A Study on Provision of QoS Services over Ad Hoc Networks by Combining TDMA and DCF Access Methods

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A Study on Provision of QoS Services over Ad Hoc Networks by Combining TDMA and DCF Access Methods

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論文の和文概要

論文題目	TDMA と DCF の組み合わせによるアドホックネットワーク上での QoS 通信の実現方式
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近年アドホックネットワークが、インフラストラクチャの不要な自律的な無線ネットワークとして注目されている。特に、音声や映像などの通信品質（QoS）を保証することが重要な課題の一つとなっている。無線 LAN においても、QoS 通信を保証する 802.11e が標準化されているが、これをアドホックネットワークに適用すると、マルチホップ通信のために十分な性能を実現することはできない。本研究では、QoS 通信に対しては TDMA（Time Division Multiple Access）を、それ以外の通信に対しては無線 LAN で使用されている DCF（Distributed Coordination Function）を使用する方法を提案する。シミュレーションによる性能評価では、提案方式が従来の方法に比べて、パケット到達率や遅延変動について高い性能を得ることができた。

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ABSTRACT

An ad hoc network does not rely on the fixed network infrastructure; it uses a distributed network management method. With the popularity of the smart devices, ad hoc network has received more and more attention, supporting QoS in ad hoc network has become inevitable. Many researches have been done for provision of QoS in ad hoc networks. These researches can be divided into three types.

The first type is contention-based approach which is the most widely used. IEEE 802.11e MAC (media access control) protocol belongs to this type which is an extension of IEEE 802.11 DCF (Distributed Coordination Function). It specifies a procedure to guarantee QoS by providing more transmission opportunities for high priority data. However, since IEEE 802.11e is designed based on the premise that access points are used, when the number of QoS flows increases, packet collisions could occur in multi-hop ad hoc network.

The second type is using TDMA-based approach. The TDMA approach can provide contention-free access for QoS traffics through the appropriate time slot reservation. The current TDMA approaches reserve time slots for both QoS traffics and best-effort traffics. However, it is difficult for TDMA as the only approach to allocating channel access time for best-effort traffics since the required bandwidth of the best-effort traffics changes frequently.

We propose a QoS scheme, which takes advantage of both contention-based approach and TDMA-based approach. In the proposed scheme, contention-based approach DCF provides easy and fair channel time for best-effort traffics, and TDMA approach serves the QoS traffics. A time frame structure is designed to manage the bandwidth allocation. A time frame is divided into two periods, specifically the TDMA periods and the DCF periods. The proportion of two periods is decided by QoS traffics. Therefore the QoS traffics are given absolutely higher priority than best-effort traffics. In order to guarantee the transmission of each QoS packet in TDMA period, a time slot assignment algorithm based on QoS data rate has been proposed. The proposed scheme also employs an admission control scheme, which rejects the new QoS user when the channel capacity is reached. In addition, we provide the configuration

of the proposed scheme in the mobile environment. The procedures are designed for route changes and new-adding users.

The proposed scheme is simulated in the QualNet simulator. In the static environment, the performance of the proposed scheme is evaluated in the case of a gradual increase in the number TCP flows and in the case of gradual increase in QoS data rate. Simulation results show that in the static environment the proposed scheme can not only provide effective QoS performance, but also can provide good support for best-effort flows. In the mobile environment, we simulated the performance of the proposed scheme at different moving speed (maximum is 5 Km/h) when the ARF (Auto Rate Fallback) is available. From the simulation results, in a specific mobile environment, the proposed scheme can support the QoS transmission well.

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1. INTRODUCTION

1.1 Wireless Ad Hoc Network

A wireless ad hoc network does not have centric control nodes nor fixed wireless infrastructure. Each node in a wireless ad hoc network plays the roles of the host and the router. As a host, a node needs to run various user-oriented applications. As a router, the node forwards the packet by running the proper routing protocol. Because the communication range of mobile nodes is limited, two nodes that are not able to talk with each other directly can communicate through the forwarding of one or multiple intermediate nodes (Figure 1). Therefore, a wireless ad hoc network may also be referred to as a multi-hop wireless network.

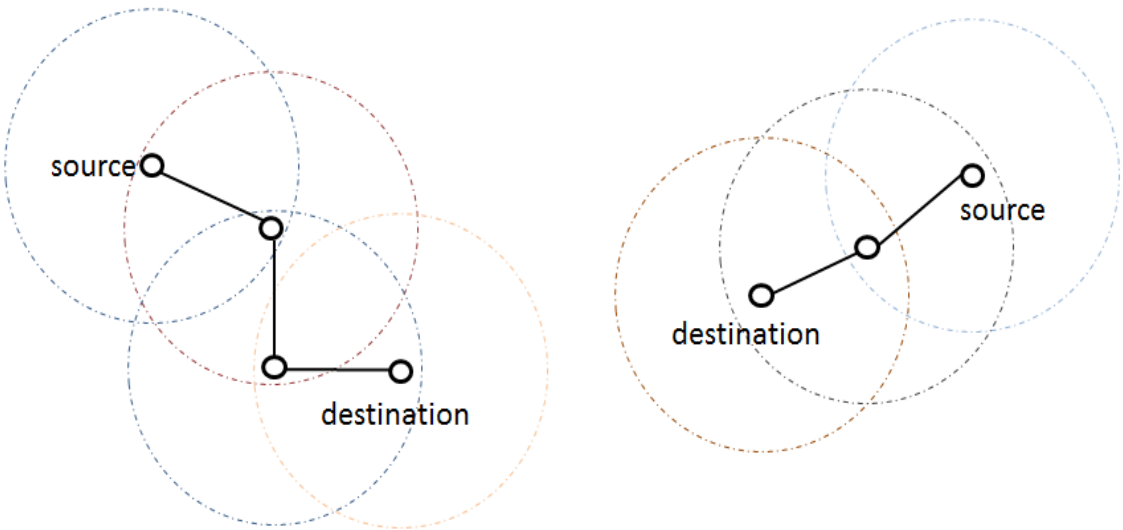

Figure 1 Multi-hop Communication of ad hoc networks.

1.1.1 Characteristics of Wireless Ad Hoc Networks

In general, a wireless ad hoc network has several characteristics as follows.

- Non-centric control unit

Ad hoc network is a peer to peer network. There is no central controller in wireless ad hoc networks. In a wireless ad hoc network, all nodes are independent and equal. The action of node's leaving or joining will not affect the operation of the network.

- Dynamically changing network topology

The variation of the transmit power, mutual interference between nodes, the network topology may change at any time due to the independent movement of nodes. The changes in the topology and the mobility are unpredictable in a wireless ad hoc network.

- Multi-hop networking

As the common infrastructure is lacking in wireless ad hoc networks, when a node wants to send data to the node outside its transmission range, two or more hops along the path are used for conveying the information.

- Limited transmission bandwidth

In general, compared with the corresponding capacity of the wired link, the capacity of the wireless link is much lower, due to multiple accesses, noise, interference and other unfavorable factors. The link capacity is time-varying when nodes move around.

- Constrained power

In general, nodes in a wireless ad hoc network are some portable mobile devices, which rely on portable batteries or other consumable methods to provide energy. In order to allow longer use of the equipment, the transmit power is often set to a low level.

- Short survival time

A wireless ad hoc network is typically created temporarily for a specific reason, and the network environment will automatically disappear after use. So the survival time of wireless ad hoc networks is short compared to a fixed network.

Due to these characteristics of wireless ad hoc networks, the protocols such as routing protocols and network management mechanisms designed for a wired network or a cellular network with some kinds of existing infrastructure may not be suitable for wireless ad hoc networks.

1.1.2 Application of Wireless Ad Hoc Networks

With the rapid development of Internet and the evolution of the small, high performance device, a wide range of the Internet services and transmission of a large number of multimedia information (voice, data, images and videos) is required. Application of wireless ad hoc network provides a very promising choice of extension to establish and maintain effective communications for these requires. The followings are the main application scenarios of wireless ad hoc networks [1].

- Tactical networks

A wireless ad hoc network that does not need to set up specific network infrastructure can be quickly deployed. Because of this characteristic, it has become the preferred technology solutions for military communications.

- Sensor networks

In many environments, the sensor network can use wireless ad hoc communication technology. Considering limited the power of the sensor device, the use of wireless ad hoc networks is a very practical solution. The wireless ad hoc networks can provide connectivity services for weather forecast sensor devices, data tracking of animal movements, and smart sensors embedded in consumer devices.

- Emergency services

After the environmental disasters such as the earthquakes, typhoons, and floods, fixed infrastructure may not work. The deployment of wireless ad hoc networks, which does not rely on any infrastructure, provides an easy communication method for rescue services. Especially in the disaster areas, it is one of the best choices for temporary communications.

- Commercial and civilian environments

With the miniaturization and popularization of the personal mobile devices, the environments such as conference rooms, classrooms, and individual buildings become another potential application areas of a wireless ad hoc network. In sports stadiums and shopping malls, wireless ad hoc networks that can be configured at lower cost is used to advertise special information to consumers. Vehicular Ad Hoc Networks (VANETs) are the special form of wireless ad hoc networks, which provides the information services for vehicular such as accident guidance, and notification of road and weather conditions.

- Entertainment

In the scenarios of multi-user games, wireless P2P (peer to peer) network, outdoor internet access, robotic pets and so on, the wireless ad hoc network is adopted, which can improve the user experience in these fields as MANETs can help the users to establish their entertainment networks quickly and easily without an additional equipment.

- Others.

A wireless ad hoc network can be used to extend the coverage of existing cellular mobile communication systems and to help connect the various IOT (Internet of Things) devices.

However, there are still a number of technical challenges remaining to apply wireless ad hoc networks to real environments. First, the communication quality is very unstable due to the interference of radio waves. It is necessary to improve this problem in the protocol of the physical / Media Access Control (MAC) layer. Second, since the node mobility, the network topology changes easily. It is necessary to develop a routing and forwarding protocol applicable to the changeable topology. Furthermore, it is necessary to design a protocol to ensure stable communication quality for providing quality of service (QoS).

1.2 Researches in Wireless Ad Hoc Networks

Many researches have been conducted for wireless ad hoc networks. These studies focused from the bottom of the physical layer to the top of the application layer.

1.2.1 Physical / MAC Layer Protocol

IEEE 802.11 is mainly and the most widely used [20]. This protocol adopts CSMA / CA (Carrier Sense Multiple Access with Collision Avoidance) as a mechanism of collision avoidance, transmits an ACK (Acknowledge) frame to the sender node, and retransmits a packet for which the ACK frame was not received.

In wireless ad hoc networks, when performing multi-hop communication, reduction of the throughput is a challenge. Furthermore, the hidden terminal problem and the exposed terminal problem is also existed.

1.2.2 Routing Protocol

Routing protocol corresponding to dynamic topology change is required in wireless ad hoc networks. There are many studies on routing protocols, which can be classified into a proactive type and a reactive (on demand) type. Also assigning IP addresses is a challenge in wireless ad hoc networks. Related routing protocols are described in section 1.4.2.

1.2.3 Transport Protocol

As a transport protocol on the Internet, Transmission Control Protocol (TCP) which is highly reliable connection type and User Datagram Protocol (UDP) which is connectionless type are generally used. Since packet loss occurs due to instability of wireless conditions, conventional TCP is sensitive to packet loss, so high throughput cannot be realized in ad hoc networks. For this reason, many studies have been done on improving TCP for wireless ad hoc networks.

1.2.4 Applications

As mentioned in 1.1.2, wireless ad hoc networks are expected to be applied to various scenes. Applications such as FTP (File Transfer Protocol) communications, video and audio communications, transmitting images and sound to Internet etc. are assumed.

1.2.5 Quality of Service (QoS)

QoS is defined as a quality of service requested from the sending node to the receiving node. Various schemes are proposed in each protocol layer to realize QoS in ad hoc networks [1] [11]. QoS metrics include throughput, delay time, delay time fluctuation (jitter), packet loss rate, etc. The QoS metrics are described in 1.3. In this thesis, we focus on providing QoS in wireless ad hoc networks. The existing QoS approaches are described in section 1.4.

1.3 QoS Metrics

The requirements of the network performance are different for the different specifications of different applications. For the applications such as high-quality video and real-time voice, the Quality of Service (QoS) is required to manage delay, packet loss etc. In contrast, the best effort service is provided for the applications which do not required for any special feature. For example, an application of VoIP (Voice over IP) requires the transmission delay under a certain level; otherwise, the call experience will be poor. The network delay for voice applications is recommended by the International Telecommunication Union (ITU) in Recommendation G.114 [2]. Three stages of one-way delay are defined as show in the Table 1.

The QoS parameters such as delay, packet loss etc. represent the requirements of the user applications. The following is two of the most common QoS parameters for evaluation of QoS can be considered:

- End-to-end delay, which is usually measured in milliseconds or microseconds, is used to measure how long it takes for a bit of QoS data to transmit through the QoS path.
- Packet delivery rate or Packet loss ratio, which is measured in percentage, is used to measure the reliability of the transmission for real-time applications that always requires a high packet delivery rate.

Table 1 Delay specifications in Recommendation G.114 [2].

The range of one-way delay (ms)	Descriptions
0 to 150	Acceptable for most user applications.
150 to 400	Acceptable provided that Administrations are aware of the transmission time impact on the transmission quality of user applications.
above 400	Unacceptable for general network planning purposes; however, it is recognized that in some exceptional cases this limit will be exceeded.

Since the nodes in a wireless ad hoc network need to transport kinds of applications and data as mentioned in 1.1.1., supporting QoS in a wireless ad hoc network is inevitable. The challenges of supporting QoS in wireless ad hoc networks include the limited transmission range, multi-hop transmission, packet loss due to conflict, and lack of a fixed infrastructure.

Many solutions have been provided for supporting QoS in wired or legacy wireless networks, but unfortunately they cannot be directly used in wireless ad hoc networks due to the unique characteristics of the wireless ad hoc networks.

1.4 QoS Approaches in Wireless Ad hoc Networks

Many researches have been done for provision of QoS in ad hoc networks. According to the function designed for supporting QoS, the approaches can be classified as shown in Figure 2 [3]. The major categories are the admission control, routing, differentiation, MAC (Media Access Control) Layer and scheduling etc. The MAC layer QoS approaches can be divided into three subcategories: CSMA approaches, TDMA approaches and Hybrid approaches. These methods are often used in combination to achieve better performance for QoS.

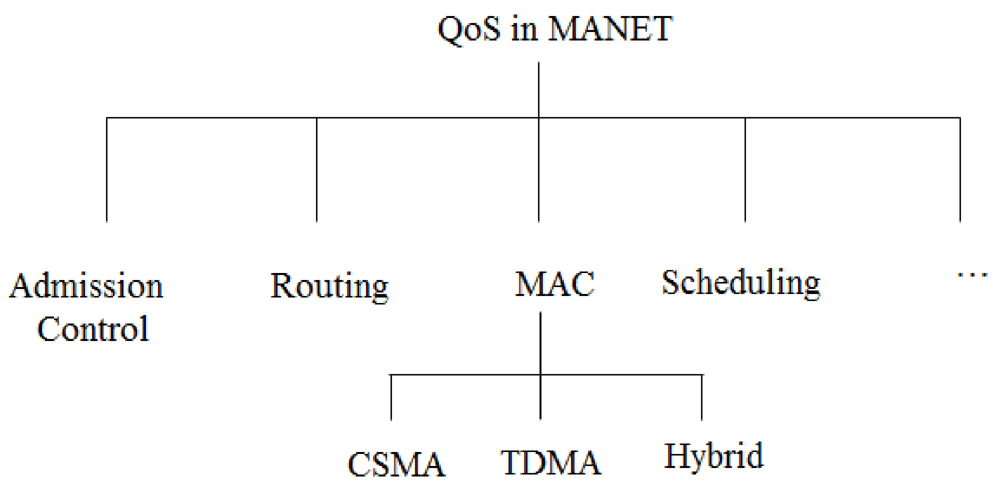

Figure 2 Provisions of QoS in wireless ad hoc networks.

1.4.1 Admission Control

Admission control determines which QoS flows are allowed to transmit and which flows are rejected in the network. It is important for connection setup and resource reservation in QoS transmission.

Xiao and Li have proposed data-control and admission-control schemes based on IEEE 802.11e MAC standard [4] for supporting QoS in ad hoc networks. Specifically, two schemes, which are named Dynamic Function Mapping (DFM) and Dynamic Traffic (DT), were addressed for data control. In the DFM scheme, in order to provide QoS for real-time traffic, each node maps the measured traffic-load condition into backoff parameters such as Contention Window (CW) and Arbitration Inter-Frame Spacing (AIFS) locally and dynamically. In the DT scheme, the backoff parameters are dynamically changed in accordance with the conditions of the traffic load.

However, [4] is discussed only for one-hop ad hoc communication.

1.4.2 QoS routing

In wireless ad hoc networks, QoS routing aims to establish one or more paths for the needs of QoS flow. There is a lot work providing solutions for QoS routing in wireless ad hoc networks. Many approaches considering QoS routing are combined with admission control. A Contention-aware Admission Control Protocol (CACP) has been proposed by Yang and Kravets [5]. In CACP, both bandwidth-aware routing and admission control are provided for QoS flows in wireless ad hoc networks. The admission control is based on the prediction of the local available bandwidth at a node and the route information through a complex reply process. CACP provides QoS guarantee by focusing on the bandwidth allocation. Su et al. have proposed QoS admission control routing protocol (QACRP) [6]. QACRP is using AODV (Ad hoc On-demand Distance Vector) routing protocol. During the route discovery phase, the admission control is performed. QACRP reduces the overhead during the routing discovery procedure.

Jia et al. proposed a routing algorithm which provides route with guaranteed bandwidth for QoS flows [7]. The algorithm computes route by considering the interference of the neighbor links. As a new coming QoS flow on a neighboring link may disrupt the existing QoS flow, they addressed a link capacity estimation model and adopted admission control with some scaling factors to solve this problem. Gupta et al. is presented Interference Aware QoS Routing (IQRouting), which is aware of the interference. IQRouting compute several paths for the QoS flow by source based method. The best path is determined by the destination node through distributed running admission control and comparing all candidate paths.

These QoS routing protocols try to reserve required bandwidth for QoS flows, but QoS guarantee for individual packet transmission cannot be realized.

1.4.3 Scheduling

Kanodia et al. proposed a Distributed Priority Scheduling (DPS) for providing QoS in terms of delay [8]. In DPS, two mechanisms have been designed for supporting QoS in wireless ad hoc networks. One is called distributed priority scheduling, by monitoring the transmitted packets, a scheduling table is created and updated by each node. The scheduling table is used for optimize the backoff algorithm in IEEE 802.11. The other one is multi-hop scheduling mechanism, in order to guarantee end-to-end QoS delay through the QoS route, the transit node can modify the priority of a QoS packet.

In order to guarantee real time traffics in IP networks on which the link is lossy and the round trip times is long, Akyilidz et al. proposed a rate control scheme called RCS [9]. In RCS, a priority scheme is designed for router to get the available network resources for QoS traffics. Dummy packets, which own low priority is used for probing the network resources. Moreover, in order to prevent the RCS from temporal signal losses, they also proposed a new scheme with high robustness. Specifically, the behavior of RCS was discussed when the packet lost due to the temporary loss of signal, the congestion in the network and the error links. Further, they also studied the delay bounds for real time traffic sources.

As these scheduling protocols are designed based on contention-based approaches, they are not able to provide strict priority.

1.4.4 QoS at MAC Layer

The provision of QoS guarantees in wireless ad hoc networks is inseparable from the support of MAC (medium access control) protocols. All upper-layer QoS methods such as QoS routing are dependent on and coordinate with the MAC protocol. The MAC protocol directly determines the validity and reliability of data transmission, which solves the collision problems among the nodes in a wireless ad hoc network.

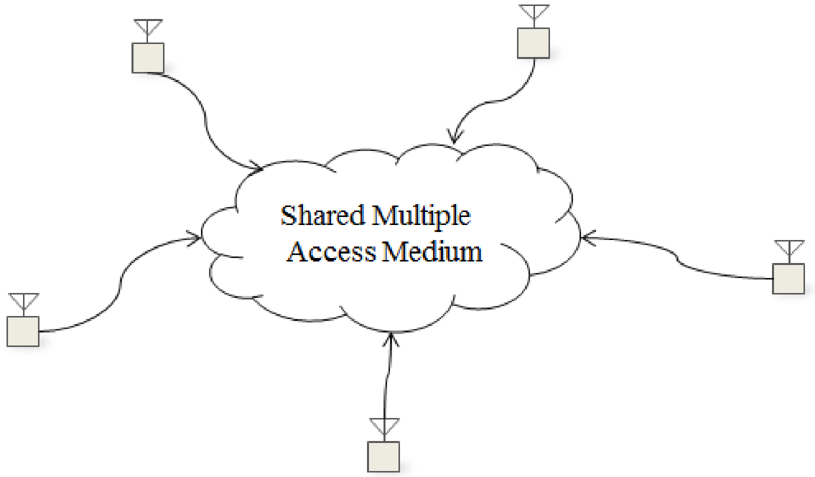

Figure 3 Shared Multiple Access Medium.

In a wireless ad hoc network, the same wireless channel is shared by the multiple neighbors (Figure 3). The QoS MAC protocols in wireless ad hoc networks that not only solves the problem of wireless media sharing, but also provides the reliable communication for real-time QoS guarantee, is the basic of QoS supporting methods for upper layers, such as QoS routing in network layer. There have been many QoS protocols focusing on MAC layer in wireless ad hoc networks. These protocols can be summarized in three categories.

The first category is the contention-based MAC (media access control) layer approach. Many QoS MAC protocols belong to this category are extensions of IEEE 802.11 DCF (Distributed Coordination Function). IEEE 802.11e [11] is a QoS specification of wireless network, which is an extension of IEEE 802.11. IEEE 802.11e specifies a procedure to guarantee QoS by providing more transmission opportunities for high priority data. Lakrami et al. proposed an enhanced EDCF algorithm, which allows modification of the transmission parameters TXOP (Transmit Opportunity) and CW_{min} (Contention Window Minimum), depending on the error rate of the channel [12]. However, [11] and [12] do not take account of the admission control in the protocol design, but only can provide relative priority to QoS flows, and therefore the bandwidth cannot be strictly guaranteed.

The second one is the TDMA-based (time division multiple access) approaches [10-13]. The TDMA approach can provide contention-free access for QoS traffics through the appropriate time slot reservation. The current TDMA approaches reserve time slots for both

QoS traffics and best-effort traffics. However, it is difficult for TDMA as the only approach to allocating channel access time for best effort flows because of the required bandwidth of the best-effort flow changes frequently. For example, the bandwidth required for TCP traffic is increased with the increase of congestion window size.

The third category is the hybrid approach which combined contention-based access and contention-free access [14, 15]. In [17], Shrestha et al. assumed that all nodes were located within the interference distance of the other nodes. With a focus on one-hop communication in a star network topology, [17] does not adequately address the channel access scheme for the multi-hop network. A time slot allocation scheme is proposed in [18] for hybrid CSMA/TDMA MAC protocol. The time slots are allocated based on queue length. The authors assumed that the size of the data packets in the network is the same and a time slot is only used for one data packet. Therefore, in ad hoc networks which are using multi-hop communication, those proposals are not a suitable choice. A hybrid CSMA/TDMA MAC protocol called Z-MAC is proposed by Rhee et al. [19] for wireless sensor networks. In a low-contention environment, Z-MAC uses CSMA for the nodes contending for the channel. In the situation of high contention, Z-MAC behaves like TDMA access method. However, the QoS assurance issue is not discussed in [19]. Overall, those existing studies do not sufficiently address the issues of multi-hop communication, service differentiation based on traffic priorities, and the adaptive adjustment of CSMA/TDMA period.

1.5 Challenges of supporting QoS in Wireless Ad Hoc Network

As the wireless resource is limited in a wireless ad hoc network, the primary purpose of a QoS protocol is to provide sufficient resources for QoS applications. But when an application will be started and who will start the transmission is unpredictable in a wireless ad hoc network. Therefore, making resource allocation for unpredictable QoS applications is very challenging.

Since the communication distance of the node in wireless ad hoc networks is limited, when a node sends a signal, the other nodes in the network may not be able to receive. And therefore a multi-hop approach is necessary. In wireless ad hoc networks, when a node receives two or more signals from other nodes at the same time, a conflict will occur because the signals are not able to be demodulated. Compared with one hop communication, the collisions are increased in multi-hop communication. To provide end-to-end QoS assurances, it is necessary to solve the collision problems as each link along a QoS route should transfer QoS packets without any redundant delay.

The movement of the nodes in wireless ad hoc networks is disordered and randomized, which result in a random variation of the network topology. Due to the node mobility, the nodes that are transmitting data may conflict with the nodes that are using the same wireless channel, the QoS performance deteriorated. The mobility should be considered when supporting QoS in wireless ad hoc networks.

1.6 Research Contributions

Provision of QoS in wireless ad hoc networks is the main objective of this thesis. For supporting QoS in an ad hoc network, a hybrid method, which combines TDMA and IEEE 802.11 DCF access method, is proposed. TDMA provides contention free transmissions for QoS traffics, and DCF is used to provide contention-based access for best effort or low priority traffics. A distributed time slot assignment algorithm is also designed to assign time slots for QoS traffics by using the precise position information. An admission control scheme is design to protect the existing communications by considering the remaining number of the time slots. The proposed scheme is simulated in the static environment for different data traffics. In the simulations, the proposed scheme is compared with IEEE 802.11e and pure TDMA.

To extend the proposed scheme to the mobility environment, the solutions for topology changes are provided. A procedure is designed for a new node attending the network. Some configurations are specified when the Auto Rate Fallback (ARF) is adopted in the mobile environment. The proposed method was also evaluated in a mobile network environment which ARF is using.

1.7 Thesis Outline

The structure of the remainder of this thesis is organized as follows.

Chapter 2 gives a brief survey of related works in wireless ad hoc networks. The details of three categories of MAC protocol are provided. For contention-based MAC protocol, IEEE 802.11 and its QoS version IEEE 802.11e is introduced. The TDMA-based and the hybrid MAC protocols are also briefly discussed in this chapter. As OLSR (Optimized Link State Routing Protocol) is supposed to use in our proposed method, the details of OLSR routing protocol is also introduced.

In Chapter 3, a TDMA/DCF hybrid QoS scheme for ad hoc networks is proposed. The specification of time frame structure is given. The control method of the TDMA period and DCF period is provided. In the TDMA period, the admission control is adopted to avoid network congestion. The control messages for admission control and their format are described. For time slot assignment in the TDMA period, three policies are designed; the details are shown in this chapter. As the time slots are assigned during the admission control phase, an example is used to illustrate the details of the procedures. In the end of the chapter, we analyse the overhead of the control messages in the proposed scheme, and we also discuss the advantages and disadvantages of the proposed scheme as compared with the existing approaches.

Chapter 4 presents the simulations conducted for the proposed method and the corresponding discussions. The details of implementation can be found in this chapter. The results of two simulations were discussed. In the first simulation, both QoS traffics and best effort traffics were using UDP. In the second simulation, both UDP and TCP traffics were simulated. In both simulations, IEEE 802.11e and pure TDMA protocol were used as the comparison and several traffic conditions were used for experimental analysis. The evaluation parameters include the throughputs, end-to-end delays, packet delivery rates and so on.

In Chapter 5, the extension of the proposed method in mobile environment was discussed. The application environments for proposed approach were discussed. The settings of parameters such as the length of time slot were defined and the solutions for changes of topology were provided. In addition, the simulation results in the mobile environment were discussed.

Finally, Chapter 6 draws the conclusions of our work and provides the directions for the future studies.

2. RELATED WORKS

In wireless MAC protocol, there are three main methods for controlling the wireless resources. The first one is contention-based method. One of the most popular protocols using this method is IEEE 802.11. Its QoS-improved version is IEEE 802.11e. The second method is contention-free method, which arrange the dedicated communication time for the nodes. TDMA MAC protocol belongs to this category. The third one is a hybrid protocol that integrates the advantages of the first and the second method.

2.1 Contention-based MAC Protocol

Nodes directly compete for the channel access opportunity in the contention-based MAC protocols. To solve the conflict problem when two nodes get communication opportunity at the same time is a critical issue in the contention-based MAC protocols. The contention-based MAC protocols are simple and adaptable to the wireless dynamic topology environment. At present, there are a lot of the contention-based MAC protocols.

The well-known IEEE 802.11 MAC protocol [20] is a kind of contention-based MAC protocols. However, IEEE 802.11 has not established the especial control mechanism for QoS traffics. The IEEE 802.11e fills the gaps of QoS in IEEE 802.11, which implements the priority transmission of QoS traffics.

2.1.1 IEEE 802.11 MAC

Now IEEE 802.11 standards have become synonymous with wireless local area network (WLAN). IEEE 802.11 standards mainly involve the following respects (Figure 4).

- The lowest physical layer specifies the data transmission rate and the radio frequency band. For example, in IEEE 802.11b, the maximum data transmission rate is 11 Mbit/s using 2.4 GHz band. IEEE 802.11a is possible to achieve a data maximum transfer rate 54 Mbit/s using OFDM modulation techniques by using band of 5 GHz.

- The protocol in MAC layer carries out the media access control through a distributed of centralized method.

In the MAC layer of the IEEE 802.11, there are two access methods as shown in Figure 4. One is Distributed Coordination Function (DCF), which assumes that collisions will occur. The other one is PCF (Point Coordination Function) method. In PCF control mode, the collision does not exist because it is a polling-based method.

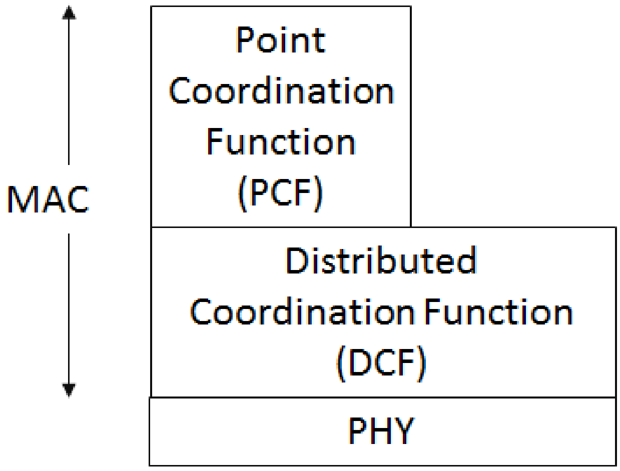

Figure 4 Architecture of IEEE 802.11.

A. DCF.

Since DCF is a simple protocol and can be easily employed, it is widely used. In DCF protocol, collisions caused by multiple nodes accessing the wireless media at the same time are avoided by using a very basic random access mechanism named Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA).

In the wireless environment, if STA 1 and STA 2 transmit data to the AP (Access Point) at the same time, AP fails in receiving data from either of the two stations due to the radio interference. In order to reduce the possibility of such situations, DCF introduces Collision Avoidance (CA) mechanism. DCF realize the CA mechanism by Inter-frame Spacing (IFS) and Backoff Algorithm.

In DCF, it is necessary for a station to wait for a corresponding IFS time before sending a frame. Priority control can be achieved by providing IFS with different length as shown in Figure 6. For example, when there is a data frame to be sent, the first thing for the wireless station to do is waiting. The waiting time is called DIFS (DCF IFS). DIFS is the longest IFS, which is used for the packets with the lowest priority such as data frame and RTS (Request to send). The waiting time for sending an ACK frame is SIFS (Short IFS) time. SIFS is the shortest IFS, which is used for transmitting the packet with the highest priority. SIFS is also used for sending CTS (Clear-To-Send) frame. There is no back-off time after SIFS. PIFS (PCF IFS) is a type of IFS which is mainly used for sending polling frame PCF. Since polling frames in PCF have a higher priority when the DCF and PCF coexist, PIFS is shorter than DIFS. In IEEE802.11, there are some other inter-frame interval parameters, such as RIFS, PIFS, AIFS and EIFS.

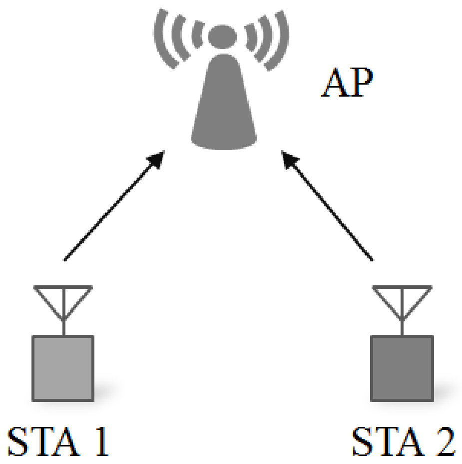

Figure 5 An Example of Wireless Collisions.

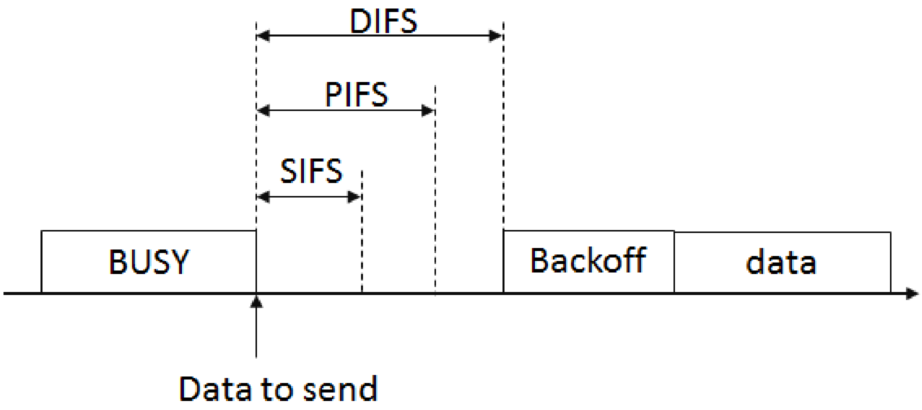

Figure 6 Priority Control by IFS.

A backoff procedure is executed if the wireless channel is not accessed for DIFS time.

After the station enters the backoff procedure, at first, a random number is selected for backoff counter, which uniformly distributed between zero and the current Contention Window size (CW) as shown in the following formula. The initial value of the CW is 0-31.

$$\text{Backoff counter} = \text{rand}[0, \text{CW}], \quad CW_{min} < CW < CW_{max}$$

The backoff time is decided by the backoff counter and the slot time. The value of the slot time is decided by the physical layer (9 us, when the physical layer is IEEE 802.11a). In the backoff procedure, after each slot time, the station listens to the channel. If the channel remains idle in a slot time, the backoff counter is subtracted by 1. When the backoff counter becomes zero, the station has the right to access the channel and the buffered frames would be sent.

If the wireless channel is accessed by the other station during the backoff procedure, the current value of backoff counter is saved. The saved value of backoff counter is used in the next backoff procedure. Each time the state of the channel changes from busy to idle, the station executes the backoff procedure after a DIFS.

The receiver station sends an acknowledgement frame (ACK) using SIFS to inform the success of receiving data frame. After the sender station successfully receives the ACK frame, the transmission completes.

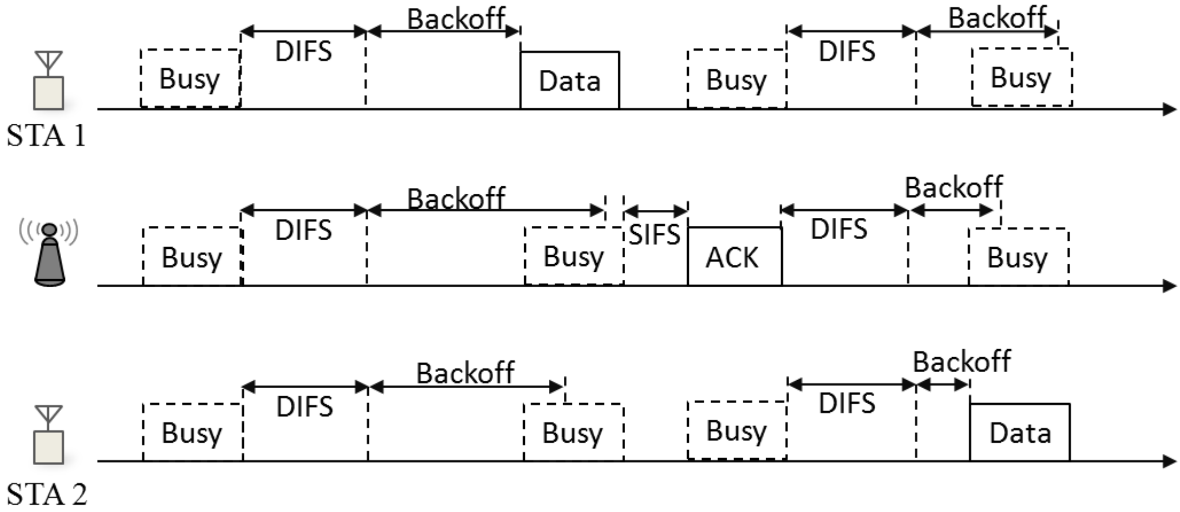

Figure 7 Backoff Mechanism in DCF protocol.

After DIFS, if the same number is selected for backoff counter in two or more stations, the backoff counters in these stations may become zero simultaneously. The collisions will occur in this situation. Especially when a network has a large number of nodes, the possibility of collision is higher. After the collision, as the CRC check fails at the receiving station due to collision, no ACK frame is fed back to any station. Each station detects the collision since ACK time out, and the data will be retransmitted. Before entering the next competition for retransmission, in order to reduce the possibility of conflict, Binary Exponential Back off (BEB) mechanism is designed to expand the contention window CW. In each retransmission due to the collision of the frame, the CW is increased using the following formula:

$$CW = (CW_{min} + 1) \times 2^n - 1 \quad \text{where n refers to the retransmission times.}$$

In DCF, the allowed maximum number of retransmissions is 7 times. The first six times, CW is increased according to the formula. At the 7^{th} retransmission, the station does not increase the value of CW. After that, the packet is discarded.

DCF provides adequate performance in a scenario with a small number of wireless nodes such as family wireless environment. DCF cannot meet the requirements of delay for sensitive applications when the number of the wireless nodes is increased.

B. PCF

PCF protocol has been provided as an option function in the IEEE 802.11. As PCF is an expansion based on DCF, PCF and DCF is compatible with each other. In the PCF model, the compatibility with DCF is actually based on an alternating working mechanism. One cycle of their alternating work is called the CFP repetition interval. Specifically, the CFP repetition interval includes two periods, one is called CP (Contention Period) and the other one is CFP (Contention-Free Period) as shown in Figure 8.

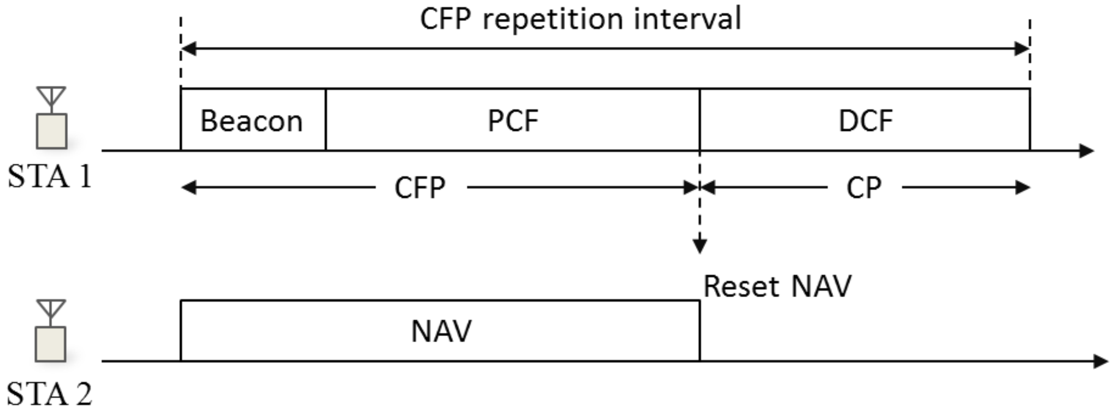

Figure 8 CFP in PCF.

- CFP: CFP is the period for the PCF operation. This period is protected by a virtual carrier sense (NAV) mechanism. The value of NAV is decided by the duration bit in the Beacon frame. The stations set their NAV after receiving a Beacon frame. During NAV, the station cannot access the channel.
- CP: CP is a period of time in which the protocol operates in the DCF mode.

In PCF, in order to control the access right of the stations, the AP acts as a point coordinator (PC), this performs centralized control. There is a polling list in AP. AP polls the stations in the order of the polling list as shown in Figure 9. Since the station cannot compete for the channel because of the NAV mechanism, the stations cannot start transmission unless the AP polls them.

The following is a typical workflow for PCF.

1. First, the AP sends Beacon to set all the stations to the NAV state by using the

duration bit.

2. If AP does not have any buffered data for sending, AP sends CF-Poll frame. After receiving the CF-Poll frame, the station starts transmission. Otherwise, AP sends data frame and CF-Poll frame at the same time.

3. If the station received data from AP, the station sends its data and CF-ACK for received data. Otherwise, the station only sends data to AP.

4. AP sends back the CF-ACK to the node to end the poll.

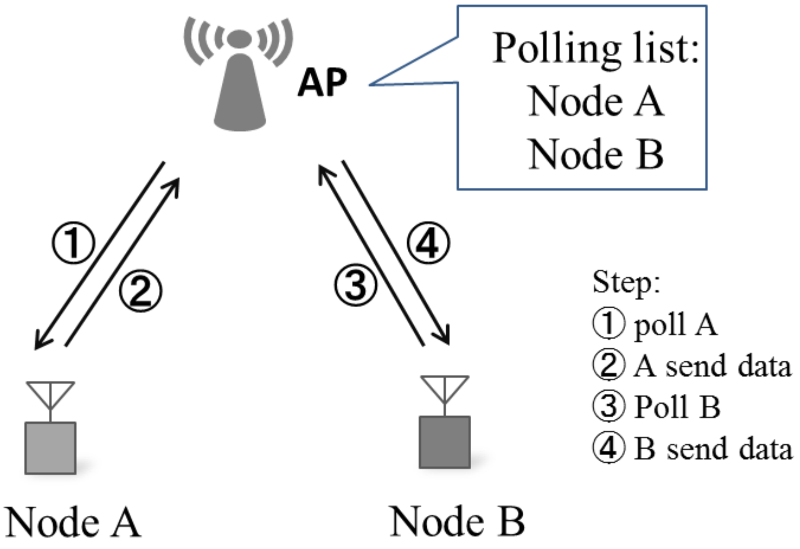

Figure 9 Polling between Node and AP.

The CF-END frame is used as the termination information at the end of CFP. Due to the characteristics of CF-END frame, it is defined as control frames, which is different from the other PCF frames. The duration bit of CF-END frame is set to 0, and the CF-END frame is broadcasted by AP. The NAV would be set to 0 after all nodes received the CF-END frame.

2.1.2 IEEE802.11e MAC

The IEEE802.11e protocol is specified to support QoS for different service types. The IEEE802.11e MAC protocol is an enhancement of IEEE802.11 MAC standard, which consists of two access method. One is Enhanced Distributed Channel Access (EDCA), and the other one is Hybrid Controlled Channel Access (HCCA) (Figure 10).

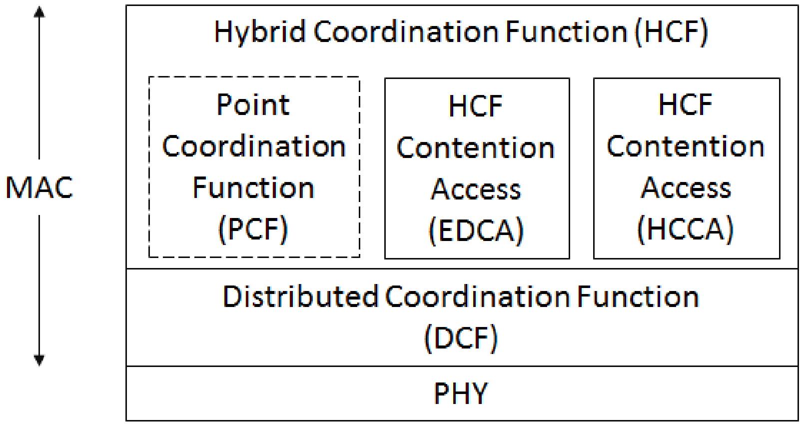

Figure 10 MAC architecture of IEEE802.11e.

A. EDCA

The EDCA is an upgraded QoS version of DCF, which is also a contention-based access method. In EDCA, it defines access category (AC) to support the priority mechanism at QoS Station (QSTA). Each QSTA has four types of AC: AC_BK for background traffics, AC_BE for best effort traffics, AC_VI for video traffics and AC_VO for voice traffics. Among ACs, the lowest priority is assigned to AC_BK, and the highest priority is assigned to AC_VO. Eight user priorities are defined for different types of AC to access the wireless media. The mapping from eight priorities to four ACs is shown in Table 2.

As shown in Figure 11, by adjusting the parameters such as CW_{min}, CW_{max}, AIFS, the AC with higher priority would get Transmission Opportunity (TXOP) earlier than the AC with lower priority. Collisions among ACs in a QSTA are called internal collisions, which are resolved initially.

In DCF protocol, DIFS is used as the waiting time before transmitting data frames. In EDCA, the Arbitration Inter-Frame Space (AIFS) in accordance with the priority of AC is used instead of DIFS. AIFS is the channel idle time that QSTA in EDCA mode must wait for to obtain transmission opportunity. Unlike DIFS, the value of AIFS is not unique. Different types of service have different AIFS values, which is allocated by QoS Wireless Access Point (QAP). The AIFS value of low priority service (such as background data and best effort data) is larger than the AIFS value of high priority service (such as video and voice). A small AIFS value means that video, voice and other real-time services can be faster access to the network than low priority services.

Table 2 The relation between user priority and ACs.

Priority	Priority	Access Category	Designation
Lowest	1	AC_BK	Background
-	2	AC_BK	Background
-	0	AC_BE	Best Effort
-	3	AC_BE	Best Effort
-	4	AC_VI	Video
-	5	AC_VI	Video
-	6	AC_VO	Voice
Highest	7	AC_VO	Voice

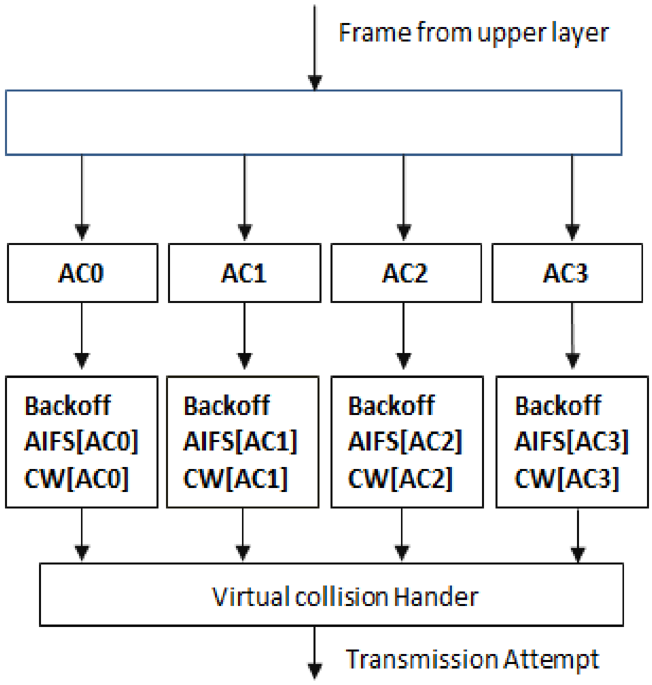

Figure 11 Access categories in EDCA.

In addition to AIFS, the following parameters are related to TXOP.

- CW_{min}: Different ACs may have different CW_{min}. High priority traffics have smaller CW_{min}.
- CW_{max}: The same as CW_{min}, the AC with higher priority has smaller $CW_{max.}$
- $TXOP_{limit}$: It means the maximum duration of TXOP for a QSTA transmit data frames from the same AC. A TXOP is defined by a starting time and the maximum duration of the transmission. The QSTA should ensure that its TXOP does not exceed the $TXOP_{limit}$.

Each AC in the QSTA contends for TXOP independently by using the above four parameters. Once an AC detects that the channel is idle after AIFS, it initiates the backoff procedure. The same as DCF, the QSTA gets the opportunity to send data frames after the value of the backoff counter comes to the end value (zero). The high-priority AC will get the TXOP when backoff counter becomes zero in multiple ACs at the same time. The above parameters AIFS, CW_{min} and CW_{max} can be configured together, so that the data of the high priority class has a high possibility to achieve TXOP.

B. HCCA

HCCA is an extension of PCF, which uses the Hybrid Coordinator (HC) as a central control unit to manage the access time of the stations. The key difference between HCCA and PCF is that, in HCCA, the time and duration of the transmission are arranged by HC according to the Traffic Specification (TSPEC) sent by QSTA. The main TSPECs are shown in Table 3. Before starting transmission, the QSTA sends a reservation request frame including TSPEC to get permission from HC. HC decides whether the QSTA can start transmission or not. If the TSPEC sent by the station cannot be supported, HC denies the request. Otherwise, HC arranges the transmission schedule for the QSTA based on the TSPEC. Then, HC informs the QSTA the transmission schedule. Since the transmission time is scheduled by the central control unit HC, there is no conflict in HCCA.

In HCCA, the transmission time is divided into CP and CFP, which is the same as PCF. In the CP phase, the EDCA mechanism is used to contend for the channel, and HCCA is used in the CFP phase. During the CFP, the QSTA can get the TXOP by receiving a QoS CF-Poll frame. The QSTA will start sending data after SIFS after receiving the QoS CF-Poll frame as shown in Figure 12. The QSTA (including HC) needs to send ACK to respond to the received frame in SIFS. The other QSTAs will not attempt to send data since the NAV is set. If the QSTA does not send data in PIFS, HC will assign the channel to other QSTAs.

Table 3 TSPEC parameters

Nominal MSDU Size
Maximum MSDU Size
Inactivity Interval
Mean Data Rate
Minimum PHY Rate
Delay Bound
Surplus Bandwidth Allowance

MSDU: MAC service data unit

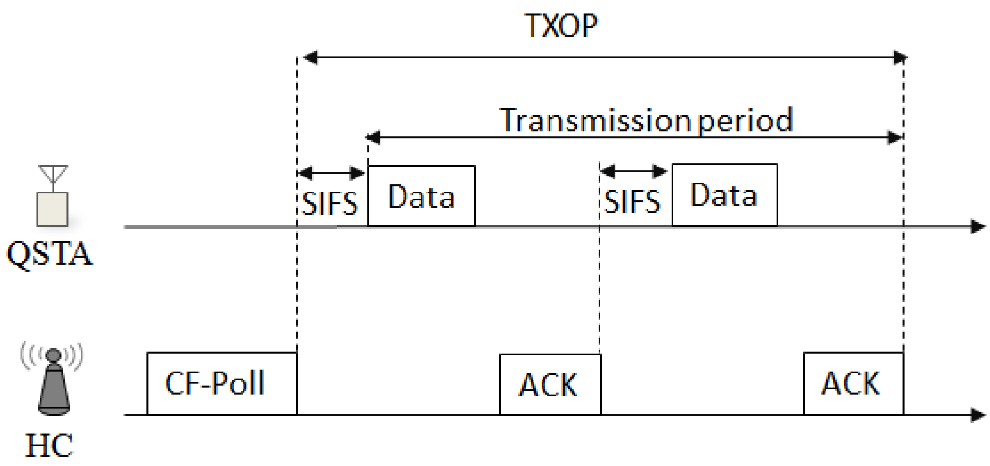

Figure 12 Access Control in HCCA.

In HCCA, HC only give the chance (TXOP) to QSTA to send QoS data, but HC does not determine which type of data traffics uses the TXOP. The priority of the traffic is determined by QSTA. However, since the HCCA should be implemented in both QSTA and HC, HCCA is difficult for HCCA to work with the legacy wireless network. As no central unit exists in wireless ad hoc networks, it is not suitable to use HCCA in a wireless ad hoc network.

2.2 TDMA MAC Protocol

TDMA is one of the best methods for provision of QoS in wireless ad hoc networks. In a wireless ad hoc network using a TDMA MAC protocol, the bandwidth is controlled by the number of the time slots. The allocation of time slots is closely related to the number of neighbor nodes and the activities of neighbor nodes. Usually, a time frame structure is used in the TDMA protocols. The time frame is a period which including several time slots (Figure 13). The approaches for time slot reservation are different in different TDMA protocols. Some of the TDMA approaches are discussed in the following sections.

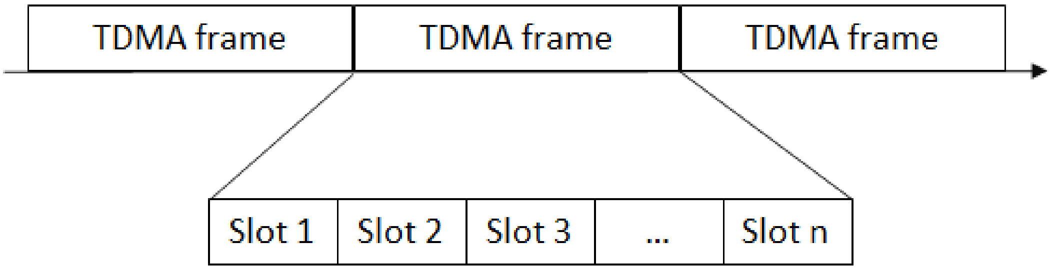

Figure 13 TDMA Frame Structure.

2.2.1 DSRP

Distributed Slot Reservation Protocol (DSRP) [27] has been proposed by Shih et al., which comprises several dynamic bandwidth allocation policies for providing QoS routing in TDMA based wireless ad hoc networks. In DSRP, the only information used for QoS routing is the one-hop neighbor information. As mentioned above, the number of time slots occupied by the link decides the bandwidth. DSRP reserves the time slots on-demand of the applications. Two types of policies are designed for time slot reservation. The first one is slot inhibited policies (SIPS), which checks all the available time slots for a link. The second policy that decides the time slot can be selected for a link, which is named Slot Decision Policies (SDPs) in DSRP. SDPs use the following three policies.

- Three-Hop Backward Decision Policy (3BDP)
- Least Conflict First Policy (LCFP)

- Most Reuse First Policy (MRFP)

Due to the inappropriate slots reservation, the originally existed QoS route is disappeared. This problem is a great challenge in wireless ad hoc networks. 3BDP policy is designed to solve this problem. In 3BDP, the node tries to make time slot reservation for the previous third link. In addition, LCFP reserves time slots for the next two links first since the problem may occur in the next two links. When multiple time slots remain after LCFP, MRFP chooses one of them by considering the utilization of the neighboring time slots. The time slot owns more users is selected first.

In DSRP, to discover a QoS route, the source node initially broadcasting a route request message (RREQ) to its neighbor nodes. The available time slots are determined by SIPS and SDPS when the RREQ is broadcasted. As a reply to RREQ, the destination node sends a route reply message (RREP). By using the RREP, the time slots for the route are reserved.

It is possible that the time slots decided by SIPS and SDPS are reserved by the RREQs for other traffics. To solve this problem, a Slot Adjustment Protocol (SAP) is proposed.

As the route path may be broken or changed due to the mobility in wireless ad hoc networks, a protocol is also designed in DSRP to maintenance the broken route or deal with the change of the route.

2.2.2 DRAND

Rhee, et al. proposed a distributed randomized time slot assignment algorithm (DRAND) [14], which realizes the distributed execution of RAND [25]. RAND provides a very efficient method for time slot scheduling.

DRAND assume that the nodes in the two-hop transmission range will conflict when they transmit simultaneously. The broadcast mode is used during the time slot reservation. Each node will get a time slot without conflicting with the other node after the setup phase is finished in DRAND.

DRAND uses four states control the nodes in the network. The state transition diagram is given in DRAND (Figure 14). The initial status of a node is IDLE. In order to get a time slot, the node in the IDLE state tries to send a request message. The node has half of the possible to run a lottery. The possibility for the node to win the lottery is preset, which depends on the estimation of the number of neighbors (including one hop and two hop neighbors) whose time slot has not yet been decided. If the node wins the lottery, the state of the node is changed to the REQUEST state and the request message is sent to its neighbor nodes. If the node does not win the lottery, the state will not be changed.

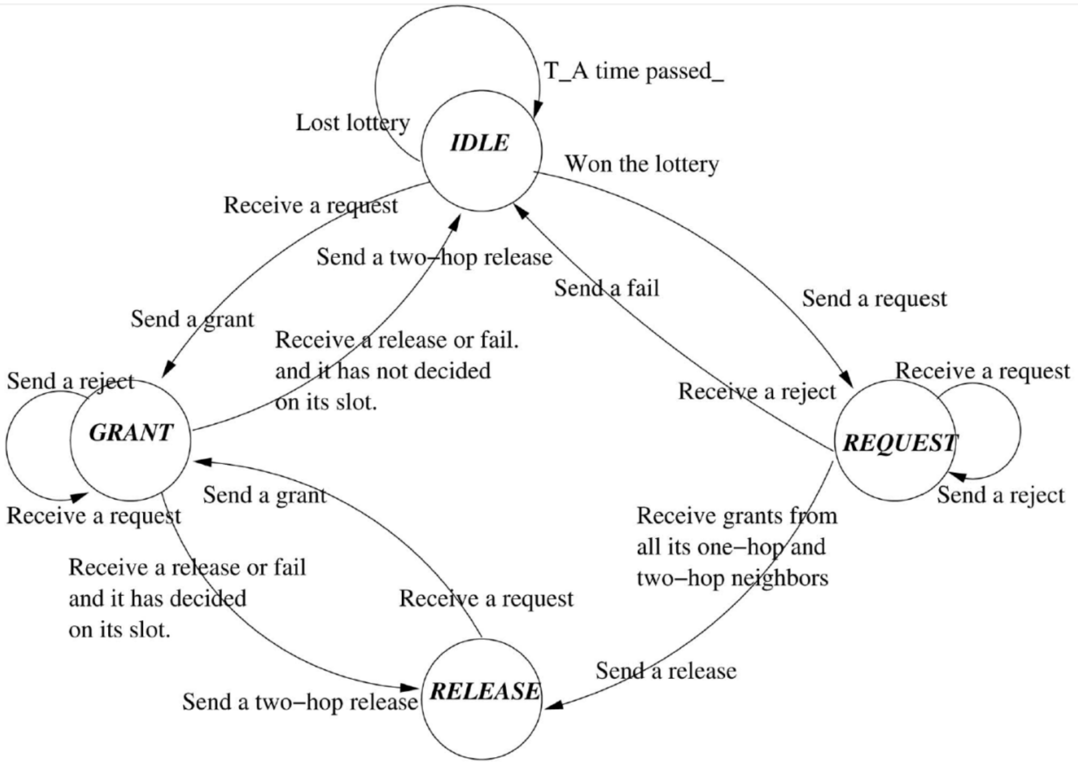

Figure 14 The state diagram of DRAND [14].

The state of one-hop neighbor is changed from IDLE or RELEASE state to GRANT state after receiving the request message. If a node changes its state to GRANT state, the node sends GRANT message as a reply for request message. If the node who sent the request message receives the grant message from all one-hop neighbors, the node selects a free time slot (the time slot is not selected by its two hop neighbor nodes) for itself. Then the node changes its state to RELEASE and broadcast a release message which includes the selected time slot to notify its neighbors (one hop and two hop neighbors).

If one-hop neighbor in the REQUEST or GRANT state receives the request message, a reject message is sent. After receiving the reject message, the node changes its state for the REQUEST state to the IDLE state. A fail message is sent by the node to inform its one hop neighbors about the failure of time slot reservation.

If the node in the REQUEST state does not receive any control message such as grant message or reject message from its neighbor nodes, the request message is retransmitted.

As the selected time slot is shared by all neighbor nodes (one-hop and two-hop neighbor nodes) through the dissemination of the release message, DRAND ensures that the time slot decided by the node is the one which is not selected by the other two-hop neighbors.

2.2.3 OA-TDMA

OA-TDMA (OLSR-Aware TDMA) is proposed by Kas et al. [15] for wireless mesh networks. The topology information in OLSR (Optimized Link State Routing) [21] routing protocol is used for reserving time slots in OA-TDMA.

The purpose of OA-TDMA is to achieve a higher throughput of the network by increasing the utilization of the time slots. OA-TDMA uses a time frame with a fixed number of time slots. Each node runs the time slot scheduler independently at the end of each time frame. The time slots reserved by the time slot scheduler will be used in the next time frame.

In OA-TDMA, the time slots are assigned in a distributed manner using a weighted scheme, by which the MPR (Multipoint Relay) owns more MPR Selectors would achieve more time slots. The following formula is used for calculating the weight of an MPR node:

$$\text{Weight} = \text{Num\_of\_MPR\_Selectors} + 1$$

When a node is selected as an MPR node, its weight equals to the number of the MPR Selectors plus 1, which means the MPR node itself.

To realize the weighting scheme, OA-TDMA extends the HELLO message to carry the weight information. Each node has the consistent information about the weight value of their one-hop and two-hop neighbors through the exchange of the extended HELLO messages.

Every node competes to win the time slots on its behalf by using the weight information.

In OA-TDMA, how to synchronize the time frame structure and time slots among the nodes is not discussed. The time slot reservation algorithm reserves the time slots for both QoS traffics and best effort traffics in OA-TDMA. However, it is inappropriate to reserve time slots for best effort traffics due to the variable features of best effort traffics.

2.2.4 ASAP/SM

Kanzaki et al. proposed ASAP/SM (Adaptive Slot Assignment Protocol with Slot Migration) [16], which is an adaptive slot assignment protocol. The amount of traffic for wireless sensor networks is considered in ASAP/SM, the time slots for the node who has low traffic load are migrated through periodically exchanging the information of data traffic loads and the channel utilization among the neighbor nodes.

The length of the time frame is changed dynamically in ASAP/SM. The nodes that newly join the network send a request message (REQ) to collect information from its neighbors by using the first time slot in the time frame. After received the information packet (INF) sent by a neighbor node, the new node would choose the suitable time slots for its self after setting the time frame length according to the INF message. The following three procedures are used for choosing a time slot:

- Getting an unsigned slot (GU)
- Releasing multiple assigned slots (RMU)
- Doubling the frame (DF)

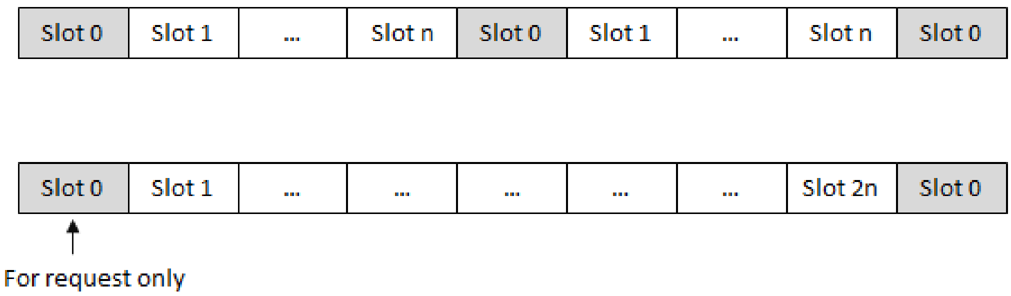

Figure 15 Frame Structure of ASAP/SM.

If no time slot is available after executing GU and RMU, the time frame is doubled and GU and RMU will be executed again until the valid time slot is arranged (as shown in Figure 15). After the setup phase, the information of data traffic is exchanged periodically. Whether to migrate an assigned time slot or not is decided by the channel requirement, the channel utilization and the gap value which can be calculated from the previous two parameters. The time slots of the node who owns low traffics are released. After the migration of a time slot, the node sends an update message (UPD) in its assign time slot. The node receives the UPD message would update its own information according to the UPD.

ASAP/SM focus on the throughput overall the network. It can keep higher throughput as the time slots assigned to the node with low traffic loads are migrated. However, the overhead of ASAP/SM is high and the QoS issue is not addressed.

2.3 Hybrid MAC protocol

As mentioned in Section 2.1, the contention-based approaches, CSMA/CA-based approaches are the most widely used as its simplicity. The node needs to make sure the channel is idle before transmission in CSMA/CA, otherwise the transmission may fail due to the collisions. The node competes with other nodes which are using the same channel. However, CSMA/CA also has disadvantages:

- The signal messages are sent before each transmission, therefore, the CSMA/CA approach is slow and the bandwidth is wasted.
- The possibility of collisions becomes high when the network becomes larger.

The TDMA approaches, which arrange time slots for the transmission nodes are more efficient than CSMA/CA approaches. But TDMA approaches also have disadvantages:

- As the TDMA approaches use the time frame to control the time division, the transmission delay may become intolerable when a large time frame is set.
- It is hard to find the optimal number of time slots to make fair access scheduling for all nodes.
- The time slot reservation is always fixed, which may not suit for the dynamically

changed network topology and time-varied traffics.

A hybrid approach, which is combing the CSMA/CA and TDMA, can avoid some of the above mentioned disadvantages of them. There have been some protocols adopting the hybrid approach.

2.3.1 CSMA/CA-TDMA

Shrestha et al. proposed a hybrid scheme by combining CSMA/CA and TDMA [17] for single hop wireless networks. CSMA/CA-TDMA uses a distributed and centralized control method. The network model used in CSMA/CA-TDMA is a star type, and there is a network coordinator in network. A superframe structure is maintained in each node for dividing the transmission time into CSMA/CA period and TDMA period as shown in Figure 16. Two schemes based on the Markov Decision Process (MDP) [30] have been designed in CSMA/CA to decide the period for transmission and the length of each period.

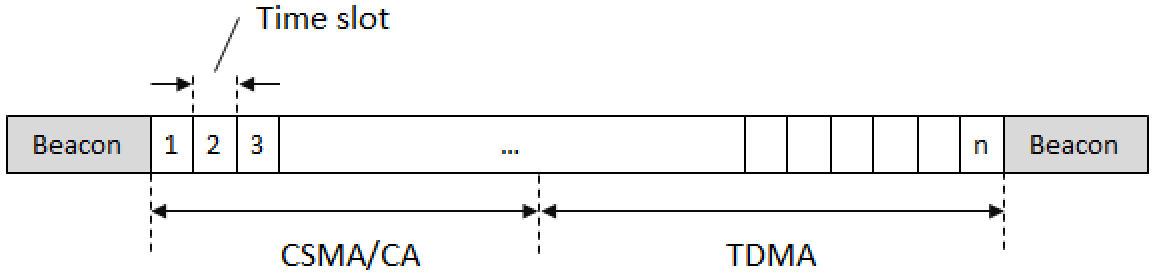

Figure 16 Superframe Structure of CSMA/CA-TDMA.

The coordinator broadcast the beacon frame in the beacon time slot. In the contention period, IEEE 802.15.4 MAC [30] is used to operate the slotted CSMA/CA. In the TDMA period, the coordinator assigns the time slots for the nodes who request for. Four status of the node activity are defined: defer transmission, transmit packet during CSMA/CA period, transmit packet during TDMA period, and transmit packet during both periods.

MDP-based Distributed Channel Access (MDCA) scheme is designed to decide the status of the node based on the packet buffer level. When the status of the node is transmitting packet during TDMA period, the node sends a request by set a special bit in the data packet which is transmitted in CSMA/CA period. The time slot is assigned by the coordinator when there are available time slots in the TDMA period.

An MDP-based Centralized Channel Access (MCCA) scheme has been developed for coordinator to decide the proportion of TDMA period and CSMA/CA period to control the energy consumption based on the traffic condition in the network.

CSMA/CA improves the network performance by considering the traffic loads in each node with a focus on one-hop communication in a star network topology. As a coordinator is used in CSMA/CA, it does not work properly for a multi-hop communication in wireless ad hoc networks.

2.3.2 Z-MAC

For sensor networks, Rhee et al. presented a hybrid MAC scheme combines TDMA and CSMA access method, which is called Z-MAC (Zebra MAC) [19]. In Z-MAC, CSMA is used as the main access mode, and TDMA is used when the contention level is high in the network.

DRAND [14] is adopted to assign time slot. Berkeley MAC (B-MAC) [26] is adopted for nodes contending for the channel, which can also achieve lower power consumption. At the setup phase of Z-MAC, the overhead is higher, which can be ignored as the setup phase is so short as compared with a network operation cycle.

In Z-MAC, the setup phase will run at the beginning or when the network topology changes. During the setup phase, the information of all one-hop and two-hop neighbors is collected through periodically broadcasting a ping message. The list of one-hop neighbors is included in the ping message. Through the neighbor information, the node selects a time slot for itself by using DRAND. Unlike the traditional time slot scheduling method using a unique time frame for all nodes, Z-MAC proposed a new method that time frame is different in different node. The size of the time frame in a node depends on the maximum number of time slots reserved by its neighbors.

The relation between the frame size L_i and the maximum number F_i of the time slots reserved by its neighbors is provided as the following formulas, which is called Time Frame Rules (TF Rule).

$$L_i = 2^a, \qquad 2^{a-1} \le F_i \le 2^a - 1, \quad \text{where, a} = 1,2,3 \ldots$$

To control the transmission, there are two modes for each node in Z-MAC. One mode is low contention level (LCL), in which the node accesses the channel using B-MAC. The other one mode is high contention level (HCL). An explicit contention notification (ECN) message is sent to neighbors when the contention level is high. After receiving the ECN message, the node turns to the HCL mode. In HCL, if a node is the selector of the time slot, the node can compete for the current time slot with its one-hop neighbors. Z-MAC implements two modes by using the backoff parameter, CCA (Clear Channel Sensing) and LPL (Low Power Listening) interfaces of B-MAC.

Though Z-MAC assigns time slots for the nodes when the contention level is high, the one-hop neighbors can also contend for the reserved timeslot. However, the QoS assurance issue is not discussed in Z-MAC.

2.4 Routing Protocols in Wireless Ad Hoc Networks

In a wireless ad hoc network, when two nodes cannot communicate directly, the data will be transmitted with the help of the neighbor nodes. In this situation, the neighbor node operates as a router. In wireless ad hoc networks, there are many routing protocols. The routing protocols in wireless ad hoc networks can be divided into three types as shown in Figure 17.

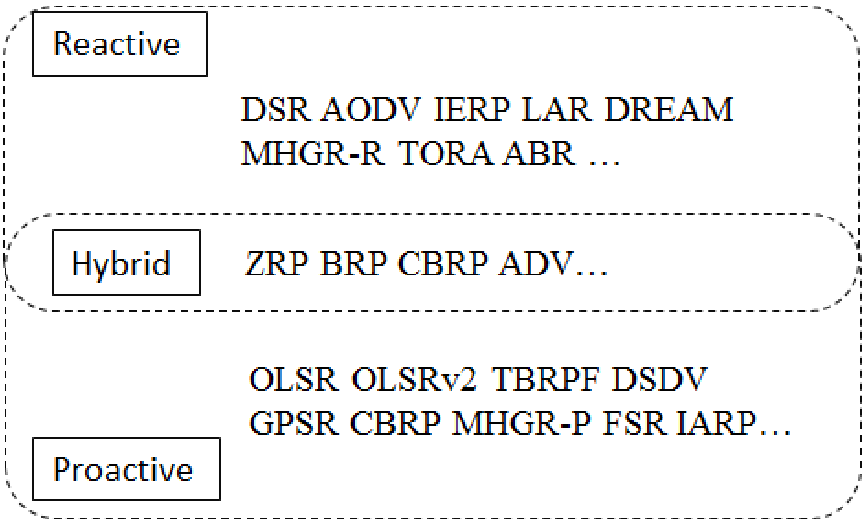

Figure 17 Routing Protocols in wireless ad hoc networks.

In the reactive routing protocols (on-demand), all routes are not saved in the routing table. A route is built only when a communication request occurs. The reactive routing protocols do not have a routing table. Before starting data transmission, the source node broadcasts the Route Request (RREQ) to probe the route. The node received RREQ broadcasts the request until the destination node receives the RREQ. A Route Reply (RREP) is sent back by destination node through the path probed by RREQ. Reactive routing protocols are suitable for the network with high mobility and low communication request. A classic reactive routing protocol is Dynamic Source Routing (DSR) protocol, which is also standardized by RFC.

In proactive routing protocols, the router forwards the packet based on the routing table. The proactive type routing protocols are also referred to table-driven protocols. In the proactive routing protocol, the packet is forwarded to the next hop according to the routing table. However, if the frequent movement exists in the network, routing table becomes quickly outdated. Since routing table needs to update at regular intervals, it requires shorter update interval when frequent mobility exists. As a result, the overhead of the routing protocol is increased. Therefore, proactive routing protocols are suitable for wireless ad hoc networks with low mobility.

2.4.1 OLSR

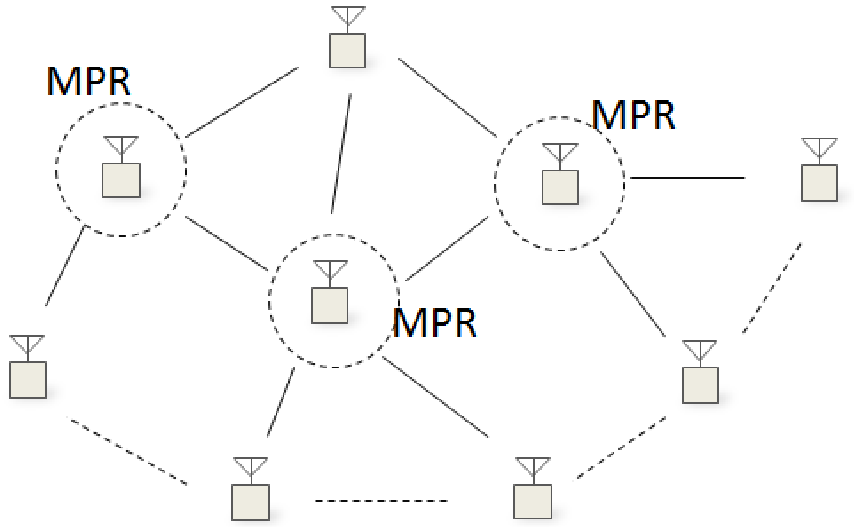

Figure 18 Concept of MPR nodes in OLSR.

OLSR (Optimized Link State Routing) [21] a type of proactive routing protocol. OLSR introduces MPR (Multipoint Relay) to reduce the amount flooding messages which affects the normal transmission in a scaled network. Figure 18 shows a conceptual view of the MPR nodes of OLSR. Each node maintains an MPR set and MPR Selector set. MPR node is the only node that relays the forwarding message.

In OLSR, each node holds the Willingness values for MPR selection, which is defined in the range of 0 to 7 as shown in Table 4. The value represents the willingness of each node for retransmission. A node with higher willingness is selected as MPR by the other nodes in a higher possibility.

Table 4 Willingness in OLSR

Parameter	Value
WILL_NEVER	0
WILL_LOW	1
WILL_DEFAULT	3
WILL_HIGH	5
WILL_ALWAYS	7

OLSR creates the topology table and the routing table by regularly sending and receiving HELLO messages (default: 2 seconds) and TC messages (default: 5 seconds) among the nodes in the network.

- HELLO message

In OLSR, each node periodically informs the existence to the neighbor nodes by broadcasting a HELLO message including its one-hop neighbor list and the value of willingness (Figure 19). Thus each node can also acquire the neighbor information, which is used for computing the MPR node. The HELLO message is broadcasted in the range of only one hop.

Reserved		Htime	Willingness
Link Code	Reserved	Link Message Size	
Neighbor Interface Address			
Neighbor Interface Address			

. . .

Link Code	Reserved	Link Message Size	
Neighbor Interface Address			
Neighbor Interface Address			

. . .

Figure 19 HELLO Message in OLSR (RFC3626) [21].

- TC message

In contrast to the HELLO message, TC message must be broadcasted to the whole network through the MPR nodes. TC message notifies the topology of the entire network to each node. TC message contains the information of MPR selectors at least (Figure 20). Through the TC message, the topology of the network is shared through all nodes. Each node creates SPF (Shortest Path First) Tree based on the received TC messages. Each node constructs the routing table by using SPF Tree. Rather than using the actual topology consists of all of the links in the network, OLSR only uses the links between MPR and MPR selectors for broadcasting TC message. Therefore, the total information for flooding is reduced.

ANSN	Reserved
Advertised Neighbor Main Address	
Advertised Neighbor Main Address	

. . .

Figure 20 TC Message in OLSR (RFC3626) [21].

- TC (Topology Control) Table

TC table is a table for managing the topology information of the network. The topology only consists of the MPR selector set rather than all the nodes in the network. This table is created by the TC message which is periodically flooded through the network by MPR nodes.

- Routing Table

Routing table is a table for managing route information between any two nodes in the network, which is created based on the TC table. All nodes can know the MPR set of the other nodes by flooding the TC message. It means that the path of the last one hop to the destination is shared over the nodes in the network. Then the node creates the routing table by using Dijkstra algorithm.

Currently, there are many researches about the OLSR routing protocol. OLSR is compared with different routing protocols (AODV, DSDV, DSR) in wireless ad hoc networks in [31]. Through the result of comparisons, OLSR can provide good performance. Further, while making scheduling, the information generated from OLSR is very useful.

3. PROPOSED APPROACH

3.1 Introduction

With the popularity of the smart devices, wireless ad hoc networks have received more and more attentions, supporting QoS (Quality of Service) in ad hoc network has become inevitable. In a wireless ad hoc network, all nodes share the same wireless channel, of which bandwidth is limited. A collision will occur when multiple pairs of nodes communicate at the same time in a wireless ad hoc network. Even though the QoS node is given a higher priority in some researches such as IEEE 802.11e standard [42], the increase in the best effort traffics or QoS traffics makes the possibility of collisions become higher. In this situation, the performance of the QoS applications becomes worse in terms of delay and packet delivery rate. To solve this problem, a hybrid scheme combining IEEE 802.11 DCF and TDMA is proposed in this chapter to provide QoS assurance in wireless ad hoc networks. The proposed approach is aim to provide QoS for the real-time applications which is easily affected by best effort applications.

As TDMA is a contention-free method by planning all communications previously, it is considered to promise to accommodate QoS traffics. The contention-based method (IEEE 802.11 DCF) can provide easy and fair channel time for best effort traffics. The proposed approach combines the strength of TDMA and DCF to support QoS applications.

In the proposed approach, the transmission of each QoS applications is independent of the best effort applications by dividing the transmission time to TDMA period and DCF period. In TDMA period, the time slots are assigned on a distributed method, which is on-demand of the QoS flows using the information of node positions according to the data rate of the QoS flow. Separate time slots are assigned to each QoS packet so that the collisions among the QoS flows could be avoided. Admission control is used to reject the QoS flows when network is saturation. In DCF period, the best effort packets and the control messages are transmitted by contending for the channel. A TDMA period and a DCF period make up a time frame, of which size is fixed. The length of DCF period is decided by the TDMA period, which dynamically changes according to the necessary number of time slots for QoS flows in the network.

In the proposed approach, all nodes in a wireless ad hoc network keep the clock synchronization and maintain a structure of time frame cycle. The proposed scheme requires accuracy time synchronization in order to satisfy the time division. Considering the capacity of a wireless ad hoc network, a physical layer approach, such as [22], is a good choice for time synchronization. In [22], S. Niranjayan et al. proposed a time synchronization scheme uses physical-layer UWB (ultra-wide band) round-trip time-of-flight measurements to achieve precise timing between any two nodes, and fast re-timing based on UWB pulse broadcasting and diversity combining. In the proposed scheme, the time synchronization runs at the beginning of each frame cycle, and after time synchronization, the start time of each frame cycle is determined.

Some of the TDMA slot assignment algorithms assumed that the conflicting nodes are within the two-hop transmission range (e.g. [16], [32- 35]) in a wireless ad hoc network. In practice, this assumption may not work well since the interference range exceeds twice of the transmission range. The proposed approach uses the position information of each node to check whether two nodes are in the interference distance of each other or not. The proposed approach assumes that each node is able to get its own position information by using GPS-like (Global Positioning System) services. Recently, GPS module has become a basic configuration in portable electronic devices, especially in smart phones. The accuracy of GPS is about 7.8 meters according to [32], which is enough for the proposed approach as compared with the interference range of a wireless station.

In the proposed approach, the performance of each node such as the wireless radio power and the computing power, is considered the same or close to the same in a wireless ad hoc network. All the nodes use OLSR (multi-hop routing method) for transferring packets, which can provide up-to-date route and handle the node mobility efficiently. The backbone formed by MPR nodes in OLSR is used for forwarding admission control messages in the proposed approach so that the amount of overhead can be reduced.

3.2 Design of the Frame

Delay is one of the main parameters required by QoS applications, if the packet buffering in a node cannot be sent in time, then the delay caused by waiting for transmission will affect the performance of QoS. Therefore, we use a variable time frame structure to make restriction for end-to-end delay. Each time frame includes a TDMA period and a DCF period. Through the division of the transmission time, the QoS packets can be transmitted independently from the best effort packets. Figure 21 shows the structure of the time frame. Each frame appears once again after *i* frames, which is called a frame cycle. The size of a frame cycle is set depending on the minimum data rate of QoS flows. The size of a time frame decides the maximum data rate of QoS flows in the network. The size of a frame cycle and a time frame is fixed and set in the initial period.

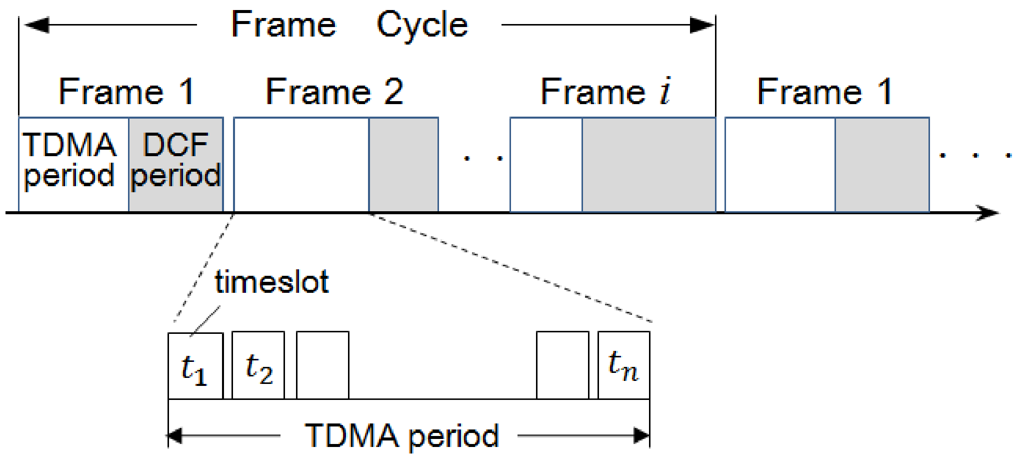

Figure 21 Structure of time frame in proposed scheme.

3.2.1 TDMA Period

TDMA period (contention-free access) is designed for QoS flows. The QoS node reserves time slot in a distributed method with the help of admission control mechanism. Time slots in TDMA period only serve QoS flows. Due to the high quality of transmission in TDMA period, no time slot is arranged for retransmission of the lost frame in proposed scheme. A node has a higher QoS traffic load achieves more time slots in a frame cycle. These time slots may distribute on one or more TDMA periods in a frame cycle. Through the newly introduced QoS-synchronization (QSYN) message, all nodes share the information of reserved time slots including the position information of corresponding nodes. When the number of QoS traffics increases, as more time slots are arranged in a time frame, the size of TDMA period increases from 0. If a QoS flow finishes its transmission, the reserved time slots for the flow are released. When all the users of a time slot are released, the time slot is removed from the TDMA period. In this situation, the length of the TDMA period is subtracted by the number of removed times slots. In this way, the length of the TDMA period in a time frame is dynamically increased or decreased in accordance with the necessary number of time slots for QoS traffics.

3.2.2 DCF Period

DCF period (contention-based access) uses IEEE 802.11 DCF method to allow the best effort flows content for the channel in proposed scheme. When there does not exist any QoS flows in a wireless ad hoc network, TDMA period is not existed, which means that only DCF mechanism is available for providing best effort service in this situation. When the length of TDMA period becomes longer, the length of DCF period becomes shorter accordingly. Since the control messages are exchanged in the DCF period, the minimum length of the DCF period equals a SIFS and a transmission time for control messages (as shown in Figure 21). Therefore, TDMA period cannot occupy the whole time frame. By using this hybrid TDMA/DCF approach, the best effort flows can be served without violating the performance of QoS flows.

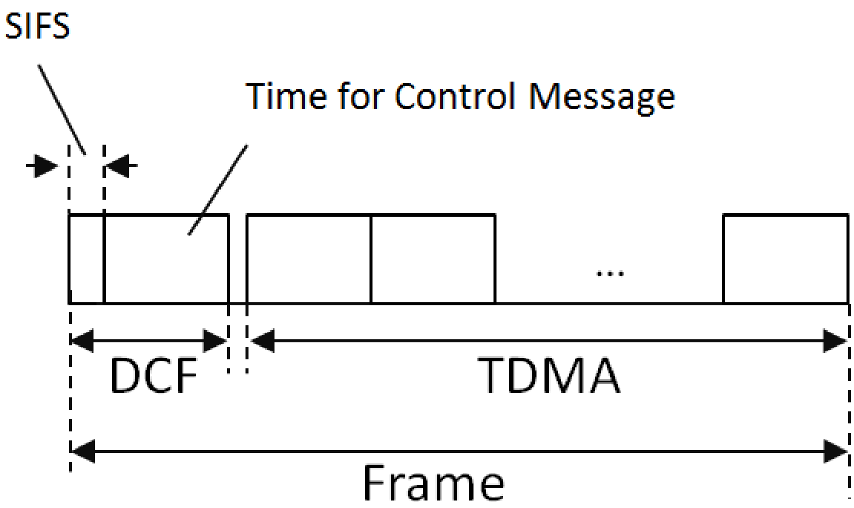

Figure 22 The minimum length of DCF period in a frame.

3.2.3 Time slot in TDMA period

The length of a time slot is determined by the transmission time of a QoS data packet in physical layer. Because each QoS packet has been assigned a separate transmission time for, there is no conflict between the QoS packets. In other words, the transmission rate of the physical layer directly determines the transmission time.

For example, there is a UDP-based QoS application in an ad hoc network. The physical layer transmission rate of 6 Mbps in IEEE 802.11a standard is used for transmitting UDP data. As shown in Figure 23PLCP (Physical Layer Convergence Protocol) header MAC header, LLC header, IP header and UDP header is added to the data frame for transmission. In the end of the frame, FCS (Frame Check Sequence) is attached to check the frame sequence.In this case, the transmission time for sending a UDP packet of 512 bytes is transmitted is about 756 us. The length of a time slot for transmitting a UDP packet of 512 bytes can be set to 800 us including guard time.

PLCP Header	MAC Header	LLC Header	IP Header	UDP Header	Data Frame	FCS
24bit	26bytes	8bytes	20bytes	8bytes	512bytes	4bytes
4μs	34μs	10μs	26μs	10μs	667μs	5μs

PLCP : Physical Layer Convergence Protocol
LLC: Logical Link Control
FCS: Frame Check Sequence

Figure 23 Frame of IEEE 802.11a 6Mbps.

3.3 Admission Control

As mentioned in Section 1.1.1, the capacity of a wireless ad hoc network is limited. If the amount of QoS traffic is beyond the capacity of the network, it is difficult to provide QoS communication guarantee. To solve this problem, an admission control mechanism is adopted in the proposed scheme to decide which QoS flows can be admitted without violating the previously made guarantees. When the time slots for all links along the route of a QoS flow are reserved, the QoS flow is consider to be admitted. At the end of the QoS flow, the assigned time slots are released.

As shown in Figure 24, when a node (node S in the Figure) tries to start QoS transmission, the node checks the bandwidth of the link between itself and the next hop node. When the bandwidth of the link does not meet the QoS requirement, the node rejects the QoS communication. Otherwise, the node generates a QoS Request (QREQ) message, and sends it to the next node through the route determined by OLSR routing protocol. QREQ message is composed of flow ID, bandwidth requirements, the source node address, the destination node address and a time slot field. Before forwarding a QREQ message, the node creates a candidate time slot set for communication with the next hop node. The candidate time slot set for the link between the node and next hop node is added to the time slot field of the QREQ message.

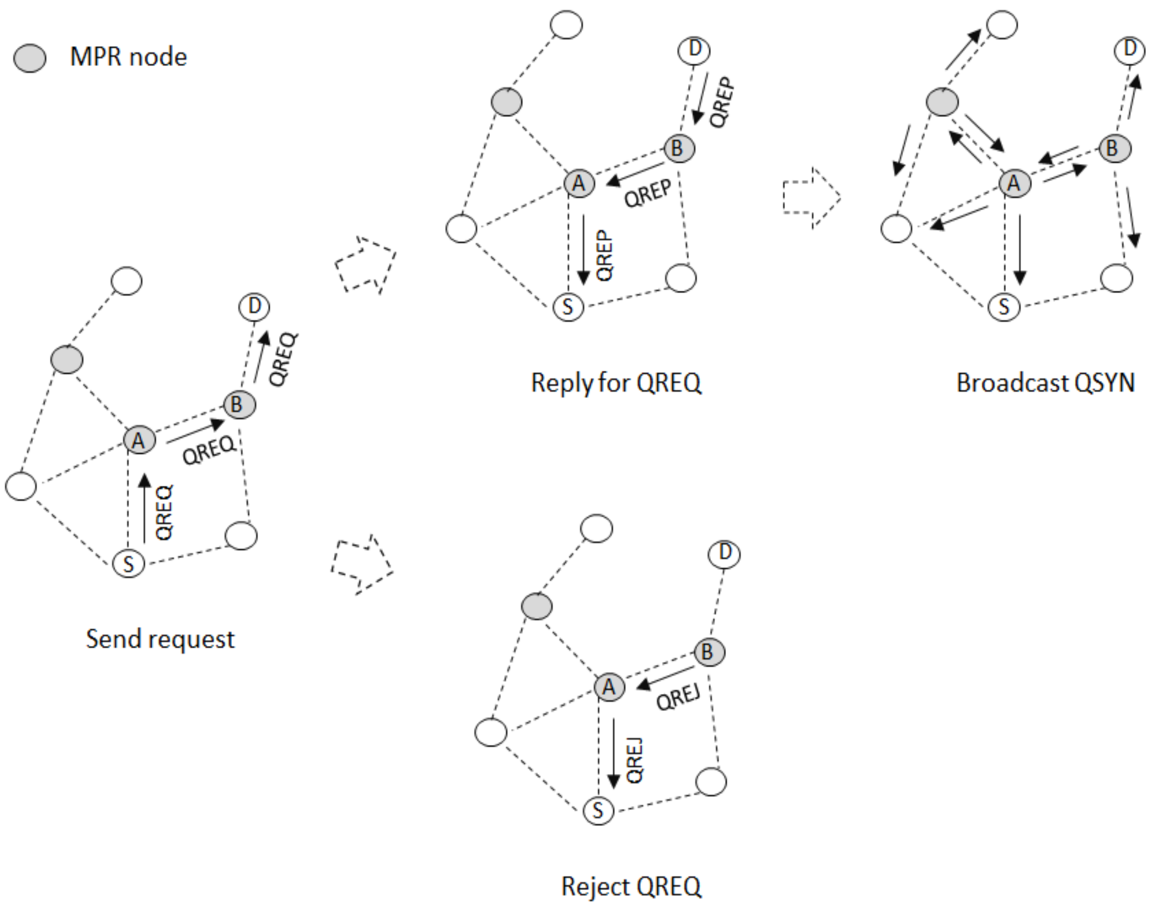

Figure 24 Admission Control.

The node (node A or node B in Figure 24) forwards a received QREQ message only if it can provide the bandwidth required by QoS applications. Before forwarding the QREQ message, the node selects a proper time slot from the candidate time slot set for the previous link. Then, the node selects a candidate time slot set for the next link. The decided time slot for previous link and the candidate time slot set for the next link are also added to the QREQ message. However, if there does not exist a suitable time slot for the link, the node reject this QoS communication by QoS Reject (QREJ) message.

The admission control is completed when the destination node (node D in the figure) receives the QREQ message and decides a time slot for the last link. Reserved time slots are sent back along the reverse path of the QREQ message by using QoS Reply (QREP) message. The node confirms the decided time slots for its self and adjusts the TDMA period in the time frame if necessary. Moreover, the MPR nodes use QoS Synchronization message to notify all the nodes about the information of the reserved time slots including the position of the corresponding nodes.

After receiving the QREP message, the source node of a QoS flow starts transmitting QoS data as the QoS communication flow is permitted.

The following control messages are designed for admission control mechanism in the proposed scheme.

· QREQ: QoS request message is created by the source node of a QoS flow. The nodes along the QoS route forward it until it reaches the end of the route. This message includes the requested QoS requirements of the flow such as the data rate, the maximum packet size. The corresponding flow ID, the reserved time slots, and the time slot candidate sets to be assigned over the link is also added to the message. (Figure 25).

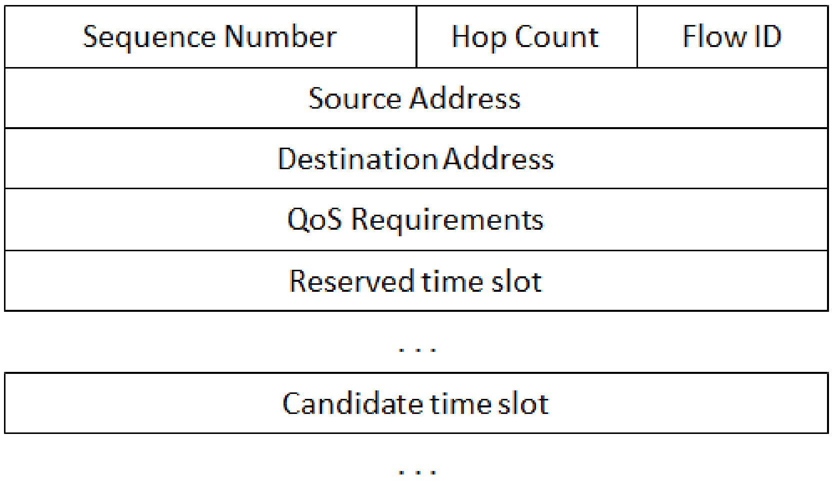

Figure 25 Format of QREQ Message.

· QREP: QoS reply message is sent from the destination node to the source node in the reverse direction of QREQ message. It includes the flow specification the receiver agreed, and the reserved time slots for all of the links belong to the QoS path (Figure 26).

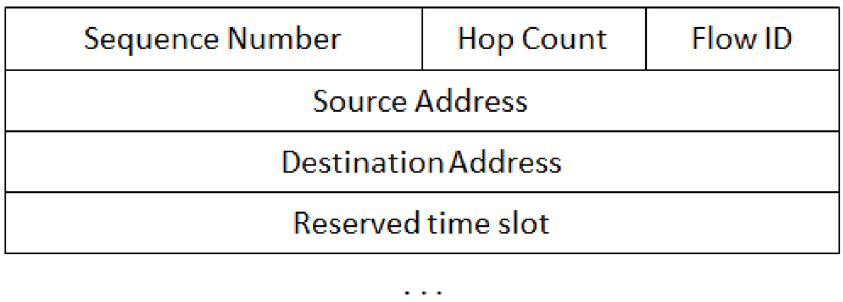

Figure 26 Format of QREP Message.

· QREJ: QoS reject message as a reply for QREQ message. It is used to inform the source node of a QoS flow that the QoS flow is rejected. Receiving a QREJ message means the specification of a QoS is too high to enter the network (Figure 27).

Sequence Number	Flow ID
Source Address	
Destination Address	

Figure 27 Format of QREJ Message.

· QSYN: QoS-synchronization message is used to inform all the nodes about the information of the newly added time slots or the information of a QoS flow to be released. The ID of the corresponding QoS flow and the information of newly added time slots are included in the message. When QSYN is used for releasing the time slots of a QoS flow, only the flow ID for the flow is added to the message. QSYN needs to be disseminated throughout the network. The node called MPRs (Multipoint Relays) sent it to its MPR selectors or the other MPRs (Figure 28).

Sequence Number	Flow ID
Time slot For update	
. . .	

Figure 28 Format of QSYN Message.

3.4 Time Slot Reservation

In order to store the information of the time slots, all the nodes maintain a time slot table in the proposed scheme as shown in Figure 29. The time slot table mainly consists the slot ID, the QoS flow ID, the position information of the nodes using time slot. The time slot table is updated by QSYN message. The length of TDMA period in a frame can be calculated according to the number of the time slot in the frame. The following is the formula for calculating the length of TDMA period. According to the formula, TDMA period does not exist in the frame when n equals 0.

$$T_{TDMA} = T_{time\ slot} \times n$$

T_{TDMA}: the length of TDMA period

$T_{time\ slot}$: the length of a time slot

n: the number of time slots

When a QoS flow is going to start transmission, the time slots are reserved by the nodes along the path of the flow in a distributed method. The two nodes of a QoS link cooperate with each other to reserve a time slot by the following three policies.

- Policy of Selecting the Optional Time Slots.
- Policy of Reusing a Time Slot.
- Policy of Determination of Multiple Available Time Slots.

The sender node of a QoS link first selects a candidate time slot set for the link according to the policy of selecting the optional time slots and the policy of reusing a time slot. The receiver of the link selects a time slot by checking the candidate time slot set from the sender according to the policy of reusing a time slot and the policy of determination of multiple available time slots.

Frame Cycle												
$Frame_1$				$Frame_2$				…	$Frame_i$			
T_1^1	T_1^2	…	T_1^n	T_2^1	T_2^2	…	T_2^n		T_i^1	T_i^2	…	T_i^n

Time slot T_i^n				
USER				
Sender	position	Receiver	position	*FlowID*
a	(a_x, a_y, a_z)	b	(b_x, b_y, b_z)	F_1
b	(b_x, b_y, b_Z)	h	(h_x, h_y, h_z)	F_2
g	(g_x, g_y, g_z)	f	(f_x, f_y, f_z)	F_3
…				

T_i^n indicates the nth time slot in $Frame_i$

Figure 29 An Example of Time Slot Table.

3.4.1 Policy of Selecting the Optional Time Slots

Time slot assignment is designed to adopt different data rates of QoS flows in TDMA period. In case of QoS data flows, the traffic packets are generated with constant bit rate (CBR). In CBR frames, the amount of output data per time segment remains constant. The transmission interval (TI) of each segment can be calculated as,

$$\mathrm{TI} = \frac{Packet\ Size}{Data\ Rate}$$

The sets of time slots for a QoS flow need to be scheduled in the range of TI. Otherwise, congestion may occur, and a larger delay results in poor performance. According to formula, when the packet size is the same, QoS flows of which has higher data rate owns smaller TI. The size of a frame should be equal to or smaller than the TI of the maximum data rate of QoS flows, which have the smallest TI. For example, when the packet size is 512 bytes, in order to support a QoS traffic with 1024 Kbps data rate, the size of the frame should be set as equal to or less than 4 ms (Figure 30).

The time slots allocated to a QoS flow should match the data rate of the QoS flow. If the allocated time slots are insufficient to support the requested data rate, the QoS is violated. In contrast, if the allocated time slots are much more than the requirement, the channel utilization is inefficient due to the waste of some time slots. Therefore, we introduce a frame cycle approach to control the time slot assignment. In a frame cycle, if only one QoS packet is carried from the source node to the destination node for a QoS flow, the waiting time for transmission of the next QoS packet equals to the length of the frame cycle. In order to send QoS packet in time, all admitted QoS nodes should have at least one opportunity (one time slot) to transmit QoS packet in a frame cycle. The larger the frame cycle is the better the efficiency. If the smallest data rate of QoS flows in the network is 64 Kbps (packet size is 512 byes), the maximum possible TI is 32 ms. In this case, when the size of the frame is 4 ms, the frame cycle can be set to 8 or less than 8 (Figure 30).

QoS flows in the network	
Packet size	512 bytes
Max data rate	1024 Kbps
Min data rate	64 Kbps

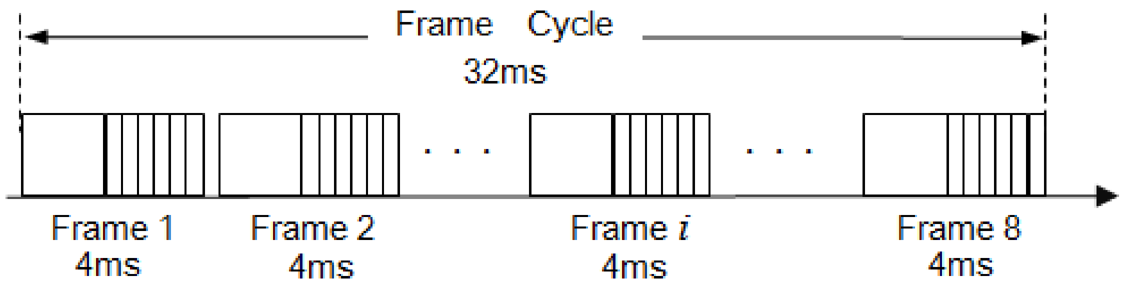

Figure 30 An Example of Setting Frame.

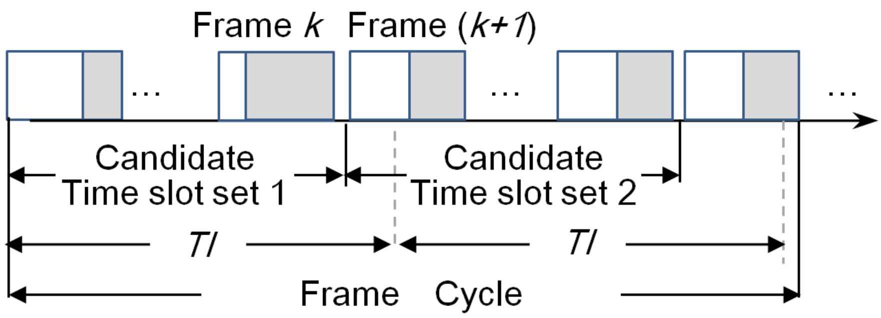

Figure 31 Distribution of the time slot.

The candidate sets of time slots are different for different data rates of QoS flows. As shown in Figure 31, if TI of a QoS flow is larger than the length of k frames and less than (k+1) frames, the candidate time slots set will cover k frames. The number of candidate time slot sets in a frame cycle equals to the number of transmission intervals (TI). In the proposed scheme, the sender of a link calculates TI and generates the candidate time slot sets for the corresponding link.

Figure 32 shows an example of time slots assignment for different data rates of QoS flows in a network. Since the smallest data rate is 256 Kbps, the length of frame cycle is set to 4. The length of a frame is set to 4ms as the maximum data rate of QoS flows is 1024Kbps. We can see that the time slots for the flow (x, z) appear in every frame while the time slots for the flow (m, p) only appear once in a frame cycle. For the flow (x, z), the time slot should be scheduled in every 4ms, which is the TI of the flow. Otherwise, the performance in terms of delay will become worse. Therefore, there are total eight time slots for flow (x, z) in a frame cycle. Since the TI of flow (x, z) is 8ms, the time slots for the node in the flow should exist in each 8ms. So the total number of time slots for flow (x, z) is six. As the TI of flow (m, p) is four times than the TI in flow (x, z), each time slot only appears one time in a frame cycle. The total number of time slots for flow (m, p) is 4, which equals to the number of hops in the flow.

QoS flow	**data rate (*Kbps*)**	**TI (*ms*)**
x→y→z	1024	4
a→b→c→d	512	8
m→n→o→p→q	256	16

<table>
<tr><td rowspan="4">Frame Cycle</td><td>Frame 1
(4 ms)</td><td>x→y
a→b</td><td>y→z
b→c
m→n</td><td colspan="3">DCF</td></tr>
<tr><td>Frame 2
(4 ms)</td><td>x→y</td><td>y→z
n→o</td><td>c→d</td><td colspan="2">DCF</td></tr>
<tr><td>Frame 3
(4 ms)</td><td>x→y
a→b</td><td>y→z
b→c</td><td>o→p</td><td colspan="2">DCF</td></tr>
<tr><td>Frame 4
(4 ms)</td><td>x→y</td><td>y→z</td><td>c→d</td><td>p→q</td><td>DCF</td></tr>
</table>

Figure 32 An example of time slots assignment for different data rates of QoS flows.

3.4.2 Policy of Reusing a Time Slot

In a wireless network, multiple devices within the interference range of each other cannot transmit packet at the same channel in the same time due to the radio interference. There exist two interference patterns as shown in Figure 33. When the nodes which are in the transmission range transmit data simultaneously to the other one, a collision occurs (Figure 33 (A)). In addition, if the node receives a packet from multiple nodes, a collision occurs (Figure 33 (B)).

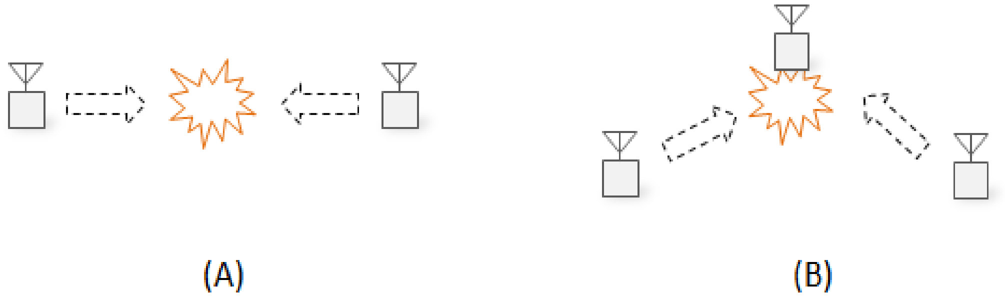

Figure 33 Two Interference Patterns in Wireless Network.

In the TDMA period of the proposed approach, the policy of reusing a time slot are specified for time slot reservation in order to avoid interference shown in Figure 33. The first one is that the nodes exist in the interference range of each other should not select the same time slot for sending data. The other one is that the node should not use a time slot for receiving data from multiple senders. In addition to these two restrictions, in order to improve the channel utilization efficiency, the same time slot is selects by the nodes of multiple links if they do not interfere with each other. Figure 34 shows an example, where four nodes separate with the distance of average transmission range. Two links can use the same time slot in the transmission ① and ②.

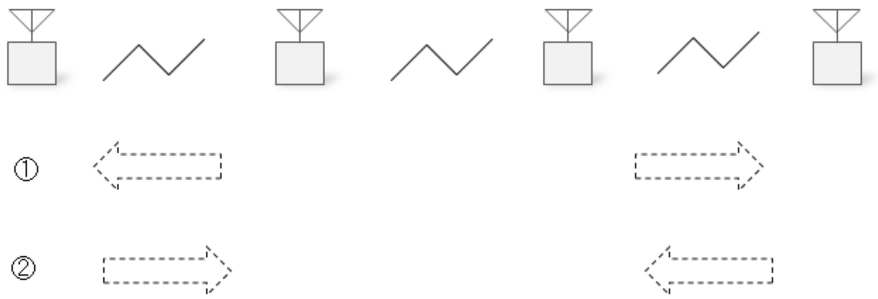

Figure 34 Example of the same time slot assignment.

Figure 35 shows an idea how to check the concurrent transmissions from multiple sender nodes at the same time slot. Here, we suppose that node N_S is going to send QoS data to node Nr with time slot t_a. Figure 35 (a) shows the process of node N_S to check whether time slot t_a is available. It checks the nodes in the interference range and which receive data with time slot t_a. In case of s1, if N_S send data with the same time slot, a collision occurs. On the other hand, even if a node in N_S's interference range is a sender, time slot t_a does not interfere with N_S in the case the receiver is outside of interference range (case s2). Therefore, for a sender N_S, it is important to check whether there exists a receiver using the same time slot in its interference range. If there is no conflicting receiver, N_S can select this time slot as a candidate for itself.

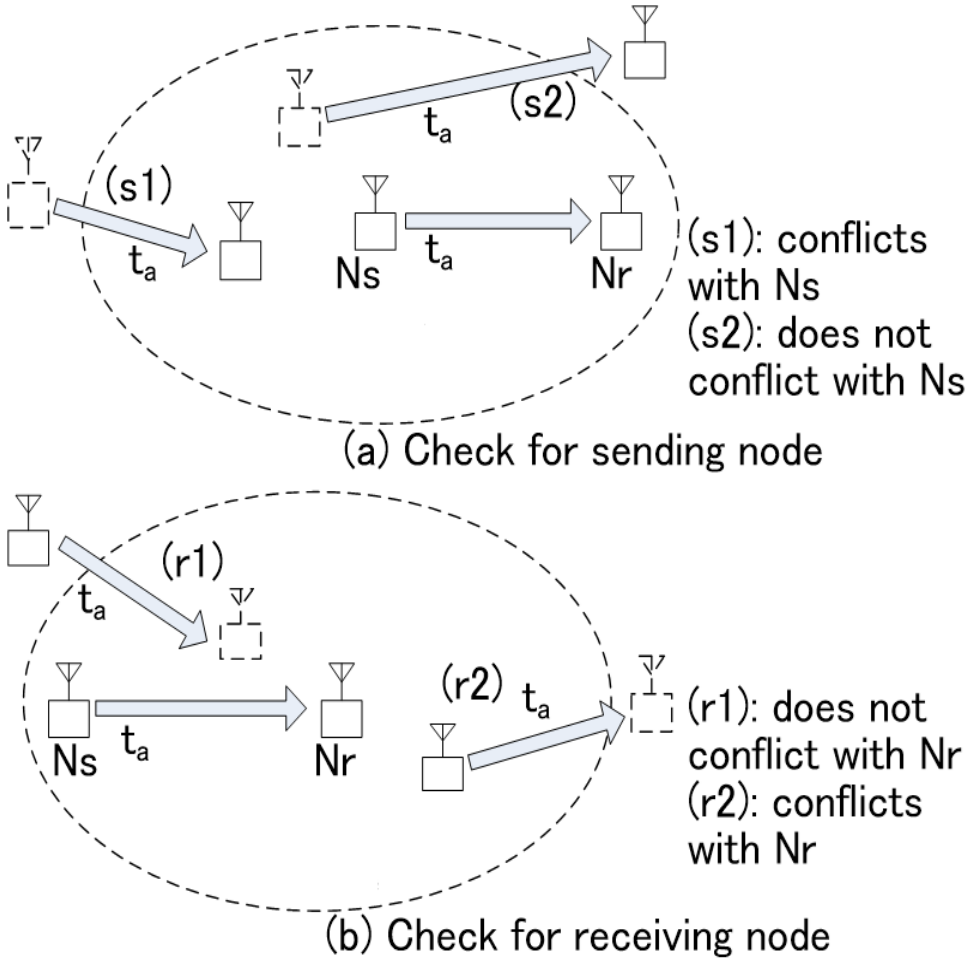

Figure 35 Check for reusability of the time slots.

On the other hand, for receiver Nr, it needs to confirm whether any node in the interference range is a sender for the same time slot or not. If there is no sender within interference range, receiver Nr can use the time slot for itself. Since all nodes know the information on network topology and the time slots assigned to other QoS flows, in the case of a new QoS flow joins the network, the nodes related to the new QoS flow specify the time slots by considering the reuse.

3.4.3 Policy of Determination of an Available Time Slot

After the existing time slots in the TDMA period are screened by the above two policies, there are two situations. One situation is that any one of the existing timeslot is not suitable. The other one is that there are multiple time slots can be selected.

For the first situation, the node checks whether the TDMA period reaches the maximum limitation or not. If the TDMA period is reaches the maximum, it means that the bandwidth is saturated, and it is unable to accommodate a new QoS flow. Therefore, the QoS flow which requests for a time slot will be rejected. Else if there is a space for inserting a new time slot in the frame, the node creates a new time slot, and the length of TDMA period is increased by a time slot.

When there are multiple selectable timeslots, the node selects an available time slot according to the following two rules.

1. Select the time slot has the most number of users.

This is the highest-priority rule. The more users use a common time slot the network will be more efficiency.

2. Select the earliest timeslot.

This rule is used when there are multiple time slots with the same number of users. The earliest time slot in the frame should be selected so that the QoS packet can be transmitted as soon as possible.

By using these two rules, the timeslot for a link is determined.

3.5 Announcements and Conflict Resolution

As mentioned in Section 3.3, the QSYN message is used to announce the information of the time slots when new time slots are added or released. With the help of the OLSR, the redundant messages can be reduced by performing the information dissemination using the forwarding nodes called the MPRs. Through the dissemination of QSYN messages, all nodes share the information about the reserved or released time slots (as shown in Figure 24).

As shown in the Figure 36 (1), when a node receives QSYN message with a newly added time slot, the node extends the length of TDMA period and reduces the length of DCF period. If the time slot in the QSYN message already exists, the node just adds the necessary information (the flow ID and the position information of the corresponding nodes) to the existing time slot as shown in the Figure 36 (2).

QSYN message is also used to release the time slot. When a QoS flow is closed, the source node sends a QSYN message containing the QoS flow ID to release the corresponding reserved time slot. The nodes that received this QSYN message delete the corresponding users from the time slot table. Then the nodes check the number of users of each time slot in the time slot table. If a time slot is not used by any user, it should be removed from TDMA period. Each node adjusts the TDMA period by itself after receiving a QSYN message for releasing time slots.

When the MPR node detects the route of a QoS flow needs to be updated, the MPR node sends a QSYN message containing the ID of the QoS flow. All the time slots for the QoS flow are released after the nodes receive the QSYN message. After reception of the QSYN message, the source node of the QoS flow sends the QREQ along the new path to request the new time slot for transmission.

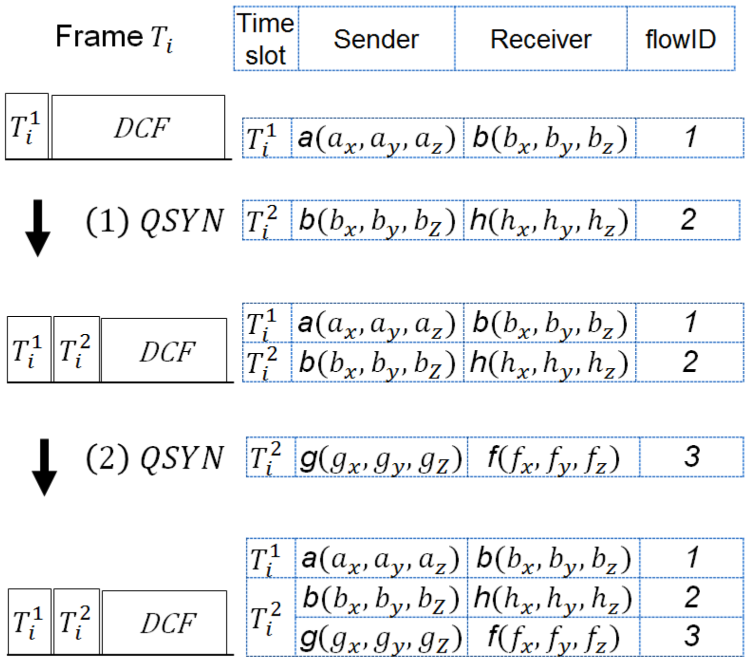

Figure 36 Add a new time slot to the frame according the QSYN message.

When two QoS flows request the time slots at the same time, a conflict may occur as shown in Figure 37. Node s1 and node s2 request for the time slot simultaneously, and therefore a conflict occurs when they select the same time slot ta for transmission. After the dissemination of the QSYN message, according to the position information of the nodes using the time slot ta, the nodes in each flow would detect the conflict. In this situation, the QoS flow that owns the smaller ID (i.e., the flow from s1 to r1 in the figure) can use the time slot ta. The source node s2 sends a QSYN message to release the time slot ta and QREQ message to request the new time slot.

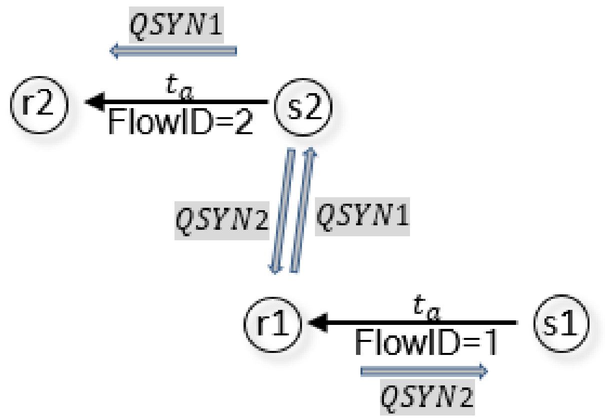

Figure 37 An example of the time slot conflict.

3.6 Control of Data Transfer at the End of DCF Period

Since the proposed approach combines TDMA period and DCF period under a strict timing requirement, the data transfer in DCF period needs to be controlled at the end of this period.

During DCF period, the complete transmission time for a data frame includes the time for transmitting data packet, the time for transmitting the ACK, and the SIFS for ACK. The transmission time can be calculated using the following formula.

$$T = T_{data} + SIFS + T_{ACK}$$

When backoff counter becomes 0, the node checks whether the remaining time of DCF is enough for transmitting a data frame or not. If the remaining time is enough, the data frame will be sent. Otherwise, the transmission will be banned. After entering the TDMA period, the DCF controller sets the NAV equals to the length of the TDMA period. This ensures that during TDMA, the node will not compete for transmission using DCF mechanism.

As shown in Figure 38, if the remaining time of a DCF period is not sufficient for a data frame transmission, the transmission is postponed to the next DCF period. In the postponed data transfer, the CSMA/CA procedure is newly invoked and the backoff time is recalculated. In Figure 38, we assume that there is no other data transmission at the beginning of the next DCF period, and therefore the conventional backoff procedure is not executed (the frame is sent without backoff).

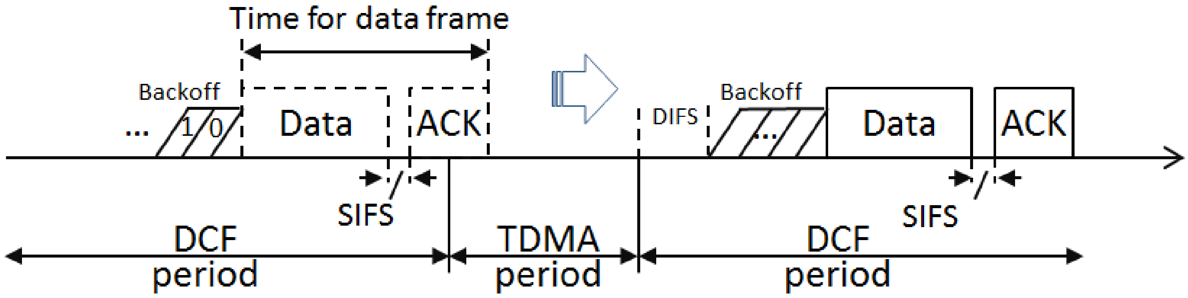

Figure 38 An example for controlling the data transfer at the end of DCF period.

3.7 Algorithm Detail of the Time Slot Reservation with Admission Control

This section describes the detail about the time slot reservation with admission control. Figure 39 shows an ad hoc network with nine nodes. The frame cycle in the network is set to four frames, and the size of each frame is 4 *ms*. In this figure, two QoS flows (*a* to *s*, and *b* to *e*) have been started. In this situation, node *s* attempts to begin a QoS flow with node *d*. Through the dissemination of QSYN messages, all nodes know the reserved time slots, and the information of the corresponding nodes using the slots.

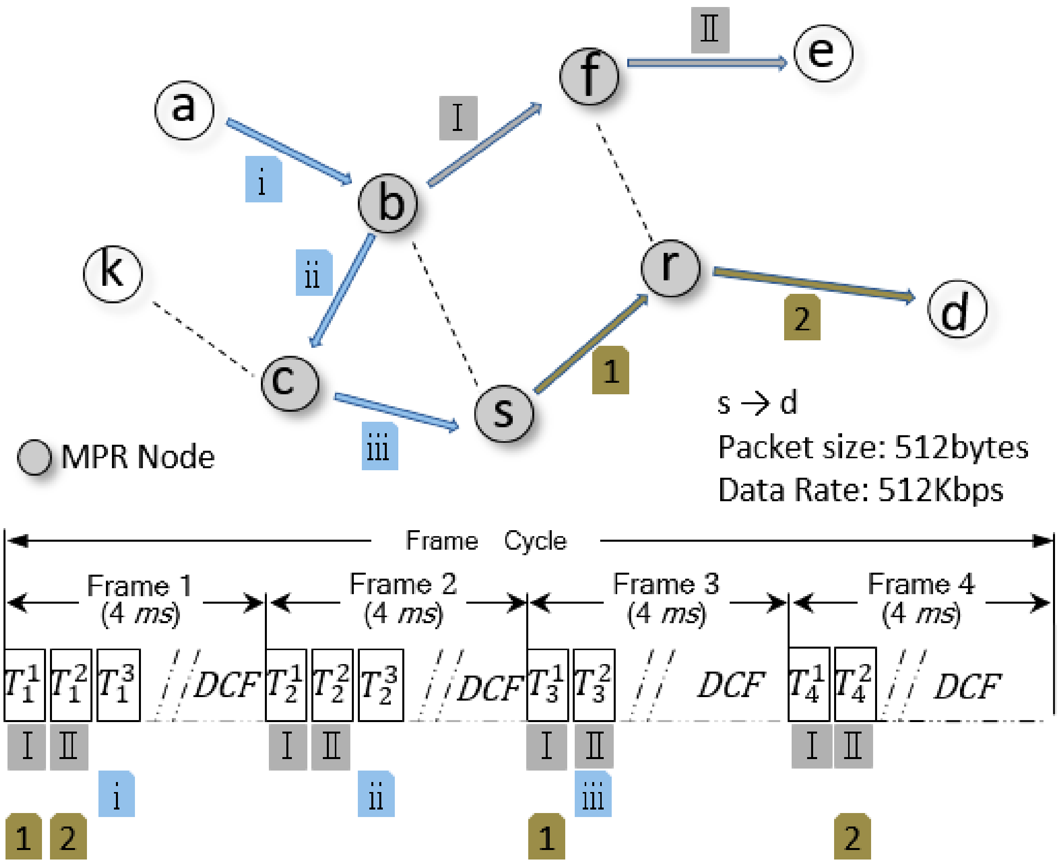

Figure 39 An example of the time slot reservation with admission control.

The time slots for links *s* to *r*, and *r* to *d* are determined according to the following steps.

Step1:

Node *s* selects the candidate time slots for links *s* to *r*. According to the Section 3.4b), node *s* calculates *TI* of the QoS flow *s* to *d*. As *TI* = 8 *ms*, two candidate time slot sets $\{T_1^1, T_1^2, T_1^3, T_2^1, T_2^2, T_2^3\}$ and $\{T_3^1, T_3^2, T_4^1, T_4^2\}$ are selected for link *s* to *r* in a frame cycle. Then, node *s* chooses the suitable time slots by checking the receiver of the time slot.

Since the position information of node *b* and *c* is shared through QSYN message, sender node *s* knows that the receiver node *b* and *c* are in its interference distance. Therefore, the time slots T_1^3, T_2^3, and T_3^2 are deleted from candidate time slot sets. So, node *s* sends a QREQ message including the position information of node *s*, the specification of the QoS flow, candidate time slot sets $\{T_1^1, T_1^2, T_2^1, T_2^2\}$ and $\{T_3^1, T_4^1, T_4^2\}$ to node *r*. Note that if there are no time slots applicable, node *s* tries to create a new time slot as a candidate time slot. In this situation, if node *s* is unable to create a new time slot (for example, when the number of time slots is full in the frame cycle), this QoS flow is rejected.

Step 2:

Node *r* checks the sender node of the time slot sets $\{T_1^1, T_1^2, T_2^1, T_2^2\}$ and $\{T_3^1, T_4^1, T_4^2\}$ in the QREQ. According to Section 3.4a), as the sender node *f* is in the interference range of node *r*, the time slots T_1^2, T_2^2, and T_4^2 are deleted from candidate time slot sets. Therefore, the remaining candidate time slot sets are $\{T_1^1, T_2^1\}$ and $\{T_3^1, T_4^1\}$. One time slot is selected from each candidate set. Here, we select the time slot T_1^1 and T_3^1 which will appear before other candidates in the corresponding frame.

After that, the same as in Step 1, node *r* lists up the time slot candidate sets $\{T_1^1, T_1^2, T_1^3, T_2^1, T_2^2, T_2^3\}$ and $\{T_3^1, T_3^2, T_4^1, T_4^2\}$ for the link from *r* to *d*. In this case, node *f* in the interference range of node *r* is using time slots $T_1^1, T_2^1, T_3^1, T_4^1$, and node *s* is using time slot T_3^2 to receive data. Node *r* deletes these time slots from candidate time slot sets. The remaining candidates time slot sets are $\{T_1^2, T_1^3, T_2^2, T_2^3\}$ and $\{T_4^2\}$. After this selection, node *r* sends a new QREQ message to node *s* containing the assigned time slot for the link from *s* to *r*, and the time slot candidate sets for the link from *r* to *d*. If no suitable time slot exists, node *r* sends QREJ back to source node *s* to reject this QoS flow.

Step 3:

Node *d*, which is the destination of the requested QoS flow, checks time slots $\{T_1^2, T_1^3, T_2^2, T_2^3\}$ and $\{T_4^2\}$ for the link from *r* to *d*. Node *d* selects time slot $\{T_1^2\}$ and $\{T_4^2\}$.

Step 4:

Node *d* then returns a QREP message containing the assigned time slots for the individual links. It also sends a QSYN message to node *r* containing the information of the reserved time slots and the ID of the QoS flow in order to ask its MPR (node *r*) to disseminate this message. If node *d* rejects the QoS flow, only QREJ is sent by node *d*.

Step 5:

Node *r* maintains the time slot assignment for links from *s* to *r* and, *r* to *d* according to the information in the QREP message, and forwards the message to node *s*. It also sends the QSYN message to other MRPs because it is selected as an MPR by node *d*.

Step 6:

Similarly, node *s* maintains the time slot assignment for links *s* to *r*, and *r* to *d* according to the information in the QREP message.

Step 7:

The QSYN message is exchanged among MRPs and then to their MPR selectors. The new QoS flow from node *s* to node *d* will start in the next frame cycle.

The following is the algorithm details for time slot reservation with admission control.

```
Algorithm of time slot reservation with admission control
FOR  each node of QoS flow DO
  IF  node is the sourece node THEN
    IF  a new k-hops QoS flow arrives  THEN
      Calculate TI
      IF  Short frame >TI  THEN
          Reject this QoS flow, goto END
      ELSE
          Set candidate sets of time slots for QoS flow
      END IF
    END IF
    IF receive a QREP message  THEN
      Start QoS transmission
    END IF
    IF  receive a QREF message  THEN
      reject this QoS flow, goto END
    END IF
    Create QREQ Message
  END IF
  IF  node is sender of link[α] THEN
    Create a Candidate Slot List for link[α]
    FOR  each candidate set {{N_{ni+1}}, {N_{ni+2} } .. {N_{2ni}}}  DO
      FOR  Exist Reserved Slot  DO
          IF  distance ([Sender], Receiver of the Slot)
                          > Interference Distance  THEN
          Put the Slot into Candidate Slot List
        END IF
      END DO
      IF  Candidate Slot List is empty  THEN
        Try to set a new slot into the List, IF fail THEN
        Reject this QoS flow
        Send QREF Message IF NOT first node
      END IF
```

Figure 40 The algorithm for time slot reservation with admission control.

3.8 Discussion

3.8.1 Analysis of Overhead of the Proposed Approach

The objective of this section is to discuss the overhead of the proposed approach. In the proposed approach, the QSYN messages are disseminated through the whole network as other messages such as QREQ messages are only transmitted along the QoS path. Therefore, the overhead of the proposed approach is mainly caused by the QSYN messages during allocating and releasing time slots for the QoS flows. The strategy of the dissemination of QSYN is to use MPRs which are generated by OLSR protocol. We can see that the overhead in the proposed approach depends mainly on the size of the network and the occurrence frequency of the QoS applications.

We use the method of [43] to analyze the overheads of the proposed approach. We use some parameters to model the network (see Table 5). We suppose that the number of nodes in the network is fixed, and the links between the nodes are stable (no mobility). In Table 5, N indicates the number of nodes in an ad hoc network. As MPRs are used for optimizing the dissemination (reducing the number of messages), parameter O_p $\left(0 \leq O_p \leq 1\right)$ denotes the dissemination optimization factor [43] which is related to the density of nodes in the network. Let R_{QoS} denote the average QoS application generation rate per node per second. Another influent parameter is the average size of QSYN message, denoted by S_{QSYN}. In the proposed approach, the cost for dissemination of each QSYN packet is O_pN transmissions. Considering the whole network, the overhead of $R_{QoS}O_pN$ packets occurs per second, and the bandwidth for the overhead is $S_{QSYN}R_{QoS}O_pN$.

Table 5 Parameters for analysis of the proposed approach.

Parameters	Meaning
N	The number of nodes in the network
O_p	Optimization factor for dissemination
R_{QoS}	Average QoS application generation rate
S_{QSYN}	Average size of QSYN messages

Through the formula $S_{QSYN}R_{QoS}O_pN$, we can observe that when the QoS application generation rate is high in a unit time, the overhead will become large, and the QSYN may not arrive to all the nodes in time. In this situation, some QoS applications would be refused by the admission control mechanism (Section 3.3).

As the overhead of the proposed approach becomes large when the number of nodes increases, the proposed scheme is better suited to work in a network with a lower node density. In a scenario with 50 nodes displayed in a 1500m×300m field, we suppose 10 QoS applications are generated or released in 60s, $R_{QoS} \approx 0.17$. Supposing the use of IEEE 802.11a 6 Mbps in the physical layer, the average size of QSYN messages is supposed to be 256 bytes including PLCP header, IP header, FCS, and information of three time slots (three is the average hops for QoS route in this scenario). According to [43], for this scenario, parameter O_p can be estimated as 0.16. In this situation, the overhead of the proposed approach in this situation is 1.36 packets/s. The bandwidth for overhead is 348.16 bytes/s. Compared with the 6 Mbps data rate in the physical layer, 348.16 bytes/s is considered to be acceptable.

3.8.2 Compare with the Existing Approaches

In this section, we compare the proposed method with the existing approaches (Table 6). In the proposed approach, the admission control is adopted for protection of the previous allocations. If the remaining bandwidth is not enough for the new QoS flow, the admission control rejects the QoS flow. The necessary bandwidth for a QoS flows means necessary numbers of time slots in the proposed approach. Therefore, whether a QoS flow can be admitted or not can be easily decided by check the remaining time slots in the frame without additional control messages. In CACP [5] and QACRP [6], they estimate the bandwidth for admission control by considering both local available bandwidth and neighborhood available bandwidth which is not accuracy because of the contention. Since CACP only consider the QoS bandwidth is enough or not and QACRP only provide a QoS route with enough bandwidth, both of them cannot ensure the performance of QoS is not affected by the best effort flows.

For IEEE 802.11e EDCF [42] and [4], they provide higher priorities for QoS frames by using smaller contention window size. However, the contention-based MAC layer approach conducts the prioritization only for one hop environment, and therefore packet collisions could occur in a multi-hop environment especially when the total rate of QoS flows increases. Moreover, due to the relative prioritization scheme, these approaches could fail to satisfy the QoS constraint when the volume of the data traffic increases. For the proposed approach, the time slots are assigned one hop by one hop, and therefore multi-hop QoS communication is possible. Since the size of DCF period is decided by the TDMA period in the proposed approach, the increase in the best effort traffic would not affect the QoS traffic. And the admission control in the proposed approach prevents congestion among QoS traffics. Even admission control is adopted in [4], the effect of increasing best effort traffics cannot be avoided.

Existing TDMA protocols ([14], [15], [27]), are designed to accommodate both QoS flows and best effort flows. However, it is difficult for TDMA as the only approach to allocating channel access time for best effort flows because the required bandwidth of the best effort flow changes frequently. For example, the bandwidth required for TCP traffic is increased with the increase of congestion window size. For proposed approach, the best effort traffics are fit to contention-based structures (IEEE 802.11 DCF) which can provide easy and fair channel time for each best effort flow.

Considering the time slot assignment method, the proposed scheme is similar as DSRP [27], both of which assign the time slots on-demand for QoS flow without considering acknowledgement. The differences between proposed approach and DSRP are that the proposed scheme assigns time slots based on the QoS rate under known route and DSRP makes time slot reservation for QoS routing.

There exist some hybrid protocols combining contention-based access and contention-free access ([17], [19]). In [17], Shrestha et al. assumed that each node is located within the carrier-sensing range of the other nodes. With a focus on one-hop communication in a star network topology, [17] does not adequately address the channel access scheme for the multi-hop network. [19] (Z-MAC) behaves like CSMA under low contention environment and behaves like TDMA under high contention environment. However, the QoS assurance issue is not discussed in [19]. Overall, those existing studies do not sufficiently address the issues of multi-hop communication, service differentiation based on traffic priorities, and the adaptive adjustment of CSMA/TDMA period.

Compared with the existing method, the most important advantage of the proposed scheme is that strict QoS supporting is provided by dividing the transmission time to two different periods. Furthermore, the proposed scheme adopts admission control to solve the congestion problem among QoS flows and uses an effective on-demand time slot allocation method. In spite of these advantages, due to the overhead caused by admission control, the proposed scheme is not suitable for a network with high density of nodes. The time slot allocation method is weak when the link is not stable.

Table 6 Compare with the existing approaches.

	Admission control	QoS/BE differentiation	Access method	Multi-hop support	Strict QoS supporting	Comments
CACP [5]	○	△	CSMA	○	△	Individual QoS packet transmission is not guaranteed
QACRP [6]	○	△		○	△	
Local data control and an admission control with IEEE802.11e [4]	○	○		×	△	Performance becomes worse when the number of traffics increase.
EDCF [42]	×	○		△	△	
DSRP [27]	×	×	TDMA	△	△	It is difficult for TDMA to serve best effort traffics.
DRAND [14]	×	×		△	△	
OA-TDMA [15]	×	×		△	△	
CSMA/CA-TDMA [17]	×	×	CSMA/ TDMA	×	×	Coordinator used in the scheme is not suitable for wireless ad hoc networks
Z-MAC [19]	×	×		△	×	
Proposed	○	○		○	○	Using different access methods for QoS and best effort traffics.

4. PERFORMANCE EVALUATION

4.1 Implementation

The proposed approach was implemented on QualNet 6.1 [23], which is an event-driven network simulator. QualNet handles the events mong different functions by exchanging the timer message contains the stat time of an event.

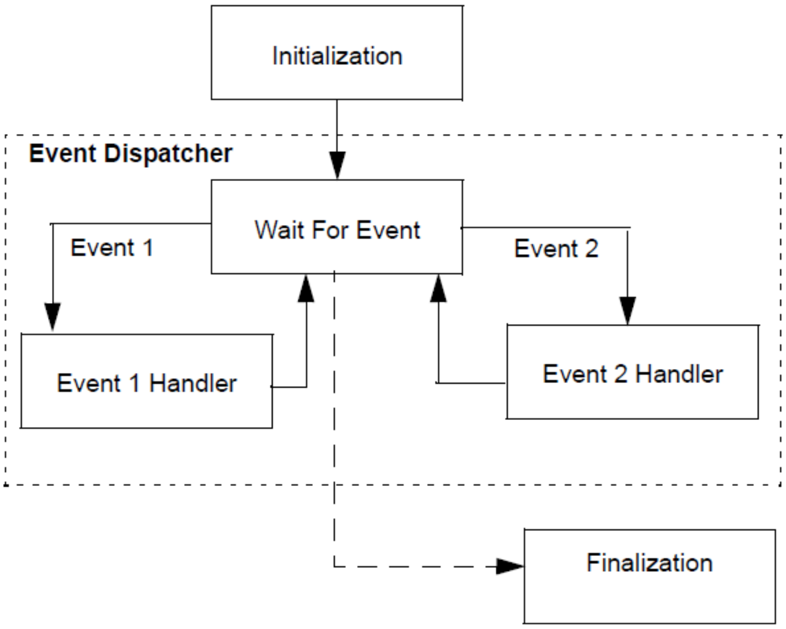

Figure 41 Event Process in QualNet [28].

The protocol stack in QualNet is the same as the stack of TCP/IP protocol, which is composed of five layers: application layer, transport layer, network layer, the MAC layer, and physical layer. MAC layer is between the network layer and the physical layer and provides a media access control service. In QualNet, APIs that used for connecting the network layer and MAC layer are shown in Table 7. Table 8 shows APIs in MAC Layer for communication with the physical layer. The proposed approach was implemented through the modification of the existing TDMA protocol in the QualNet.

In QualNet, a basic TDMA based MAC protocol has been implemented, which assigns time slots to all nodes in a round robin method. The time slot reservation in this protocol is based on one-hop, which does not reuse the time slot. The number of the time slots assigned to the nodes in network equals to the number of the nodes. A time frame stores all these time slots. The length of a frame is the summary of all the time slots and guard times. Therefore, in this protocol, each node in the network has only one chance to send a packet during a frame. Even when a node does not have a packet to send, it occupies the transmission time of one time slot. However, using the existing TDMA implementation is possible to obtain a high data loss rate and low throughput since it is not designed for the multi-hop environment.

Table 7 API for Communication with Network Layer.

MAC_OutputQueueIsEmpty
MAC_OutputQueueDequeuePacket
MAC_OutputQueueTopPacket
MAC_OutputQueueDequeuePacketForAPriority
MAC_HandOffSuccessfullyReceivedPacket
MAC_MacLayerAcknowledgement
MAC_NotificationOfPacketDrop

Table 8 APIs for Communication with Physical Layer.

PHY_StartTransmittingSignal
PHY_StartListeningToChannel
PHY_StopListeningToChannel
PHY_SetTransmissionChannel

Taking the existing TDMA protocol implementation in QualNet as a starting point, the TDMA algorithm of the proposed approach has been implemented. The existing TDMA protocol controls the MAC queue of in the process of the FIFO (First In, First Out), which not suitable for the proposed approach. The control method of the MAC queue has been modified as shown in Figure 42 so as to output the packet having the same next hop as the receiving node specified in the time slot. In addition, the implementation of the proposed approach realized the multi-hop communication. The multiple nodes are able to transmission using the same time slot. At the end of each frame, every node independently decides the time slots for the next frame.

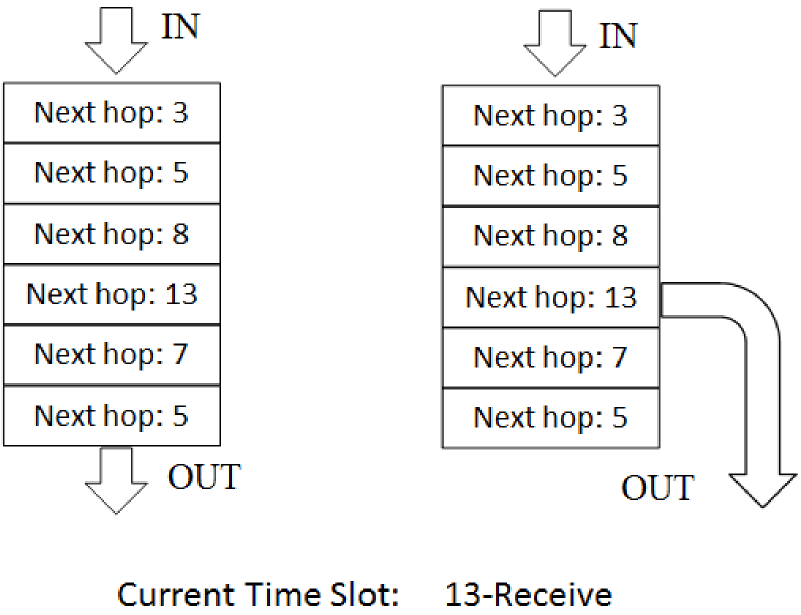

Figure 42 Modification of the Queue Process.

The proposed approach uses two different access methods to provide QoS supporting. The implementation also needs to coordinate these two methods. In TDMA period, NAV parameter is set to prevent the node contending for the channel (Figure 43). The QoS packets come from upper layer are carried to the buffer implemented in TDMA method and the best effort packets stay in the buffer of DCF method.

For comparison purposes, the pure TDMA method (TDMA-only) was used in the simulation. The implementation of the hybrid proposed approach can be easily changed to the pure TDMA mode by arranging all the time slots to the nodes. It means the DCF period is set to 0 in the pure TDMA method.

Figure 44 shows the interface of the implementation. The length of the time slot and frame can be set here. For TDMA scheduling, there are two modes. One is automatic, which is using the proposed time reservation method. The other one is using file on which hand-made time slot assignment can be realized.

Two simulations have been done for evaluation of the proposed scheme. The node mobility was not considered in both simulations. The first simulation is the network composed by 15 nodes using 6Mbps of IEEE 802.11a. All the applications in the first simulation were CBR. Three flows were used including two QoS flows and one best effort flow. The second one is the network composed by 50 nodes using 54Mbps of IEEE 802.11a. The applications in the second simulation were randomly generated. The proposed scheme was evaluated on different conditions.

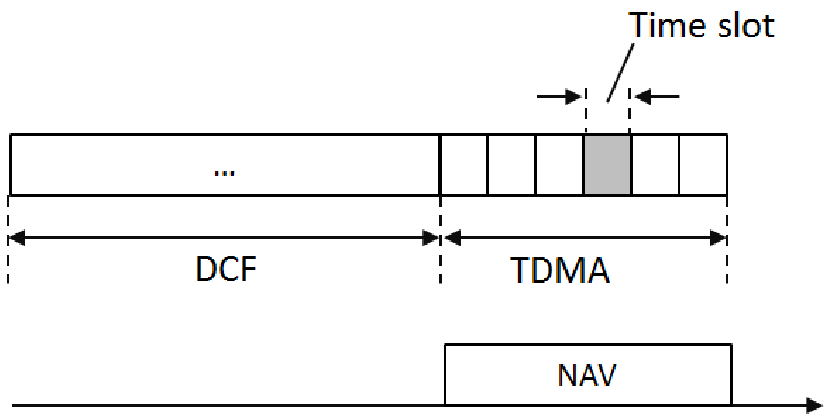

Figure 43 Set NAV for TDMA Period.

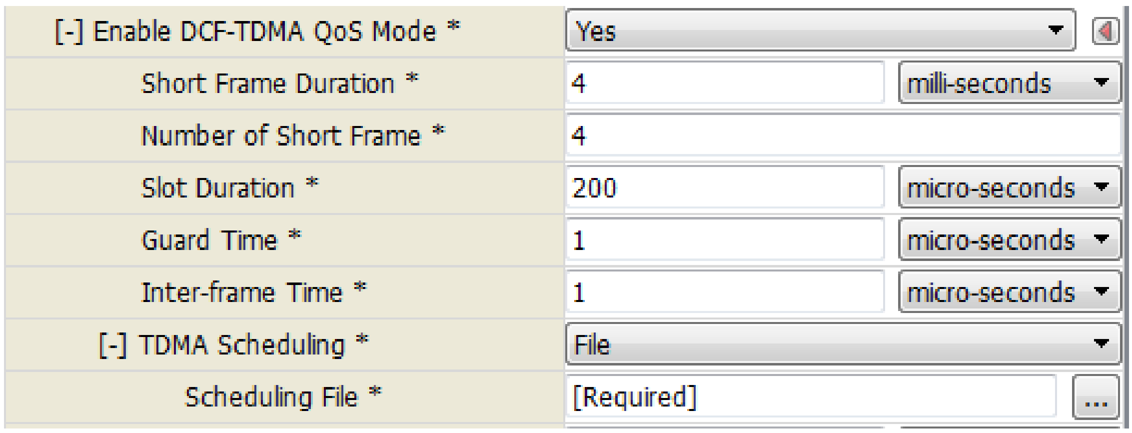

Figure 44 Interface of the implementation.

4.2 Simulation I

Simulation condition is shown in Table 9. In the simulation, 15 nodes are randomly distributed in an area of 1100m × 1100m (see Figure 45). As shown in this figure, three flows are introduced; node 10 to 15, node 1 to 3 and node 13 to 5. All of them are CBR (Constant Bit Rate) flows whose data rate is changed from 16Kbps to 1000Kbps. Each evaluation is the average of five simulation runs.

Table 9 Simulation Condition Ⅰ.

Simulation time	30 seconds
PHY	IEEE 802.11a
Routing protocol	OLSR
Channel bandwidth	6Mbps (fixed)
Transmission range	380m
Application data traffic	CBR, packet size: 512 bytes
QoS flow	node 10→15 (4 hops)
Best effort flows	Node 1→3 (4 hops) Node 13→5 (2 hops)

In the evaluation of our proposal, one flow from node 10 to 15 is handled as a QoS flow and the other two flows are handled as best effort flows. The time slot assignment is shown in Figure 45, where three time slots are used. In this simulation, the sizes of the big frame, TDMA period and DCF period are determined based on the following consideration. Typically, MP3 audio is encoded with a bit rate of 192Kbps to 320Kbps. In order to achieve this bit rate, the raw date should be transmitted with 384Kbps ～ 480Kbps. When the packet size is 512 bytes, sending one packet per second results in 4Kbps data. In order to provide 480Kbps, we have to ensure transmission of 120 data frames per second. Assuming the PHY data rate is 6Mbps, which is the lowest data rate of IEEE 802.11a, the time required to transmit a data frame (when the application data size is 512 bytes) is around 800 μs including guard time, PHCP header, IP header and FCS. Therefore, we define the size of each time slot as 800 µs. In this simulation, the size of a big frame is set to 9602µs which contains 6 TDMA slots, as shown in Figure 46.

The proposed scheme was compared with IEEE 802.11e in two settings. In one setting, the flow from node 10 to 15 is handled, as a prioritized flow and the other are background flows. In the other setting, all flows are handled as background flows without any prioritization.

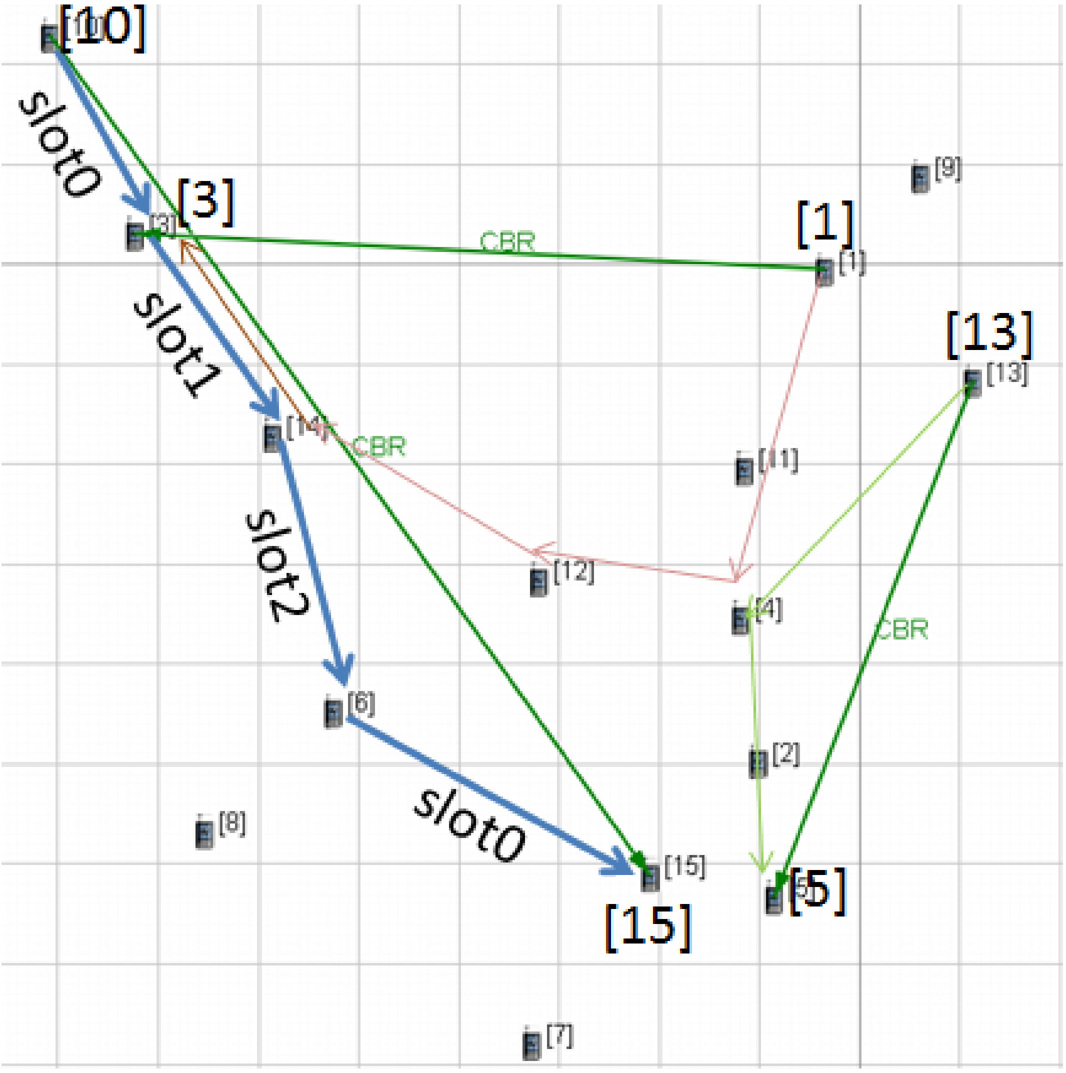

Figure 45 Topology and corresponding time slot assignment in simulation I.

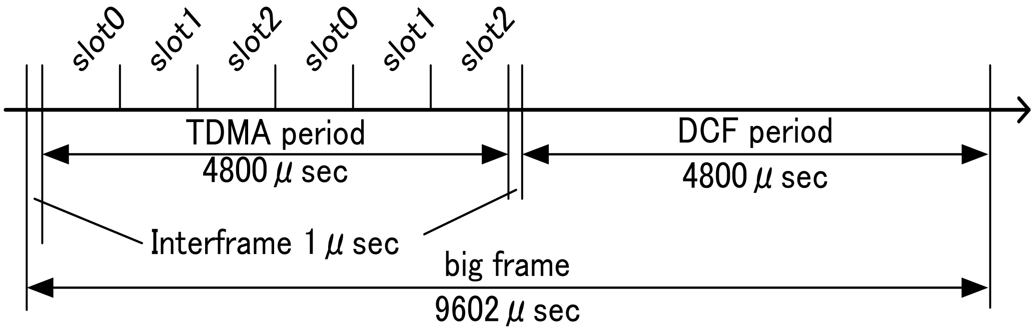

Figure 46 Setting of TDMA and DCF period.

4.2.1 Packet Delivery Ratio

Figure 47 through Figure 49 shows the packet delivery ratio (PDR in the figures) for different CBR rates. For the flow from node 10 to 15, the proposed scheme achieves 100% packet delivery ratio as a QoS flow until the channel capacity is reached (when the CBR rate is 1000Kbps). In the case of IEEE 802.11e flows with prioritization, the packet delivery ratio is around 70% to 80% for the flow with priority (node 10 to 15). On the other hand, IEEE 802.11e without prioritization, the packet delivery ratio is 100% for the CBR rates equal and lower than 256Kbps, but for higher CBR rates it drops to 10%.

For the other two flows, three schemes show the similar results. When the CBR rate is not higher than 256Kbps, the packet delivery ratio is 100%, but it drops as the CBR rate becomes high. This situation is similar with that for IEEE 802.11e without prioritization at the flow from node 10 to 15. It can be pointed out that, for the flow from node 1 to 3, the performance of the proposed scheme is slightly worse than the other schemes.

From those results, the followings can be discussed. First, in IEEE 802.11e without prioritization, actually DCF, only the CBR traffic up to 256Kbps can be delivered effectively in the configuration of the experiment here. For higher CBR rate, the delivery ratio drops sharply. Secondly, in the case of IEEE 802.11e with prioritization, the high priority flow keeps high delivery ratio until 1000Kbps CBR rate. However, the ratio is not 100% but 70% to 80%. In contrast with those two schemes, the proposed scheme realizes 100% packet delivery ratio for QoS flow. This is because IEEE 802.11e can only provide relative priority, and does not guarantee the packet delivery for the case of multi-hop delivery. The proposed scheme is able to provide strict priority to QoS flows as far as the channel capacity is enough to accommodate.

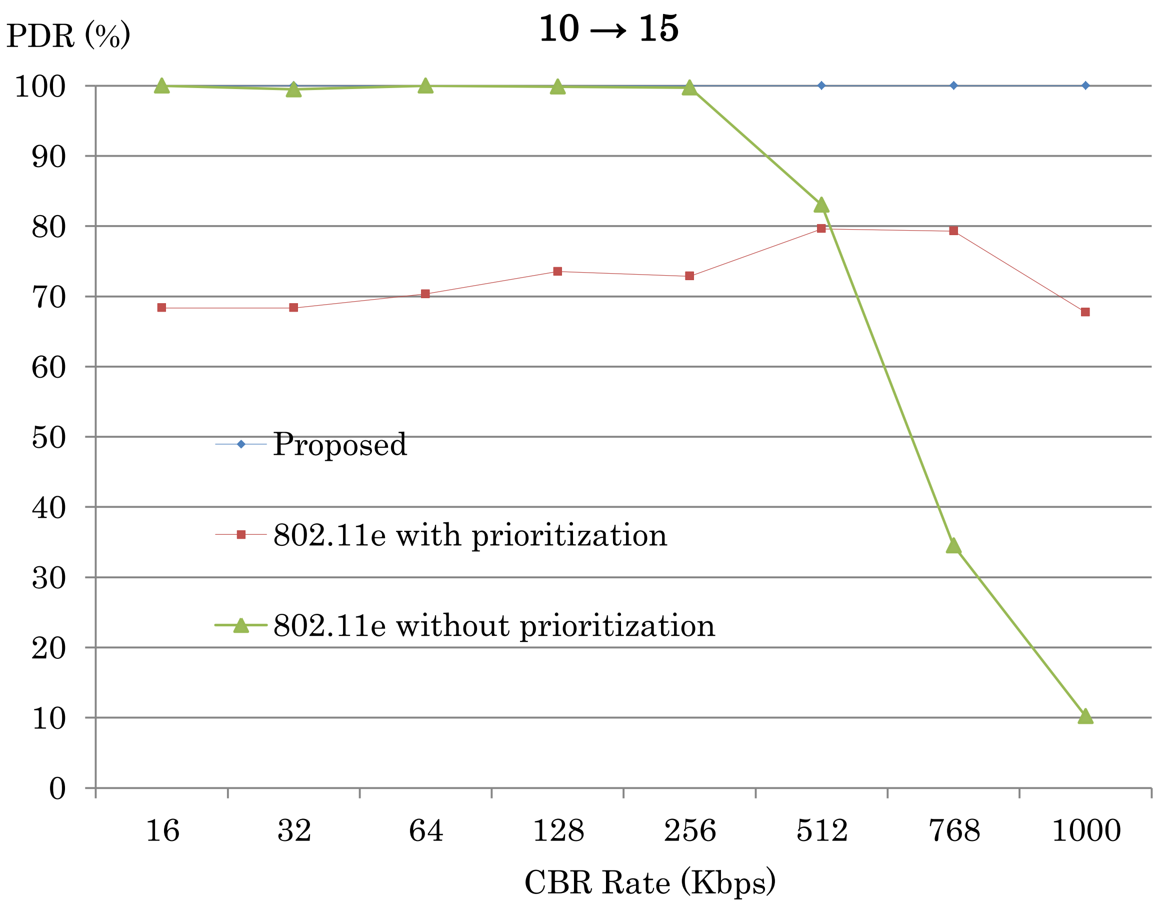

Figure 47 Packet delivery ratio of flow from node 10 to 15.

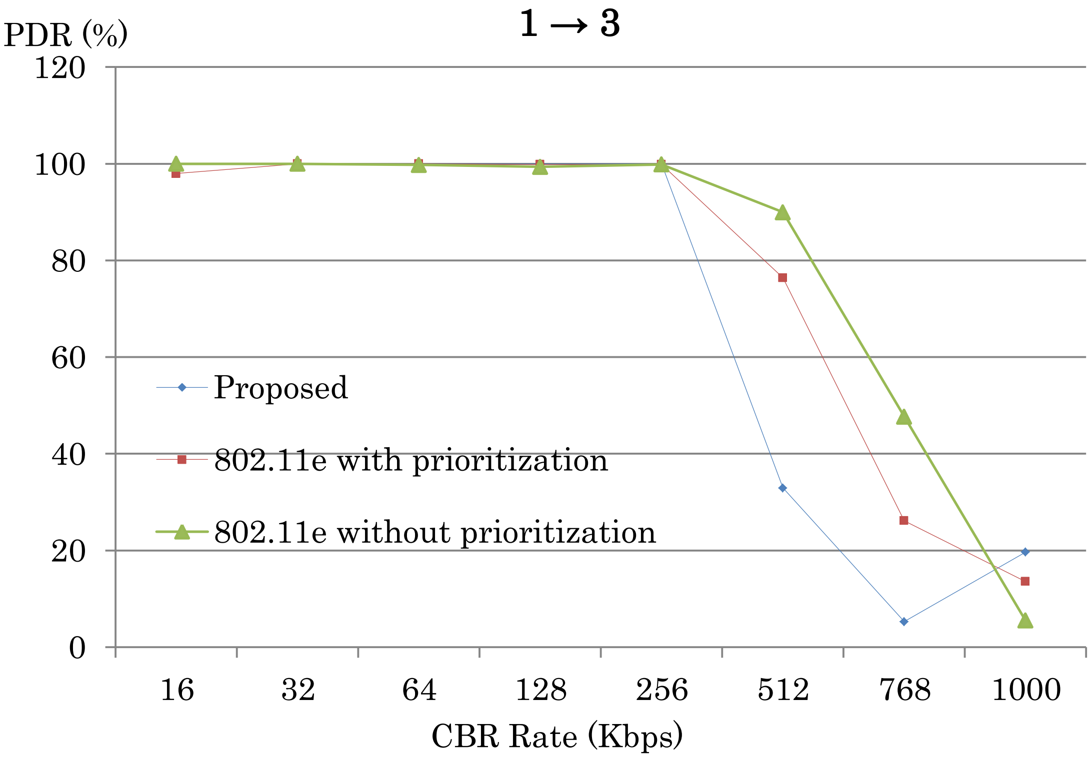

Figure 48 Packet delivery ratio of flow from node 1 to 3.

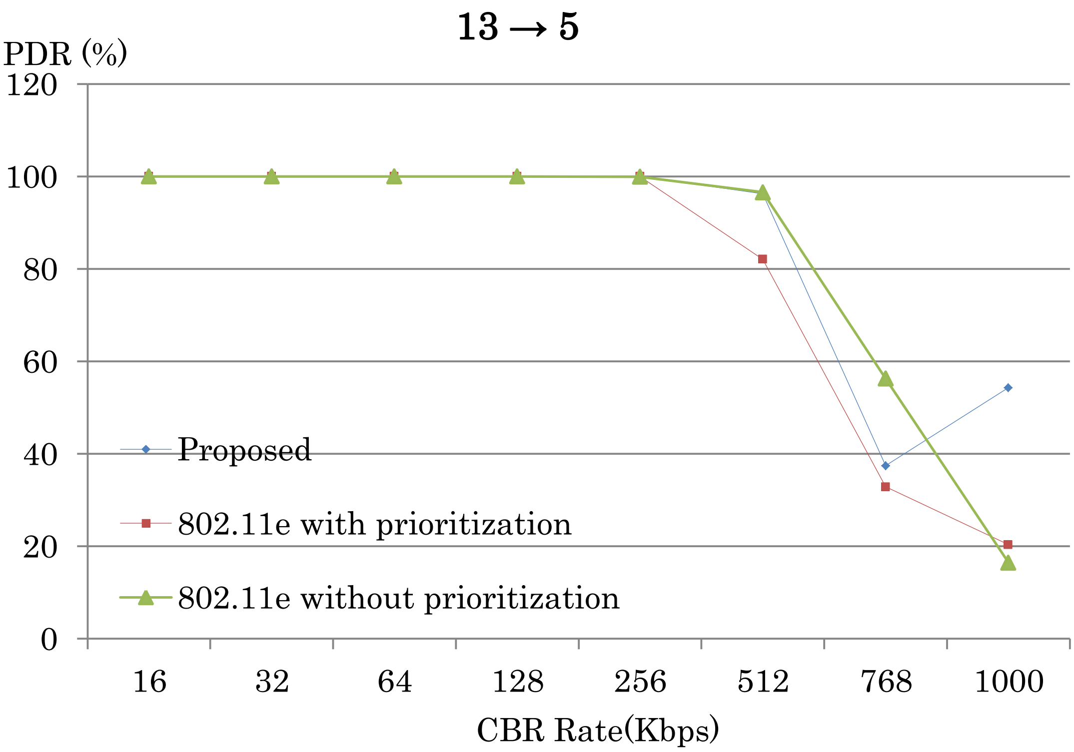

Figure 49 Packet delivery ratio of flow from node 13 to 5.

4.2.2 End-to-end delay

Figure 50 through Figure 52 show the end-to-end delay for different CBR rates. For the flow from node 10 to 15, the proposed scheme and IEEE 802.11e with prioritization attains very low delay for all the CBR rates evaluated in the experiment. On the other hand, the scheme of IEEE 802.11e without prioritization shows a large delay for the cases from 512 Kbps to 1000Kbps. This increase of delay corresponds to the decrease of packet delivery ratio in Figure 47.

Figure 51 and Figure 52 show the similar results for three schemes. When the CBR rate becomes higher than 256Kbps, the end-to-end delay increase sharply. The range of CBR rates which generates large delay correspond to the range which brings low packet delivery ratio.

From those results, the prioritization for QoS flow is effective for realizing small delay, which is important in the transfer of real-time traffic. By considering the results of packet delivery ratio and end-to-end delay, the simulation shows the efficiency of the TDMA based algorithm in the proposed scheme.

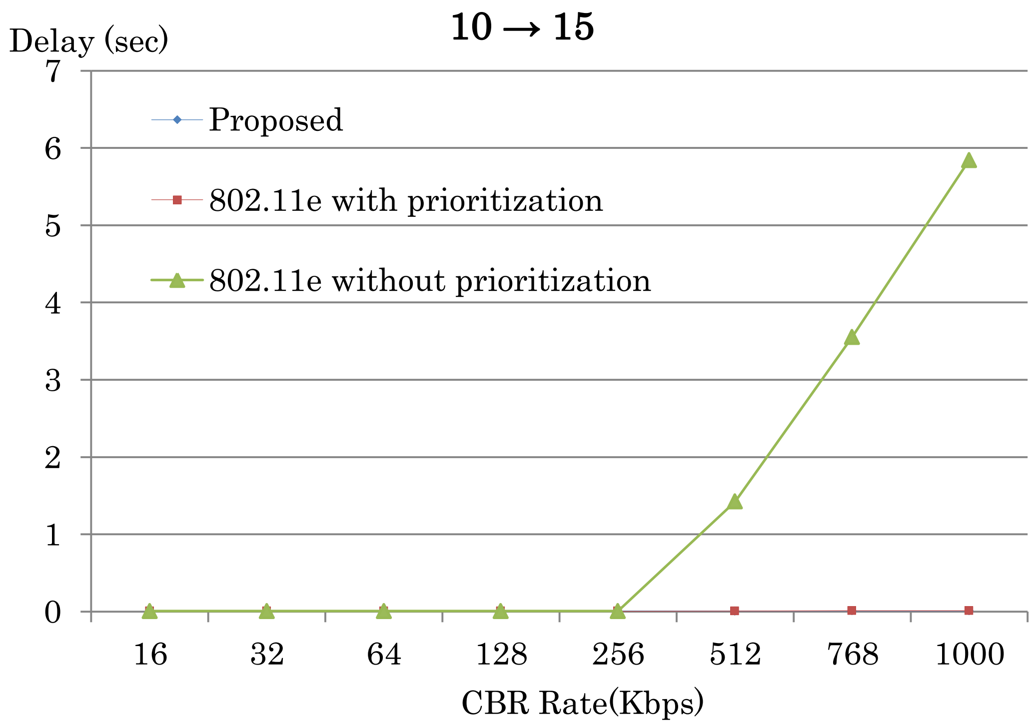

Figure 50 End-to-end delay of flow from node 10 to 15.

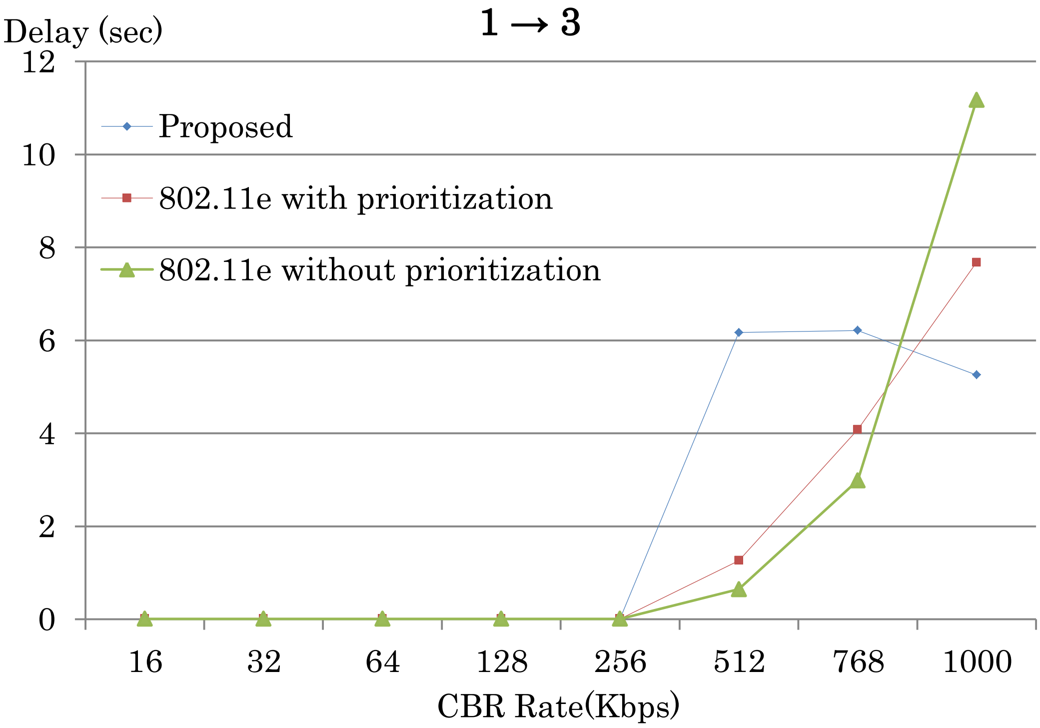

Figure 51 End-to-end delay of flow from node 1 to 3.

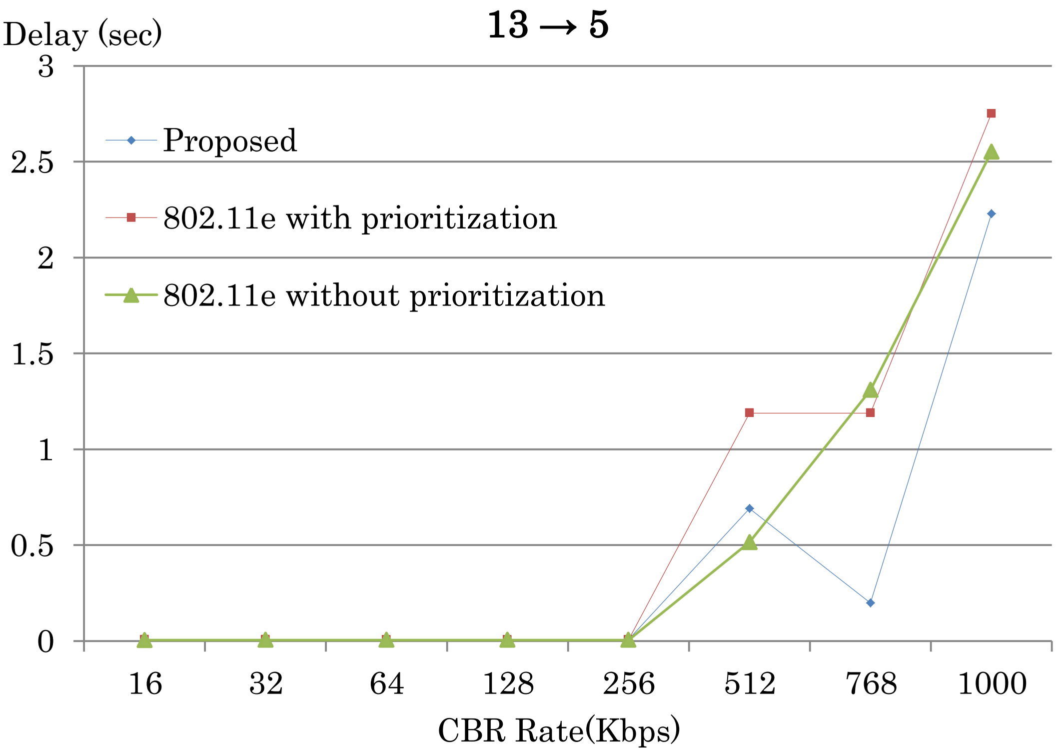

Figure 52 End-to-end delay of flow from node 13 to 5.

4.3 Simulation II

Table 10 shows the simulation environment. In the simulation, 50 nodes are uniformly deployed in a square area (1100 m × 1100 m).The simulation topology is shown in Figure 53. The PHY data rate was fixed to 54 Mbps, which is the highest data rate of IEEE 802.11g. The time required to transmit a data frame (when the application data packet size is 512 bytes) was around 200 μs including PLCP header, IP header, and FCS. Therefore, the size of each time slot was set to 200 μs for the TDMA period. At the beginning of every time slot, 1 μs guard time was added. The size of every time frame was set to 4 ms which includes 1 μs inter-frame time in the head of the frame. Therefore, the maximum achievable data rate was 1024 Kbps for the QoS flows with a packet size of 512 bytes. The length of frame cycle is set to 4 in the simulation.

Table 10 Simulation Condition II.

Simulator	QualNet 6.1
Simulation time	120 s
PHY	IEEE 802.11g 54 Mbps (fixed)
Routing protocol	OLSR
Mac protocol	Proposed, IEEE 802.11e, TDMA
Interference range	580 m
Traffic types	TCP (best effort), CBR (QoS)

Two types of data traffic, specifically CBR flows and TCP flows were simulated. All flows were randomly generated. The CBR flows were considered as QoS flows, and TCP flows were used as best effort flows. The packet size of CBR flows was 512 bytes. TCP flows started at the beginning of the simulation and CBR flows started 4 ms later. Both TCP flows and CBR flows stopped transmitting a new packet at 110 s. The route length for every flow was between 2 hops and 5 hops. The control messages of OLSR protocol are exchanged periodically in the simulation. In the proposed scheme, the messages of admission control mechanism were also simulated. In the simulation results, each value is the average of eighteen simulation runs (nine different data traffics with two different seeds in the simulator). The error bars of the figures indicate the 95% confidence intervals, which were taken from nine different data traffics.

The proposed scheme was compared with IEEE 802.11e and pure TDMA in different load conditions with different numbers of best effort flows (Section 4.3.1) and different data rates of QoS flows (Section 4.3.2).

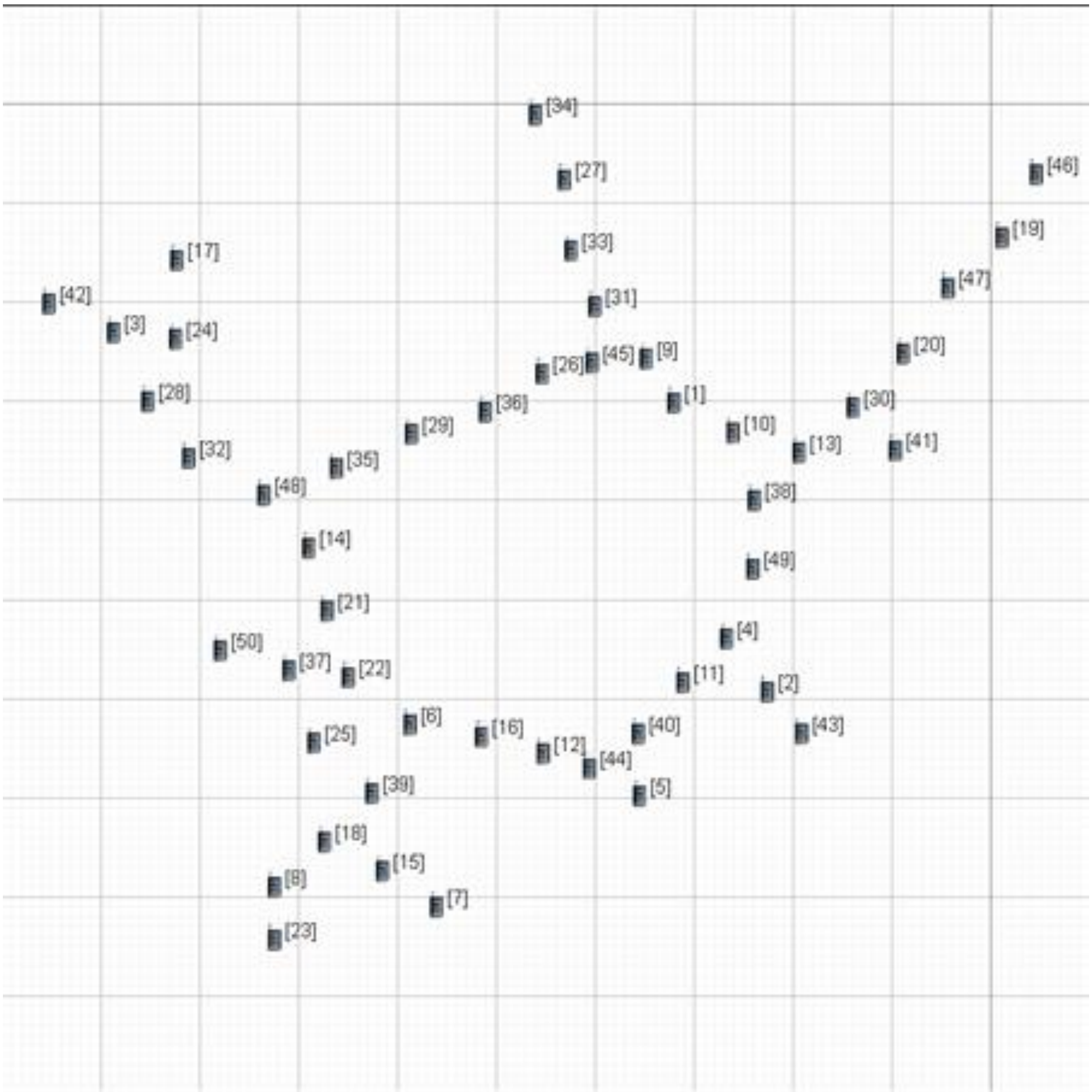

Figure 53 Network topology in simulation II.

4.3.1 Performance for the Different Numbers of the Best Effort Flows

In this simulation, the number of best effort flows was increased from 1 to 10 when the number of QoS flows was 5, and the data rate of the QoS flows was set to 1024 Kbps.

Figure 54 shows the average packet delivery ratio of QoS flows for a different number of best effort flows. In the figure, we observe that the packet delivery ratio for the proposed scheme is 100% for various numbers of best effort flows. For IEEE 802.11e scheme, the packet delivery ratio of QoS flows is around 60%. For the pure TDMA scheme, the increase in the number of best effort flows results in a decrease of the packet delivery ratio of QoS flows.

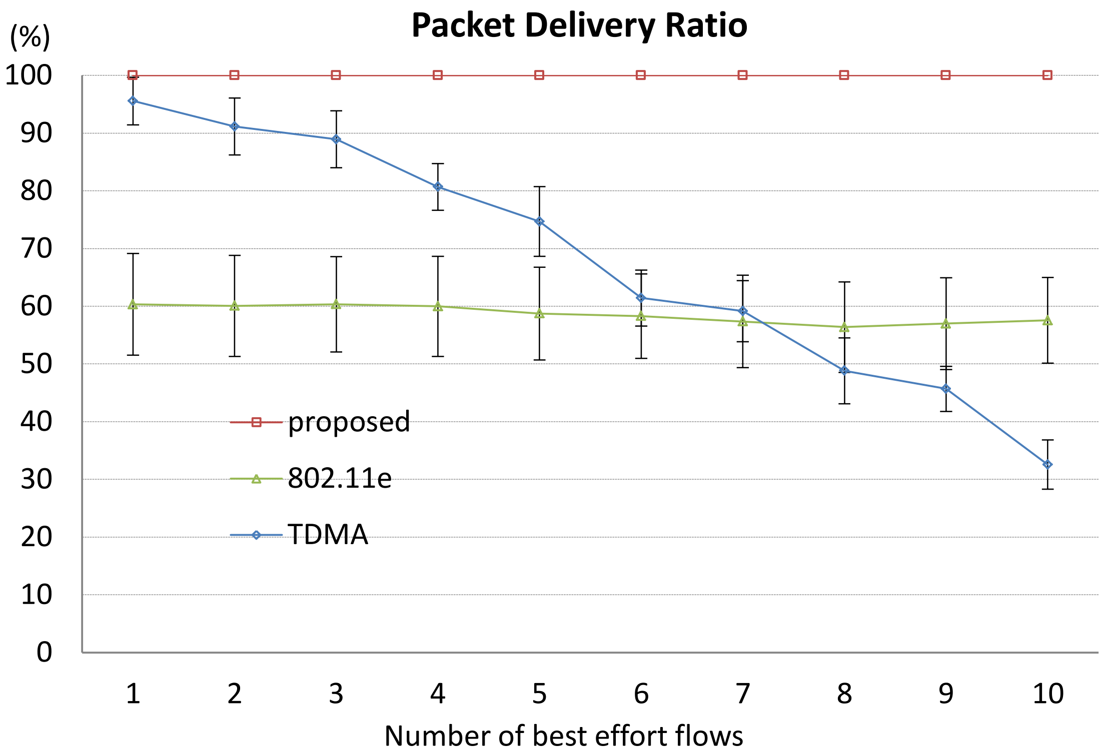

Figure 54 Packet delivery ratio of QoS flows for a different number of best effort flows.

Through the figure, we can know that both the proposed protocol and IEEE 802.11e scheme can maintain the packet delivery ratio of QoS flows in a stable state regardless of the change in the number of best effort flows. However, the performance of the IEEE 802.11e scheme is worse than the proposed scheme. In the proposed scheme, the best effort flows can only transmit packet in DCF period of which length is determined by TDMA period. For this reason, the increase in best effort flows does not have any negative impact on the packet delivery ratio of QoS flows for the proposed scheme.

In IEEE 802.11e scheme, Arbitration Inter-Frame Space (AIFS) and backoff parameters are used to differentiate the channel access among different priority traffics. The QoS traffics are mapped to a higher priority Access Categories (AC) which has shorter AIFS and backoff parameters. In contrast, the best effort traffics in lower-priority AC have longer AIFS and backoff parameters. Therefore, as shown in Figure 54, the packet delivery ratio of QoS flows for IEEE 802.11e scheme is relatively stable. However, the packet delivery ratio of QoS flows for IEEE 802.11e scheme is not 100%. This is because IEEE 802.11e scheme only provides relative priority, which could result in packet collisions (see Section 4.4 for more details).

In the pure TDMA scheme, due to the start time of QoS flows is 4 ms later than best effort flows in the simulation, the best effort flows occupy most time slots, and resulting in the QoS flows cannot get enough time slots. When the number of best effort flows increases, the time slots available for QoS flows become scarce. Therefore, the packet delivery ratio of QoS flows for the pure TDMA scheme gradually decreases as shown in Figure 54.

Figure 55 shows the average end-to-end delay of QoS flows for a different numbers of best effort flows. We can observe that the end-to-end delay of QoS flows for the proposed scheme is the smallest (about 3 ms). This is because the proposed scheme assigns time slots based on the data rate of QoS flows. Time slots for each QoS flow are scheduled in the transmission interval, which can be calculated by the formula in Section 3.4 b).

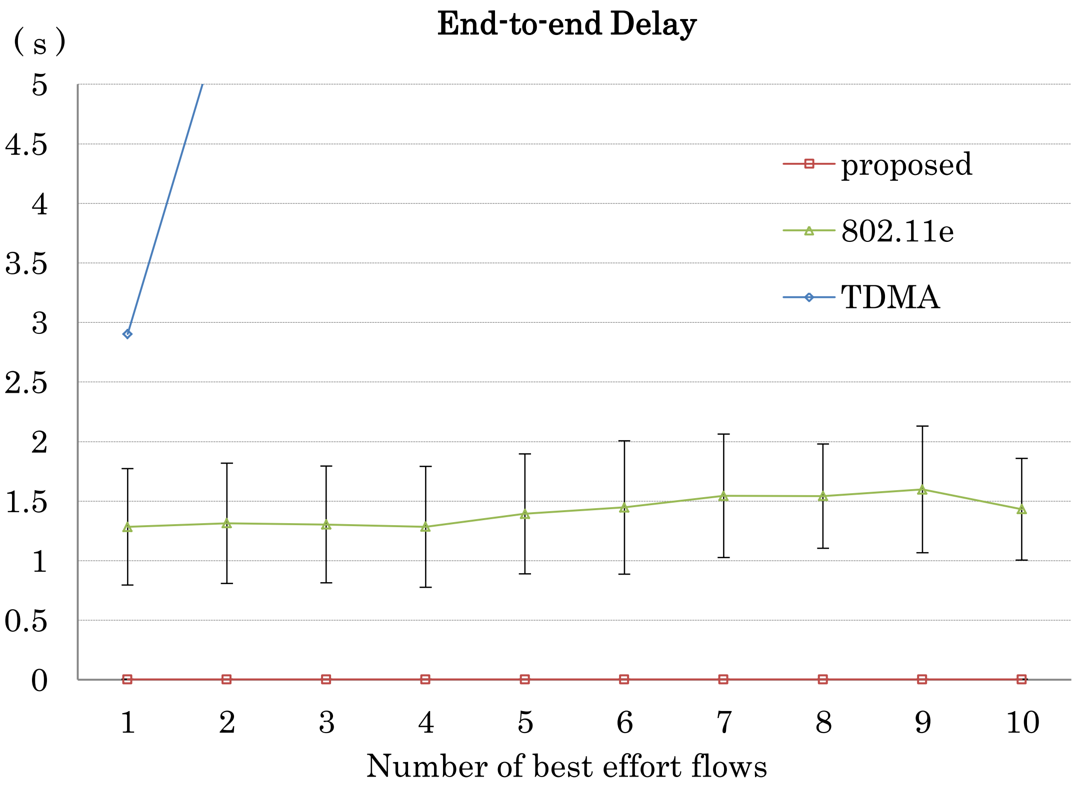

Figure 55 End-to-end delay of QoS flows for different number of best effort flows.

For IEEE 802.11e scheme, the end-to-end delay is higher than 1.3 s, which is not acceptable in most cases. The reason is the best effort flows and QoS flows contend for the channel (see Section 4.4 for more details). For the pure TDMA scheme, the time slots of the QoS flows are allocated after the best effort flows. As a result, the pure TDMA scheme shows the highest delay.

Therefore, we can conclude that the proposed scheme provides high packet delivery ratio and short delay (both are important for the transfer of real-time traffic) for QoS flows for various numbers of best effort flows. This means that the proposed scheme is able to provide strict priority for QoS flows and avoid the negative effects of best effort flows by combining TDMA with DCF.

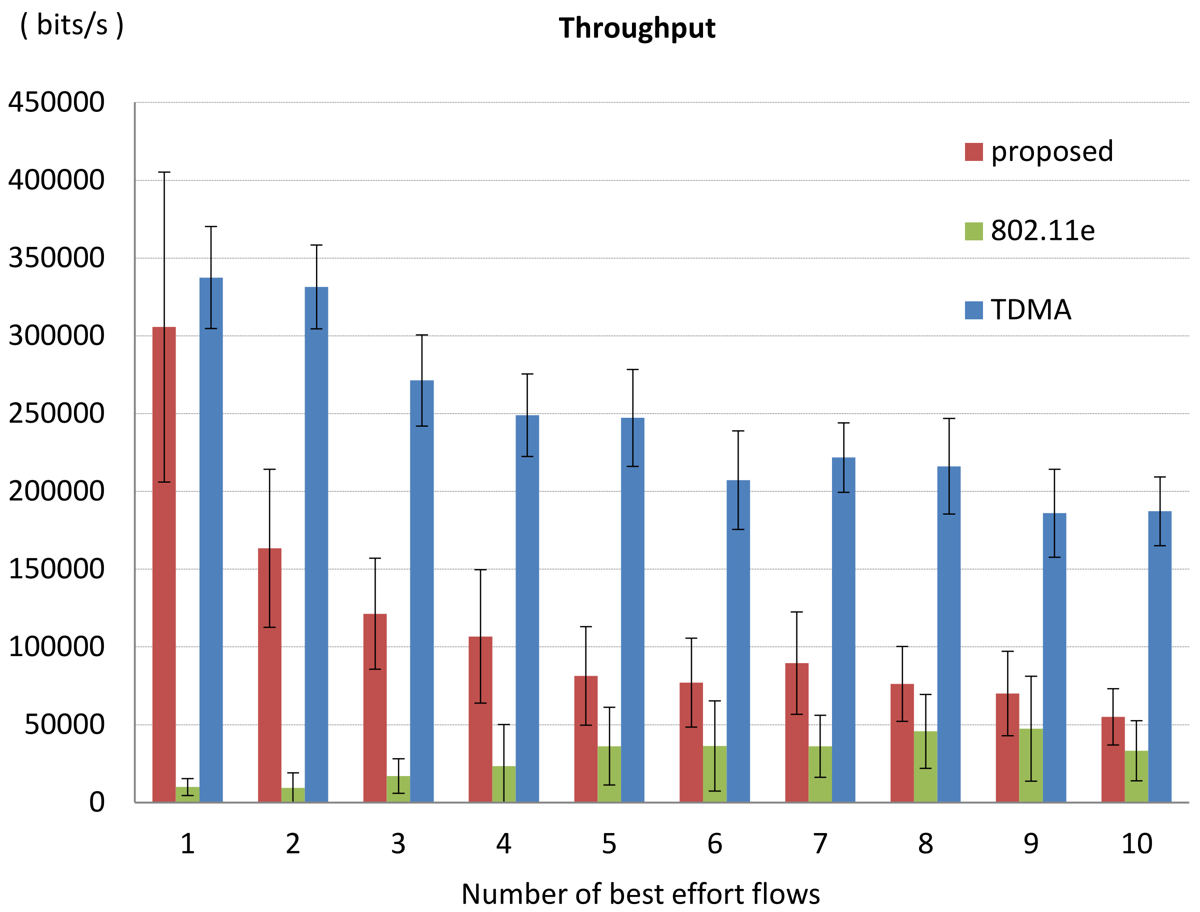

Figure 56 Throughput of best effort flows for a different numbers of best effort flows.

Figure 56 shows the average throughput of the best effort flows for a different numbers of best effort flows. The pure TDMA scheme can provide high throughput for best effort flows by scarifying the QoS flows. For the proposed scheme, the best effort flows do not compete with QoS flows due to the use of DCF period. Therefore, the throughput of best effort flows for the proposed scheme is better than IEEE 802.11e scheme.

Figure 57 shows the average end-to-end delay of best effort flows for different number of best effort flows. The pure TDMA approach maintains the lowest delay as its contention-free characteristic. The average delay of the best effort flows increases in the proposed scheme as the contention in the DCF period becomes intense when the number of best effort flows increases. For IEEE 802.11e, such intolerable delay is achieved due to the higher priority QoS flows occupy almost all the resource of the network.

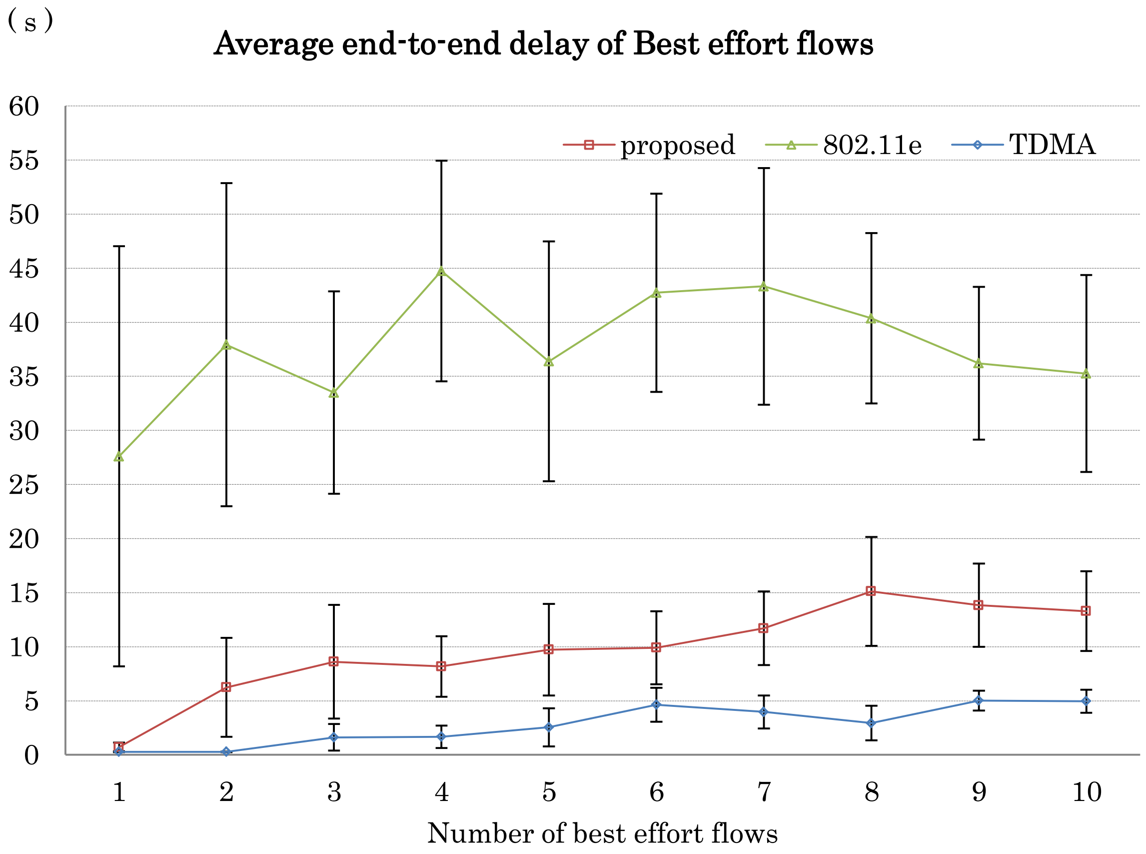

Figure 57 Average end-to-end delay of best effort flows for different number of best effort flows.

Figure 58 shows the number of retransmissions per MAC data frame for different numbers of best effort flows. Since the proposed protocol can provide strict priority for QoS flows, the number of retransmissions of QoS flows in the proposed protocol is zero. The proposed protocol also can provide a lower MAC retransmission rate for best effort flows as compared with IEEE 802.11e scheme because the protocol can provide more efficient channel access by defining two different periods for QoS flows and best effort flows. The number of retransmissions per MAC data frame for the pure TDMA scheme is zero because the pure TDMA scheme is a contention-free approach. Although IEEE 802.11e scheme assigns a higher priority for a QoS flow, the number of retransmissions per MAC data frame is high (around 1.6). This is because IEEE 802.11e scheme only can provide relative priority. Since the data rate of QoS flows is very high (1024 Kbps) in this simulation, a large number of packets need to be sent out in a short time, and therefore competition among QoS flows and the best effort flows becomes intense in IEEE 802.11e scheme (multiple senders could select the same backoff time resulting in packet collisions).

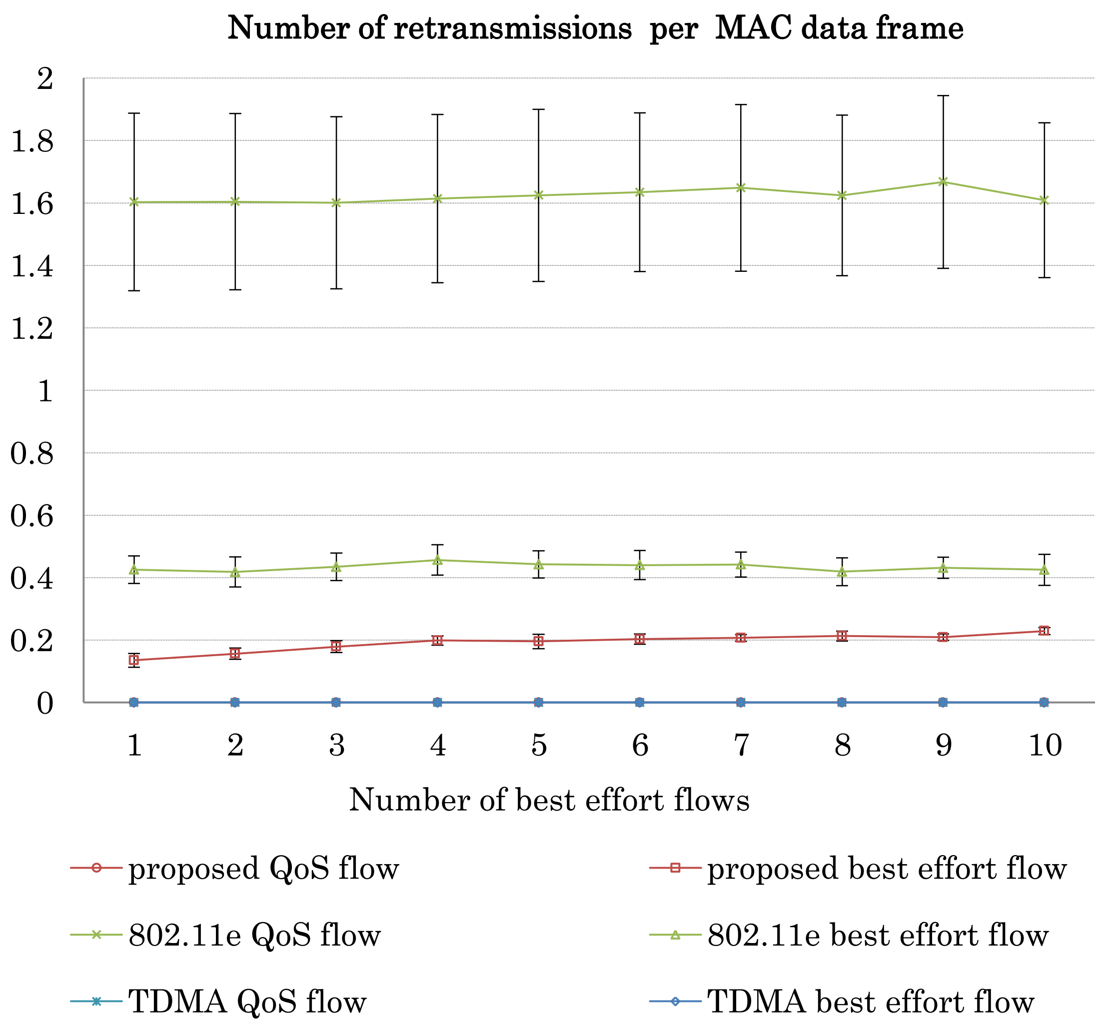

Figure 58 Number of retransmissions per MAC data frame for a different numbers of best effort flows.

4.3.2 Performance for Different Data Rates of QoS Flows

In this simulation, there were five QoS flows with data rate ranging from 16 Kbps to 1024 Kbps. The number of best effort flows was 10.

Figure 59 shows the average packet delivery ratio of QoS flows for different data rates of

QoS flows. We can observe that the proposed scheme achieves 100% packet delivery ratio. In the case of IEEE 802.11e scheme, the packet delivery ratio is lower than 80% for the QoS flows, and the ratio drops significantly when the data rate reaches 1024 Kbps. The pure TDMA scheme shows the same trend as IEEE 802.11e.

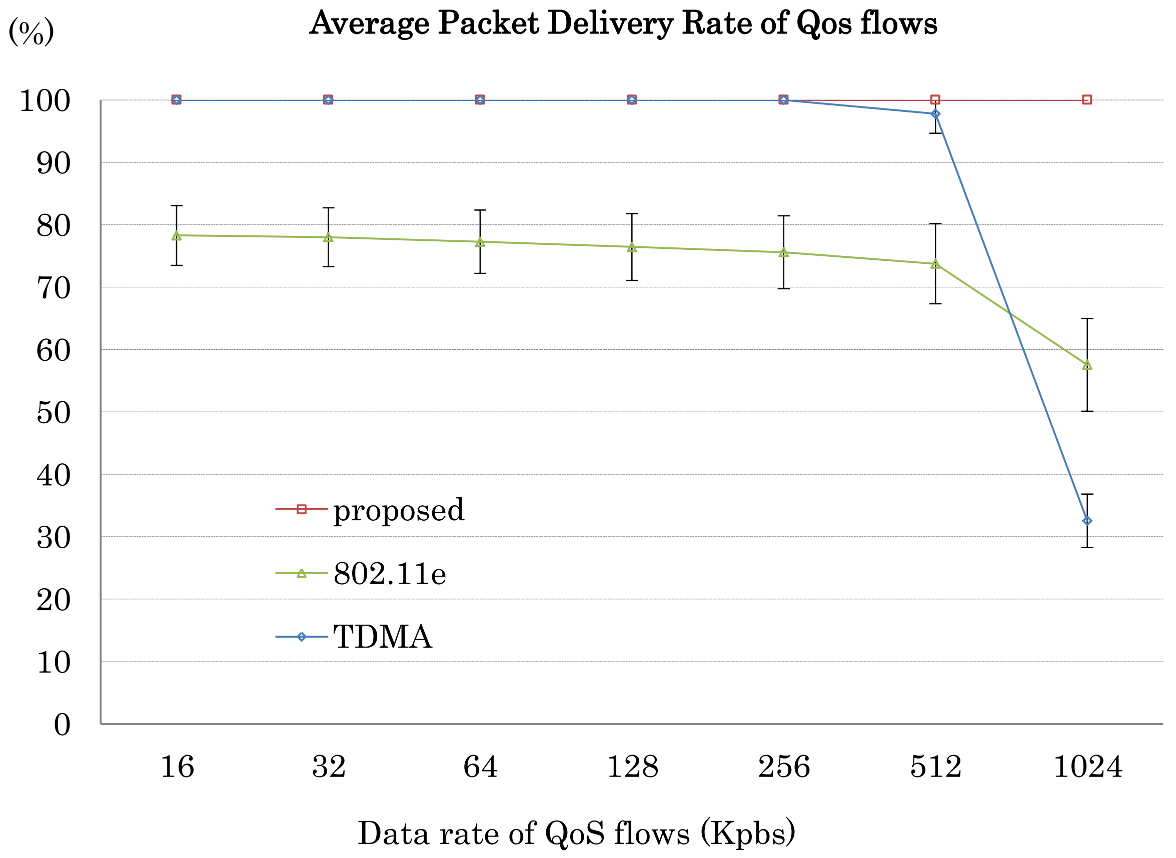

Figure 59 Packet delivery rate of QoS flows for different data rates of QoS flows.

Figure 60 shows the average end-to-end delay of QoS flows for different data rates. The proposed scheme attains very low delay for all the data rates. IEEE 802.11e scheme cannot provide short delay when the data rate of QoS flows increases to 512 Kbps. The pure TDMA scheme shows the largest end-to-end delay, which cannot satisfy the requirement of most applications (more than 1.5 s when the data rate is higher than 512 Kbps).

IEEE 802.11e scheme shows high packet delivery ratio and small end-to-end delay when the data rate is lower than 512 Kbps (see Figure 59 and Figure 60). However, as mentioned before, when the data rate of QoS flows becomes higher than 512 Kbps, the performance drops due to the high competition among QoS packets. This can also explain why the packet delivery ratio of QoS flows for different numbers of best effort flows for IEEE 802.11e scheme is lower than the proposed protocol (see Figure 54) and why the end-to-end delay of QoS flows is large (see Figure 55). For the pure TDMA scheme, although the packet delivery ratio is high (100%) when the data rate of QoS flows is lower than 512 Kbps as shown in Figure 59, the end-to-end delay is beyond the tolerable value (see Figure 60).

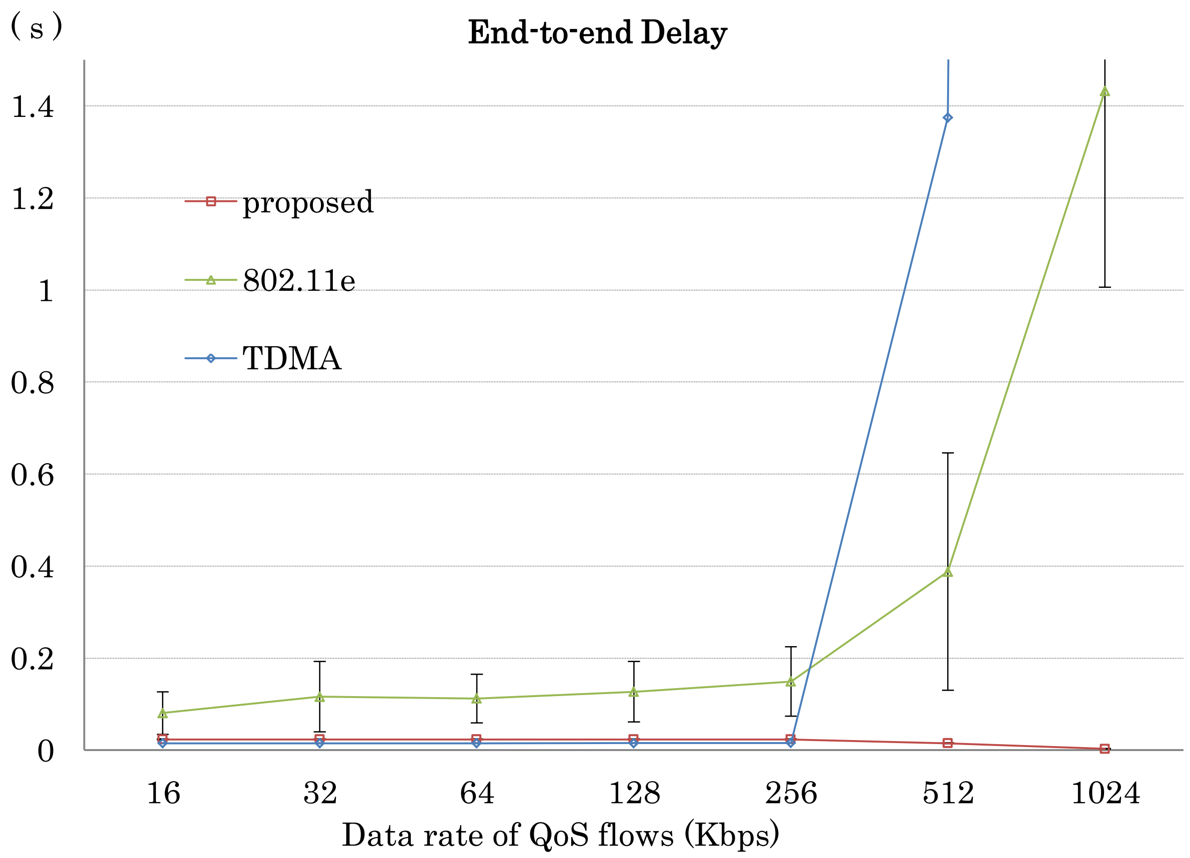

Figure 60 End-to-end delay of QoS flows for different data rates of QoS flows.

In the proposed scheme, the TDMA period changes dynamically according to the required number of time slots for QoS flows. When the data rate of QoS flows becomes higher, the required number of time slots in a short time becomes larger, thus the TDMA period becomes larger accordingly. For the proposed protocol, the increase of data rates has no negative impact on the delay and the throughput performance (see Figure 59 and Figure 60).

Figure 61 shows the average throughput of best effort flows for different data rates of QoS flows. When the data rate is high, the proposed protocol can provide higher throughput for the best effort flows as compared with IEEE 802.11e. This is because the proposed protocol handles the best effort flows and QoS flows using different periods, which is more efficient in terms of channel utilization. For contention-based channel access (IEEE 802.11e), the channel access efficiency drops significantly with the increase of the number of contending nodes. This is why the throughput of IEEE 802.11e drops significantly when the data rate of QoS flows increases.

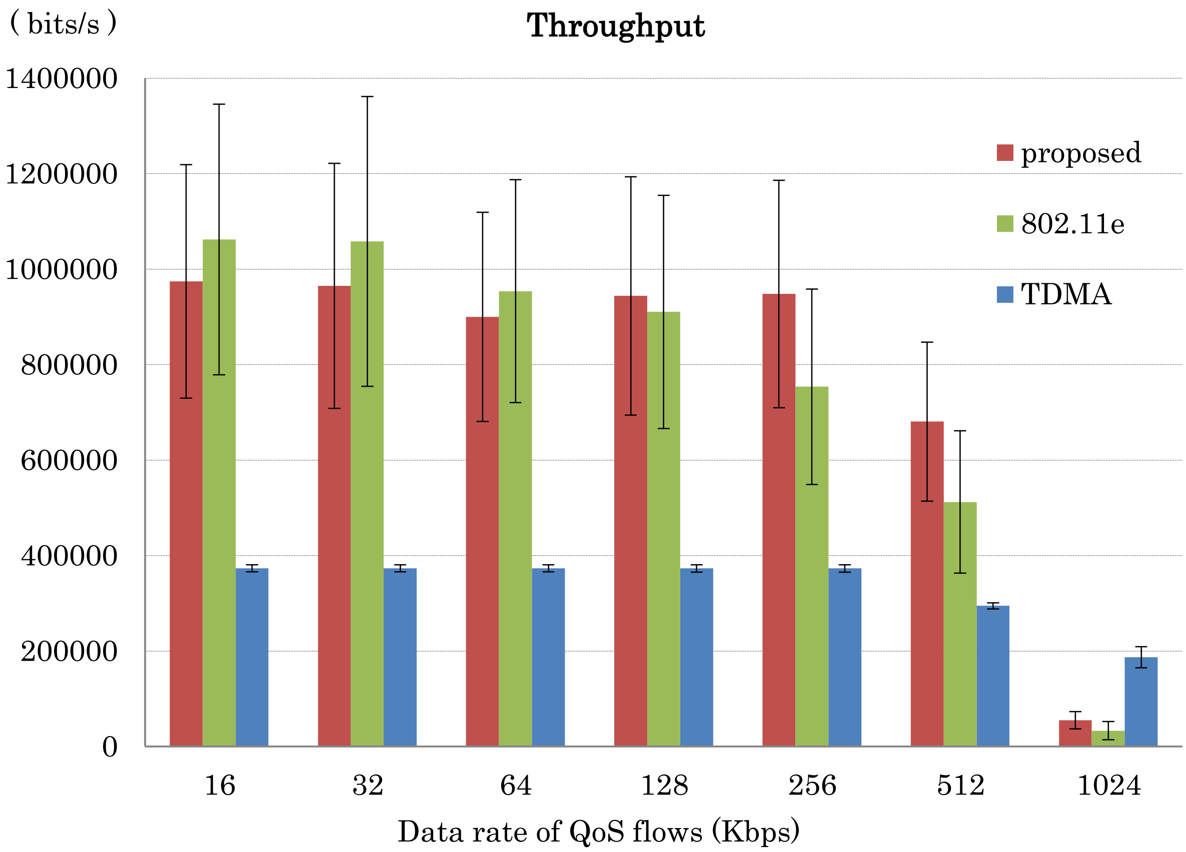

Figure 61 Average throughput of best effort flows for different data rates of QoS flows.

Figure 62 shows the average end-to-end delay of best effort flows for different data rates of QoS flows. Since TDMA is a contention-free method, the best effort traffics which transferred by TDMA can achieve extremely low delay. For IEEE 802.11e protocol, the end-to-end delay is around 10s when the data rate of QoS flows is lower than 512Kbps. The end-to-end delay of best effort flows comes to a high level after increasing the data rate of QoS flows to 1024Kbps. The reason is the higher data rate the high contention in IEEE

802.11e. For the proposed scheme, as the TDMA period is almost the same when the QoS data rates is lower than 512Kbps, the delay is around 7s. When the data rate of QoS is more than 512Kbps, the end-to-end delay raises to 12s since the DCF period becomes smaller.

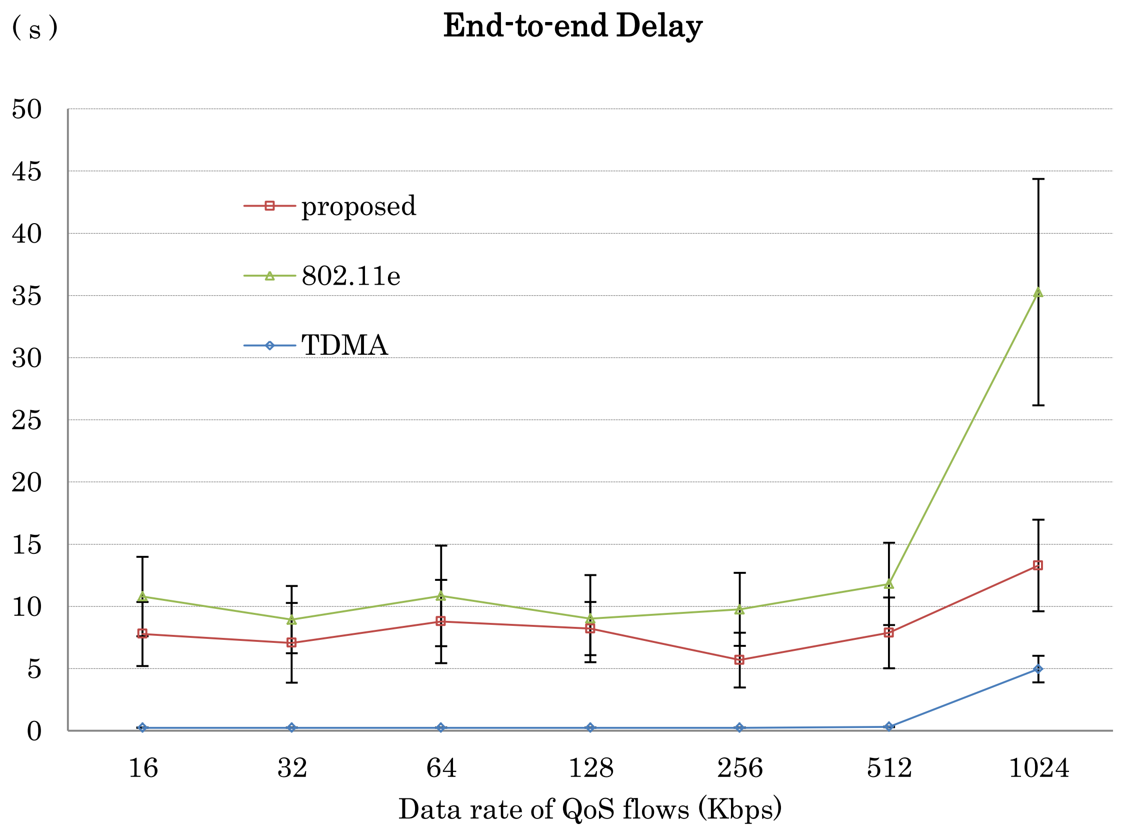

Figure 62 Average end-to-end delay of best effort flows for different data rates of QoS flows.

Figure 63 shows the number of retransmissions per data frame for various data rates of QoS flows. Since the proposed protocol uses TDMA period to allocate time slots for QoS flows, the number of retransmissions is zero. For IEEE 802.11e scheme, the number of retransmissions rate increases drastically with the QoS data rate. This is due to the packet collisions, which could occur between QoS data packets, or QoS data packets and best effort data packets. The contention between QoS traffics and best effort traffics also result in low TCP throughput as shown in Figure 61. For the proposed scheme, the performance of TCP throughput is affected by the length of DCF period. The throughput of best effort flows becomes lower as the length of DCF period becomes shorter. In Figure 61, when the data rate is lower than 256 Kbps since the DCF period is the largest in this simulation, TCP throughput of the proposed scheme is the highest.

In IEEE 802.11e scheme, the number of retransmissions increases significantly as the data rate of QoS flows increases as shown in Figure 63. This is another reason for the performance degradation of IEEE 802.11e scheme in Figure 59 and Figure 60. Since the best effort flows in the proposed scheme have an independent period (DCF period) for transmission, the number of retransmissions for the proposed scheme is smaller than IEEE 802.11e. The simulation results show that the TDMA/DCF hybrid method in the proposed scheme is of great benefit to both QoS flows and best effort flows.

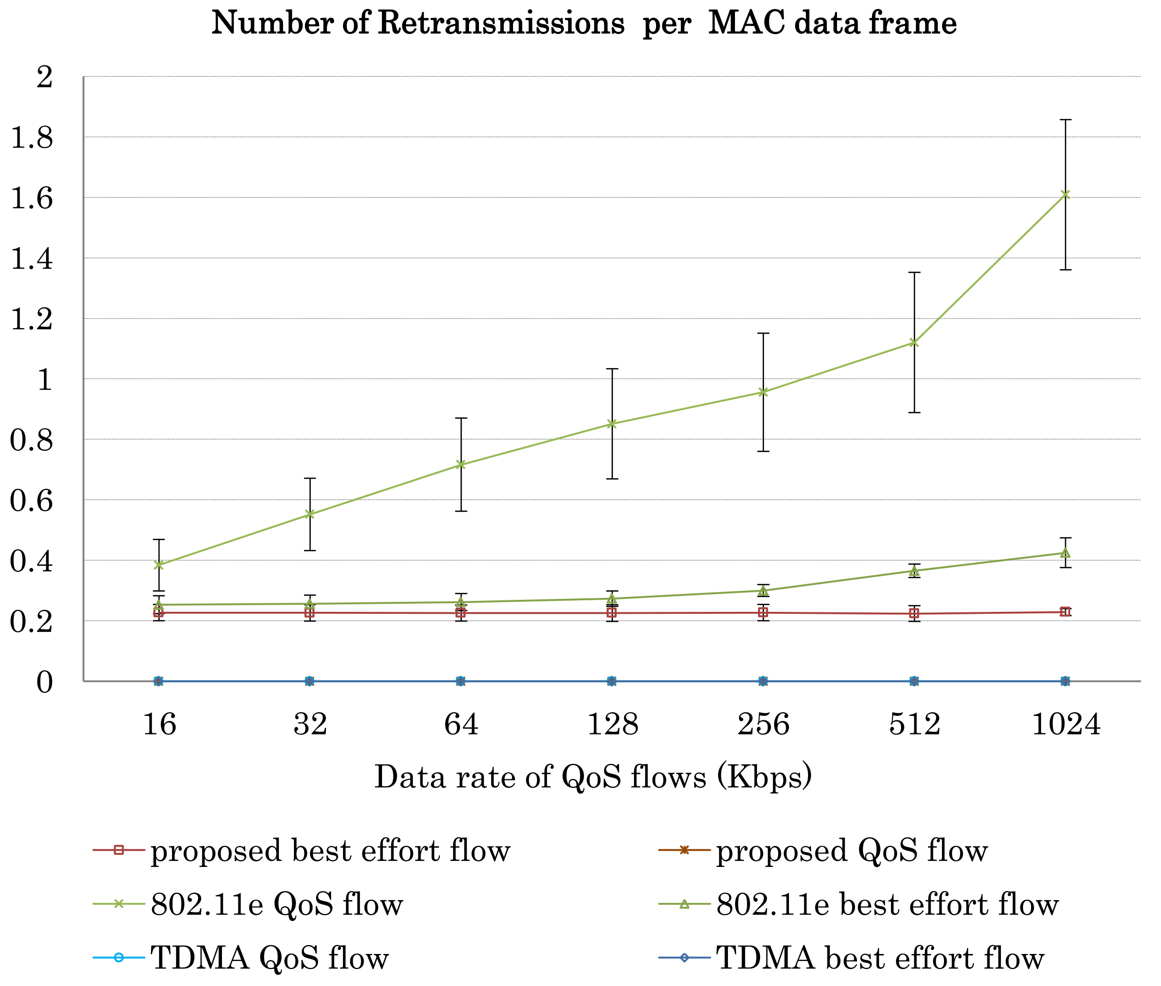

Figure 63 The number of retransmissions per MAC data frame for different data rates of QoS flows.

4.4 Simulation III

In Simulation III, a wireless ad hoc network with 100 nodes which has a higher node density than Simulation II was simulated. The parameters setting is shown in Table 11. 100 nodes are uniformly deployed in a square area (300 m × 300 m). The simulation topology is shown in Figure 53. The PHY data rate was fixed to 36 Mbps, which is the highest data rate of IEEE 802.11g. The time required to transmit a data frame (when the application data packet size is 512 bytes) was around 250 μs including PLCP header, IP header, and FCS. Therefore, the size of each time slot was set to 250 μs for the TDMA period. At the beginning of every time slot, 1 μs guard time was added. The size of every time frame was set to 4 ms which includes 1 μs inter-frame time in the head of the frame. Therefore, the maximum achievable data rate was 1024 Kbps for the QoS flows with a packet size of 512 bytes. The length of frame cycle is set to 4 in the simulation.

Table 11 Simulation Condition Ⅲ.

Simulator	QualNet 6.1
Simulation time	60 s
PHY	IEEE 802.11g 36 Mbps (fixed)
Routing protocol	OLSR
Mac protocol	Proposed, IEEE 802.11e, TDMA
Interference range	580 m
Traffic types	TCP (best effort), CBR (QoS)

Two types of data traffic, specifically CBR flows and TCP flows were simulated. All flows were randomly generated. The CBR flows were considered as QoS flows, and TCP flows were used as best effort flows. The packet size of CBR flows was 512 bytes. Both TCP flows and CBR flows started at the beginning of the simulation. Both TCP flows and CBR flows stopped transmitting a new packet at 55 s. The route length for every flow was between 1 hops and 5 hops. The control messages of OLSR protocol are exchanged periodically in the simulation. In the proposed scheme, the messages of admission control mechanism were also simulated. In the simulation results, each value is the average of ten simulation runs (five application sets with two seeds in the simulator). The error bars of the figures indicate the 95% confidence intervals.

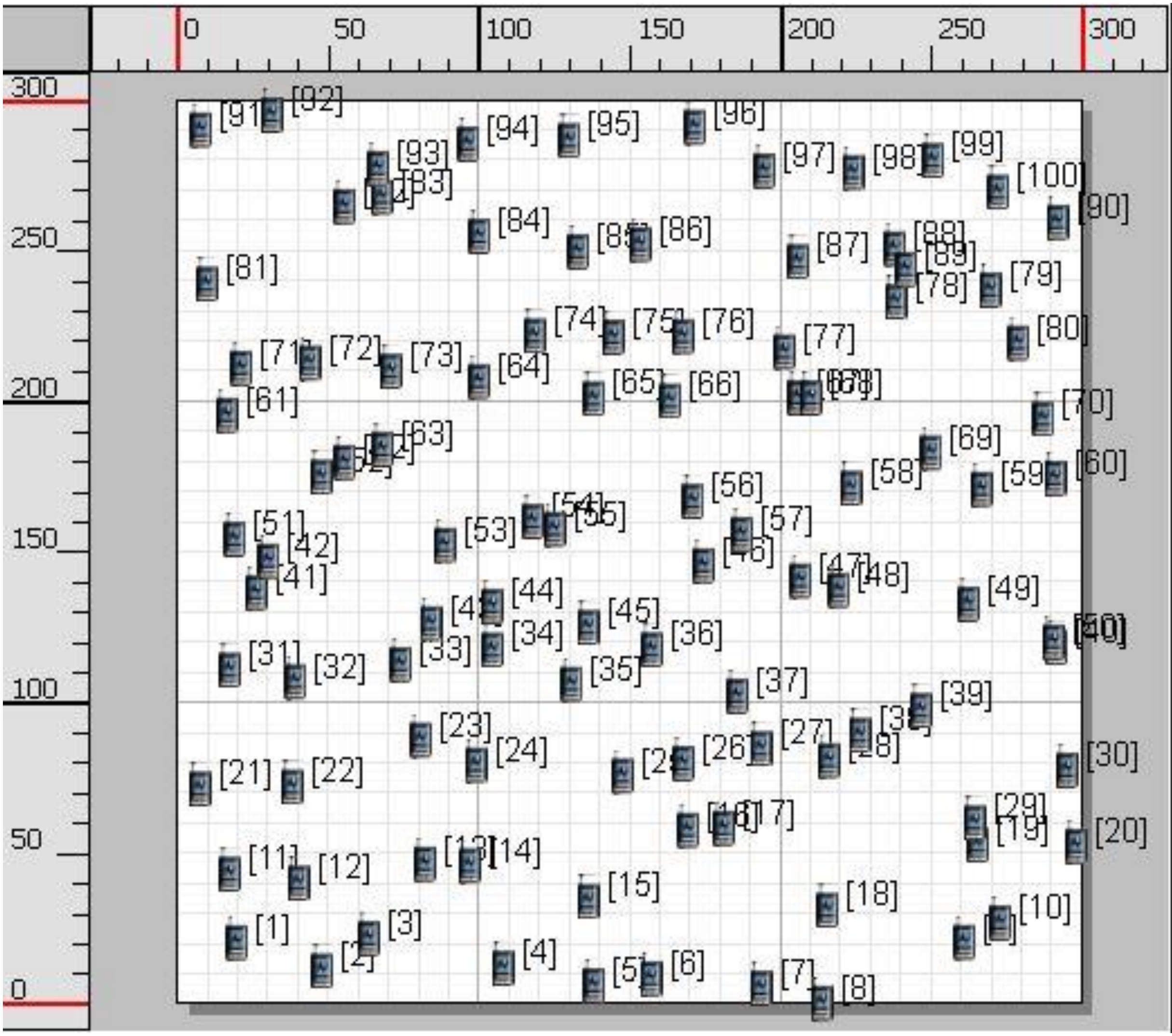

Figure 64 Network topology in simulation III.

The proposed scheme was compared with IEEE 802.11e in the following different load conditions.

A) Different number of best effort flows.

B) Different data rates of QoS flows.

C) Different number of QoS flows.

4.4.1 Performance for the Different Numbers of the Best Effort Flows

In this simulation, the number of best effort flows was increased from 1 to 9 when the number of QoS flows was 5, and the data rate of the QoS flows was set to 512 Kbps.

Figure 65 shows the average packet delivery ratio of QoS flows for a different number of best effort flows. In the figure, we observe that the packet delivery ratio for the proposed scheme is 100% for various numbers of best effort flows. For IEEE 802.11e scheme, the packet delivery rate of QoS flows is nearly 100%. Compared with Simulation II, because the data rate of QoS flows is lower in Simulation III (which is 512 Kbps), the packet delivery rate of QoS flows in IEEE 802.11e is better.

Through Figure 54 and Figure 65 in Simulation II and Simulation III separately, we can observe that the proposed protocol can maintain the packet delivery ratio of QoS flows in a stable state regardless of the change in the number of best effort flows even when the node density becomes higher. The performance of the IEEE 802.11e scheme is worse than the proposed scheme. In the proposed scheme, data packets of the best effort flows can only be transmitted within the DCF period, thus not affecting the QoS communication.

Figure 66 shows the average end-to-end delay of QoS flows for a different numbers of best effort flows. We can observe that the average end-to-end delay of QoS flows for the proposed scheme keeps a steady value. This is because the proposed scheme designs a separate period (TDMA period) for QoS flows. Since the reserved time slots were the same for QoS flows, the end-to-end delay is the same. The average end-to-end delay of QoS flows gradually increases with the increase of best effort flows for IEEE 802.11e.

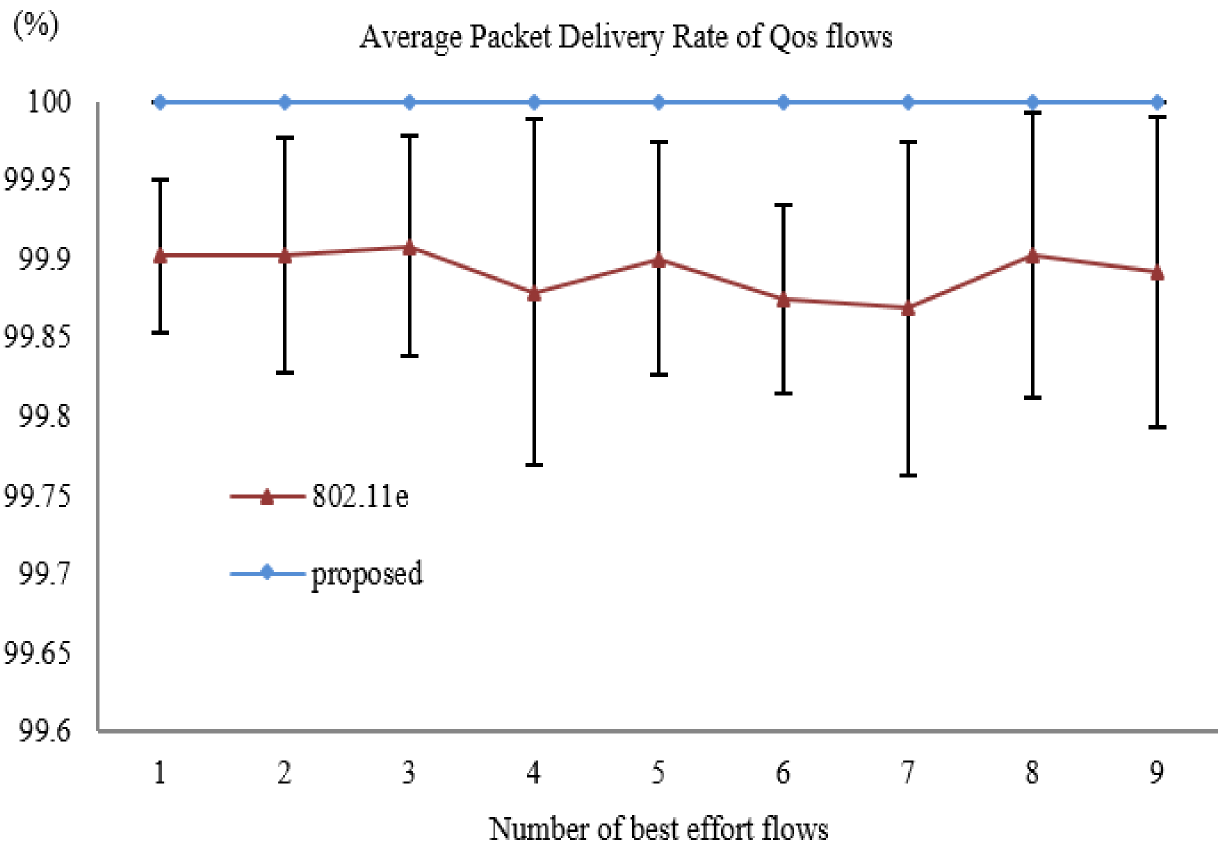

Figure 65 Average packet delivery rate for different number of best effort flows.

In IEEE 802.11e scheme, as mentioned in Section 4.3.1, QoS traffics have higher priority than best effort traffics by using smaller AIFS and backoff parameters. When the number of best effort flows becomes larger, the competition between QoS flows and best effort flows becomes fierce, the average end-to-end delay of IEEE 802.11e becomes larger.

Through the results shown in the Figure 65 and Figure 66, we can conclude that the proposed scheme maintains better performance than IEEE 802.11e for different numbers of best effort flows. We can see the effectiveness of period division of the proposed method.

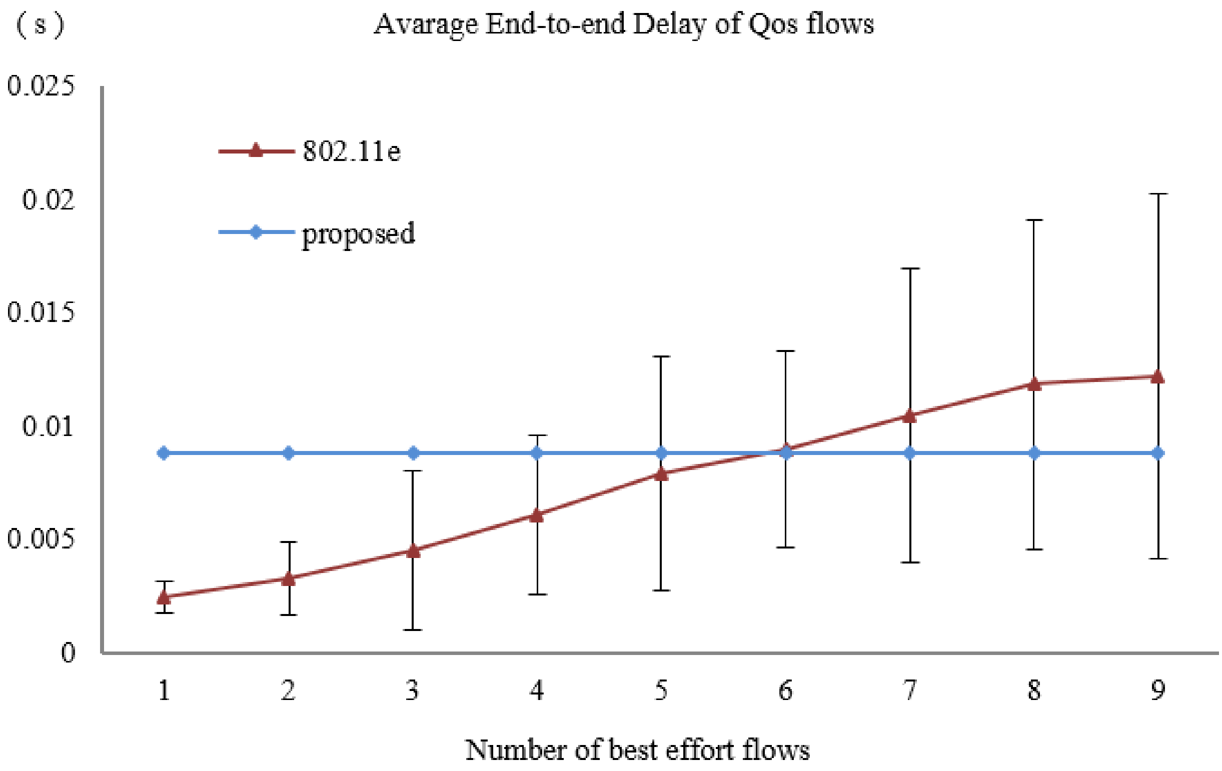

Figure 66 Average end-to-end delay of QoS flows for different number of best effort flows.

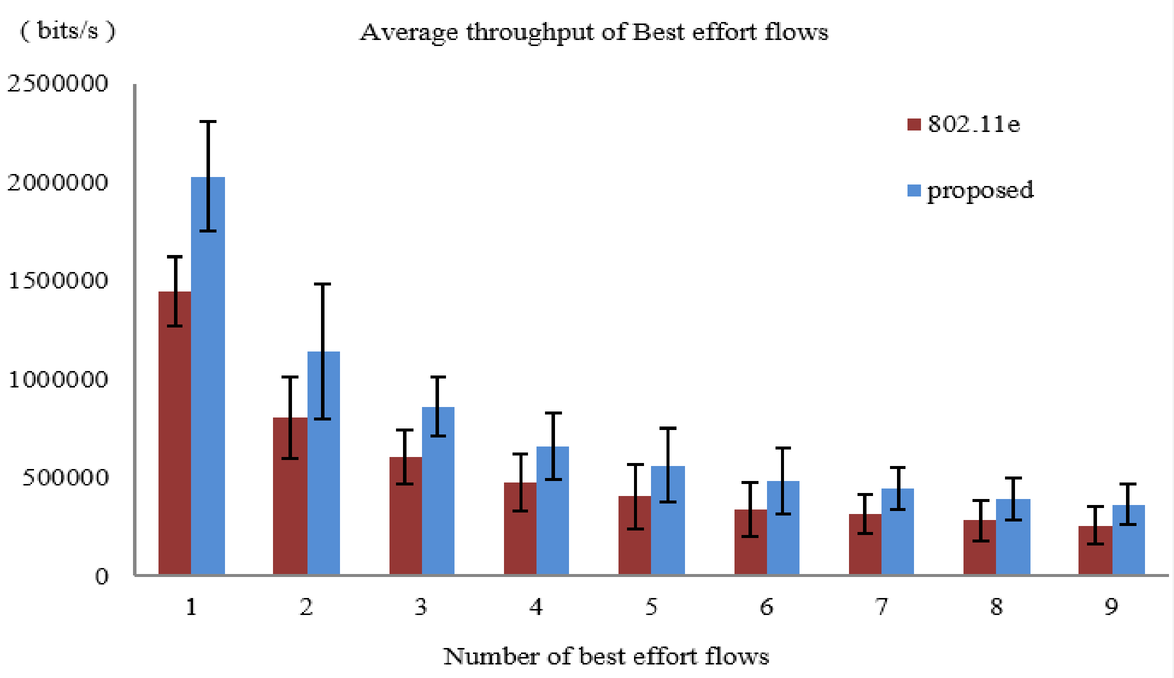

Figure 67 Average throughput of best effort flows for different number of best effort flows.

Figure 67 shows the average throughput of the best effort flows for a different numbers of best effort flows. For the proposed scheme, the best effort flows do not compete with QoS flows due to the use of DCF period. Therefore, the throughput of best effort flows for the proposed scheme is better than IEEE 802.11e scheme. The best effort throughput of both the proposed scheme and IEEE 802.11E scheme decreased when the number of best effort flows increases since contentions among best effort flows become intense.

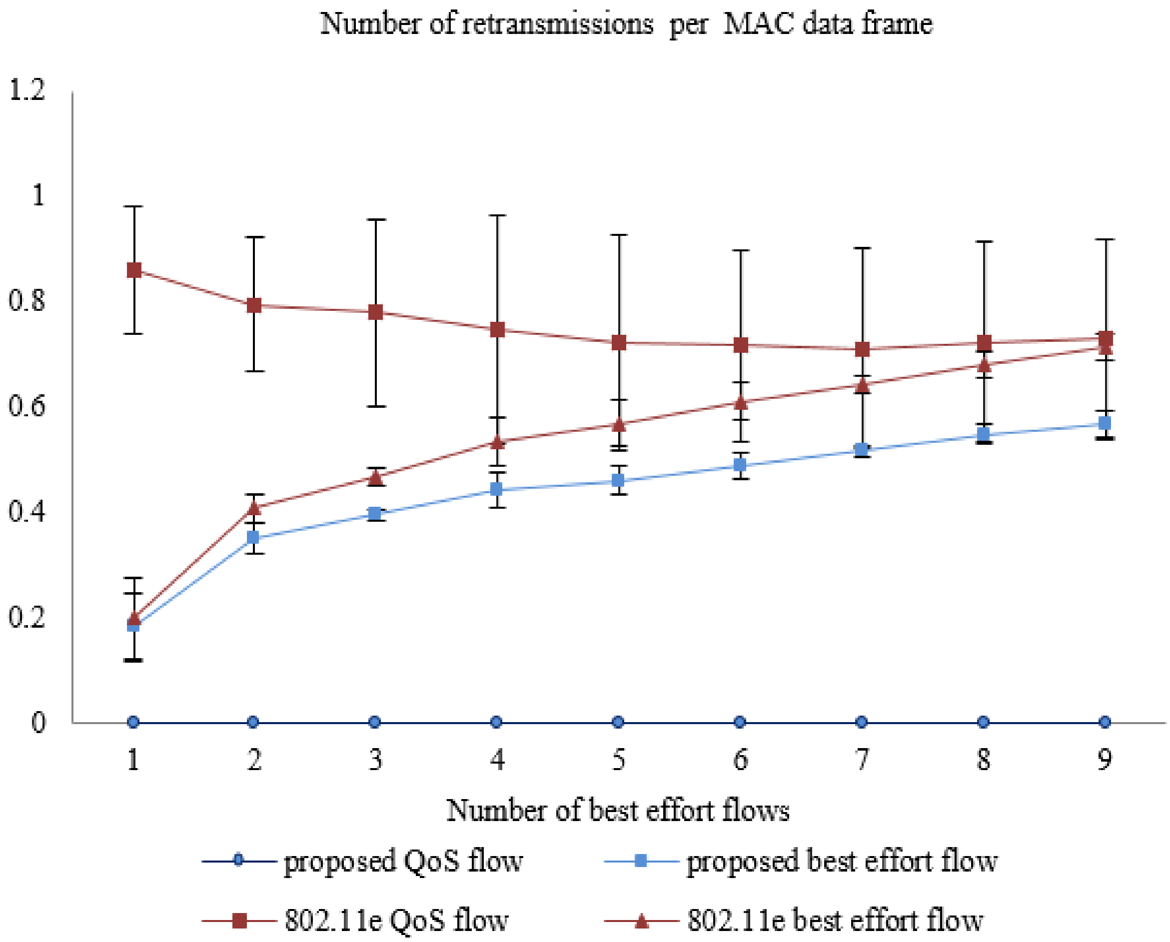

Figure 68 Number of retransmissions per MAC data frame for different number of best effort flows.

Figure 68 shows the number of retransmissions per MAC data frame for different numbers of best effort flows. In the proposed protocol, as the QoS frames can be transmitted successfully in TDMA period, the number of retransmissions per MAC data frame of proposed QoS flows is 0. TDMA period and DCF period support the QoS transmission and the best effort transmission separately, the contentions becomes smaller, thus the number of retransmissions per MAC data frame of proposed best effort flows is smaller than the number of retransmissions per MAC data frame of IEEE 802.11E best effort flows. Although IEEE 802.11e scheme assigns a higher priority for a QoS flow, the number of retransmissions per MAC data frame is high (around 0.7).

4.4.2 Performance for Different Data Rates of QoS Flows

In this simulation, there were five QoS flows (CBR flows) with data rate ranging from 16 Kbps to 1024 Kbps. The number of best effort flows was 5.

Figure 69 shows the average packet delivery rate of QoS flows for different data rates of QoS flows. We can observe that the proposed scheme achieves 100% packet delivery ratio. In the case of IEEE 802.11e scheme, the packet delivery rate drops significantly when the data rate reaches 1024 Kbps.

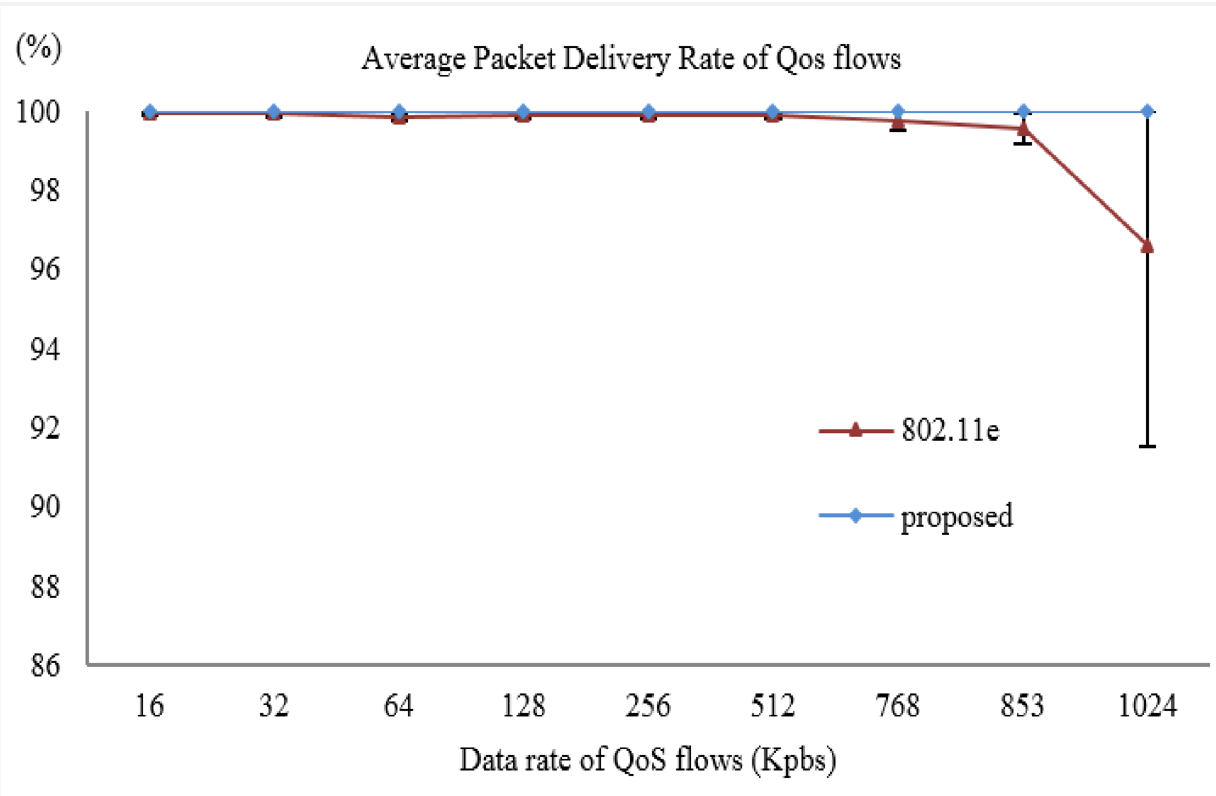

Figure 69 Packet delivery rate of QoS flows for different data rates of QoS flows.

Figure 70 shows the average end-to-end delay of QoS flows for different data rates. For different data rates of QoS flows, the proposed scheme maintains low delay for QoS flows which is an important QoS metric. For IEEE 802.11e scheme, when the data rate of QoS flows is higher than 853 Kbps, the delay of QoS flows becomes large.

IEEE 802.11e scheme shows high packet delivery ratio and small end-to-end delay when the data rate is lower than 853 Kbps (see Figure 69 and Figure 70). However, as mentioned above, when the data rate of QoS flows becomes higher than 853 Kbps, the performance drops due to the high competition among QoS packets.

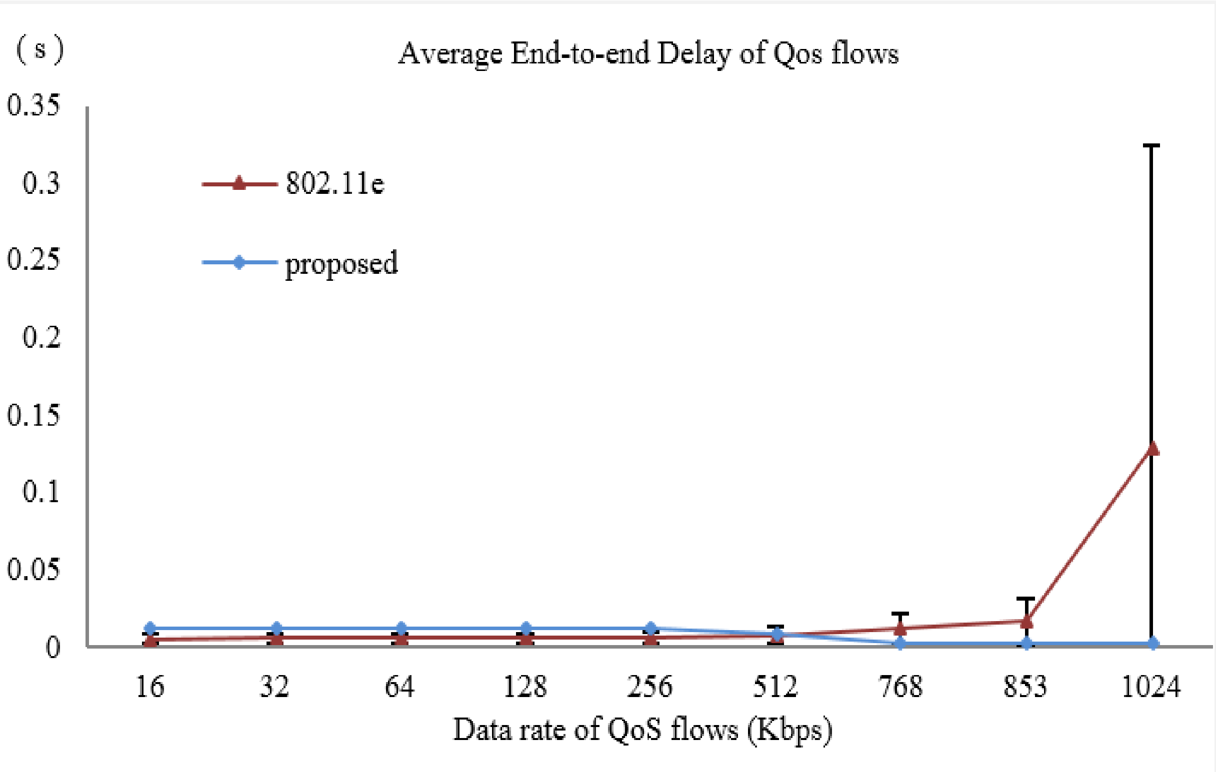

Figure 70 End-to-end delay of QoS flows for different data rates of QoS flows.

In the proposed scheme, when the data rate of QoS flows becomes higher, more time slots are required, thus the TDMA period becomes larger, DCF period becomes smaller accordingly. The performance of the best effort flows (throughput) becomes worse when the data rate of QoS flows increases (see Figure 71). The proposed protocol can provide higher throughput for the best effort flows as compared with IEEE 802.11e. As mentioned in Section 4.3.1, this is because the proposed protocol handles the best effort flows and QoS flows using different periods, which is more efficient in terms of channel utilization. For contention-based channel access (IEEE 802.11e), the channel access efficiency drops significantly with the increase of the number of contending nodes. This is why the throughput of IEEE 802.11e drops significantly when the data rate of QoS flows increases.

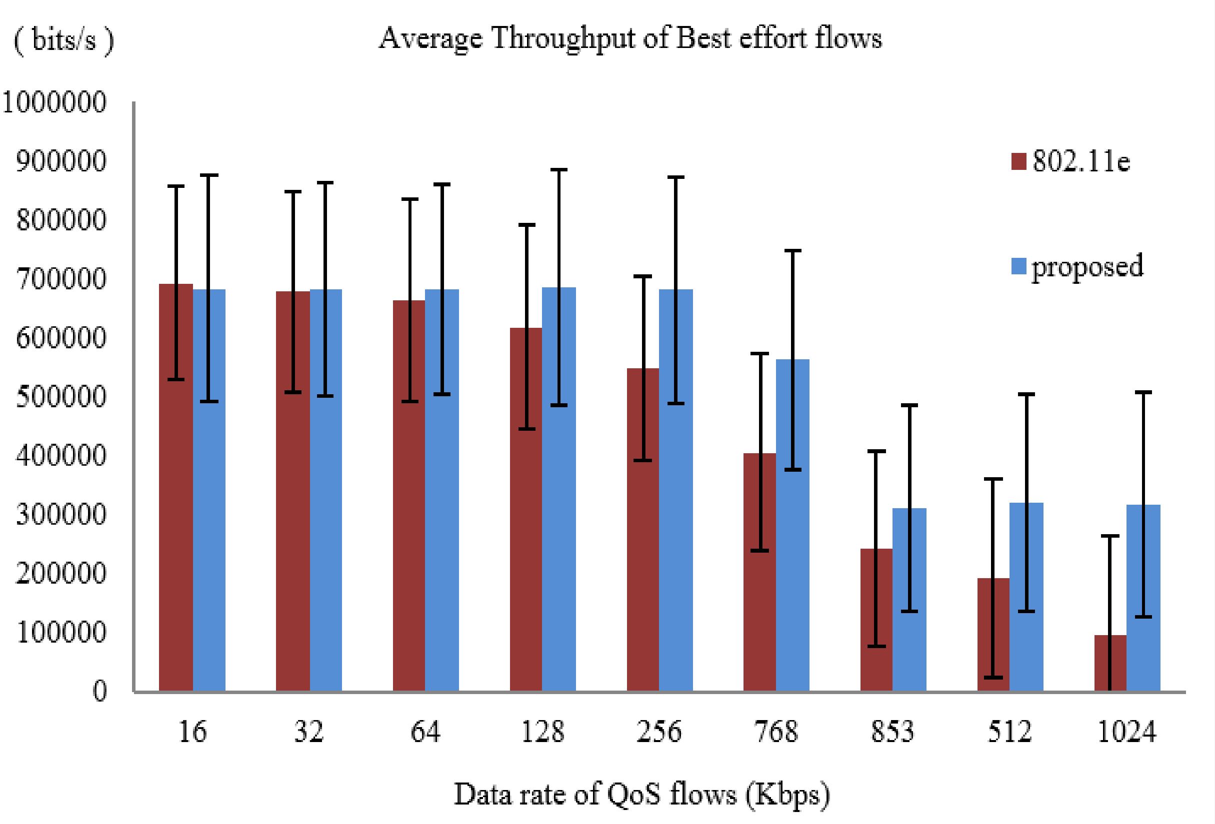

Figure 71 Average throughput of best effort flows for different data rates of QoS flows.

Figure 72 shows the number of retransmissions per data frame for various data rates of QoS flows. The number of QoS retransmissions is 0 in the proposed protocol. For IEEE 802.11e scheme, the number of QoS retransmissions rate increases drastically with the QoS data rate which is the same as Simulation II, the reason is packet collisions occur among QoS data packets in the 802.11e scheme. By using the TDMA/DCF division method, the best effort data packets are transmitted in an independent period (DCF period), the number of retransmissions for the proposed scheme is smaller than IEEE 802.11e. The simulation results show that the TDMA/DCF hybrid method in the proposed scheme can provide better performance for both QoS flows and best effort flows as compared with IEEE 802.11e scheme.

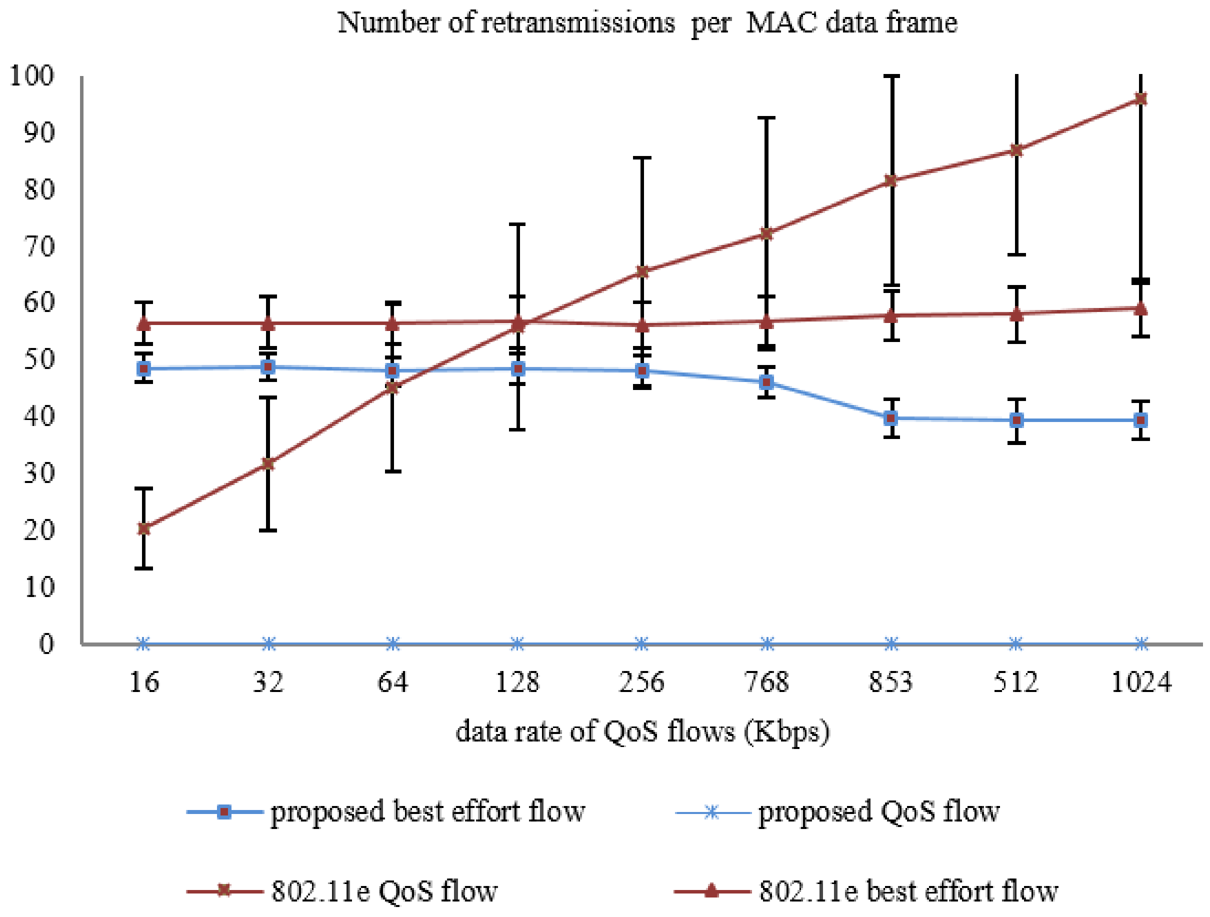

Figure 72 The number of retransmissions per MAC data frame for different data rates of QoS flows.

4.4.3 Performance for Different number of QoS flows.

In this simulation, the number of QoS flows was increased from 1 to 9 when the number of best effort flows was 5, and the data rate of the QoS flows was set to 512 Kbps.

Figure 73 shows the average packet delivery ratio of QoS flows for a different number of QoS flows. In the figure, the packet delivery ratio for the proposed scheme is 100% for various numbers of QoS flows. For IEEE 802.11e scheme, the packet delivery rate of QoS flows is nearly 100% when the number of QoS flows is less than 5. However, when the number of QoS flows is more than 5, the packet delivery rate of QoS flows for IEEE 802.11e gradually becomes lower (around 95% when the number of QoS flows is 9.

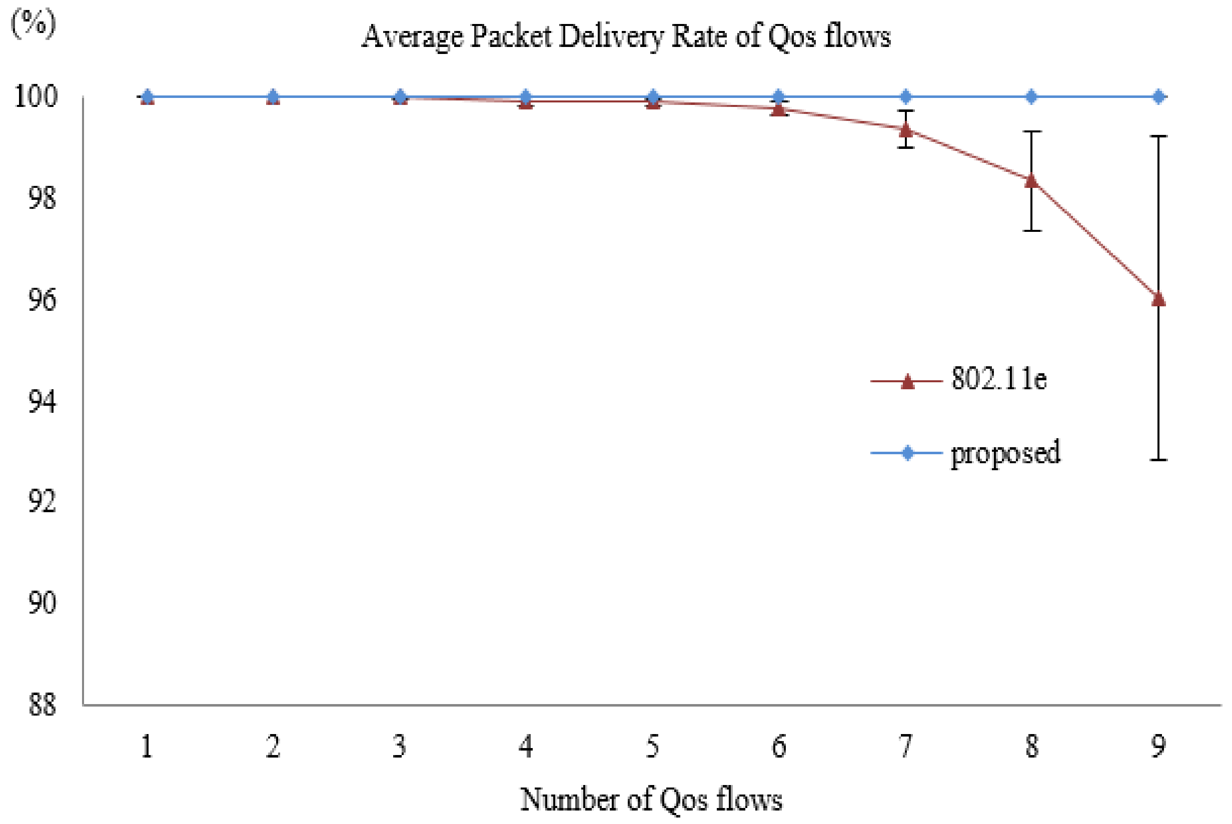

Figure 73 Average packet delivery rate for different number of best effort flows.

In the proposed scheme, time slots are reserved for individual QoS packets, thus even when the number of QoS flows increases, the proposed scheme maintains high packet delivery rate. For the IEEE 802.11e scheme, as the packet collisions becomes intense when the number of QoS flows increases, the packet delivery rate decreases when the number of QoS flows is more than 5. For the same reason, we can find in Figure 74 the average end-to-end delay of QoS flows becomes high when the number of QoS flows is more than 6.

In Figure 74, the proposed scheme maintain small delay for QoS flows even when the number of QoS flows increases.

Through analysis of the packet delivery rate and the end-to-end delay of QoS flows, we can conclude that the proposed scheme maintains better performance than IEEE 802.11e for different numbers of QoS flows.

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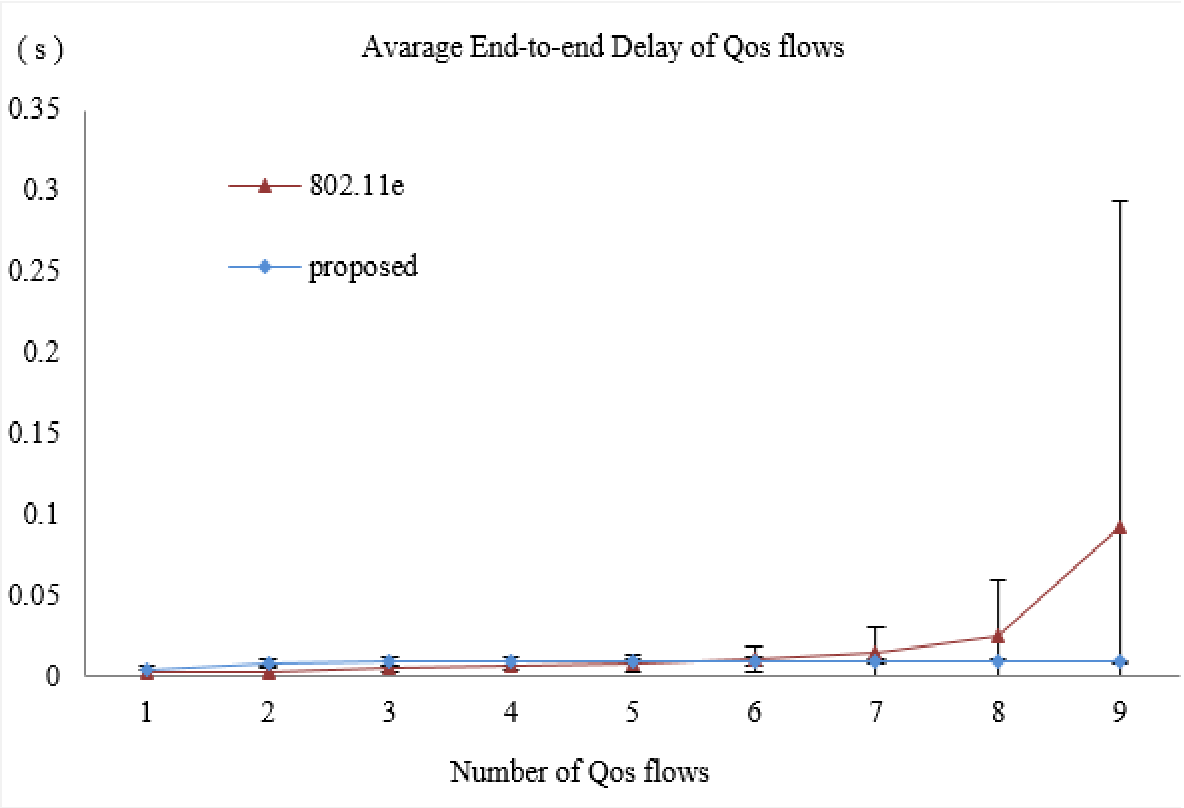

Figure 74 Average end-to-end delay of QoS flows for different number of best effort flows.

Figure 75 shows the average throughput of the best effort flows for a different numbers of QoS flows. As mentioned in 4.4.2, in the proposed scheme, DCF period is decided by TDMA period, when the number of QoS flows increases the TDMA period becomes bigger, the DCF period becomes smaller, thus the throughput of best effort flows decreases in the figure. Since the competitions between best effort flows and QoS flows have been avoided, the throughput of best effort flows for the proposed scheme is better than IEEE 802.11e scheme.

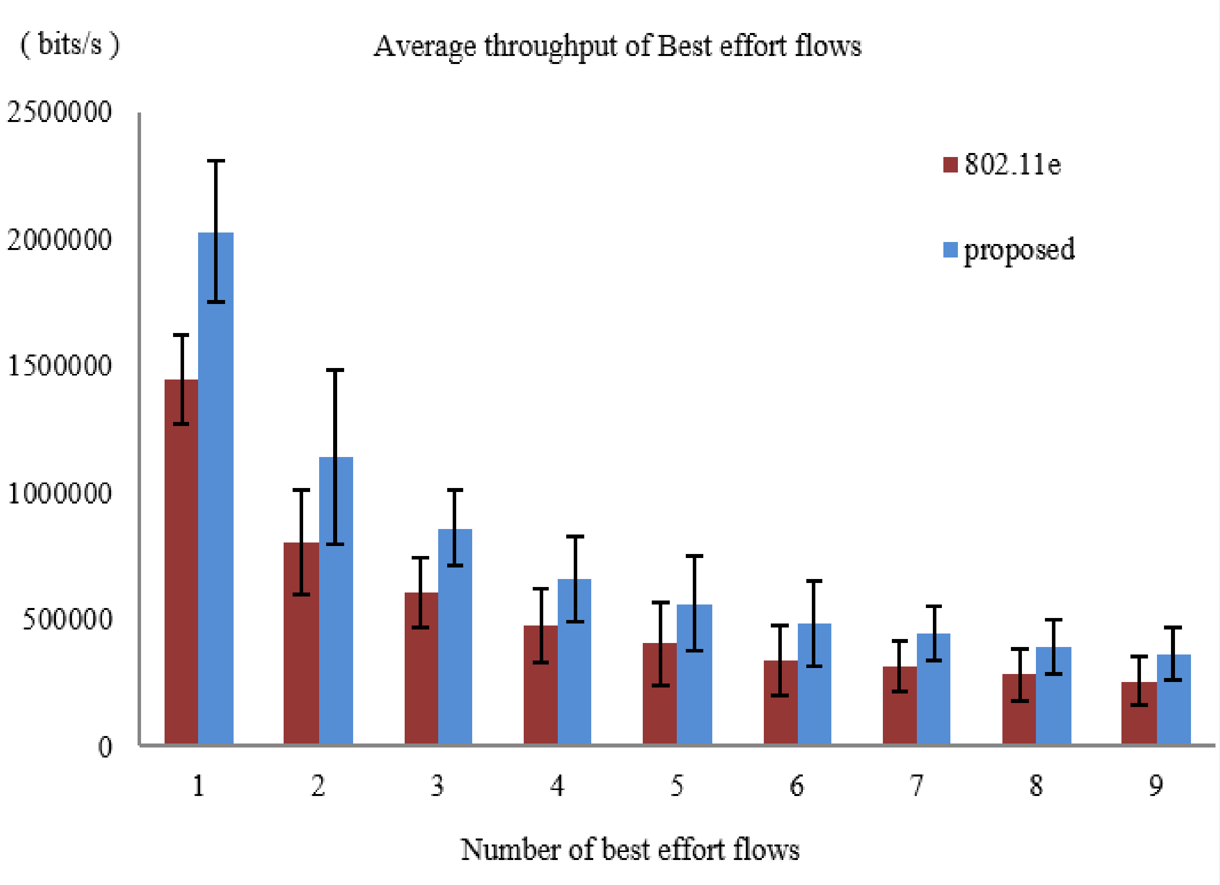

Figure 75 Average throughput of best effort flows for different number of best effort flows.

Figure 76 shows the number of retransmissions per MAC data frame for different numbers of QoS flows. In the proposed protocol, as the QoS frames can be transmitted successfully in TDMA period, the number of retransmissions per MAC data frame of proposed QoS flows is 0. TDMA period and DCF period support the QoS transmission and the best effort transmission separately, the contentions becomes smaller, thus the number of retransmissions per MAC data frame of proposed best effort flows is smaller than the number of retransmissions per MAC data frame of IEEE 802.11E best effort flows.

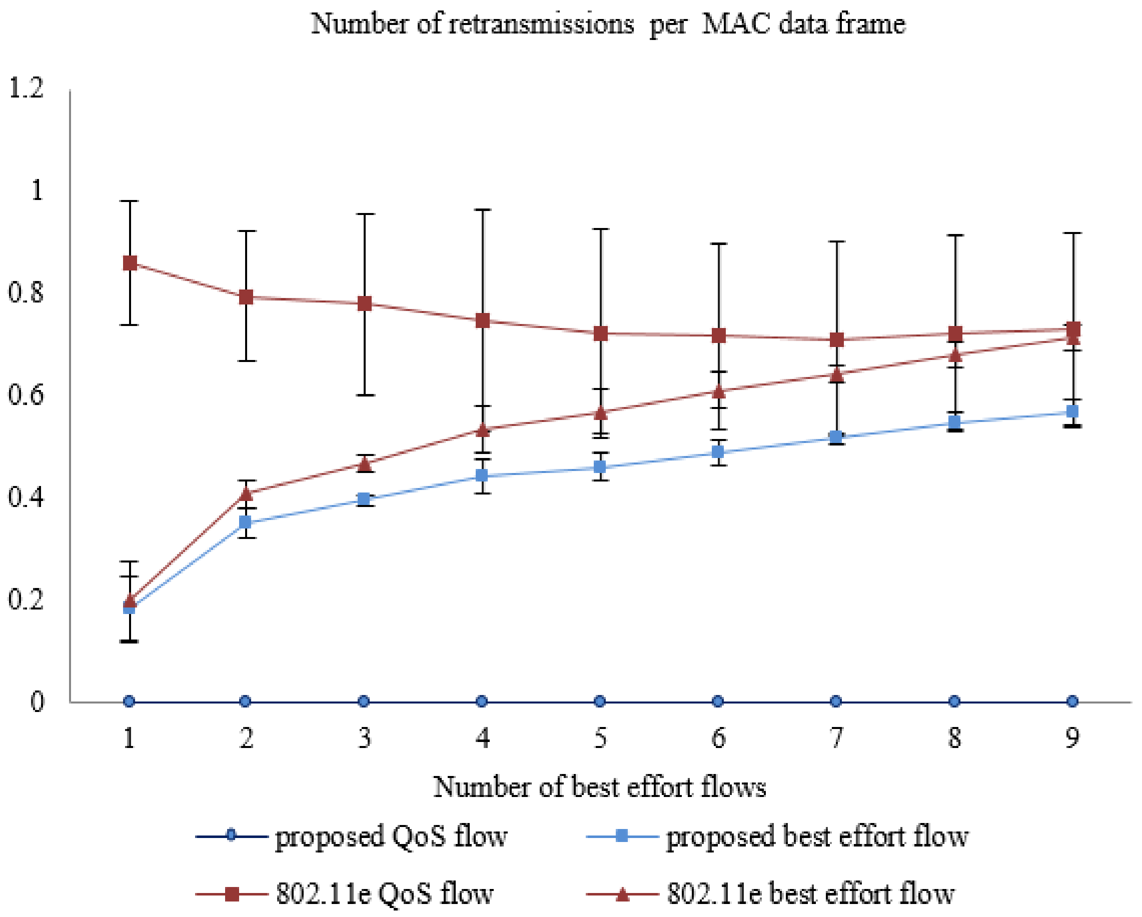

Figure 76 Number of retransmissions per MAC data frame for different number of best effort flows.

5. EXTENSION OF THE PROPOSED METHOD IN MOBILE ENVIRONMENT

5.1 Introduction

Wireless ad hoc networks can be employed anytime, anywhere without any fixed infrastructure. As mentioned in Section 1.1.2, the mobile ad hoc network has many application environments. Among these application environments, VANET (Vehicular Ad hoc Network) use travelling vehicle as mobile nodes which have higher mobility. A scenario with higher mobility will not be discussed in this thesis because it is difficult to provide a high QoS for multi-hop ad hoc communication. The proposed approach mainly focuses on supporting QoS for the following scenarios.

1. The scenarios in which the nodes are immobile.

For example, in the wireless sensor network, the proposed QoS approach can be used for transmitting some real time data such as measurement data for the weather forecast. The ad hoc network can also be used to deploy a surveillance camera system for the place such as a car park, historic sites or a museum where is difficult to deploy a wired system [39] (Figure 77). In such scenarios, where the mobility does not exist, the proposed QoS approach can be used directly as all the nodes are preconfigured and the topology of the network does not change after the system start working.

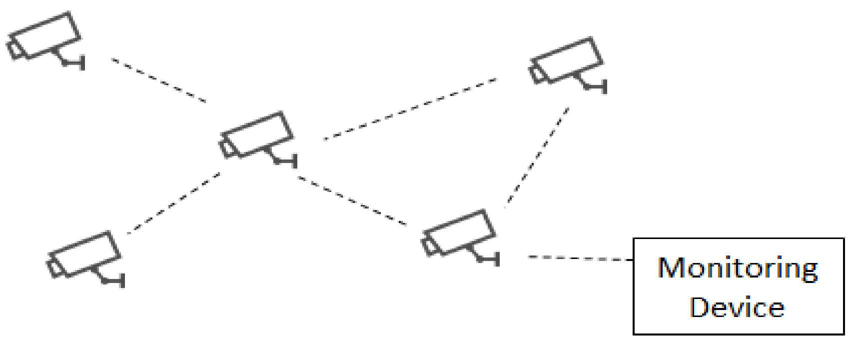

Figure 77 An ad hoc surveillance camera system.

2. The scenarios that the nodes move using the speed of pedestrian.

The ad hoc communication system for construction site is an application scenario. The ad hoc communication system can be easily and quickly set up among the construction workers without fixed infrastructure. The similar system can also be applied to the place such as a golf center, a stadium, a theme park, a meeting room and university. In all these places, a communication device held by person is treated as a node in the ad hoc networks. In these environments, pedestrians are the fundamental basis for the node mobility. The mobile ad hoc networks are also gaining effort with different kinds of applications in these scenarios. With the popularity of the smart devices, ad hoc network has received more and more attention, supporting QoS (Quality of Service) in ad hoc network has become inevitable. Due to the uncertainty of human movement, the network topology may change in these scenarios. As shown in Figure 78, when node A moves out of the transmission range of node S, some links disappear from the network. The new topology is formed and the new route between node D and node S is established.

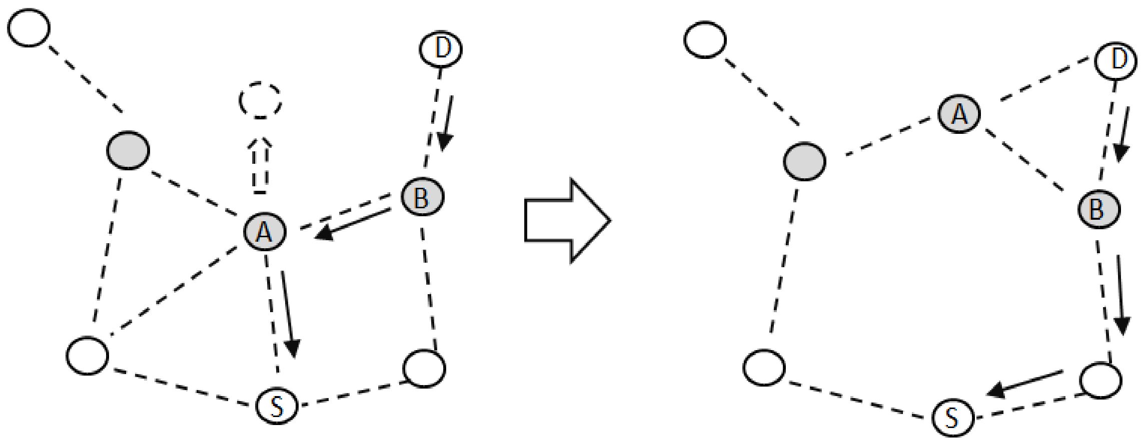

Figure 78 An Example of Topology Change.

The QoS approach proposed in Chapter 3 does not address the issue for the scenarios in which the node mobility exists. In this Chapter, an extension of the proposed approach is provided which is targeted at a mobile ad hoc network where the node mobility is equal to or lower than 5 Km/h, which is the range for plausible moving speed of pedestrians. As the distance between two nodes also changes, the transmission rate changes. The setting for the changing transmission is discussed in Section 5.2. The solutions for the topology change are provided in Section 5.3.

5.2 Setting of Proposed Method in Mobile Environment

The wireless medium is highly volatile due to its characteristic such as fading, attenuation, especially the mobility of nodes. To achieve a high performance under varying conditions such as the change of inter-node distance, the nodes need to adapt their transmission rate dynamically. In the physical layer of IEEE 802.11a/g is based on OFDM (Orthogonal Frequency Division Multiplexing) technology, there exist eight types of transmission rates for selection (up to 54 Mbps as shown in Table 12).

Table 12 Transmission Rate in IEEE 802.11a/g

Tx rate (Mbps)	Modulation	Code Rate
6	BPSK	1/2
9	BPSK	3/4
12	QPSK	1/2
18	QPSK	3/4
24	16-QAM	1/2
36	16-QAM	3/4
48	64-QAM	2/3
54	64-QAM	3/4

.

In the mobility environment, the ARF (auto rate fallback) is supposed to be used in the physical layer. ARF [40] is the first commercial implementation that exploits multi-rate capability. The basic principle of ARF is that the node uses the status of previously transmitted packets to select transmission rates for the next frame. Once a node successfully transmits frame after a certain number of times, the node will select a higher transmission rate for the next frame. On the other hand, if the node fails twice in transmission, the node will select a lower transmission rate for the next frame. The node changes the transmission rate to the previous one immediately if the transmission is unsuccessful after raising the transmission rate.

The ARF shows a high performance when the mobility of the network is not high. The application environment of ARF is consistent with the application environment of the proposed approach. When the ARF mechanism is adopted, the length of a time slot equals to the transmission time when a data frame is sent at the lowest transmission rate.

When the ARF is enabled in IEEE 802.11a, the lowest transmission rate (6 Mbps) is selected for computing the length of a time slot. As mentioned in Section 3.2.3, the length of a time slot indicates the transmission time of a QoS packet. The transmission time of a QoS data frame in the lowest transmission rate is the longest. Since the length of a time slot for 6 Mbps is longer than the time slot for 54 Mbps, the total number of the time slots in a unit time becomes smaller when the lowest transmission rate is selected. The Simulation Ⅰ (Subsection 4.2) shows that the proposed approach is also effective in the transmission rate of 6 Mbps. Therefore, when the proposed approach is applied in a mobility environment, the setting of ARF should be available and the length of the time slot in TDMA period should be set according to the lowest transmission rate of the physical layer.

5.3 Solutions for Topology Changes

When the ARF is enabled, a pair of nodes can communicate at a low data rate at a long distance. If the effective communication distance is long, the link will not be easily broken by the node mobility. In a mobile ad hoc network, the cost for probing a new route is high for both proactive and reactive routing protocols. Therefore, we propose to use ARF in the mobile environment, so as to minimize the frequency of topology changes.

The route may changes in the mobile environment, even ARF is enabled. In this situation, the new time slots need to be assigned along the new QoS route. When the MPR node detects the route of a QoS flow needs to be updated, the MPR node sends a QSYN message containing the ID of the QoS flow. All the time slots for the QoS flow are released after the nodes receive the QSYN message. After reception of the QSYN message, if necessary, the source node of the QoS flow sends the QREQ along the new path to request the new time slots for transmission according to the time slot reservation policies as mentioned in Section 3.4.

When a new node joins the network, it firstly waits for the clock synchronization. After clock synchronization, the new node can know the start time for a frame cycle. Then the new node sets the DCF period to the minimum size so that it would not violate the current communication in the network as shown in Figure 79. By using the DCF period with the minimum size, the new node informs the attendance to the MPR node and waits for the QSYN message for the MPR node. The MPR node sends the new node a QSYN message which includes all the current information of time slots in the TDMA period. The new node changes the sizes of DCF period and TDMA period according to the QSYN message. After this, the new node can start transmitting either best effort data or QoS data to the other nodes in the network.

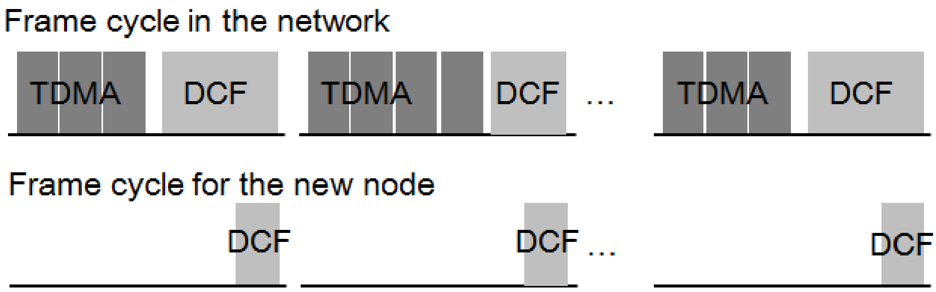

Figure 79 Setting of frame at new node.

5.4 Simulation

Table 13 Simulation Condition Ⅲ.

Simulator	QualNet 6.1
Simulation time	120 s
PHY	IEEE 802.11g (ARF)
Routing protocol	OLSR
Mac protocol	Proposed, IEEE 802.11e, TDMA
Interference range	580 m
Traffic types	TCP (best effort), CBR (QoS)

We also evaluated the proposed scheme in the mobile environment. The simulation condition is shown in Table 13, which is similar to simulation Ⅱ in Section 4.3. In the simulation, 50 nodes are uniformly deployed in a square area (1100 m × 1100 m). An example of simulation topology is shown in Figure 80. The physical layer was using IEEE 802.11g, and the ARF mechanism was enable in this simulation. Since the lowest data rate of IEEE 802.11g is 6 Mbps, the time required to transmit a data frame (i.e., when the application data packet size is 512 bytes) was around 800 μs. The size of a time slot was set to 800 μs. The size of every time frame was set to 4 ms which includes 1 μs inter-frame time in the head of the frame. Therefore, the maximum achievable data rate was 1024 Kbps for the QoS flows with a packet size of 512 bytes. The length of frame cycle is set to 4 in the simulation.

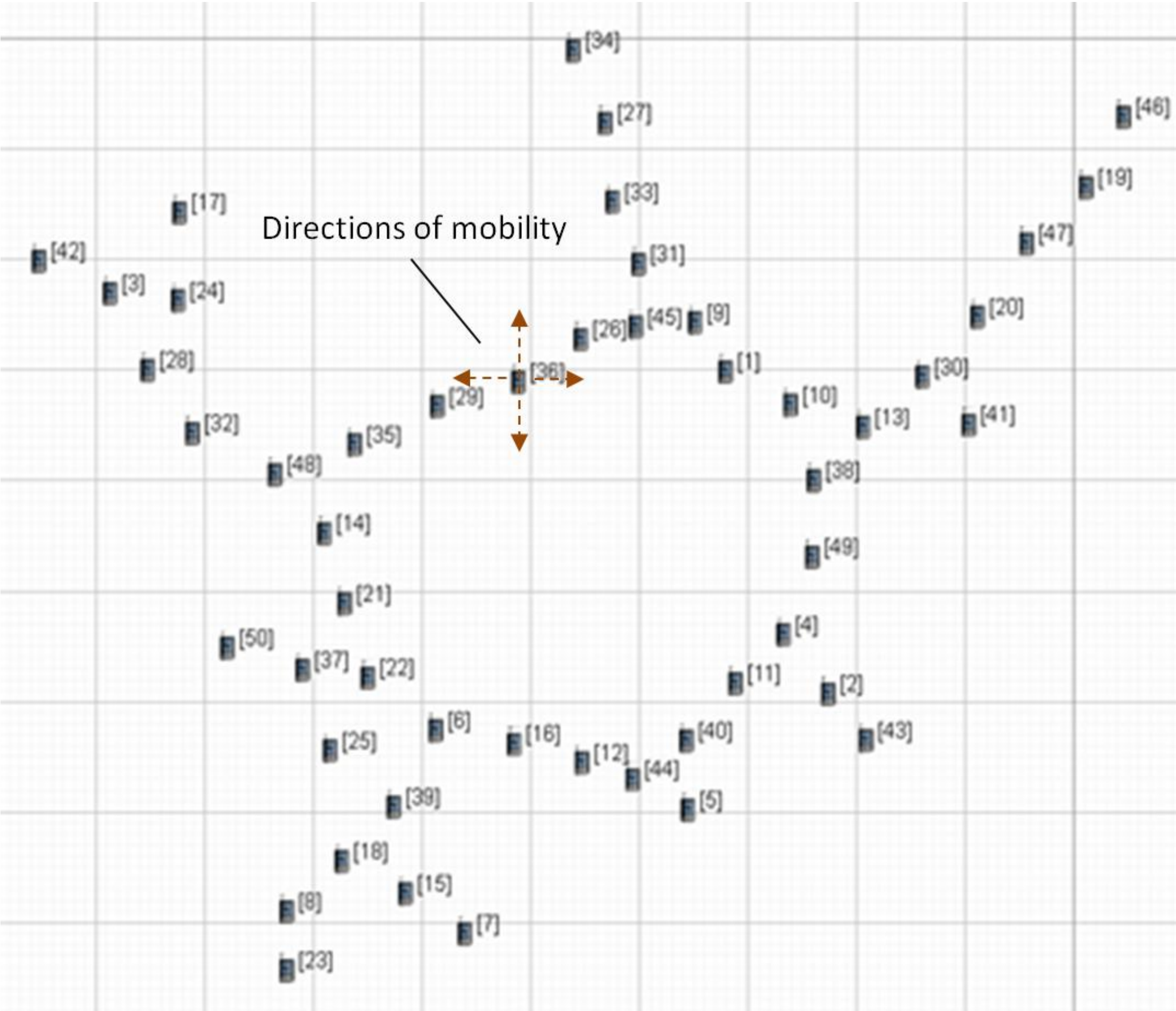

Figure 80 An example of simulation topology.

Two types of data traffic, specifically CBR flows and TCP flows were simulated. All flows were randomly generated. The CBR flows were considered as QoS flows, and TCP flows were used as best effort flows. The packet size of CBR flows was 512 bytes. TCP flows started at the beginning of the simulation and CBR flows started 4 ms later. Both TCP flows and CBR flows stopped transmitting a new packet at 110 s. The route length for every flow was between 2 hops and 5 hops. The control messages of OLSR protocol are exchanged periodically in the simulation. In the proposed scheme, the messages of admission control mechanism were also simulated. In the simulation results, each value is the average of eighteen simulation runs. The error bars of the figures indicate the 95% confidence intervals.

The proposed scheme was compared with IEEE 802.11e and pure TDMA. There were 3 QoS flows (256 Kbps) and 5 TCP flows in this simulation.

Figure 81 shows the average packet delivery rate of QoS flows in the mobile environment. Since ARF is enabled, the node movement incurs a change of transmission rate frequently. We can observe that the proposed scheme shows the highest packet delivery rate of QoS flows even when the moving speed becomes higher. The reason is that the time slot allocation is strictly based on the position information and the data rate of QoS flows, and therefore each QoS packet can be transmitted in an independent time slot in TDMA period. Since the TDMA time slot is set based on the lowest possible transmission rate (6 Mbps), the proposed protocol can work well in a mobile environment. This also explains why the proposed scheme shows lower average end-to-end delay in Figure 82.

For IEEE 802.11e scheme, when the node mobility does not exist, the average packet delivery rate is around 95%. When the moving speed increases, the average packet delivery rate drops to 72%. This is due to the increase of a number of retransmissions per MAC data frame as shown in Figure 84 (QoS flows and best effort flows compete for the wireless resources, and the competition result will become worse when the transmission rate decreases due to the mobility). This is the reason why the average packet delivery ratio of IEEE 802.11e scheme becomes lower when the mobility exists.

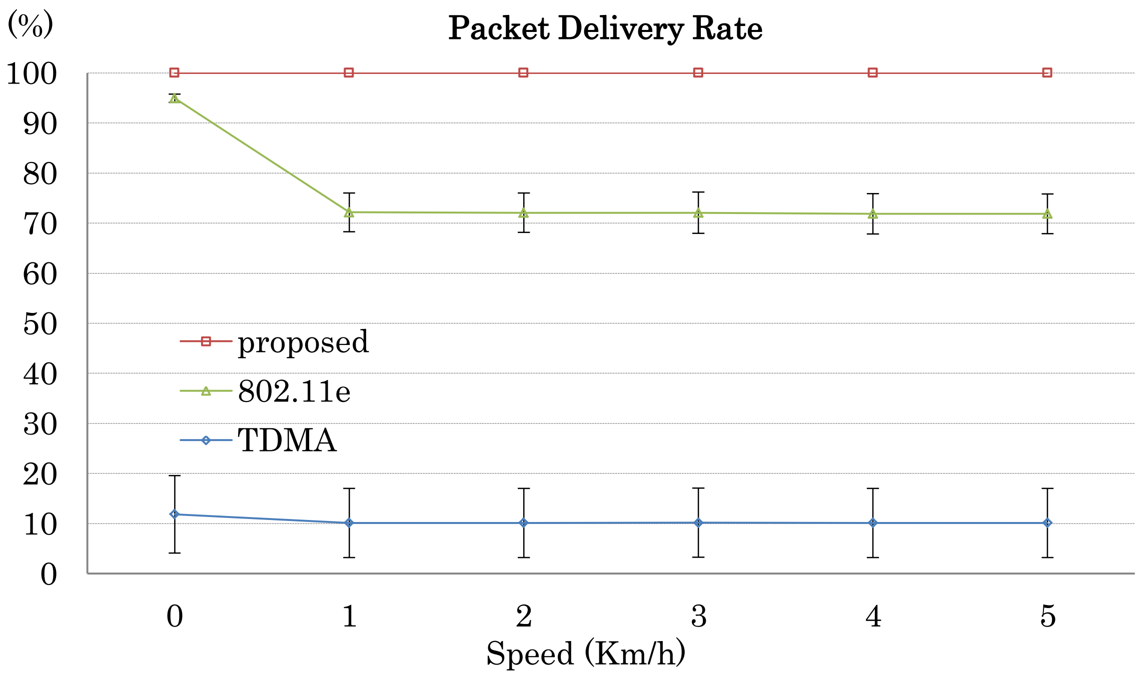

Figure 81 Average packet delivery rate of QoS flows in mobile environment.

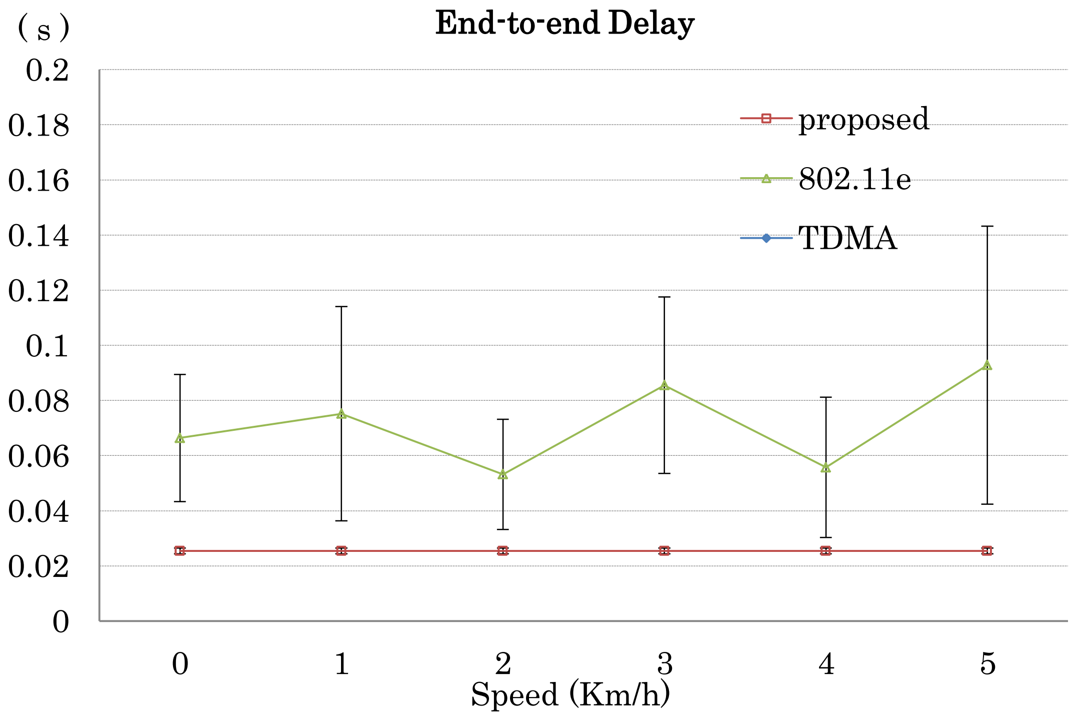

Figure 82 Average end-to-end delay of QoS flows in mobile environment.

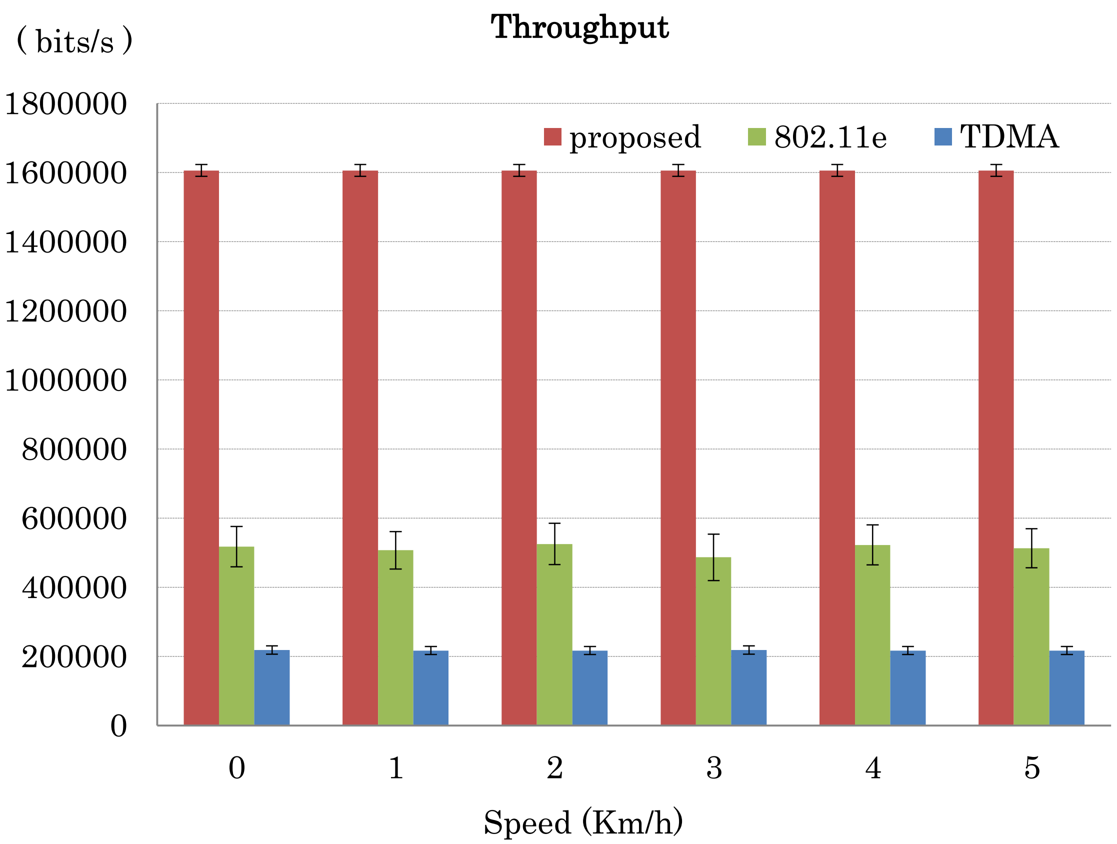

Figure 83 Average throughput of Best effort flows in mobile environment.

For the pure TDMA scheme, the performance of QoS flows becomes extremely worse. This is because the length of the time slot becomes larger in this simulation, and thus the number of time slots in a time unit becomes smaller than the previous simulations. The best effort flows occupy most time slots that make network resources even scarcer. Therefore, the time slots for QoS flows are inadequate, and the QoS performance of the pure TMDA is low (the average packet delivery rate is around 10% as shown in Figure 81; the average end-to-end delay of QoS flows is around 43 s, which is not shown in Figure 82).

Figure 83 shows the average throughput of best effort flows in the mobile environment. The proposed scheme shows the highest performance. Since the number of the best effort flows is 3, which is less than previous simulations, the throughput of the best effort flows is higher than the result of 256 Kbps in Fig. 18.

Figure 84 shows the number of retransmissions per MAC data frame in the mobile environment. Since no retransmissions exist in TDMA methods, the QoS flows in the proposed scheme, the QoS flows and the best effort flows in the pure TDMA scheme show zero retransmissions in Figure 84.

The simulation results show that the proposed scheme can also provide a better performance in the mobile environment with the maximum moving speed of 5 Km/h as compared with IEEE 802.11e and the pure TDMA method.

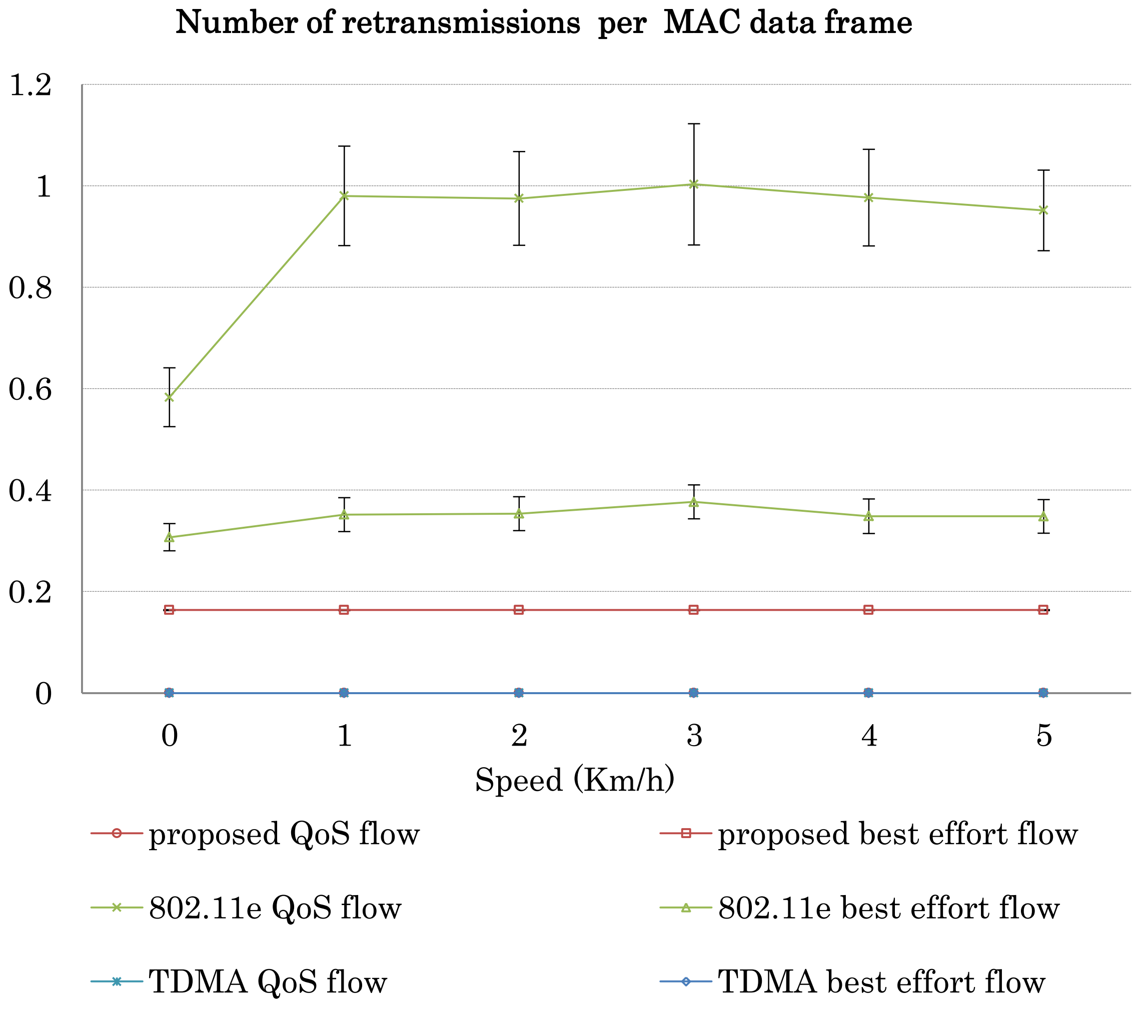

Figure 84 The number of retransmissions per MAC data frame in mobile environment.

5.5 Discussion

The simulations in Section 5.4 only considered the mobile environment using ARF but without considering the other factors such as route changes. The challenges and problems for the application of the proposed scheme in the mobile environment are discussed in this section.

In the mobile environment, the network topology is dynamic changing. Since it is difficult to provide a high QoS for multi-hop ad hoc communication in a scenario with high mobility, the proposed scheme is better suited to work in a scenario where the node mobility is equal to or lower than 5 Km/h. Even in the network with low mobility, a route path may break or change when it is in use. When the route changes, the time slots for the old path are released and the new time slots are assigned to the new path. Packet loss occurs in this situation, and there is a delay when the QoS flow waits for the new time slots to be allocated. The size of the delay directly affects the QoS performance. As the QSYN messages are disseminated through the whole network, the larger the network size, the greater the delay caused by time slot reallocation. The recommended scenario for the proposed scheme is with a low node density.

In a scenario with low mobility (less than 5 Km/h), the introduction of ARF would reduce the route changes and let network be in a relatively stable state, so that the proposed scheme would work better. In this situation, as the size of the time slot is decided by the lowest transmission rate of physical layer, the time slot with a bigger size is using. When the transmission rate is large, some bandwidth is not used effectively because the time slot is extravagant. Therefore, in a mobile environment, the QoS capacity of proposed scheme becomes small.

6. CONCLUSION AND FUTURE WORK

6.1 Conclusion

This thesis has discussed the methods for supporting QoS in mobile ad hoc networks. In order to transfer QoS data in a wireless ad hoc network, a priority approach, IEEE 802.11e has been specified. It provides higher priorities for QoS frames by using smaller contention window size. However, this approach gives the prioritization only to one hop environment, and so, if it is applied in a multi-hop environment, it is possible that high priority packets to be forwarded make collisions in adjacent hops. This collision may drop the efficiency significantly when the total rate of QoS flow increases.

In this thesis, a scheme has been proposed for supporting QoS in ad hoc networks. The scheme divides the channel time into two periods, specifically TDMA period and DCF period, which handle QoS traffic and best effort traffic, respectively. The two periods are dynamically changed according to the network condition. The proposed scheme provides strict bandwidth guarantee for QoS flows by using the TDMA period, and an admission control mechanism. A dynamic time slot allocation mechanism has been proposed, where frame cycle and frame size are determined based on the QoS data rate. Since the time slot is reserved for each QoS packet, the collisions among QoS packets are avoided. By using the admission control mechanism, the QoS data can be transmitted within the capacity of the network. Therefore, the proposed scheme can achieve the required quality of service in ad hoc networks.

The proposed scheme was implemented in QualNet simulator. The proposed scheme is compared with the IEEE 802.11e and the pure TDMA method under different traffic conditions. The simulation results showed that the proposed scheme could guarantee the QoS communication without giving a large impact on best effort communication.

The proposed scheme has been extended to the mobility environment with the moving speed of a pedestrian. To achieve a high performance under the mobility environment, ARF mechanism is adopted. The length of the time slot is set according to the lowest transmission rate of the physical layer. The MPR nodes release the time slots when the change of QoS route is detected. The operation for a new node adding to the network is also designed. The simulation in the mobility environment showed the extension of the proposed scheme can also provide strict priority for QoS.

6.2 Future works

Although plenty of works have been done for providing QoS in ad hoc networks, there is still a lot of unsolved issues. To support QoS in ad hoc network more efficient and reliable, future works will consider the following issues.

1. Estimation the link quality is very important to develop an efficient and reliable QoS solution. When the time slots are assigned to the QoS nodes, the link quality should be considered. The proposed approach is currently assigning the time slots without considering the link quality. A more realistic physical layer model will be considered in the future.

2. Future work on an accurate admission control should be considered. The reserved bandwidth should be adequate for the QoS traffics. A new QoS flow should not violate the previously made guarantees. Therefore, admission control is important for providing QoS assurance. The admission control in the proposed approach only focuses on the number of the time slots. In the future work, an accurate admission control for ad hoc networks considering mobility and link status will be considered.

3. QoS multicast method should be considered in the future work. More and more applications will be transferred over ad hoc networks. Not all of these applications are sent to only one destination. For example, in the stadium, the ad hoc network is used for sending the real time video to multiple viewers. In this situation, a QoS multicast protocol is necessary. In the future work, TDMA-based QoS multicast protocol will be proposed for ad hoc networks.

4. This thesis has proposed an efficient QoS approach mainly focus on the MAC layer. But supporting QoS should consider different layers. Especially, the collaboration of physical layer, network layer and MAC layer is very important for supporting QoS. It might be interesting if a cross layer method is proposed in the future work.

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LIST OF ABBREVIATIONS

MANET:	Mobile Ad Hoc Network
BAN	Body Area Networks
VANETs:	Vehicular Ad Hoc Networks
IOT:	Internet of Things
IETF:	Internet Engineering Task Force
MANET WG:	Mobile Ad Hoc Network Working Group
QoS:	Quality of Service
MAC:	Media Access Control
TDMA:	Time Division Multiple Access
DCF:	Distributed Coordination Function
DFM:	Dynamic Function Mapping
DT:	Dynamic Traffic
CW:	Contention Window
AIFS:	Arbitration Inter-Frame Spacing
CACP:	Contention-aware Admission Control Protocol
AODV:	Ad hoc On-demand Distance Vector
TXOP:	Transmit Opportunity
EDCA:	Enhanced Distributed Channel Access
HCCA:	Controlled Channel Access
ARF:	Auto Rate Fallback
OLSR:	Optimized Link State Routing Protocol
PHY:	Physical Layer
CSMA/CA:	Carrier Sense Multiple Access/Collision avoidance
PCF:	Point Coordination Function
CA:	Collision Avoidance
IFS:	Inter-frame Spacing
DIFS:	Distributed Inter-frame Spacing
CTS:	Clear To Send
PIFS:	Point Inter Frame Space
NAV:	Network Allocation Vector
CP:	Contention Period
CFP:	Contention-Free Period
PC:	Point Coordinator

AP:	Access Point
P2P:	Peer to Peer
ACK:	Acknowledgement
AC:	Access Category
QSTA:	QoS Station
AIFS:	Arbitration Inter-Frame Space
QAP:	QoS Wireless Access Point
TSPEC:	Traffic Specification
DSRP:	Distributed Slot Reservation Protocol
ASAP/SM:	Adaptive Slot Assignment Protocol with Slot Migration
RREQ:	Route Request
RREP:	Route Reply
DSR:	Dynamic Source Routing
MPR:	Multipoint Relay
VoIP:	Voice over IP
ITU:	International Telecommunication Union
UDP:	User Datagram Protocol
TCP:	Transmission Control Protocol
PLCP:	Physical Layer Convergence Protocol
GPS:	Global Positioning System
QREQ:	QoS Request
QREP:	QoS Reply
QSYN:	QoS Synchronization
QREJ:	QoS Reject
CBR:	Constant Bit Rate
TI:	Transmission Interval
FIFO:	First In, First Out)
FCS:	Frame Check Sequence

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LIST OF PUBLICATIONS RELATED TO THE THESIS

Journal Paper

Jing Lin, Celimuge Wu, Satoshi Ohzahata, and Toshihiko Kato, "A TDMA/DCF Hybrid QoS Scheme for Ad Hoc Networks," IEICE Transactions on Communications, Vol.E100-B,No.01,pp.-,Jan. 2017.

(Related to the content of Chaper3, Chapter4, and Chapter5)

International Conference

[1] Jing Lin, Celimuge Wu, Satoshi Ohzahata, and Toshihiko Kato, "A QoS supporting ad hoc network protocol combining admission based TDMA and 802.11 DCF," Network Operations and Management Symposium (APNOMS), 2014 16th Asia-Pacific, Hsinchu, 2014, pp. 1-4.

(Related to the content of Chaper3 and Chapter4)

[2] Jing Lin, Celimuge Wu, Satoshi Ohzahata, and Toshihiko Kato, "Performance evaluation of time slot based QoS aware ad hoc network scheme for CBR and TCP flows," Network Operations and Management Symposium (APNOMS), 2015 17th Asia-Pacific, Busan, 2015, pp. 139-144.

(Related to the content of Chaper3 and Chapter4)

Workshop

[1] Jing Lin, Celimuge Wu, Satoshi Ohzahata, and Toshihiko Kato, "[Poster Presentation] A Study on QoS Support in Ad Hoc Networks Using TDMA and 802.11 DCF," IEICE Technical Report, CQ2014-19, pp.25-30, (2014.7).

[2] Jing Lin, Celimuge Wu, Satoshi Ohzahata, Toshihiko Kato, "Performance Evaluation of QoS Supporting Ad Hoc Scheme Combing TDMA and 802.11 DCF," IEICE Technical Report Vol.114 No.404, CQ2014-92, pp.35-40, Jan. 2015.

[3] Jing Lin, Celimuge Wu, Satoshi Ohzahata, and Toshihiko Kato, "An Efficient Time Slot Allocation Scheme for QoS flows in Ad Hoc Networks," IEICE Tech. Rep., vol. 115, no. 95, IN2015-19, pp. 43-48, June 2015.

[4] Jing Lin, Celimuge Wu, Satoshi Ohzahata, and Toshihiko Kato, “Performance comparison between a hybrid DCF/TDMA QoS scheme and the pure TDMA approach,” IEICE Tech. Rep., vol. 115, no. 408, CQ2015-95, pp. 13-18, Jan. 2016.