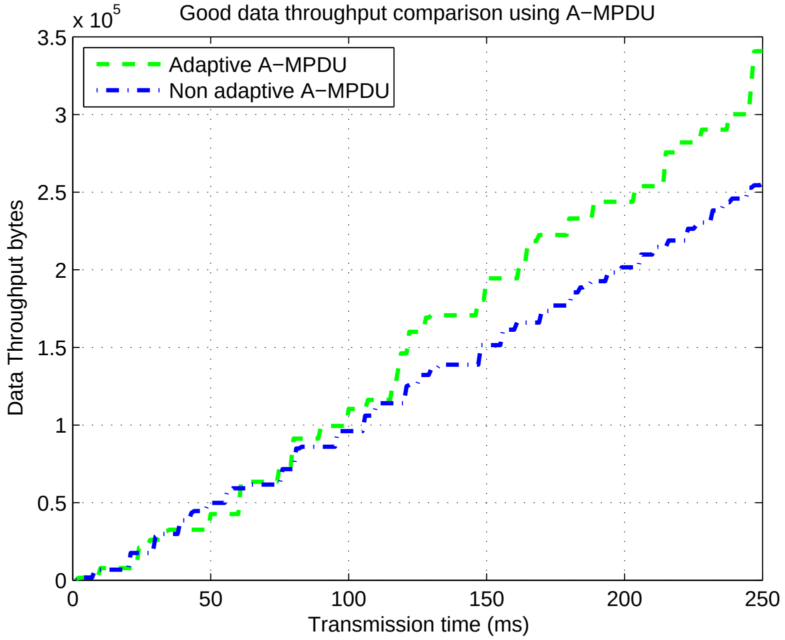

Figure 4.5: Good data throughput comparison using A-MPDU aggregation

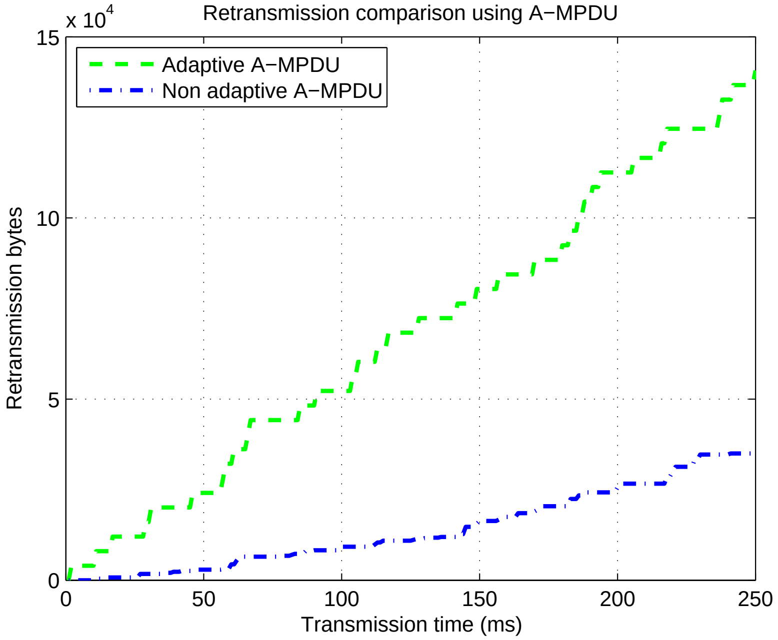

Figure 4.6: Retransmissions comparison using A-MPDU aggregation

signal strength of the current wireless channel. Therefore, the overhead of the data frames in our scheme is also decreased.

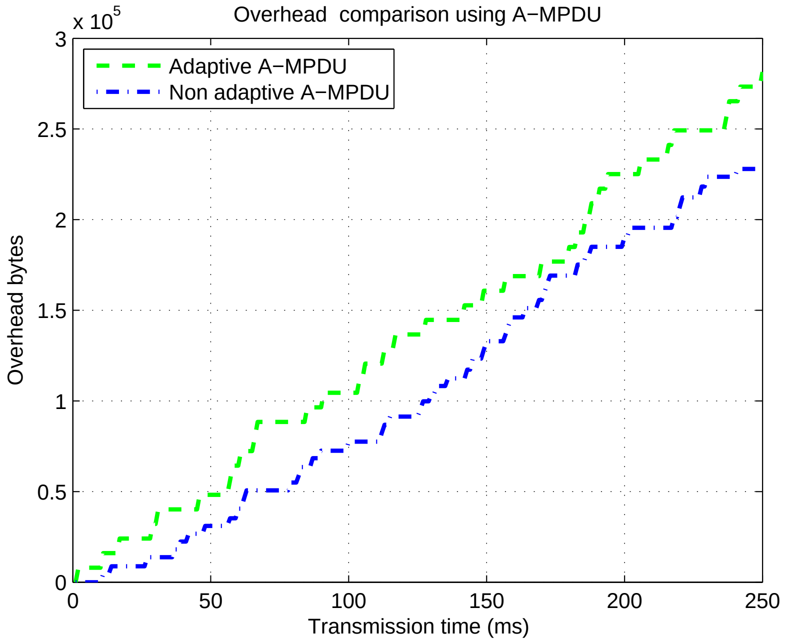

Figure 4.7: Overhead comparison using A-MPDU aggregation

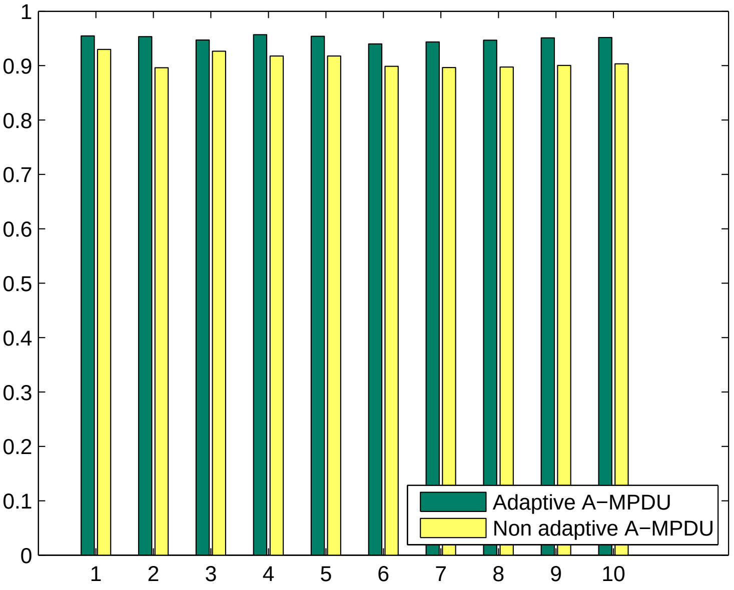

Figure 4.8: Transmission efficiency comparison using A-MPDU aggregation

Fig. 4.8 shows the transmission efficiency comparison using adaptive and non-adaptive schemes. We use the previous TE calculation equation to demonstrate efficient data throughput during all transmissions as shown in Y-axle. X-axle in Fig. 4.8

represents the accumulated transmission time with 25ms intervals. For instance, 1 in X-axle means the past 25ms. 2 in X-axle means the past 50ms. 10 in X-axle means the past simulation time 250ms. Fig. 4.8 demonstrates that our adaptive scheme has superior transmission efficiency to non-adaptive scheme.

We also simulate our adaptive frame length strategy using 802.11 A-MSDU aggregation frame and compare our scheme with a non-adaptive scheme. Fig. 4.9-Fig. 4.12 show the related results in data throughput, retransmissions, overhead, and transmission efficiency using A-MSDU aggregation. These results also demonstrate the superior performance of our adaptive scheme in data throughput and overhead saving, when compared to the non-adaptive scheme. Since A-MSDU aggregates less than 2324 bytes, the overhead savings are not as significant as A-MPDU if the original packets are not small enough. Therefore, we can see that the transmission efficiency in the adaptive A-MSDU aggregation scheme is not significantly better than in non-adaptive A-MSDU schemes (Fig. 4.10).

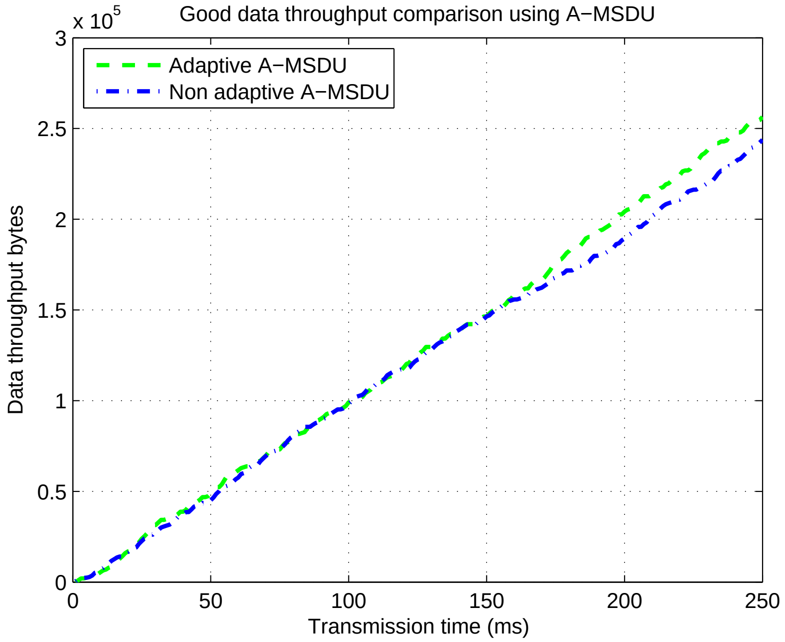

Figure 4.9: Data throughput comparison using A-MSDU aggregation

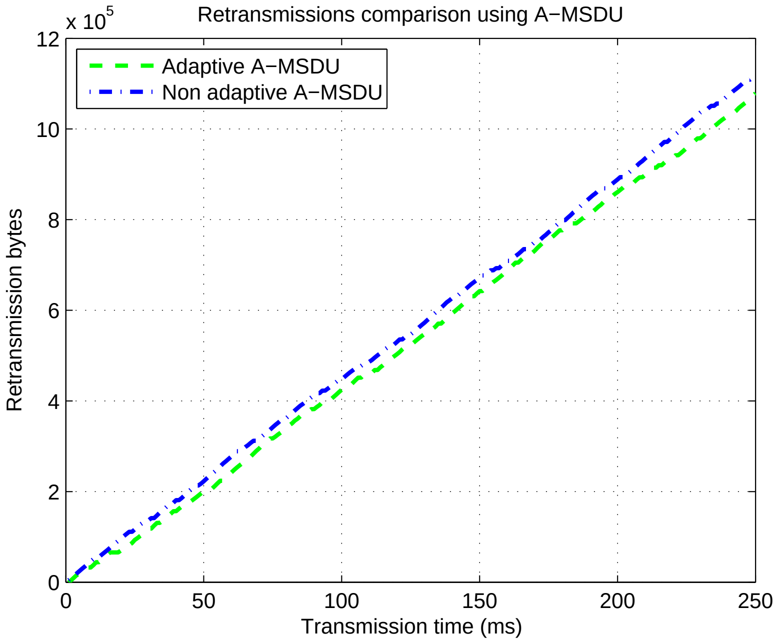

Figure 4.10: Retransmissions comparison using A-MSDU aggregation

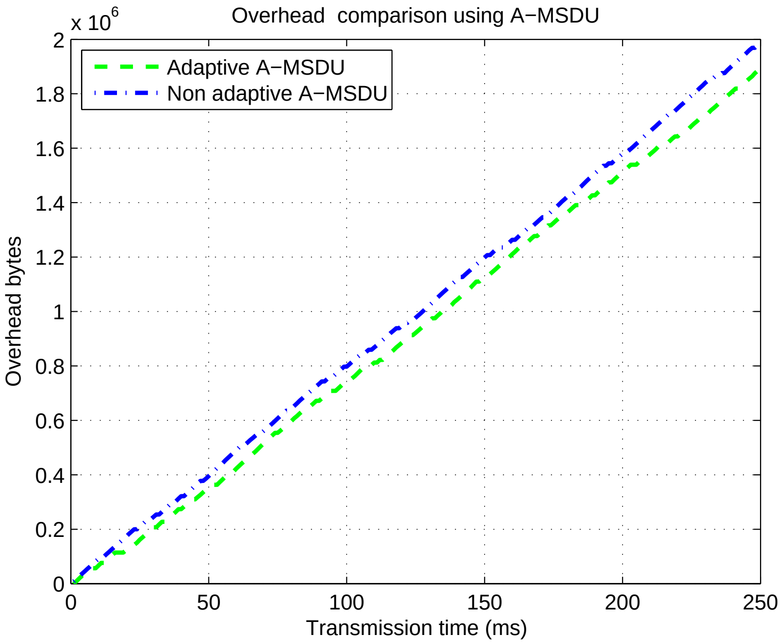

Figure 4.11: Overhead comparison using A-MSDU aggregation

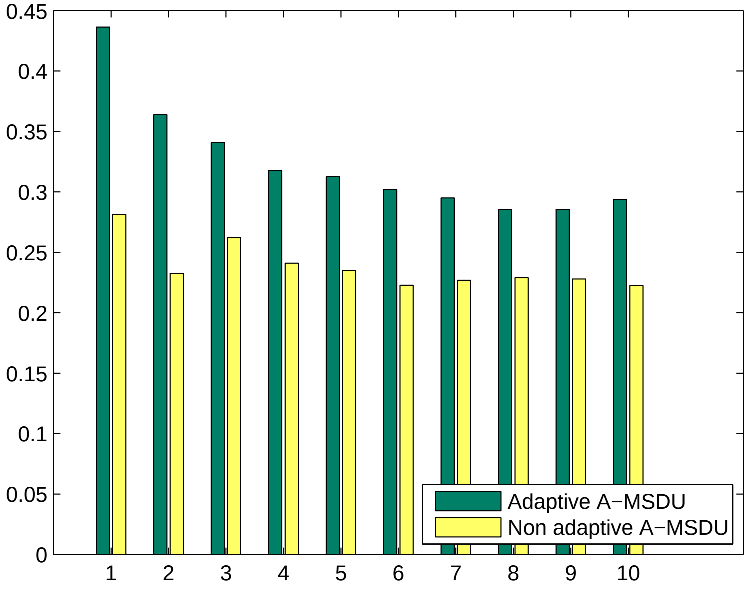

Figure 4.12: Transmission efficiency comparison using A-MSDU aggregation

4.6.2 Simulation results - Adaptive aggregation strategy and non-aggregation strategy

We simulate our adaptive aggregation schemes in A-MPDU aggregation, A-MSDU aggregation, and non-aggregation in order to distinguish between two aggregation schemes of 802.11 under different scenarios. A-MPDU can aggregate up to 65535 bytes in one frame while A-MSDU aggregates up to 2324 bytes. However, A-MSDU may require less delay to transmit the aggregated data compared to A-MPDU, when the accumulated data packets are insufficient for A-MPDU aggregation. Different wireless channel status (SNR) and varying sizes of original incoming packets are considered in the comparisons. Fig. 4.13-4.15 show data throughput comparison results under different sizes of incoming frames, and different SNR detected in wireless channels. From these figures, we can see that both A-MPDU and A-MSDU show a higher good throughput than non-aggregation schemes. The data throughput does not change significantly when the wireless channels are much better (raising 10dB) and the original frame lengths are much smaller. These figures show that the receiver

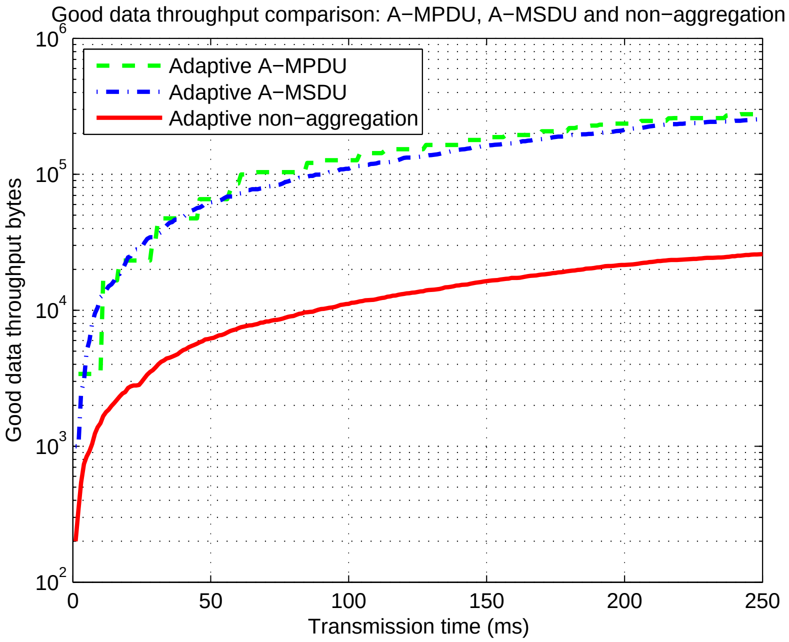

Figure 4.13: Data throughput SNR∈(15,30dBm) length<2000 bytes

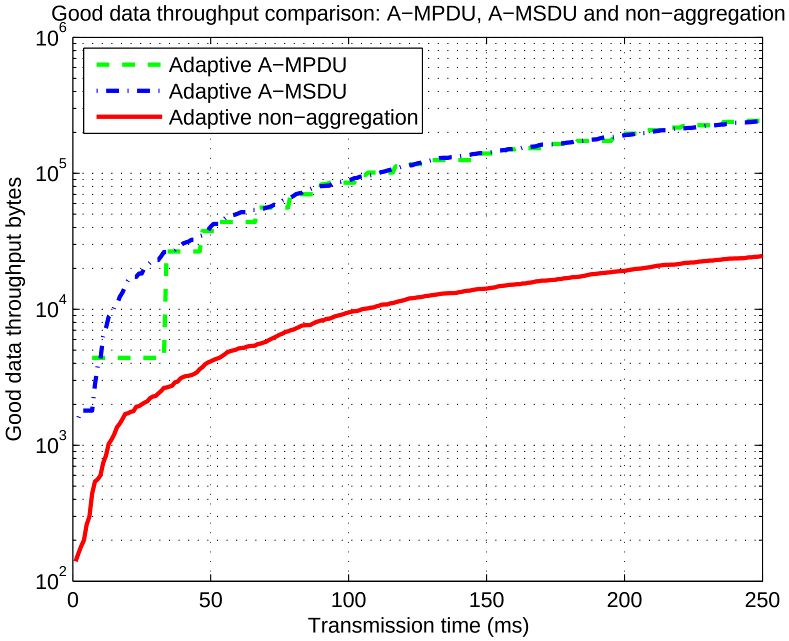

Figure 4.14: Data throughput SNR∈(25,40dBm) length<2000 bytes

correctly receives almost the same amount of data under different wireless conditions and variable frame sizes.

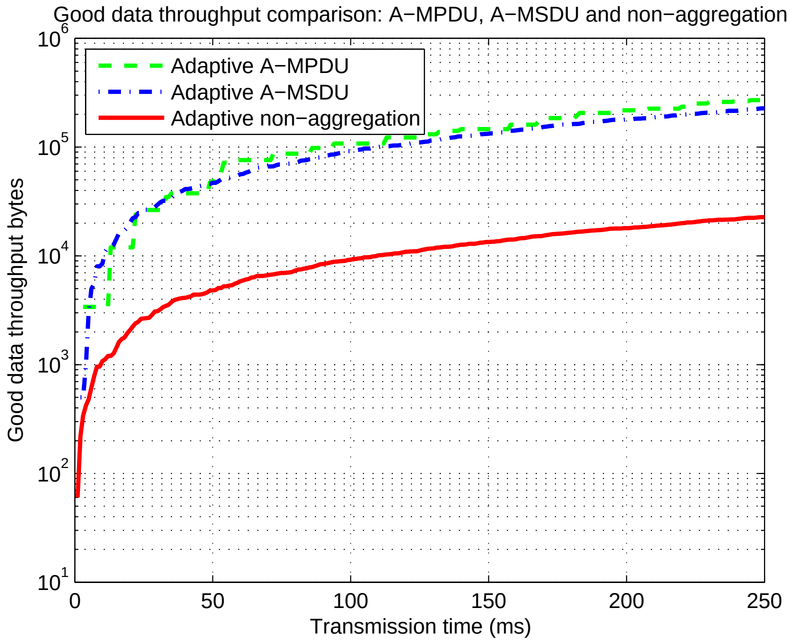

Figure 4.15: Data throughput SNR∈(15,30dBm) length<200 bytes

However, from the retransmission figures (Fig. 4.16-Fig. 4.18) we can see that A-MPDU retransmission is higher than A-MSDU and the non-aggregation scheme when the wireless channels are very good ($SNR > 25dBm$). This retransmission rate is higher mostly because A-MSDU and non-aggregation frames have shorter lengths, and may have a higher probability of being correctly received compared to longer A-MPDU frames. Therefore, retransmissions in A-MSDU and non-aggregation schemes decrease.

We can see the overhead change from Fig. 4.19 to Fig. 4.21. Under different SNR and sizes of incoming packets, the overhead of A-MPDU is the lowest, and A-MSDU is the second lowest. When the wireless channel SNR is better than 25 dBm, A-MPDU does not show significant improvement compared to A-MSDU and the non-aggregation scheme.

In vehicular high mobility and volatile topology environments, wireless channels fluctuate frequently so that SNR may be sufficient. A-MPDU demonstrates better data throughput and fewer retransmissions than A-MSDU and non-aggregated

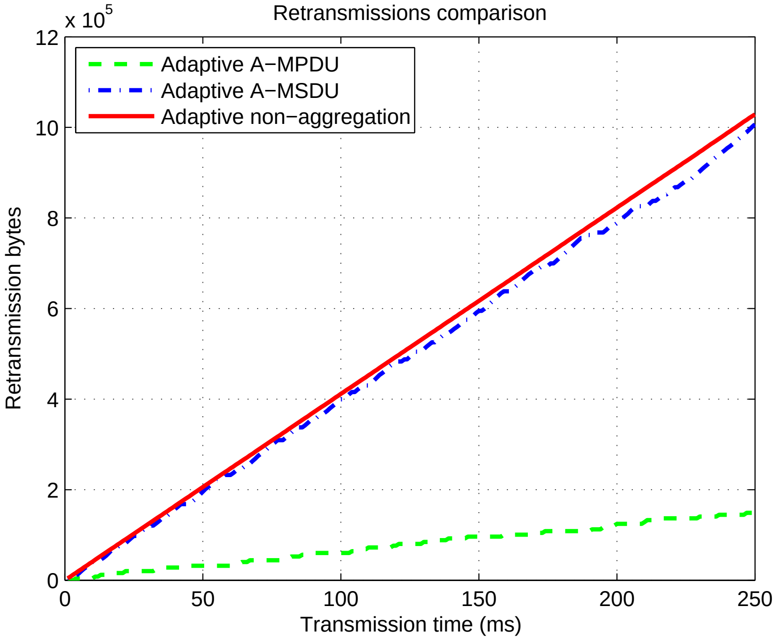

Figure 4.16: Retransmissions SNR∈(15,30dBm) length<2000 bytes

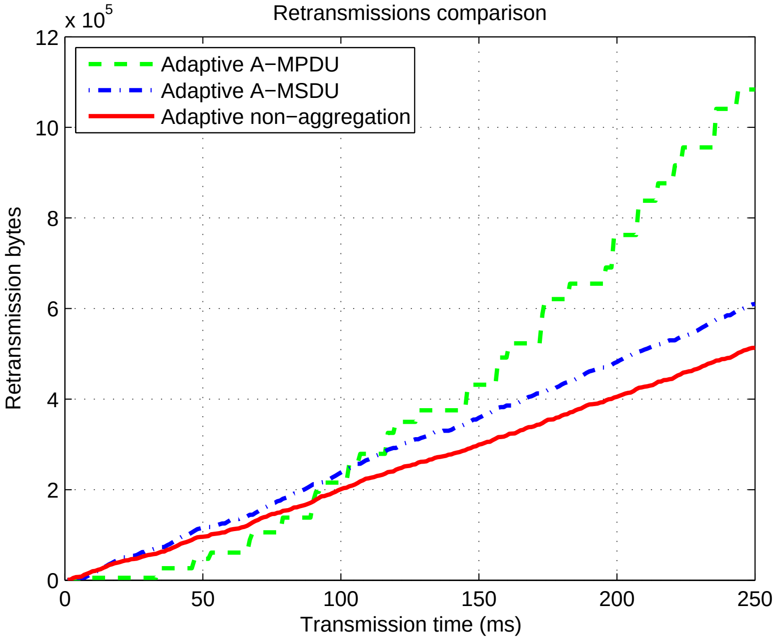

Figure 4.17: Retransmissions SNR∈(25,40dBm) length<2000 bytes

scheme, if we do not consider latency.

From all of the above simulations, we can conclude that our adaptive frame

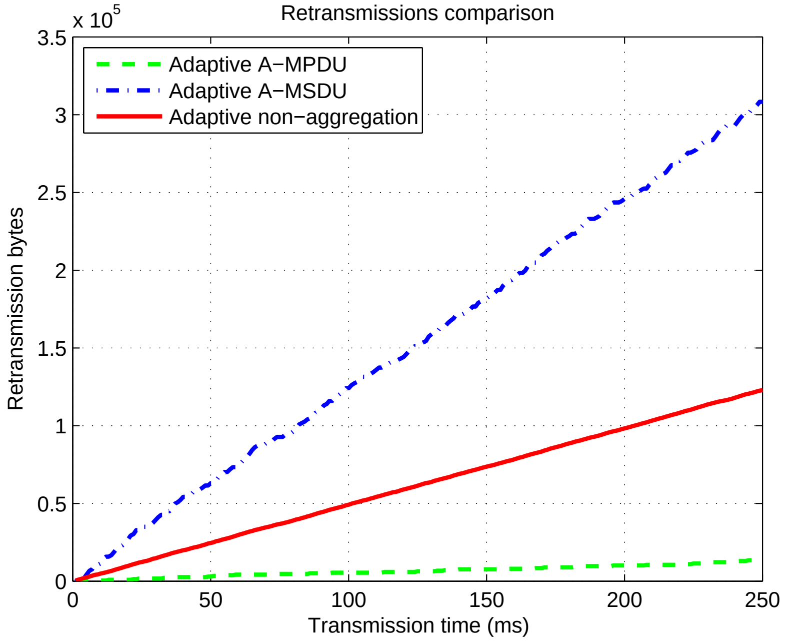

Figure 4.18: Retransmissions SNR∈(15,30dBm) length<200 bytes

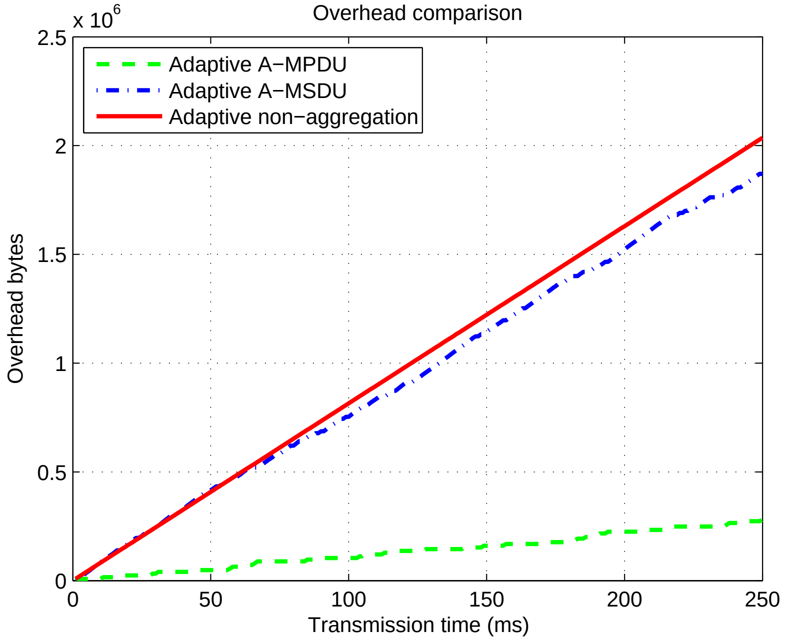

Figure 4.19: Overhead SNR∈(15,30dBm) length<2000 bytes

length aggregation works better in this challenged environment. In addition, the A-MPDU aggregation strategy demonstrates better overhead and retransmissions than

A-MSDU in high mobility and volatile topology networks.

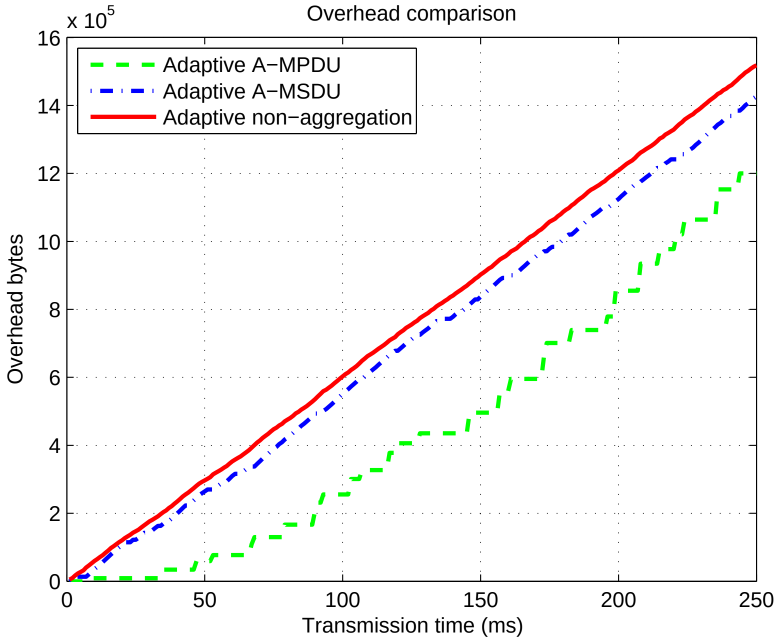

Figure 4.20: Overhead SNR$\in$(25,40dBm) length<2000 bytes

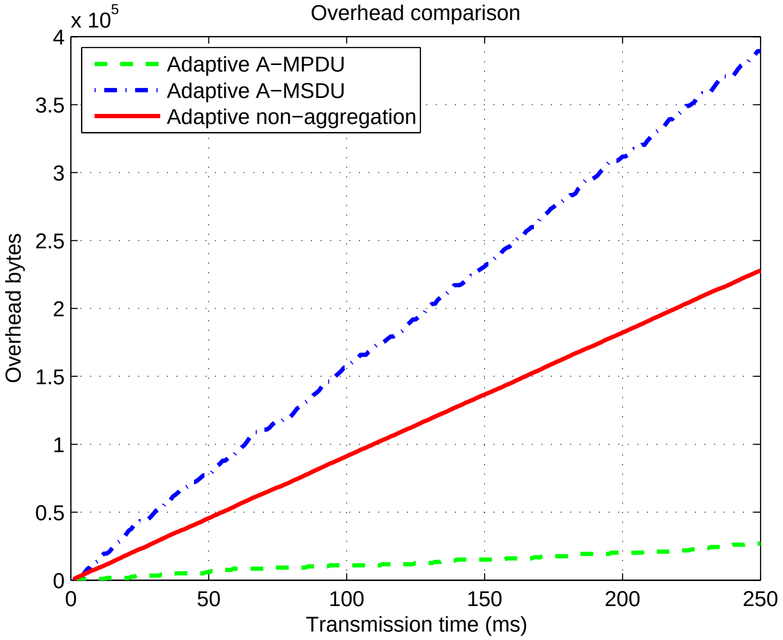

Figure 4.21: Overhead SNR$\in$(15,30dBm) length<200 bytes

4.6.3 Delay consideration

AFLAS introduces extra delay to frames when the data frames are accumulated in the vehicles. The duration of delay which is introduced by our aggregation strategy depends on:

Wireless channel status: Current signal noise ratio level directly determined the aggregation level and thus introducing delay: High SNR level may result in high volume of data packets transmission and short delay. Low SNR level leads to less data packets transmission and more packets may stay in the queues.

Queue management: Data in $Queue[0]$ always has the first priority to transmit. The latency in this queue is minimized. The data packets in other queues have to wait for the good channel status. The latency in these queues is larger than the latency without aggregation.

4.7 Conclusion

This chapter introduces an adaptive frame length aggregation scheme (AFLAS) of the MAC layer in a Vehicular Networks environment. When upper layer packets are received, our scheme accumulates these packets in different priority queues to save de-aggregation time on the relay or receiver side. We deduce the relationship between SNR and the frame length of the MAC layer according to the probability of collision and transmission error. Our aggregation algorithm is proposed to adapt the aggregated frame length to the current SNR using different priority queues. Our simulation results demonstrate that our adaptive frame length scheme outperforms non-adaptive frame length strategies with respect to data throughput, retransmissions, and transmission efficiency.

Chapter 5

Energy efficiency in Green Sensor Networks

5.1 Introduction

Many applications in Wireless Sensor Networks (WSN) are delay-tolerant, and can wait seconds or days for data transmissions in order to extend network longevity. For instance, environmental monitoring sensors collect air or water information, and transmit to data sinks when communication channels are available; mobile sensors in buses can detect road surface problems and transmit them to data headquarters; body sensors explore human body thresholds, and transmit to data center when there are data connections. Delay-Tolerant Sensor Networks (DTSNs) have become a topic of interest in industrial and academic fields. In a DTSN, the nature of sensing and data harvest is tolerate of latency. Furthermore, the delay in a DTSN may be unpredicted and can vary throughout a large range, due to intermittent connections between sensors that have duty cycle and are limited in power. Thus, DTSN environments create challenges in efficient data transmission strategies in terms of regarding energy, throughput, reliability, etc.

Energy conservation is always an essential concern in sensor networks. Most sensors operate on a battery supply, equipped with less memory and fewer computation capabilities in order to reduce energy cost. These sensors also use duty cycle to extend their battery usage, thus extending the longevity of the entire network. Many MAC and routing protocols in sensor networks are designed to decrease energy consumption as well as data transmission. Meanwhile, new recent sensor networks require multimedia support with high throughput. For instance, road surveillance or tracking applications may collect a high volume of video data from sensors, which require high throughput as well as energy conservation. Therefore, improving throughput as well as energy conservation is key for performance in delay-tolerant sensor networks.

The MAC layer is a suitable layer for improving energy conservation and throughput in DTSNs. This layer is responsible for assigning common unstable wireless channels to multiple users, and can thus manage energy consumption related to transmission and receipt of data packets within each sensor. The scheduled data transmissions in MAC protocols can improve throughput while accessing wireless channels. Therefore, MAC energy efficiency with throughput and energy consumption can be an important metric for developing new MAC strategies, such as the design of the MAC data frames, the scheduling process, and multiple access algorithms.

MAC energy efficiency is often defined as energy over time, such as Joules per second. Data throughput is defined as data packets over time, bits per second. These two metrics may not be suitable when latency in the time dimension is relaxed in delay-tolerant sensor networks. Transmission strategies in DTSNs can use data packets over energy as energy efficiency to demonstrate the efficiency under the requirements of high data volumes and energy conservation. On the other hand, improving throughput may also increase energy consumption during MAC transmissions. Sensor's duty cycle, and other MAC schemes for energy conservation often degrade throughput. The trade-off between throughput and energy consumption in the MAC layer also increases the requirements of a performance metric to evaluate energy and throughput efficiency during transmissions. Therefore, energy efficiency in DTSNs is redefined as data packets transmitted over energy consumption in this paper.

Hundreds of MAC protocols have been developed in WSN, and different schemes of MAC adjustment are used in the MAC layer. However, very little research has examined and analyzed MAC parameters from an aspect of delay-tolerant sensor environments, such as energy efficiency in DTSNs. This section aims to analyze several MAC parameters related to MAC energy efficiency in DTSN. MAC frame length, overhead and number of hops are examined in reservation-based and contention-based MAC approaches under DTSN environments. We point out the impacts of these parameters to improve MAC energy efficiency, and provide guidance for the design of new MAC strategies in DTSNs. Simulations have shown that our analysis results match the performance of energy efficiency with current MAC protocols in DTSNs.

5.2 Related work

Energy consumption has been a primary MAC design aspect in sensor networks [5]. MAC parameter impacts have been studied in relation to energy issue. Several strategies are used in many MAC protocols to save energy: reducing collisions, reducing overhead and decreasing the time of overhearing and idle listening. These strategies often affect each other within one MAC approach. For instance, in reservation-based approaches such as S-MAC [25] and T-MAC [26], which are collision-free, central nodes are often introduced to assign timeslots or channel resources to neighboring sensor nodes. Overhearing and idle listening can also be reduced with the use of a specific transmission schedule. However, reservation-based approaches require knowledge of the network topology to establish a schedule that allows each node to access the channel and communicate with other nodes; periodically listening to the synchronization and scheduling list consumes extra energy for each sensor. In addition, the central nodes are depleting quickly since they are active for a long period in order to arrange and coordinate neighboring sensors. In contention-based approaches, such as B-MAC [87], transmissions upon request instead of arrangements may conserve energy when traffic is unpredictable. Extra timeslots for synchronization and transmission may be saved, and central nodes, which coordinate the sensors, are also saved to conserve energy. However, reducing collisions in contention-based approaches depends on multiple access strategies: ALOHA, CSMA, MCSA, etc. [139]. Channel availability detection in every sensor may consume extra energy, and extra overhead messages are applied in contention-based strategies to avoid hidden terminal problems, such as Request-to-send (RTS) and Clear-to-send (CTS) [21]; high traffic density may raise high overhearing and idle listening periods in these approaches.

Much research has studied MAC impacts on throughput. Throughput can be improved by scheduling more data frames and number of transmissions during the sensor's active mode. Reducing overhead, collisions and retransmissions can also improve throughput. However, in the early stages of MAC protocols, throughput and energy conservation cannot both be satisfied [140]. Duty cycle is used in most sensor networks to save energy. It also reduces the connectivity and data transmission opportunities, thus impacting throughput. In contention-based approaches, collisions, overhead, overhearing and idle listening increase when sensor nodes have large data transmission requirements. Energy conservation and throughput conflict in these scenarios. Therefore, only low or medium traffic can be applied in contention-based

MAC approaches to ensure network longevity. Timeslots can be reserved for heavy traffic requirements in reservation-based MAC approaches to improve peak throughput performance; thus, energy may waste after peak data transmissions, when extra timeslots are scheduled and overhearing and idling listening increases.

Recent research has begun to focus on adaptive energy conservation to varying traffic demands. Z-MAC [49] combines the strengths of TDMA and CSMA to achieve high channel utilization and low latency in high contention areas with TDMA, and low duty cycle and fewer collisions in low contention areas with CSMA at a low energy cost. [141] also uses an adaptable CSMA/TDMA hybrid channel access method, by applying some modifications to the 802.15.4 standard to improve energy and throughput. EM-MAC (Efficient Multichannel MAC) [142] protocol avoids using individual channels that are currently heavily loaded, by enabling sensor nodes to dynamically select wireless channels based on the channel conditions without using any reserved control channel. PIP (Packets in Pipe) [143] is another MAC protocol using the transport module to achieve high throughput in multi-hop, TDMA-based sensor networks. However, there is no indicator for evaluating energy and throughput efficiency among these MAC protocols.

Energy efficiency is defined in different scenarios in sensor networks. For example, energy efficiency uses the sum of total transmitting power and coordinating power when one data packet is transmitted in WSNs [144]. Reliability is correlated with energy consumption as energy efficiency in [145]. In a delay-tolerant environment where delay constraint is loosened, throughput improvement is limited to energy consumption, which is important to the longevity of the entire network. Since very few MAC protocols discuss data packet transmissions and energy consumption simultaneously, we view the energy efficiency indicator as data packets transmitted over energy consumption in delay-tolerant sensor networks, to evaluate management and transmission effectiveness of MAC protocols.

5.3 A Network model

We consider a random network model similar to that introduced by Gupta and Kumar [146]. There are M mobile sensor nodes distributed uniformly in a random 3-dimensional area with the density of ρ. Each node transmits at a constant bit rate *Rate* bits per second to a chosen destination.

The mobility model of these sensors can vary according to application requirements [6]. For instance, the randomly way-point model randomly selects destination, speed, and pause duration; the i.i.d. mobility model has no motion constraints; and the random walk model selects the next position from current neighboring positions. Mobility models affect the number of hops and transmission routes, which may be experienced by the data transmission in the MAC layer of wireless networks. Since the i.i.d. mobility model is used in general wireless network scenarios, we choose the i.i.d. mobility model in our simulations.

According to the wireless channel path loss models, the transmission range r is specified with the transmission power of these sensors and network requirements of Signal-to-Noise Ratio(SNR). With the node density ρ and node distributions (assuming that the nodes are uniformly distributed), the number of neighbors n around one node is $(\pi \times r^2)\rho - 1$. The number of nodes M in one area is directly related to the node density ρ.

In this paper, a transmission model without retransmissions is used to simply the analysis. An acknowledgment message may be applied to the MAC protocols of this model. Since broadcast, multicast and unicast are widely used in the MAC protocols of sensor networks, we consider them in the scheduling and management aspects of MAC strategies. In the section relating to data transmission, we calculate only unicast throughput and energy consumption as a result of simplifying our computation.

5.4 MAC Energy efficiency in DTSN

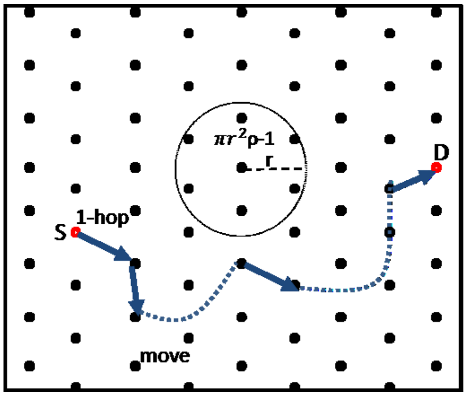

Figure 5.1: Data transmission in a DTSN

In this chapter, MAC energy efficiency is calculated in two types of MAC protocols to demonstrate the impact of the MAC parameter design in DTSN: reservation-based and contention-based. Since TDMA and CSMA are the typical MAC protocols of these two types, we use them as the basic schemas for analyzing energy efficiency.

Figure 5.1 shows the data transmission steps in a DTSN. The source node carries data frames and waits for transmission opportunities within its coverage range r. When the data frames are transmitted to the relay nodes, they are carried by this relay node, which forwards these data frames. After several hops, the data frames may reach their destination of data sink.

5.4.1 TDMA-based MAC energy efficiency

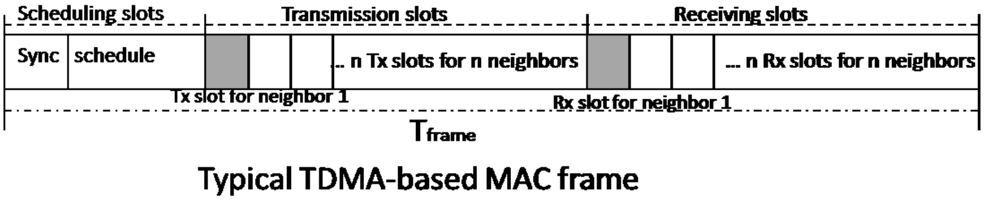

Figure 5.2: TDMA frame structure

In TDMA, sensor nodes are synchronized with one central node according to their current locations. The mobile nodes can only send or receive data frames to or from their nearest central node. We first calculate one-hop-throughput for a singer node or multiple nodes. Throughput for multi-hop source-to-destination transmissions can be calculated by the entire one-hop-throughput over the average number of multiple hops.

The basic TDMA frame structure shows the common slots of scheduling parts and synchronizing parts, and slots for transmissions in this area (Figure 5.2). Each node listens to the common slots to synchronize, and obtains a scheduling list. Then, it can find its particular transmission slot for sending or receiving packets.

As we relax the delay requirements, the scheduling strategy for latency is not considered in DTSN. The length of overhead messages, which include the synchronization and scheduling components, affect both the throughput and the energy consumption. We use α to represent the percentage of the overhead messages. The time for the synchronization and scheduling parts counts for $\alpha \times T_{frame}$, where T_{frame} is the time duration for transmitting this entire frame. Tx and Rx slots are data transmission slots for all the neighbor nodes around the central node. The time duration of these transmission slots is $(1-\alpha) \times T_{frame}$. Since there are n neighbors to use these slots, one-hop-throughput for one user can be described as below.

$$Th_{T-one-hop} = \frac{T_{slot} \times Rate}{T_{frame}} = \frac{Rate \times (1-\alpha)}{n} \tag{5.1}$$

Therefore, the entire one-hop-throughput for multiple users in this area can be described as $Rate \times (1-\alpha)$.

The overall source-to-destination throughput in multi-hop links of this area depends on the number of hops required for data communications. The number of hops for one data communication is determined by:

1. The distance between the source nodes and the destination node;
2. The density of nodes;
3. The mobility of the source, destination and the relay nodes;
4. The method of choosing candidate senders or receivers in the MAC schemes.

In the TDMA strategy, the scheduling algorithms may affect the number of hops, in that the unscheduled nodes may move out of this area and seek other opportunities to send or relay the data packets. We use No_{hops} to describe the average number of hops that are experienced during one data communication. Therefore, the overall throughput for source-to-destination transmissions under the TDMA MAC scheme can be described as follows:

$$Th_{TDMA} = \frac{Rate \times (1-\alpha)}{n \times No_{hops}} \tag{5.2}$$

The energy consumption in a basic time unit in different modes of a sensor can be described as transmitting E_{t0}, receiving E_{r0}, listening E_{l0} and sleeping E_{s0}. Since listening consumes almost the same amount of energy as receiving, we replace E_{l0} with E_{r0}. The energy consumed in sleeping mode is far less than in transmitting and receiving; therefore, we treat E_{s0} as 0 in this chapter. To simplify the equations, E_{t0} and E_{r0} can be exchanged with a constant γ with $\gamma \geq 1$ when $E_{t0} = \gamma \times E_{r0}$. Therefore, we can use γ and E_{r0} as the basic unit for calculating energy consumption in TDMA-based MAC schemes.

During synchronization and scheduling, there are one transmitter (central node) and multiple receivers (neighbor nodes). The average energy consumption for one user in this component can be calculated as below.

$$E_{sync+schedule} = \alpha \times (E_{t0} + n \times E_{r0})/n \tag{5.3}$$

Data transmission in one hop for one user requires one slot transmission and one slot acknowledgment. Therefore, energy consumption in the data transmission component can be calculated as below:

$$E_{dataslots} = 2(1-\alpha)(E_{t0} + E_{r0}) \tag{5.4}$$

The energy efficiency can be described as teh average value of throughput over energy consumption for every user through this communication link.

$$TE_{TDMA} = \frac{Throughput}{Energy} = \frac{\frac{Rate \times (1-\alpha)}{n \times No_{hops}}}{E_{sync+schedule} + E_{dataslots}} \tag{5.5}$$

We replace E_{t0} with γ and E_{r0} and arrange the formula as follows:

$$TE_{TDMA} = \frac{Rate}{No_{hops}E_{r0}} \frac{n(1-\alpha)}{n(2+2\gamma+\alpha(2\gamma-1))+\alpha\gamma} \tag{5.6}$$

As seen in the equation 5.6, energy efficiency in TDMA is a hyperbola function of n (the number of neighbors nearby in a MAC frame), when data rate and number of hops are steady. The function of energy efficiency TE_{TDMA} increases according to the number of nodes n. Therefore, in the TDMA MAC strategies, if the overhead part α has a relatively stable increase in the number of nodes, the energy efficiency depends largely on the node density in the networks when the data rate and number of hops are steady.

We can conclude that these MAC parameters in the TDMA scheme from the above equations:

1. Energy efficiency in the TDMA scheme demonstrates better performance when node density is high.

2. Fewer overhead messages, including synchronous and scheduling messages, will

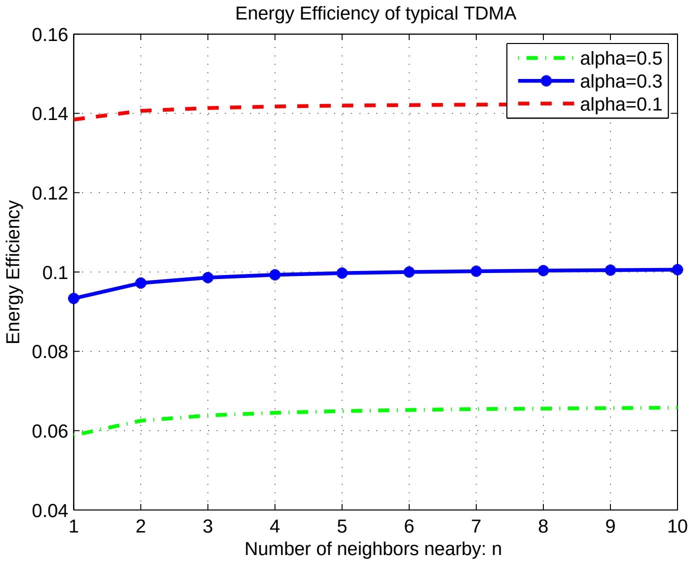

Figure 5.3: Energy efficiency in TDMA

result in an increase in energy efficiency.

3. MAC scheduling algorithms, which reduce the number of hops in one packet transmission, will increase energy efficiency.

5.4.2 CSMA-based MAC energy efficiency

In a contention-based CSMA-CA approach, sensor nodes compete for the use of the wireless channels, and only the winner of this competition is allowed to access the channel and transmit. A node holding data packets to transmit first senses the channel before initiating the transmission. When the node finds the channel busy, it postpones its transmission to avoid interfering with the ongoing transmission. If the node finds the channel clear, it starts transmitting after the back-off time. CSMA is robust to node mobility and scalable to large networks, because this strategy does not rely on central nodes. We can calculate energy efficiency through a typical CSMA frame structure and procedure, shown in Figure 5.4.

The number of hops in the CSMA scheme depends on the collision avoidance method to select the senders or receivers, as well as the distance from the source and destination and their mobility patterns.

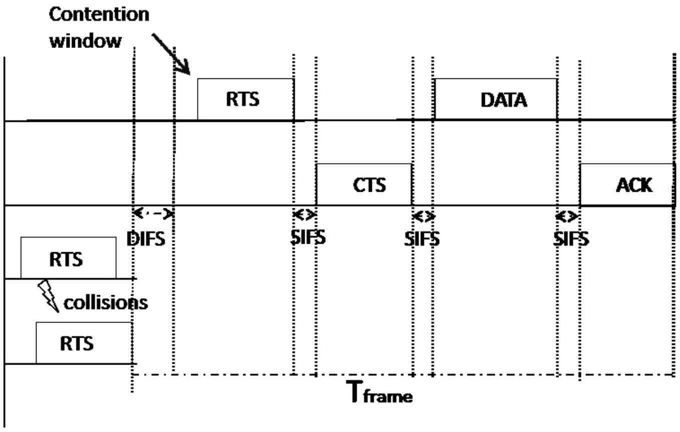

Figure 5.4: Typical CSMA frame structure and procedure

One-hop-throughput for one user in CSMA can be described as

$$Th_{C-one-hop} = \frac{T_{data} \times Rate}{T_{frame}} \times (1 - P_c) \tag{5.7}$$

where P_c is the collision probability when transmitting RTS in a contention-based environment. T_{frame} is the time duration of a one-hop transmission for one data packet. T_{frame} can be described as below.

$$\begin{aligned} T_{frame} =& DIFS + 3 \times SIFS + (CW_{min}/2) \times T_{slot} \\ &+ T_{RTS} + T_{CTS} + T_{Data} + T_{ACK} \end{aligned} \tag{5.8}$$

where $DIFS$ is the DCF Inter-frame Space; $SIFS$ is Short Inter-frame Space; CW_{min} is the minimum of the contention window. T_{slot} is the basic unit of timing for the protocol. T_{RTS}, T_{CTS}, T_{Data}, and T_{ACK} are the duration of transmissions for RTS, CTS, Data, and ACK respectively.

We introduce a variable β to specify the percentage of overhead messages in T_{frame}. Therefore, $T_{data} = (1 - \beta)T_{frame}$. We also introduce another variable m as the percentage of RTS parts in the overhead message. $m\beta T_{frame}$ is the time duration of the RTS transmission. One-hop-throughput in this CSMA structure is shown below:

$$Th_{C-one-hop} = (1 - \beta)(1 - P_c)Rate \tag{5.9}$$

The overall throughput through multiple hops can be calculated as:

$$Th_{CSMA} = \frac{(1-\beta)(1-P_c)Rate}{No_{hops}} \tag{5.10}$$

The energy consumption of one-hop transmission can be calculated as seen below. The time period in RTS transmission and the contention back-off period are multiple receivers or listeners with $(1 + P_c)$ transmissions. The energy consumption here is described as follows:

$$E_{RTS} = m\beta \times (E_{t0}(1 + P_c) + n \times E_{r0}) \tag{5.11}$$

The relationship between energy consumption and CTS, DATA and ACK frames is one-sender-one-receiver.

$$E_{other} = (1 - m\beta)(E_{t0} + E_{r0}) \tag{5.12}$$

The energy efficiency of one user in CSMA can be calculated as seen below.

$$TE_{CSMA} = \frac{\frac{(1-\beta)(1-P_c)Rate}{No_{hops}}}{m\beta(E_{t0}(1 + P_c) + nE_{r0}) + (1 - m\beta)(E_{t0} + E_{r0})} \tag{5.13}$$

We also use γ as the energy constant as above, and rearrange the equation:

$$TE_{CSMA} = \frac{Rate}{No_{hops}E_{r0}} \times \frac{(1-\beta)(1-P_c)/m\beta}{n + (\gamma + \gamma P_c - 1) + \gamma/m\beta} \tag{5.14}$$

Energy efficiency in CSMA is a function of node numbers n and collision probability P_c. According to Bianchi [135], the collision probability P_c is calculated by:

$$P_c = 1 - (1 - \tau)^n \tag{5.15}$$

where τ is the transmission probability in a virtual slot, and n is the number of neighbors existing in this slot. We can use it to demonstrate the relationship between energy efficiency and the number of nodes. Figure 5.5 shows the decreasing features of energy efficiency in CSMA when the number of neighbor nodes increases.

Equations 5.14 and 5.15 also show that collision avoidance algorithms may reduce

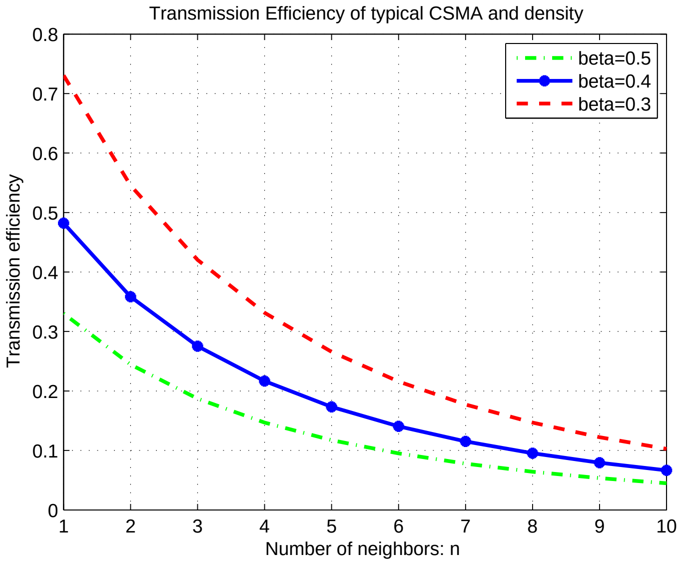

Figure 5.5: Energy efficiency in CSMA

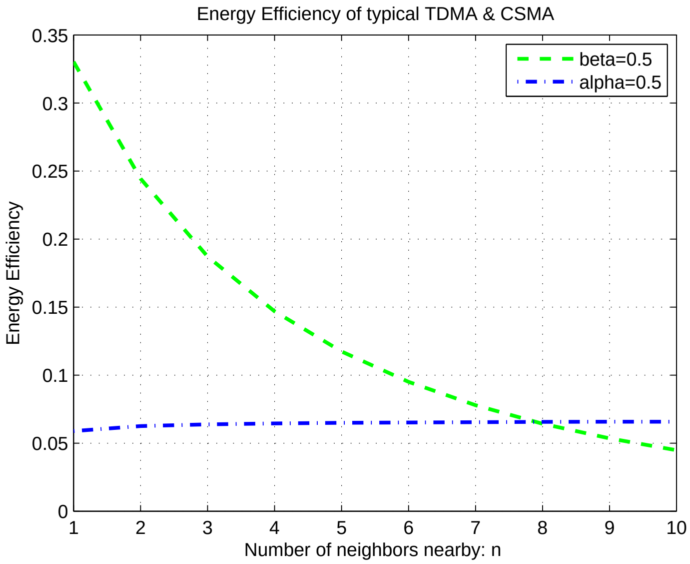

Figure 5.6: Energy efficiency comparison in TDMA and CSMA

τ, thus improving energy efficiency in CSMA schemes. At a certain point below the number of neighboring nodes, the energy efficiency in TDMA becomes lower than in CSMA. With the increase in the number of neighboring nodes, energy efficiency in TDMA is higher than in CSMA (Figure 5.6).

We also conclude these MAC parameters in the CSMA scheme from the above equations:

1. Energy efficiency in the CSMA scheme demonstrates better performance when the node density is low.
2. Fewer overhead messages that include collision detection components and control frames will result in an increase energy efficiency. Aggregation algorithms that reduce overhead will improve energy efficiency in CSMA.
3. MAC scheduling algorithms, which reduce the number of hops in one packet transmission, will increase energy efficiency.

5.5 Simulations

We use M-TDMA [50] and IEEE 802.11 [21] MAC as typical TDMA and CSMA MAC protocols, to simulate the impact of the MAC parameter on energy efficiency in DTSN. The simulations include N ($1 \leq N \leq 100$) mobile nodes, which are randomly set in a $2000m \times 2000m$ NS2 simulator. A tworayground fading model and i.i.d. mobility model are used in this simulation. Data packets of K bytes are randomly generated per millisecond among these mobile nodes to deliver to their destination nodes. K is the number of bytes of one data packet that can change the percentage of the overhead message (α or β). We record the number of receiving packets in one specific destination node from one source node, as well as the energy consumed through this delivery route. Energy consumption in transmitting, receiving, idling and sleeping are all included in these simulations. The simulation runs 100 times for each MAC protocol, with a different number of M mobile nodes.

In M-TDMA protocols (Figure 5.7), energy efficiency (throughput over energy consumption) increases when the number of nodes M in the area increases. When the percentage of data packets increases, energy efficiency improves in M-TDMA, which matches the analysis of our TDMA scheme. From the simulation results in IEEE 802.11 (Figure 5.8), energy efficiency decreases when the number of nodes increases. When overhead messages decrease, energy efficiency also increases in the 802.11 scheme. These results also match our analysis in the CSMA scheme.

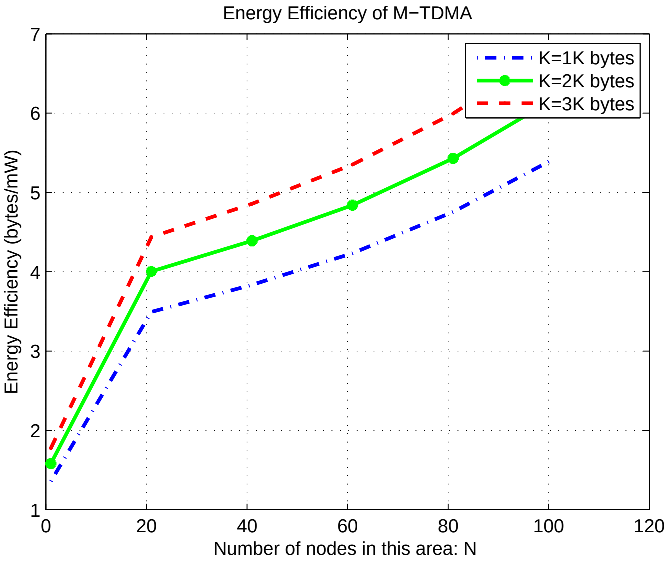

Figure 5.7: Energy efficiency in M-TDMA

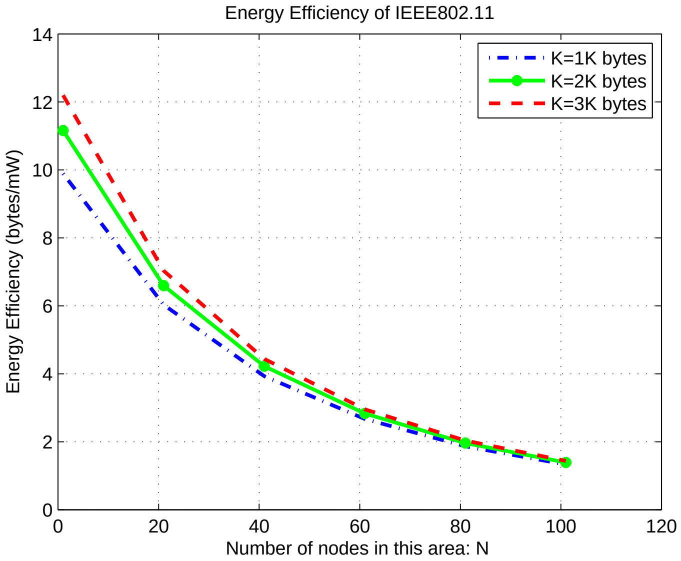

Figure 5.8: Energy efficiency in IEEE 802.11

5.6 Conclusion

Energy efficiency is essential for designing and evaluating MAC transmission strategies in DTSN environments. We redefine energy efficiency that represents data packets transmitted over energy consumption as one metric for evaluating the performance of MAC protocols. The MAC parameters related to energy efficiency are analyzed to provide a guide to develop MAC strategies in DTSN. Simulation results of two typical MAC protocols also show that MAC parameters impact energy efficiency match our analysis.

Chapter 6

Traffic Adaptive Energy Efficient MAC Protocol

6.1 Introduction

A large number of applications have been developed within delay-tolerant sensor networks (DTSNs) for various purposes such as supervising and managing resources, animal migrations and national borders. These applications allow unpredictable and longer delays with data transmissions within static and mobile environments. For instance, accelerometer sensors are used to monitor the structural integrity of bridges and buildings in [147]. Volcano activities are recorded using seismic and infrasonic sensors in [148]. The activities of sea birds are monitored in [149] via data collected from sensors detecting humidity, temperature, barometric pressure, and light. Agricultural activities are also examined through various sensors that measure temperature, humidity, and pH to obtain efficiency of using irrigation, herbicides, pesticides, and fertilisers [150], [151]. Various applications in DTSN employ static or mobile sensors to detect environmental and natural changes, as well as human activities in agriculture, industrial environmental areas.

Meanwhile, the sensors in DTSN applications have energy constraint, as they use battery powered chips, and energy is essential to network longevity. This requirement has resulted in hundreds of energy saving MAC protocols for sensor networks. Certain MAC protocols in sensor networks provide low energy consumption schemes with low traffic support, such as S-MAC and TRAMA. Some MAC protocols trade energy for throughput and delay performance. When delay is relaxed in the DTSN, new challenges arise involving energy and data transmission. Data transmissions consider energy consumption when transmitting certain amounts of data packets. Throughput is not enough to evaluate data transmission efficiency, since it is related to latency.

MAC strategies in DTSNs require energy efficiency in transmitting and receiving the collected data.

With the multimedia applications, a higher,unevenly traffic load in DTSN has become common, which is another challenge in energy efficiency for traditional MAC strategies. Traffic load is often diverse in wide ranges. Most sensors generate data packets periodically or in an event-based manner. These sensors may be in a very low traffic environment for a long period when less data is generated. When a specific event occurs, these sensors may generate a high volume of data, which requires MAC protocols to be processed in an efficient way. Reservation-based MAC strategies can accommodate heavy traffic load with considerably higher energy consumption. Contention-based MAC protocols perform well at conserving energy in low traffic environments, and experience higher energy consumption, as well as collisions and contentions, which decrease transmission efficiency. Traffic adaptive MAC strategies are the main solutions for improving energy efficiency.

Sensor mobility in DTSN brings an additional challenge to MAC protocols, with changes in topology and traffic distribution. Moving sensors without specific trajectories forms an unpredicted topology. Gathering mobile sensors also create a higher traffic load area, while scattered sensors may hardly find neighbors with which to communicate. Fixed central nodes experience frequent changes of neighbors, and require more coordinating time and flexible scheduling algorithms. Ad-hoc connected nodes may consume more energy when traffic and contentions are high. MAC approaches within DTSN environments should consider mobility, as well as topology compatibility and traffic load variety, in order to achieve energy-efficient performance.

We propose a novel, traffic adaptive, energy-efficient MAC protocol for the DTSN environment. This protocol considers both contention-based and reservation-based MAC approaches, and combines them under static or mobile sensor networks. The aim of the protocol is to provide a highly energy-efficiency scheme to minimize energy consumption with various traffic load and data transmission requirements. The contributions of our MAC solution are found in three aspects.

- We use queueing models to analyze reservation-based and contention-based MAC approaches regarding throughput, energy consumption and energy efficiency. The results of the analysis forms the cornerstone of our proposed MAC protocol.
- We propose a novel MAC protocol that can switch the working mode between

contention-based and reservation-based modes to cope with traffic changes. The duty cycle can also be adjusted to facilitate the traffic load.

- Simulations and comparisons with current traffic adaptive MAC approaches are conducted to demonstrate the superior performance in energy efficiency under DTSN environments.

The chapter is organized in the following manner. Section 6.2 introduces the current research in traffic adaptive MAC approaches. Section 6.3 analyzes contention-based and reservation-based MAC protocols from an energy efficiency perspective. Section 6.4 proposes our MAC protocol with work flow and process. Section 6.5 shows the simulation and performance results compared to other MAC protocols. Finally, Section 6.6 concludes the chapter.

6.2 Related Work

Various MAC strategies have been developed in recent years within sensor networks to work under different traffic loads. MAC parameter adjustment is one of direct approaches to cope with various traffic loads.

Burst transmissions [152] introduce an auto-adaptive algorithm that can adjust its sampling period and preamble length with different traffic patterns in body sensor networks. This mechanism auto-adapts to the current network traffic, and is energy-efficient during burst transmissions by establishing energy-efficient communications over certain paths toward the sink station. The TaMAC [153] protocol is another MAC scheme developed for a star topology of Wireless Body Area Networks (WBAN), where a central coordinator controls the entire operation of the network. The coordinator schedules and allocates resources to the nodes using their traffic patterns. In the event of emergency and on-demand traffic, resources are allocated using a wakeup radio mechanism. The scheme achieves low power consumption and desired Quality of Service (QoS) for all types of traffic using the TDMA concept. As a result of central fixed coordinators with TDMA concepts, burst transmission [152] and TaMAC [153] are not feasible for use in mobile sensor networks.

ATLAS [154] exploits the superframe structure of the IEEE 802.15.4 standard, and it adaptively uses the contention access period (CAP), contention free period (CFP), and inactive period (IP) of the superframe based on the estimated traffic load in WBAN. ATLAS uses the network capacity as the most decisive parameter for adjusting traffic load status in order to provide better energy efficiency, high capacity utilization and minimal delay. Another approach, PLA-MAC [155], also uses an adaptive super-frame structure depending on the amount of traffic load, and thereby ensures minimal power consumption. The limitation of the WPAN topology constraints ATLAS and PLA-MAC for general applications in DTSN.

The TRaffic-Adaptive Medium Access (TRAMA) [156] protocol is one of the pioneering MAC strategies which provides traffic adaptive schemes to save energy in sensor networks. TRAMA uses a scheduling-based, collision-free access approach, similar to S-MAC, with local synchronization. It employs a traffic adaptive distributed election scheme that selects receivers based on schedules announced by transmitters. Sensors exchange their neighborhood information and the transmission schedules specifying which nodes are the intended receivers of their traffic, then selects the nodes that should transmit and receive during each time slot. TRAMA uses an adaptive, dynamic approach based on current traffic patterns to switch nodes to a low power mode, thus saving energy consumption. However, the traffic adaptability only applies to a certain range in which the traffic is relatively high. In addition, local synchronizing and scheduling exhausts local center nodes in TRAMA, and consumes a great deal of energy if the traffic is very low. This has resulted in more efforts to include MAC strategies in diverse traffic environments.

Some MAC protocols suggested that the hybrid models for the MAC layer of wireless sensor networks take advantage of both reservation-based MAC and contention-based MAC protocols to adapt to different traffic patterns and loads. Contention-based MAC protocols, such as the slotted CSMA/CA, exhibit low energy consumption and efficiency in low density traffic areas, and also cause lower network throughputs due to the collisions resulting from multiple simultaneous transmissions in areas of heavy traffic. Reservation-based MAC protocols such as TDMA offer good throughput in heavy traffic load scenarios, exhaust central coordinating nodes, and consume high energy in synchronization and scheduling processes when the traffic is low. Therefore the hybrid of these two schemes fosters diverse traffic adaptability in the MAC layer.

Gilani et al. [141] propose a hybrid MAC protocol based on IEEE 802.15.4 standard to reduce energy consumption and improve data throughput in the current IEEE 802.15.4 standard. In this method, the coordinator adaptively divides the contention access period (CAP) between slotted CSMA/CA and TDMA, according to the nodes' data queue state and the level of collisions detected in the network. Data frame reserved bits have been used to acquire the queue state information from the network nodes. The protocol cannot provide general strategies in mobile DTSN due to the limitation of relatively fixed topology in WBAN.

iQueue-MAC [157] is another MAC approach which runs in CSMA in light load and TDMA in heavy load. When the load increases, the senders' queue length will be used to dynamically allocate time slots to the senders (TDMA) according to the queue length of each sensor node. During light traffic periods, iQueue-MAC works as CSMA MAC with low duty-cycle to conserve power. However, sensor mobility is not considered to implement the protocols.

The Intelligent Hybrid MAC (IH-MAC) [158] is a hybrid MAC protocol that combines CSMA, the broadcast scheduling and link scheduling dynamically to improve energy efficiency. It also reduces energy consumption by suitably varying the transmission power, and reduces latency by exploiting the concept of parallel transmission. However, latency reduction and energy conservation strategies in this protocol are not suitable for delay-tolerant sensor networks. The hybrid strategy can be applied in DTSN for purposes of increasing energy efficiency.

Duty cycle is widely used in sensor networks to save energy, reduce latency and improve throughput. Byun et al [159] propose an adaptive duty cycle control mechanism based on queue management for power saving and delay reduction. The scheme uses the local queue length to indicate traffic variations or changes in network conditions and provides a control-based MAC approach with a distributed duty cycle to conserve energy and reduce latency. Self-Adaptive Duty Cycle MAC (SEA-MAC) [160] is another duty cycle adjustable scheme which makes the nodes active duration adaptive to variable traffic load. The SEA-MAC strategy is designed to schedule more data transmissions in bursty and high traffic loads to reduce latency, and assign nodes into Sleep mode timely under the light traffic load to save energy. However, rather than latency, energy efficiency is more essential in delay-tolerant environments [120, 130]. We could adjust the duty cycle to improve energy efficiency in DTSN.

6.3 Energy efficiency of MAC Protocols

MAC protocols are designed to share common wireless channels between many sensor nodes, and manage communication in the MAC layer. There are two major prototypes of MAC approaches, according to the methods of access to the medium: contention-based and reservation-based approaches [5]. In reservation-based approaches, some nodes periodically send synchronization packets to inform neighboring nodes about time cycle, address, frame length, scheduling list etc. The neighboring nodes listen to the channel for synchronization packets, then follow the cycle. From the synchronization and scheduling frames, the listener may find a transmission opportunity for a sender or a receiving slot from the scheduling list. Multiple transmissions can be scheduled during the contact period. In a contention-based approach without global synchronization, sensor nodes compete for the use of the wireless channels, and only the winner of this competition is allowed to access the channel and transmit, enabling rapid dissemination of data and reduction of latency. Within the light traffic load, nodes enter the sleep mode in a timely manner, mitigating idle listening and conserving energy. When the node finds the channel busy, it postpones its transmission to avoid interfering with the ongoing transmission. If the node determines the channel is clear, it starts transmitting after back-off time.

Fig.6.1 shows the scenarios of using two major MAC approaches within a sensor's transmission range: Reservation mode and Contention Mode. Multiple transmissions can be performed in reservation-based protocols simultaneously, while at most one transmission can be set up in a contention-based MAC approach within the sensors' transmission range.

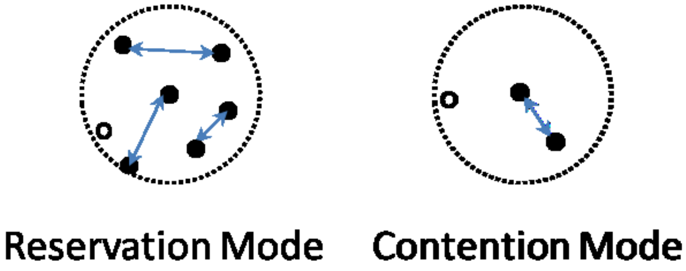

Figure 6.1: Scenarios of using reservation-based or contention-based MAC

Queueing theory can be applied to analyze the traffic adaptability and energy efficiency of MAC approaches in sensor networks. Since the sensors may collect data either periodically or in an event-based manner, the data traffic load vary even with static sensors. In addition to mobile sensors, which form uneven traffic distributions in sensor networks, the traffic load may diversify in a large range. Therefore, the arrival of data packets to the MAC can be treated as a random distribution in the queueing model. As MAC approaches provide channels for transmission among sensors, these channels can be treated as the servers in a queueing model. The transmission time for each data packet varies depending on the size of the packet, which is the service time in a queueing model. At the same time, energy consumption can be derived from the serving time and waiting time for MAC data transmissions. Therefore, by using the queueing theory under different traffic loads, we can analyze energy consumption as well as the number of data packets transmitted to indicate energy efficiency in reservation-based and contention-based approaches.

We suppose that sensors generate data packets in the system with rate $\lambda = \gamma N$, where N is the number of sensors in the system and γ is the generation rate of data packets for one sensor. We assume that data packets arrive in the MAC layer according to Poisson process with rate λ, which means the inter-arrival times are independent, exponentially distributed random variables with parameter λ. The service time of data packets is also assumed to be independent and exponentially distributed with parameter μ, where μ is the average transmission time for one data packet. Furthermore, all involved random variables are supposed to be independent from one other.

In a contention-based MAC approach, at most one transmission occurs between sensors within their transmission range. An $M/M/1$ queueing model can be used with memoryless random traffic arrivals and random service time (transmission and receiving time in sensors' scenario). Since at most one connection can be set up for transmission in contention mode, the connections between two sensors is referred to as one server in a queueing model. When $\lambda/\mu > 1$, the system is overloaded because the arrivals occurs faster than the leaving packets. This indicates the needs of more transmission channels in the MAC layer.

In a reservation-based MAC approach, the coordinating sensor schedules multiple connections among sensors within the transmission range of the central sensor to boost transmissions in high traffic load scenarios. Maximum c connections among sensors can be scheduled by the coordinator, referred to as c servers in an $M/M/c$ queueing model. Arrivals occur at rate λ according to a Poisson process in the $M/M/c$ queues.

$$\lambda_k = \begin{cases} \lambda, & \text{if} \quad k < c, \\ 0, & \text{if} \quad k \geq c. \end{cases} \tag{6.1}$$

We suppose that each data frame in the MAC layer has the same size of L_{data} bytes. Every incoming data packet can be divided into i frames according to length where $\hat{i}$ is the expectation value of i. Therefore, the average processing time for each data packet μ is the multiplication of $\hat{i}$ and the transmission time for a MAC frame T_{dc}. We suppose that processing times for MAC frames have an exponential distribution with parameter μ in the $M/M/1$ and $M/M/c$ queues.

$$\begin{aligned} &\mu = \hat{i} * T_{dc} \quad \text{in M/M/1 queue} \\ &\mu_k = k\mu, \quad \text{k=1,2,...,c.} \quad \text{in M/M/c queue} \end{aligned} \tag{6.2}$$

Suppose the typical MAC frames and process in reservation-based and contention-based MAC frames are listed as indicated in Fig. 6.2. In reservation mode, each sensor should wake up and listen to the synchronization ($SYNC$) and scheduling ($SCHED$) frames. When a sensor has data to send, it first sends a request to the central coordinator and waits for the scheduling list in $SCHED$. When a sensor hears the scheduling list and locates its transmission slot, it transmits or receives data frames in that specific timeslot. The sensors then enter inactive mode when they finish transmitting and receiving to save energy. When a sensor hears no allocation slots for it in $SCHED$, it turns to inactive mode until the duty cycle T_{dc} completes.

In contention mode, the sensors with data to send contend for transmission by first listening to the channel, and broadcasting RTS if the channel is clear. If collision occurs, the sensors wait for a random period and re-send RTS, the receiver responds to the sender with CTS when it hears RTS, and the CTS also inhibits other sensors from accessing the channel in this transmission range. The winning sender transmits $DATA$ frames and the receivers use ACK as positive acknowledgement of receipt of the data. Sender and receiver may then both enter inactive mode until this duty cycle T_{dc} ends.

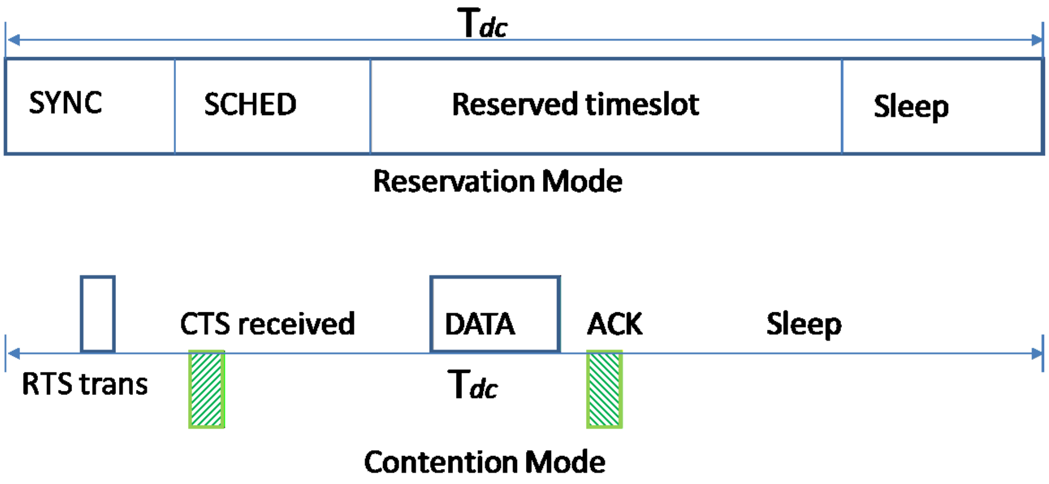

Figure 6.2: Reservation-based and contention-based MAC frame structure

6.3.1 Throughput Analysis

In DTSN, throughput is often compromised by energy, latency, fairness, reliability or scalability. However, when latency is relaxed in DTSN scenarios, the number of data bytes that have been transmitted is essential for evaluating energy efficiency for MAC protocols. We use DT as the data packets transmitted over a certain period of time.

Since we assume that the data with arriving rate λ will be transmitted though the MAC protocols, the data bytes transmitted in contention mode DT_c and reservation mode DT_r are λT where T is the time period we examined.

$$DT_c = DT_r = \lambda T \tag{6.3}$$

6.3.2 Waiting Time

Even though latency is relaxed in DTSN, the waiting time for a data transmission is still important for the considerations of energy conservation. When a sensor waits for transmission opportunities, it competes and listens to other sensors until it obtains the channels. The energy consumption during this period should also be considered for evaluating a MAC protocol.

Contention mode

According to the mean queue length of $M/M/1$ queueing model, the mean waiting time W_c for one data packet can be described as the waiting queueing length in the MAC layer in contention mode.

$$W_c = \tfrac{\varrho^2}{1-\varrho} \tag{6.4}$$

where ϱ is equal to λ/μ to simplify equations.

Reservation mode

In a $M/M/c$ queue model, the waiting probability is referred to as Erlang C formula $C(c,\varrho)$. The mean queue length in the reservation mode is waiting time W_r.

$$C(c,\varrho) = \frac{\frac{\varrho^c}{c!}\frac{c}{c-\varrho}}{\sum_{k=0}^{c-1}\frac{\varrho^k}{k!} + \frac{\varrho^c c}{c!(c-\varrho)}} \tag{6.5}$$

$$W_r = \frac{\varrho}{c-\varrho}C(c,\varrho) \tag{6.6}$$

6.3.3 Energy Consumption

In typical sensor applications, the energy consumption is dominated by the nodes' radio consumption [5]. Since the radio is controlled by the MAC, the MAC is central to optimizing the lifetime of WSN. It can be concluded that power consumption in sleeping mode is negligible to the power consumption in active mode. Thus, we only consider the sensors' energy consumption of active radio as transmitting, receiving and listening. We use E_{t_0} as the energy consumed in transmitting during one millisecond, and E_{r_0} as the energy consumed from receiving and listening during one millisecond, since radios in states of receiving and listening consume similar amount of energy.

Contention mode

The energy consumption during a duty cycle T_{dc} in contention mode contains energy for transmitting and receiving RTS/CTS/DATA/ACK frames, the collisions of RTS, and inter-frame listening. Since the sensor may not always have data to send, energy consumption should also consider the busy time of this sensor.

$$\begin{aligned}
EC_{c-busy} &= P_{c-busy}(E_{rts} + E_{cts} + E_{data} + E_{ack} + E_{ifs}) \\
E_{rts} &= (1 + P_{c-c})(E_{t_0} + kE_{r_0})L_{rts} \\
E_{cts} &= (E_{t_0} + kE_{r_0})L_{cts} \\
E_{data} &= (E_{t_0} + E_{r_0})L_{data} \\
E_{ack} &= (E_{t_0} + E_{r_0})L_{ack}
\end{aligned} \tag{6.7}$$

where E_{rts}, E_{cts}, E_{data}, and E_{ack} are the energy consumption for transmitting and receiving RTS/CTS/DATA/ACK frames respectively. E_{ifs} is the energy consumption of inter-frame listening during one duty cycle. L_{rts}, L_{cts}, L_{data}, and L_{ack} are the time lengths of RTS/CTS/DATA/ACK frames. k is a integer indicating the number of possible listeners for RTC/CTS frames, and k is a function of coverage radius r and the density N/S_{area} of the sensor nodes.

$$k = (\frac{N}{S_{area}})\pi r^2 \tag{6.8}$$

According to Bianchi [135], the conditional collision probability in CSMA is calculated by:

$$P_{c-c} = 1 - (1 - \tau)^{k-1} \tag{6.9}$$

where τ is the transmission probability in a virtual slot.

The mean busy period of the $M/M/1$ model in contention mode is as follows:

$$P_{c-busy} = \frac{1}{\mu - \lambda} \tag{6.10}$$

where $\mu > \lambda$ which indicates that the system is not overloaded.

The energy consumption during the waiting time in one duty cycle is:

$$EC_{c-wait} = W_c(E_{RTS} + E_{CTS}) \tag{6.11}$$

The energy consumption in contention mode during a time period T is:

$$EC_c = (EC_{c-busy} + EC_{c-wait}) \times T/T_{dc} \tag{6.12}$$

Reservation mode

The energy consumption during one duty cycle in reservation mode contains energy for transmitting and receiving $SYNC/SCHED/ReservedTimeslot$.

$$\begin{aligned} EC_{r-busy} &= P_{r-busy}(E_{sync} + E_{sched} + mE_{rt}) \\ E_{sync} &= (E_{t_0} + kE_{r_0})L_{sync} \\ E_{sched} &= (E_{t_0} + kE_{r_0})L_{sched} \\ E_{rt} &= (E_{t_0} + E_{r_0})L_{timeslot} \end{aligned} \tag{6.13}$$

where E_{sync}, E_{sched} and E_{rt} energy consumption for transmitting and receiving $SYNC/SCHED/ReservedTimeslot$; P_{r-busy} is the busy period and is always 1 in reservation mode for synchronization; m is the mean number of busy timeslots in reservation mode, and is equal to ϱ in $M/M/c$ model. k is the same integer as in contention mode, which indicates the number of possible listeners for $SYNC/SCHED$ frames.

For the reserved timeslots, the energy consumption E_{rt} is the multiplication of the number of sensors in the duty cycle and energy consumption in one timeslot.

The energy consumption during the waiting time is:

$$EC_{r-wait} = W_r(E_{sync} + E_{sched}) \tag{6.14}$$

The energy consumption in reservation mode during time period T is:

$$EC_r = (EC_{r-busy} + EC_{r-wait}) \times T/T_{dc} \tag{6.15}$$

6.3.4 Energy Efficiency

Energy efficiency is an essential metric for evaluating transmitted data packets and energy consumption in DTSN environments. When a certain amount of data is collected by the sensors, they can choose to send the data to the sink immediately, or send the data in an energy-efficient way with a compromise in latency . The energy consumption for the transmission of certain amounts of data is essential for DTSN to extend the network longevity while finishing the work of transmitting data. We use the data transmitted in a certain period of examined time over the energy consumption during this time as an indicator of energy efficiency for DTSN in this chapter.

$$EE = \frac{\Sigma Data \quad packets \quad transmitted}{\Sigma Energy \quad consumption} \tag{6.16}$$

$$EE_c = \frac{DT_c}{EC_c} \quad \text{in contention mode} \tag{6.17}$$

$$EE_r = \frac{DT_r}{EC_r} \quad \text{in reservation mode} \tag{6.18}$$

Energy consumption includes the energy consumed in transmitting/receiving duty cycles and in waiting duty cycles.

6.3.5 Analysis Results

The analysis results show that the energy consumption accumulated from the sensors around a central node when these sensors wait for data transmissions (Fig. 6.3) and when the sensors transmit and receive data packets (Fig. 6.4).

When the traffic load is low or the number of sensors with arrival rate λ is less than half of the processing rate μ, waiting times in both reservation mode and contention mode are very short, and the energy consumption during waiting times are low. However, during busy period of data transmission processing, the energy consumption in reservation mode is higher than in contention mode, since the control messages $SYNC$ and $SCHED$ consume more energy than RTS and CTS.

When the traffic load is higher, or the number of sensors with arrival rate λ is close to but no larger than the processing rate μ, the energy consumption in contention mode during both waiting times and busy times is much higher than in reservation mode. The waiting time increases significantly with the traffic load, and results in higher energy consumption during waiting times. It also brings high collisions, which consume more energy during busy periods. In reservation mode, the traffic load λ is far more below its processing rate $c\mu$. This indicates that energy conservation is significant in reservation mode, when multiple transmissions can be scheduled during one duty cycle to adapt to the heavy traffic load.

When the traffic load λ is larger than the processing rate μ in contention mode, the system is overloaded and the MAC strategy may no longer work. However, for the MAC strategy in reservation mode, the traffic load λ is less than $c\mu$, the energy consumption is acceptable and the MAC scheme works as usual until λ reaches $c\mu$.

In contention mode, the energy efficiency in Fig. 6.5 is high when the traffic load is low. When the traffic load is close to or larger than the processing rate, the energy efficiency drops lower than in reservation mode. In reservation mode, it is not efficient to introduce longer $SYNC$ and scheduling list frames in every duty cycle. However, when the traffic load is high, reservation MAC scheme demonstrates high energy efficiency, since it can accommodate more transmissions during one duty cycle.

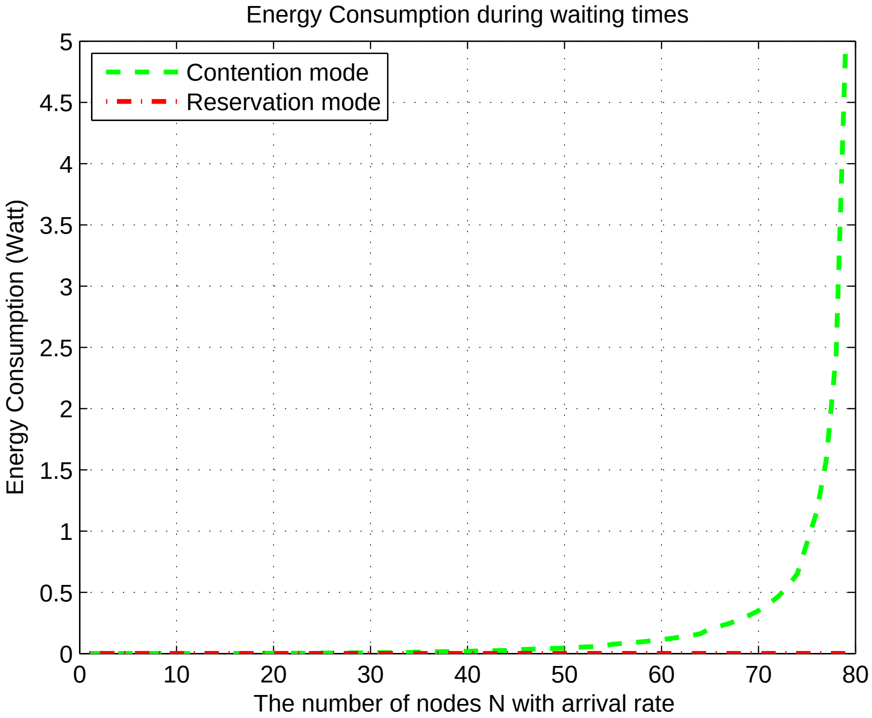

Figure 6.3: Energy consumption during waiting times

From the above results, we can conclude the MAC design principles to improve energy efficiency in different traffic load scenarios.

1. Traffic load adaptability. The MAC strategies may alternate reservation-based or contention-based approaches according to the current traffic load. When the traffic load is low or medium, contention-based approaches demonstrate better

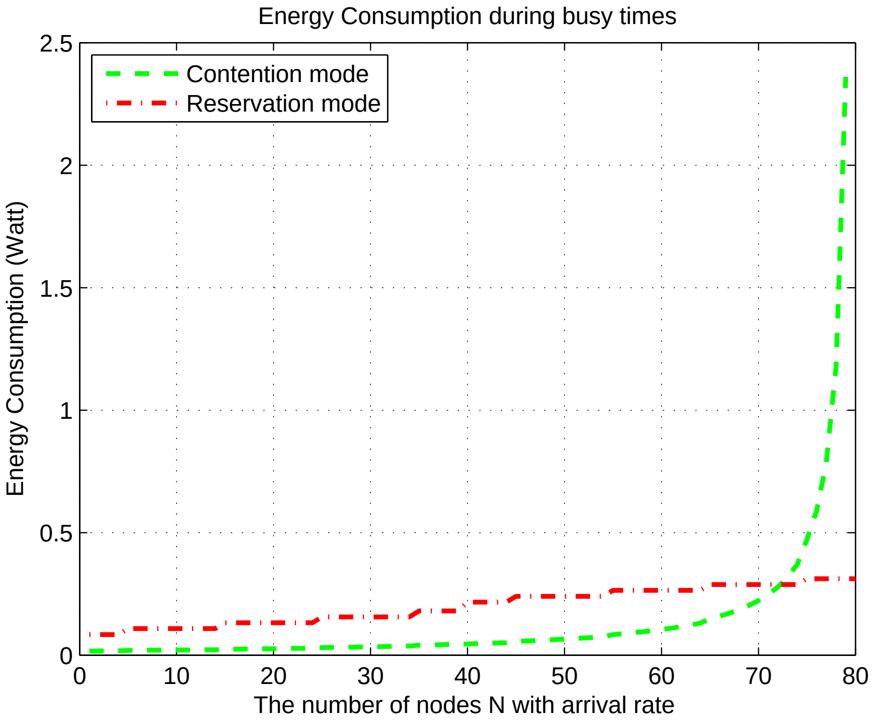

Figure 6.4: Energy consumption during busy times

energy efficiency than reservation-based ones. On the contrary, the reservation-based approaches consume less energy with the same packet transmissions than contention-based ones when the traffic load is high. The traffic adaptive MAC approach may use traffic load to trigger the working mode changes between reservation-based and contention-based schemes.

2. Energy consumption. Overhead, collisions and over-listening consume extra energy in addition to data transmissions. The MAC design of the length of the control messages and the collision resolution algorithms may improve energy efficiency in DTSN.

3. Duty cycle. The length of the duty cycle affects the processing rate μ. The longer the duty cycle, the lower processing rate μ. As a result, the traffic load may be easily close to or larger than μ and causes the system to become overloaded. Fig. 6.6 shows impact of duty cycle length on energy efficiency. When the energy efficiency is below 0, the system is overloaded. With a shorter duty cycle, contention-based strategies can work under higher traffic mode than

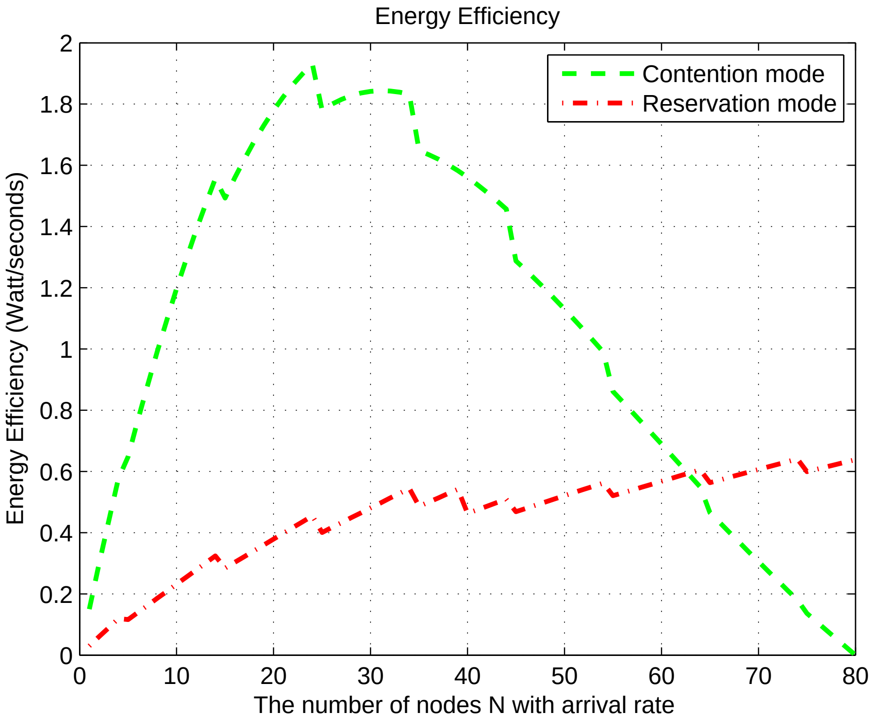

Figure 6.5: Energy efficiency

longer duty cycle. However, by using longer duty cycle, energy efficiency improved in reservation-based approaches.

6.4 The Proposed MAC protocol

From the analysis of MAC energy efficiency under different traffic loads, we propose a traffic-adaptive MAC approach to improve energy efficiency in DTSN environments. The proposed MAC protocol works under variable traffic loads and mobile environments. Reservation-based and contention-based schemes are applied to different traffic load scenarios. Since there are no fixed central nodes to maintain the topology of the DTSN, the protocol can scale to large networks. The aim of our protocol is to provide energy efficient transmissions when sending and receiving the same amount of data packets under DTSN scenarios.

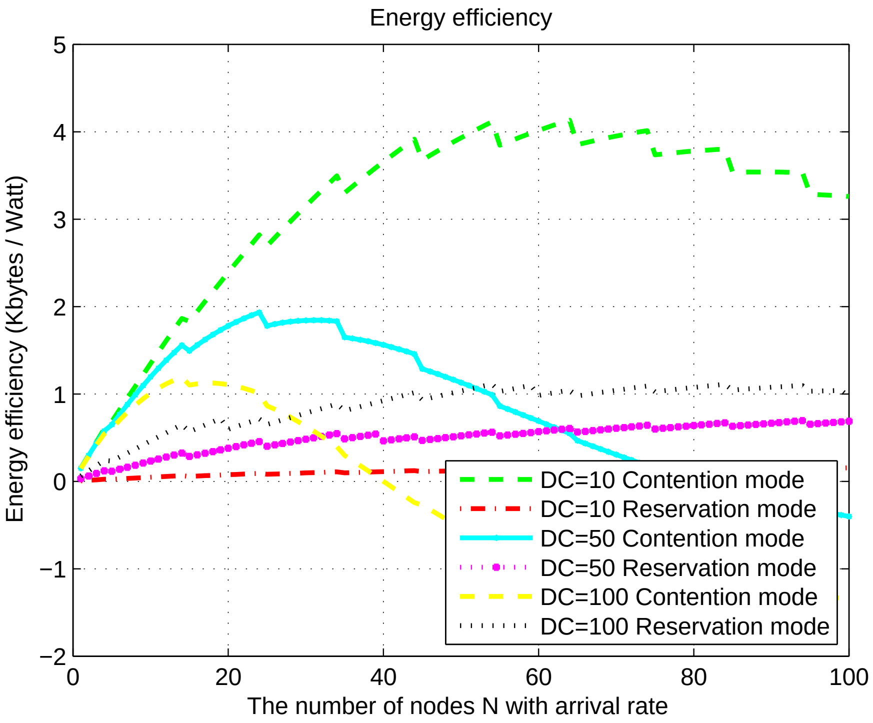

Figure 6.6: Duty Cycle impact on energy efficiency

6.4.1 Scenarios

The sensors can move or be static in the scenario of our MAC protocol (Fig. 6.7). Sensor mobility changes the network topology. Sometimes they form a group and then separate. Sometimes only a few sensors are nearby. The connections and topology between sensors change as the sensors move. Therefore, no central node permanently exist that can coordinate the sensor communications, and global synchronization does not exist in this scenario. However, local accumulated sensors may form a temporary cluster and transmit data packets among them. A single node seeks nearby sensors to set up connections to transmit.

The sensors may stay in active mode and sleep mode to conserve energy. During active mode, sensors can transmit and receive data packets or listen to wireless channels. During sleep mode, sensors shut down the transceivers for transmission and receiving, and stay in sleep mode with very low energy consumption. The time duration of one duty cycle of all these active and sleep modes is fixed with value T_{dc}.

Each node has a fixed transmission radius r and a fixed sensing range R. We assume a single, time-slotted channel for both data and signalling transmissions.

6.4.2 Sensors Work Flow

As indicated in the Fig. 6.7 illustration of topology, when multiple sensors are in one transmission range, multiple transmissions may be required during one duty cycle. Therefore, the central coordinator can reserve several timeslots for these sensors and schedule their transmissions. When only one sensor can be connected during one duty cycle, reservation timeslots and scheduling are not necessary. We design a traffic adaptive MAC protocol which combines reservation-based and contention-based strategies in mobile sensor networks in order to improve energy efficiency in DTSN. During one transmission cycle, a reservation-based approach requires synchronization of neighbor nodes, information gathered from sensors present, and/or transmission requests. A single sensor then acts as a temporary coordinator, broadcasting the schedules of transmission/receiving timeslots to nearby sensors and reserving the timeslots in the cycle. After that, the sensors go into sleep mode and wake up in another cycle to save energy.

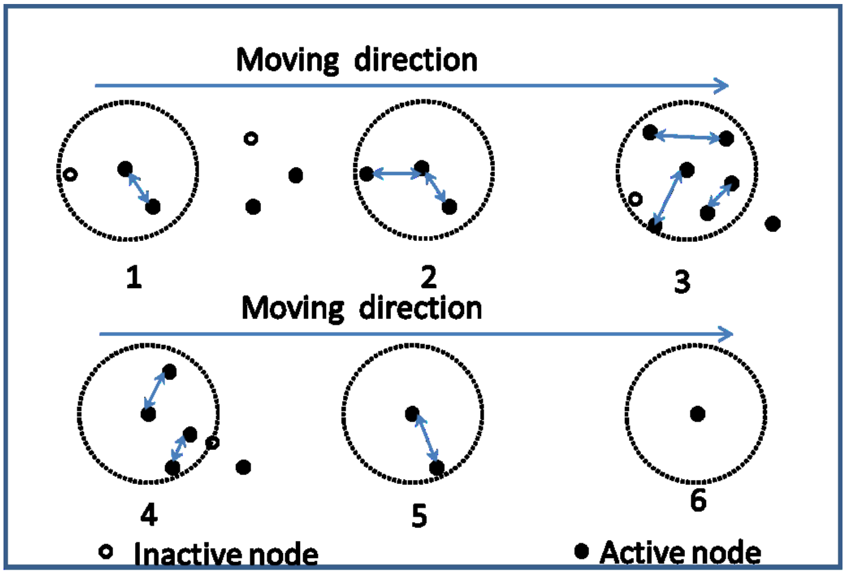

Figure 6.7: Sensors moving scenarios

- A single node stays in active/inactive mode with T_{dc} duty cycle.
- When a single node has data ready, it builds connections and transmits data frames to another sensor.

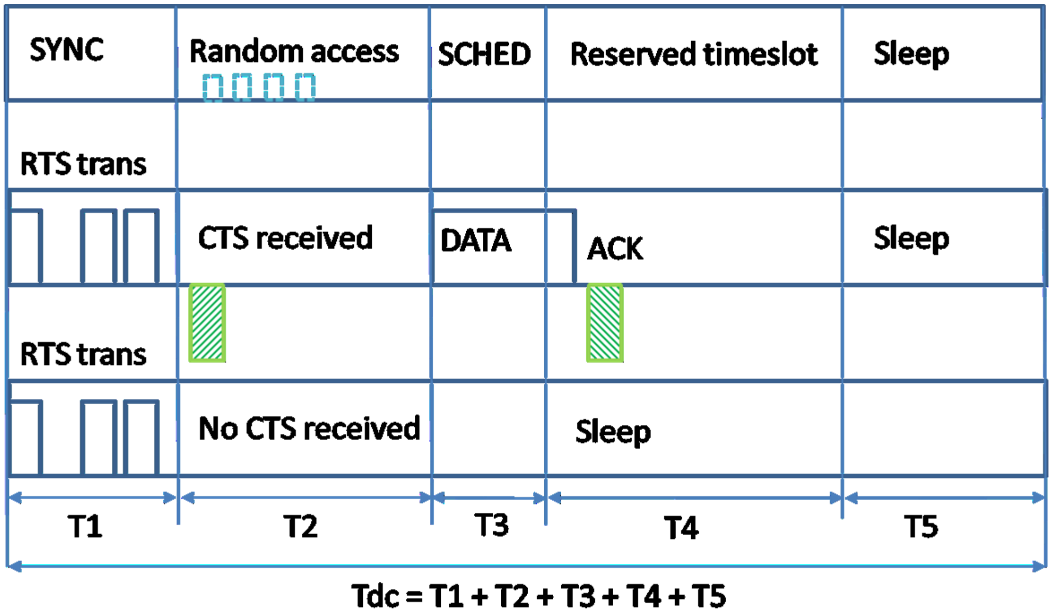

Figure 6.8: Time schedule in Contention and Reservation Mode

- This sensor finds more than one active sensors in its transmission range that require data communications.
- This sensor becomes a central coordinator for scheduling and communicating with other sensor nodes.
- This sensor adjusts the transmission schedule and working modes for the next cycle, when the number of nearby sensors decreases.
- There is one connection left for communication between two sensors.

The node can revert to the some stages during the process. The working mode and the coordinator remain unchanged until the cycle ends.

When the sensors move under DTSN environments, they experience different transmission and receiving stages. The time sequence of one duty cycle is shown in Fig. Section 6.3 analyzes contention-based and reservation-based MAC protocols from an energy efficiency perspective. 6.8. One duty cycle is composed of T1 to T5 slots. In reservation Mode, $SYNC$ is broadcast in T1 slot by the coordinator. The random access messages as senders or receivers are sent in T2 by multiple sensors other than the coordinator. Scheduling messages are broadcast in T3 by coordinator. The transmissions are followed by scheduling list in reserved timeslots in T4. If ant time remains in a duty cycle, the sensors could fall asleep in T5 and wake up in the next duty cycle.

In Contention Mode, multiple RTS messages can be broadcast in T1 by different requesters. Only the first CTS by a receiver can be heard, as it inhibits other CTS messages. The transmission between these two sensors occurs in T3 and T4 through $DATA$ and ACK messages. If there is still time left in a duty cycle, the sensors could fall asleep in T5 and wake up in the next duty cycle. If no CTS is received in T2, the sensor assumes there is no active sensor nearby and sleeps in T3, T4 and T5 till next duty cycle.

The frames formats are listed in Fig. 6.9 as Contention Mode frames and Fig. 6.10 as Reservation Mode frames. The type field indicates the message properties. The duration field shows the frame length. RA and TA are the source address and destination address of sensor nodes, respectively. FCS fields is the frame checking sequence as CRC code. In $SCHED$ and $DATA$ messages, an indicator of the working mode is included for all sensors. The $SCHED$ message includes scheduling list with a TS number. The TS number indicates that the following reservation slots will be used: for transmission, the $TxSlot$ will function as RA and for receiving, $RxSlot$ will be used for TA.

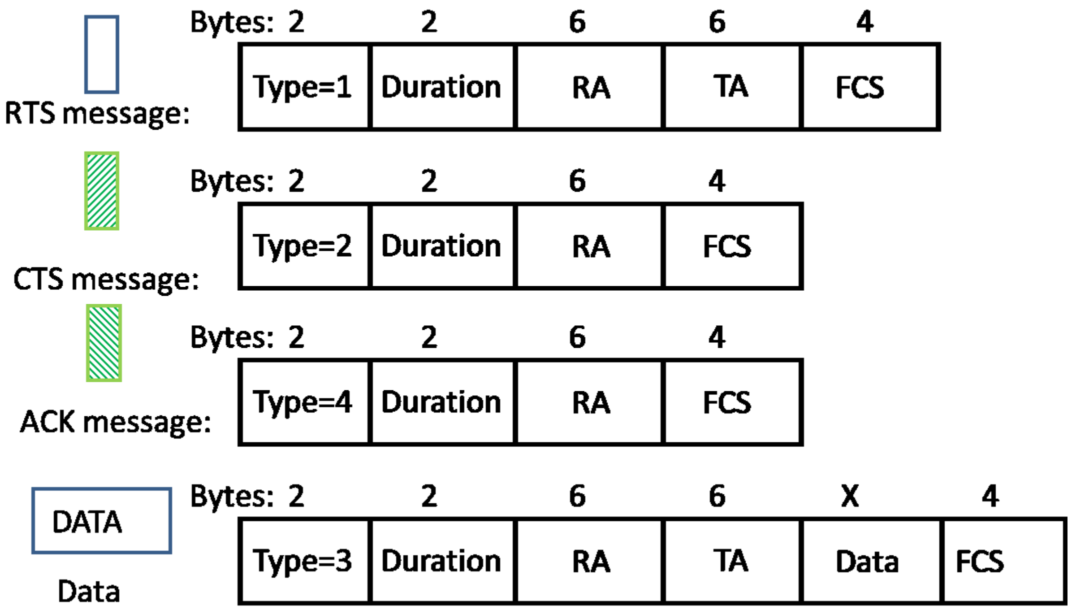

Figure 6.9: Frame format in Contention Mode

The protocol transmission procedure can be described as follows:

1. Every node listens to at least one data transmission cycle T_{dc} before it sends any packets. This ensures that node receives messages in one $SYNC$ slot, and knows the following data transmission cycle is in reservation mode and contention mode. In active mode, the sensor listens to the $SCHED$ or $DATA$ frame in T3 to decide the timing of $SYNC$ T1 and the working mode: reservation or contention.
2. If the sensor carries data and receives $SCHED$ frames in T3 of its last duty cycle, it listens to $SYNC$ frame and sends random access in Reservation Mode to request transmission and timeslots. It follows the $SCHED$ information, and transmits in the specific timeslots. The ACK message from the receiver indicates the successful transmissions.
3. If the sensor carries data and receives $DATA$ frames in T3 of its last duty cycle, it sends RTS during T1 with carrier sensing and back-off counter in Contention Mode. If no CTS is received in T2, the sensor will sleep till next T1 comes. If the CTS received is not its receiver, the sensor will listen to the $DATA$ in T3 to receive information that the next duty cycle is reservation or contention mode. Then it falls asleep and wakes up in the next duty cycle. If a CTS is received from its receiver, it counts the RTS received in T1 and calculates its Mode in the next duty cycle. Then it sends $DATA$ with Mode indication, and expects ACK in T3 and T4. The sensor may change its working mode to Reservation as a temporary coordinator after this duty cycle.
4. The coordinator sends $SYNC$ in T1 and listens to random access in T2. The working mode of the next duty cycle is decided according to the number of random access messages and requests from senders and receivers. It is then sent out as $SCHED$ in T3, along with the scheduling list. The next duty cycle may change to Contention Mode.
5. If the sensor carries data and hears no $SCHED$ or $DATA$ frames, it sends RTS according to its own time schedule.
6. If the sensor carries no data, it wakes up and listens for $SCHED/DATA$ or RTS. If no $SCHED/DATA$ or RTS is received, it falls asleep according to its

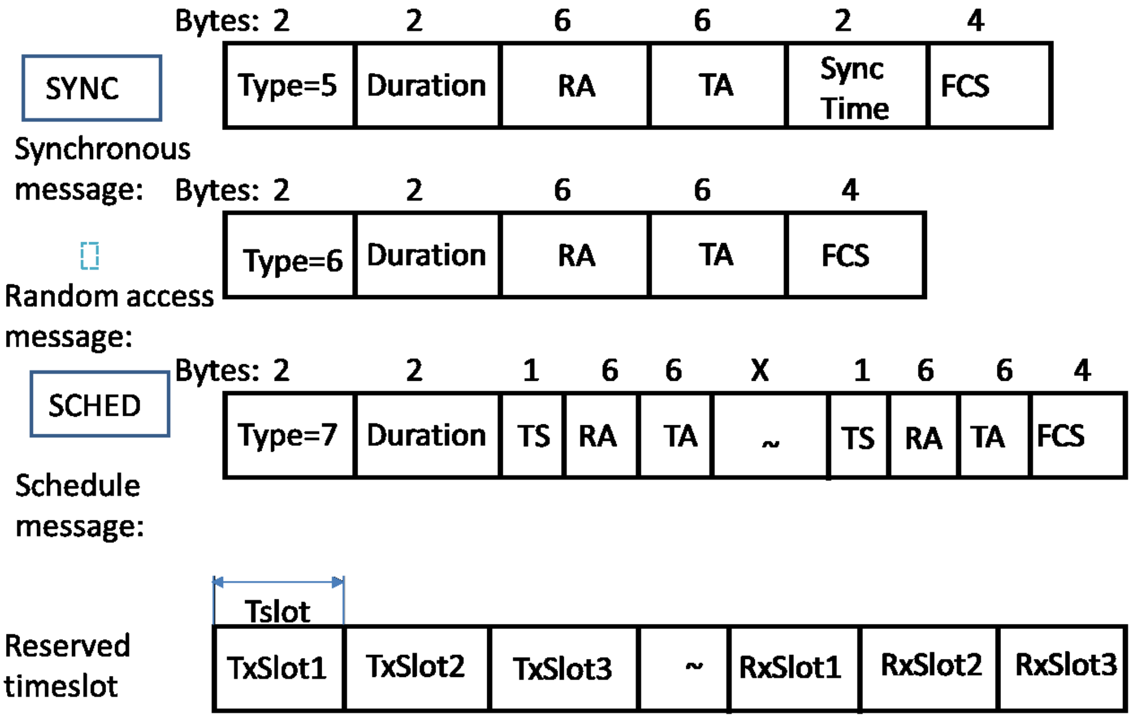

Figure 6.10: Frame format in Reservation Mode

own schedule.

The working procedure for sensors in Reservation Mode is described in Fig. 6.11. Initially, sensors are not coordinators until specific requirements are satisfied in subsection 6.4.3. As a coordinator, the sensor broadcasts $SYNC$ messages and listens to random access messages from other nearby sensors . The coordinator decides the working mode for the next cycle, and prepares the scheduling list regarding the random access messages. The coordinator then broadcasts $SCHED$ messages to nearby sensors, which follow its schedule to transmit or receive data in specific timeslots. If the sensor is not a coordinator, it listens for $SYNC$ messages and sends random access messages to indicate itself as a receiver or sender. Then it listens for a $SCHED$ message to see if there are reserved timeslots for its transmissions. The sensors do no act until the next cycle.

Fig. 6.12 shows a sensor's working procedure in Contention Mode. The sensor may locate the T1 slot if it hears $DATA$ or $SCHED$ in T3 of last duty cycle and knows this cycle is in Contention Mode. If the sensor has data to send, it senses the carrier and sends RTS at a randomly selected slot in T1. It listens for other RTS

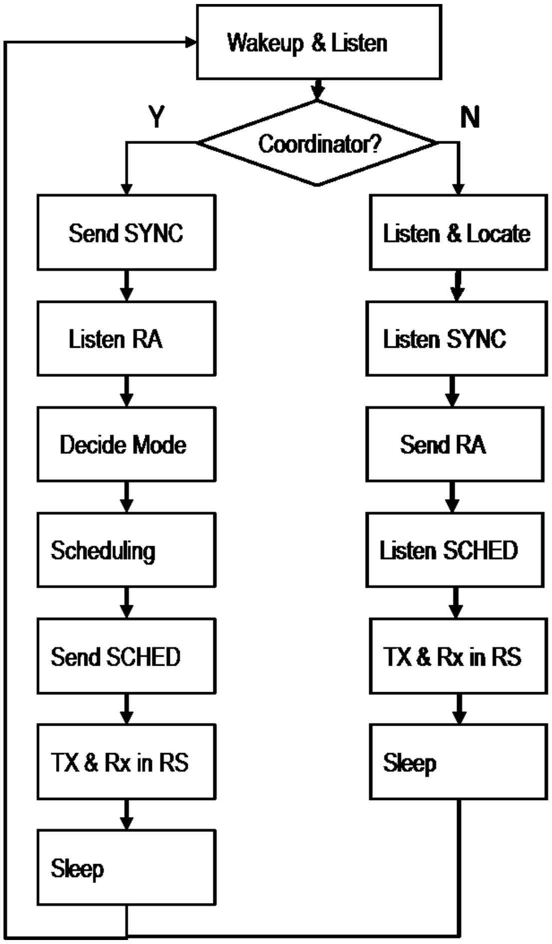

Figure 6.11: Working procedure in Reservation Mode

and CTS. The Received CTS indicates the only sender, which decides the working mode in the next duty cycle. The sender sends $DATA$ message and waits for ACK. If the next duty cycle is in Reservation Mode, this sensor will work as a coordinator and broadcast $SYNC$ in T1. If the sensor has no data and works as a potential receiver, it listens for RTS and may respond with CTS. $DATA$ and ACK messages follow with the sender and the receiver. If the sensor is not a potential receiver, it falls asleep until the next cycle.

6.4.3 Mode changes

The condition for changing modes is decided by the number of nodes which have transmission requests ι and the duty cycle length T_{dc}. Transmission requests ι are

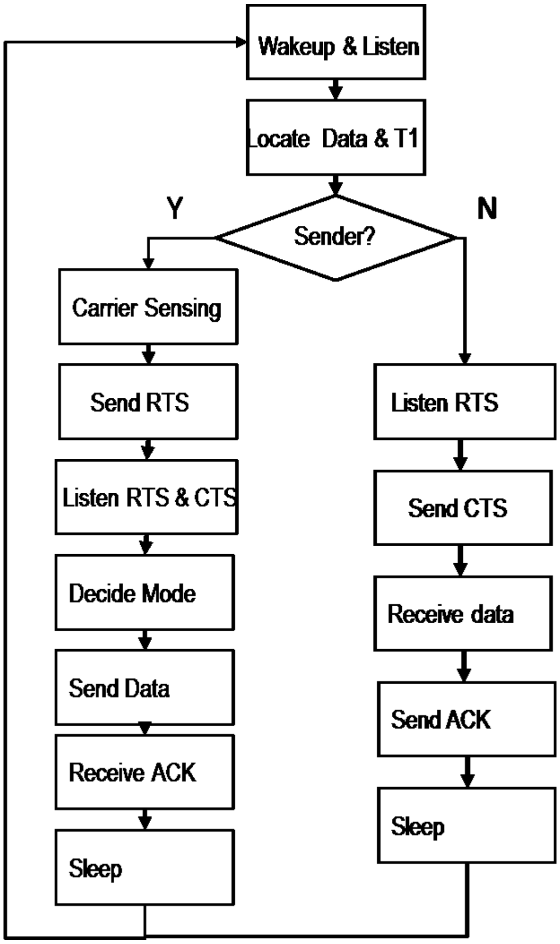

Figure 6.12: Working procedure in Contention Mode

interpreted as RTS requests in Contention Mode and random access requests in Reservation Mode. These two parameters indicate the traffic generation rate λ of the protocol in Section 6.3. When the received RTS requests RT in this duty cycle is larger than pre-set threshold Cm_r during an examined period T_e, the working mode changes to Reservation Mode (Mode=R) in the next duty cycle. If the received random access requests RT in this duty cycle are less than pre-set threshold Cm_c, the working mode changes to Contention Mode (Mode=C) in the next duty cycle (Alg. 5).

Algorithm 5: Mode change

```
$t = T_e$;
while $t$ do
    if $Mode = C$ then
        $\iota = RT/T_e$;
    else
        $\iota = RT/T_e$;
    $\lambda = \iota * T_{dc}$;
    if $\lambda < Cm_c$ and $Mode = R$ then
        $Mode = C$; $t = T_e$;
    else
        if $\lambda > Cm_r$ and $Mode = C$ then
            $Mode = R$; $t = T_e$;
    $t - -$;
```

6.4.4 Duty Cycle Adjustment

The length of the duty cycle is stored in each sensor and broadcast when it becomes a coordinator. In order to save energy in Contention Mode, the length of the duty cycle can be extended when RTS or CTS messages RT from nearby sensors, as it is lower than the threshold Dc_{low} during an examined period Ta. While the request of RTS goes up to Dc_{high}, the duty cycle is shortened to adapt to the traffic (Alg. 6).

Algorithm 6: Duty Cycle adjustment

```
$t = T_a$;
while $t$ do
    if $RT/T_a < Dc_{low}$ and $Mode = C$ then
        if $T_{dc} < Dcmax/2$ then
            $T_{dc} = 2 * T_{dc}$; $t = T_a$
    if $RT/T_a > Dc_{high}$ and $Mode = C$ then
        if $T_{dc} > Dcmin * 2$ then
            $T_{dc} = T_{dc}/2$; $t = T_a$
    $t - -$;
```

6.5 Evaluation and Simulations

In order to demonstrate the energy efficiency of our proposed MAC protocol, TREE is implemented through the NS2 simulator and is compared to traditional CSMA, TDMA MAC sensor protocols as well the traffic-adaptive protocols TRAMA. Scenarios of both static sensors and mobile sensors are used for different traffic loads. The data packet generator uses Exponential object/Pareto/CBR to simulate the different traffic generation.

The simulation area is $500m \times 500m$ with sensors in traffic generation rate from $100kbps$ to $1000kbps$. The simulation results, as energy consumption and data packets transmitted, are accumulated every 5 seconds. The simulation time is 100 seconds. Each simulation scenario is executed 20 times. Table 6.1 shows the simulation parameters.

Table 6.1: Simulation parameters

Propagation Model	TwoRayGround
Routing Protocols	AODV/GPSR
Mobility Model	Static/Random Waypoint
Traffic generator	Exponential/Pareto/CBR
MAC protocols	TREE/CSMA/TDMA/TRAMA
Radio Range	<100m
Number of Nodes	1-20
Mobility	Static/Random mobility
Simulation Time	100s

6.5.1 Received Data

We examine received data throughout the simulation process using these four protocols. In our analysis, the wireless channel condition is not considered. However, by using a specific propagation model and routing protocols in simulations, the communication between sensors may experience poor conditions and error transmission. The sent data packets may not be received by the correspondent nodes. Therefore, as the traffic load becomes heavier from $100kbps$ to $1000kbps$, the received data from the correspondent nodes is shown in Fig. 6.13. TDMA and our protocol TREE demonstrate good performance in received data from low to heavy traffic. TRAMA works in low traffic status, and cannot handle heavy traffic load. Received data in CSMA works well in low traffic, and performs fairly in heavy traffic loads.

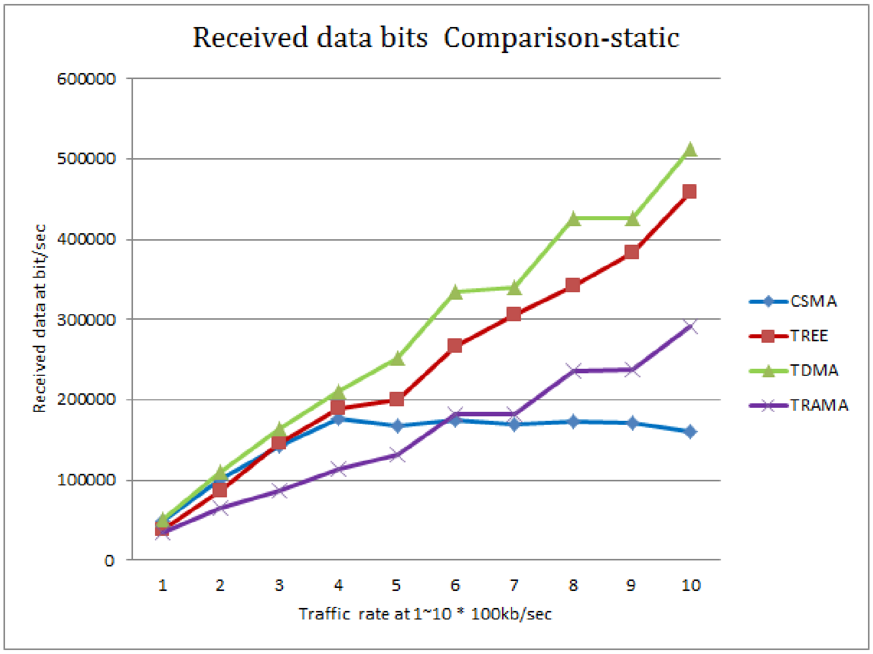

Figure 6.13: Received Data Comparison

Within mobile environments, the data received during transmission is less than that in static environments (Fig. 6.14). TDMA and TREE demonstrate good performance from low to heavy traffic.

6.5.2 Packet Loss

We also examine the packet loss during transmission in order to find the transmission efficiency of each MAC protocol with static sensors. With an increase of traffic load, CSMA, TDMA and our protocol begin to lose more data packets during transmissions (Fig. 6.15). The collisions and channel errors increase when the packet sending requests are high. TRAMA shows a stable packet loss rate, since it did not send the request even when the traffic is high.

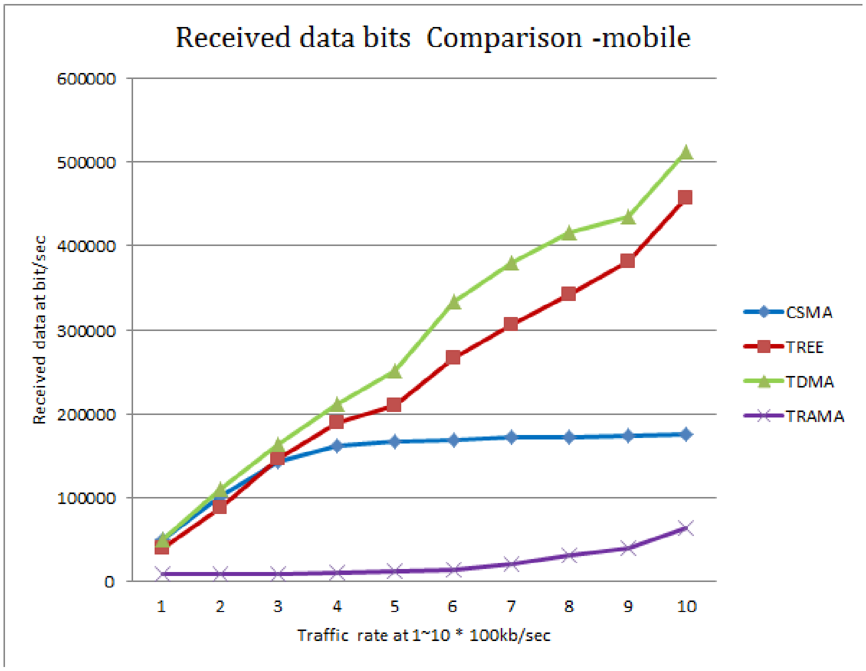

Figure 6.14: Received Data Comparison

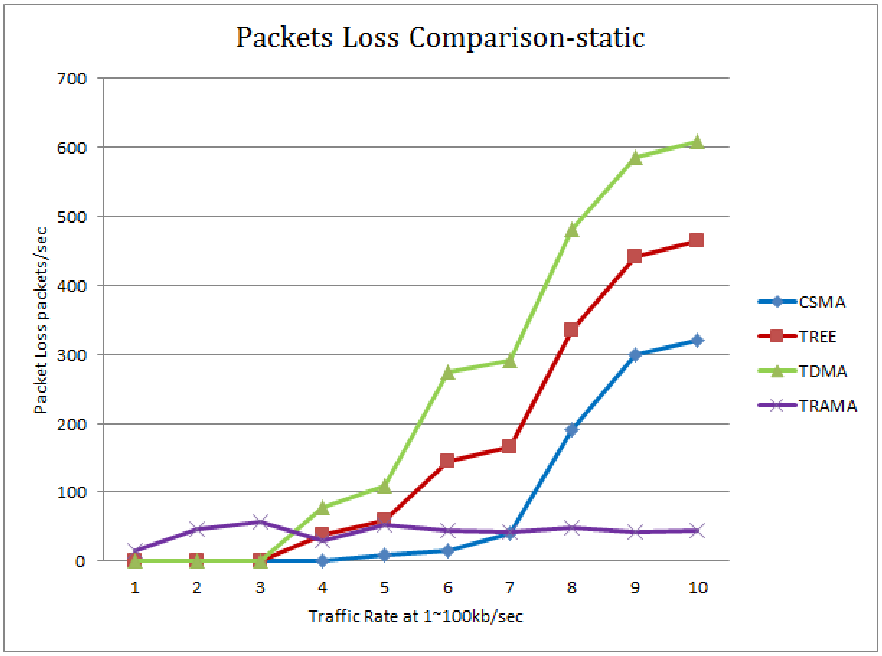

Figure 6.15: Packet Loss Comparison

With mobile sensors, the packet loss increases in four MAC approaches (Fig. 6.16). CSMA shows more packet loss than the other three protocols. The collision and hidden terminal problems are severe, and cause packet loss when traffic is high. The other three protocols use schedule-based transmission strategies, which avoid the hidden terminal and collisions, thus exhibiting better performance than CSMA.

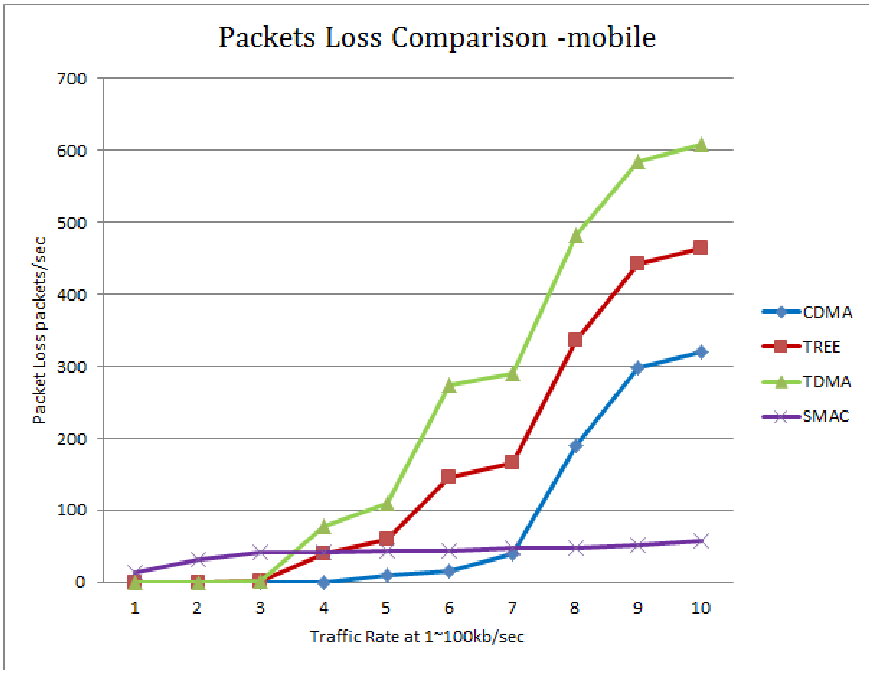

Figure 6.16: Packet Loss Comparison

6.5.3 Energy Consumption

The initial energy for every node is set to 1000Joules. The transmission, receiving, listening and sleep power consumption are set to $0.6, 0.3, 0.3, 0$ Joules per node respectively. The energy residue after the simulation is calculated in static environments, and shown in Fig. 6.17. TRAMA and CSMA exhibit low energy consumption throughout the simulations. The TDMA scheme shows high energy consumption due to more overhead messages and involved nodes. Energy consumption in our protocol shows more energy than CSMA and TRAMA and less energy than TDMA, since our protocol adapts both CSMA and TDMA strategies and combines them.

Due to similar strategies in energy conservation, the four MAC protocols with mobile sensors show similar energy consumption to those with static sensors (Fig. 6.18).

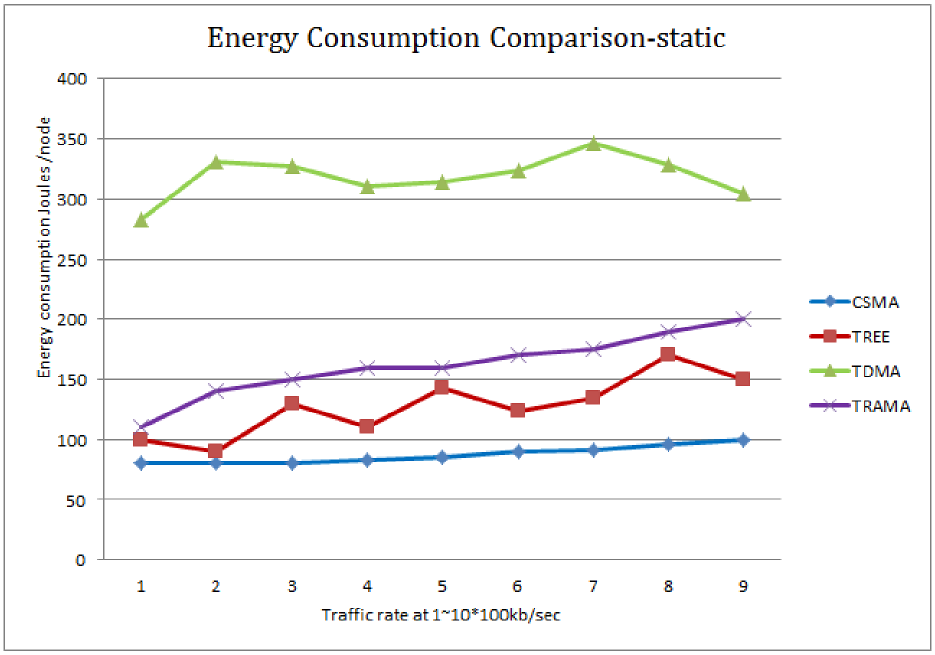

Figure 6.17: Energy Consumption Comparison

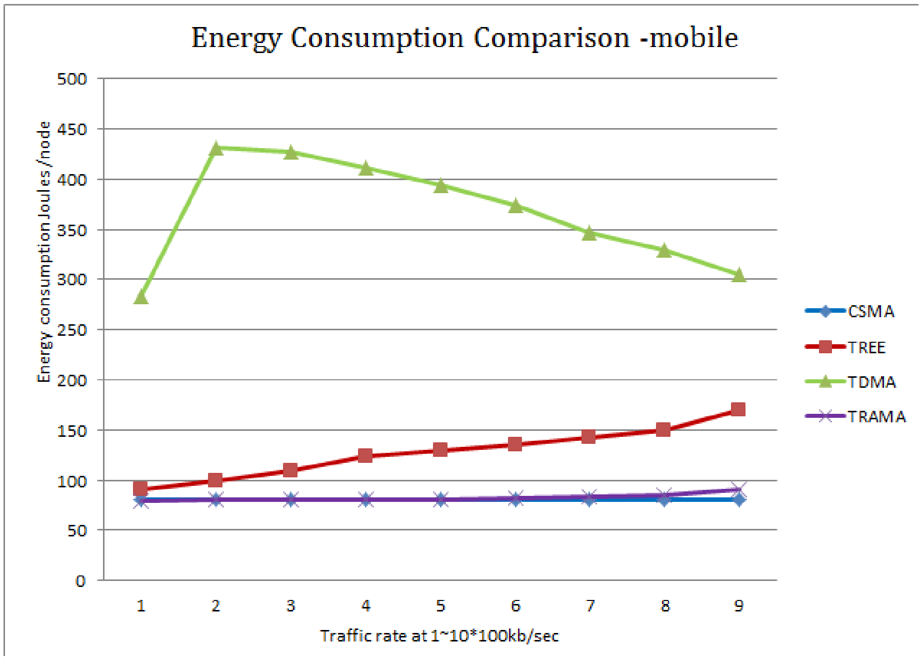

Figure 6.18: Energy Consumption Comparison

6.5.4 Energy Efficiency

Energy efficiency is essential for finishing transmission tasks and conserving energy in DTSN. When traffic is less than $600kbps$ with static sensors, CSMA exhibits better energy efficiency than the other three protocols (Fig. 6.19). However, with an increase in traffic load larger than $600kbps$, our protocol demonstrates about 20 percent or more energy efficiency than other protocols. When the traffic load is diverse in a large range, our protocol will show good performance in data throughput and energy consumption. Using mobile sensors, TREE demonstrates more energy-efficient performance than other three protocols when the traffic is above $500kbps$. Even in trafficis less than $500kbps$, TREE also shows similar performance as CSMA and better performance than TDMA and TRAMA (Fig. 6.20). For the overall dynamic traffic environments, TREE should perform better than the other three protocols.

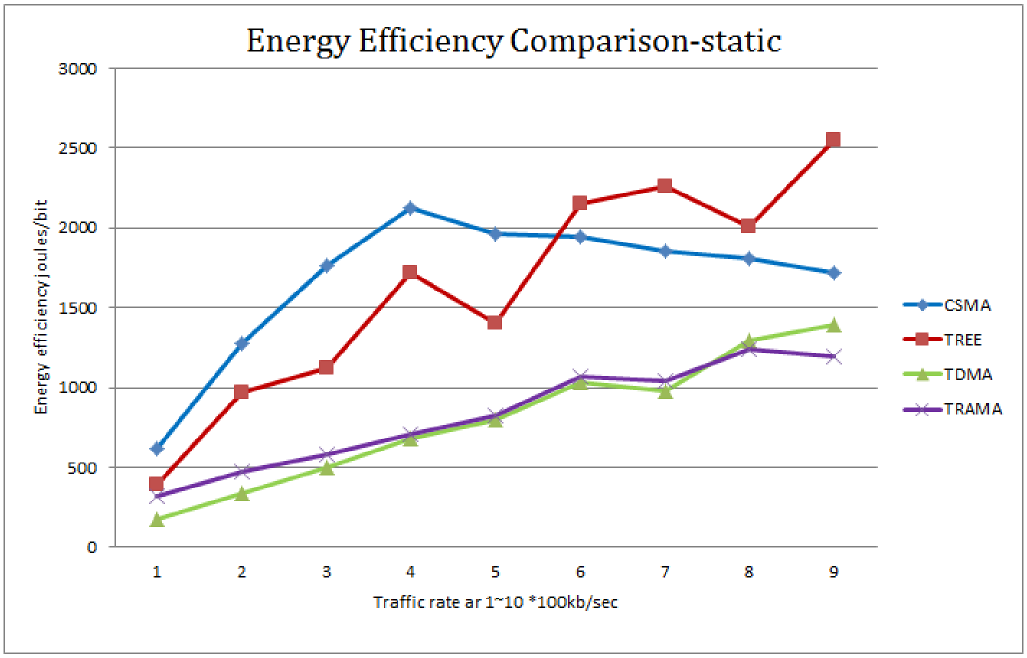

Figure 6.19: Energy Efficiency Comparison

6.5.5 Traffic adaptability

From the overall simulations, our protocol exhibits better performance in term of traffic adaptability and energy efficiency than the schedule-based MAC protocol TDMA,

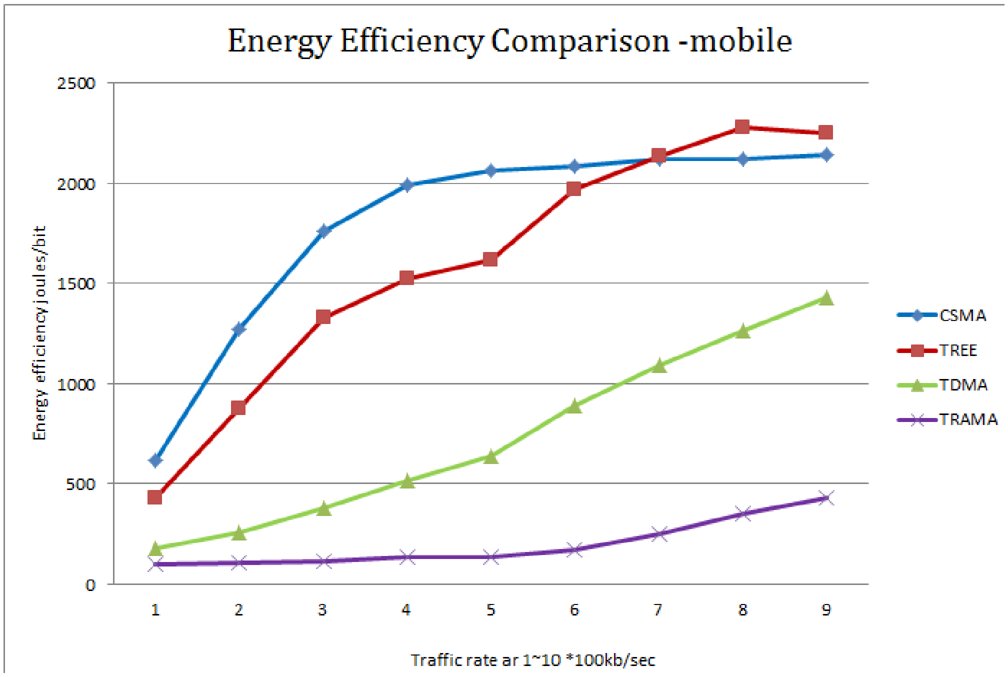

Figure 6.20: Energy Efficiency Comparison

the contention-based protocol CSMA, and the traffic adaptive protocol TRAMA. When traffic adaptability and energy efficiency are very important in mobile delay-tolerant sensor networks, our TREE strategy is a good choice of MAC protocol in these environments.

6.5.6 Mobility and Scalability Considerations

By using temporary coordinators, our protocol has no requirements for fixed central nodes or coordinators. This allows for easily compatibility for between mobile nodes and our protocols. In unevenly distributed traffic environments, our protocol can adjust its working mode and duty cycle to save energy and accommodate data transmissions. This protocol is scalable to varying amounts of nodes and types of areas.

6.6 Conclusion

Delay-tolerant sensor networks require energy efficient MAC transmission strategies with flexible traffic loads and mobility supports. This chapter analyzes the current MAC protocol from an energy-efficient prospective under DTSN environments. Reservation-based and Contention-based MAC schemes are examined with throughput and energy consumption by using queue models. We propose a traffic adaptive, energy-efficient MAC protocol TREE to achieve better data transmissions as well as energy consumption. In this protocol, reservation and contention modes are combined to adapt to traffic load and improve energy efficiency. The duty cycle is also adjustable to conserve energy. Simulation results demonstrate that our protocol shows better energy efficiency under high dynamic traffic DTSN environments than other MAC protocols.

Chapter 7

Conclusion and Future Work

This thesis presents three different data communication approaches for green wireless networks to improve throughput, energy and overhead performance. CPMAC proposes an efficient MAC approach for sparsely connected Vehicular networks. With the prediction of the sensor-sink contact interval, the sensor uses three transmission algorithms to efficiently send out the collected data to the sink in a manner that balances data throughput and energy. This MAC solution is compared with two other classic MAC protocols through simulations and shows better performance in terms of data throughput, one transmission delay and power-saving aspects in sparse Vehicular networks. AFLAS examines the relationship between SNR and the frame length of the MAC layer according to the probability of collision and transmission error and proposes the aggregated frame length to the current SNR using different priority queues. Simulations in AFLAS also demonstrate that our adaptive frame length scheme outperforms non-adaptive frame length strategies with respect to data throughput, retransmissions, and transmission efficiency. Considering energy efficiency is essential for designing and evaluating MAC transmission strategies, we redefine energy efficiency that represents data packets transmitted over energy consumption as one metric for evaluating the performance of MAC protocols. The MAC parameters related to energy efficiency are analyzed to provide a guide to develop MAC strategies in green wireless networks. Traffic adaptive, energy-efficient MAC protocol TREE combines reservation and contention modes to adapt to traffic load and improve energy efficiency. Simulation results in TREE demonstrate better energy efficiency under high dynamic traffic green wireless networks environments than other MAC protocols.

7.1 Future Work

After the research on three MAC solutions and extensive study on MAC and routing protocols in delay-tolerant networks, we still find more improvements and extensive work could be studied in the future as the followings:

- *Contact-Interval Prediction:* In CPMAC, the hidden node problem may affect the accuracy of contact-interval prediction when the interference from hidden or exposed nodes presents high level. Although the solution applies history records to compensate the prediction errors, good prediction of contact interval would be our future work to improve this MAC solution. In addition, the transmission efficiency within the network level should also be implemented to improve multi-hop data transmission in this solution.

- *Aggregation Queue Optimization:* In AFLAS, the aggregated frames are queued in three types of priority groups and wait for aggregation procedure. The waiting time and the service priority can be optimized using mathematical analysis and simulations to improve the performance of throughput and energy efficiency in AFLAS.

- *Delay Analysis:* In the delay-tolerant network applications, latency can be scaled into various levels according to the type of data transmission services. The MAC transmission approaches could also be adapted to the requirements of latency and the performance in throughput, energy consumption and reliability. Further MAC designs and simulations could be implemented with scaled latency requirements.

- *Scalability Issue:* In TREE solutions, combined reservation-based and contention-based approach may compromise the scalability while improving the energy efficiency in MAC data transmission. The scalability impact of this MAC strategies can be further studied and simulated with other MAC strategies.

- *MAC and routing Cross-layer Design:* Opportunistic routing have been extensively researched in delay-tolerant networks. Cross-layer designs may contribute MAC solutions in energy conservation, overhead reduction and contention-resolution to opportunistic routing protocols in delay-tolerant scenarios. End-to-end data transmission performance could be extensive examined and improved through elegant designs with MAC and routing protocols for diverse applications in wireless networks.

The further analysis and implementations are my future research. I hope the work may inspire others into this research interests.

7.2 Thesis Conclusion

Information and communication transmission strategies are designed for multiple users accessing unstable wireless channels with delicate considerations in data throughput, energy consumption, latency, reliability and network scalability. When delay can be relaxed in green wireless networks networks, the performance matrices can be improved with the trade-off of latency. The thesis extensively studies MAC designs, implementation, performance evaluations and applications in sensor networks, vehicular networks and delay-tolerant networks. It summarizes the characteristics in delay-tolerant networks with energy, topology, mobility concerns and proposes three MAC data transmission designs in delay-tolerant networks: CPMAC applies power and rate adaptation with contact interval prediction to improve energy-saving MAC transmissions in sparse connected vehicular networks. AFLAS implements aggregated MAC frames to save overhead messages to improve data throughput efficiency in vehicular networks. TREE adapts to traffic density and alternate using collision-free access and contention-based access to achieve high energy efficiency in sensor networks. The performance are evaluated by simulations regarding data throughput, energy consumption, retransmission and overhead messages, and energy efficiency. The three MAC protocols demonstrate 15 to 20 percent improvement when comparing with other classical MAC protocols in similar scenarios of wireless networks. Extensive work related MAC data transmissions for green wireless networks are discussed for further research interest.

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