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Research Article

A Scalable MAC Protocol Supporting Simple Multimedia Traffic QoS in WSNs

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Abstract
Wireless sensor networks (WSNs) are a vibrant research field for the last several years. Especially, design of MAC protocols supporting multimedia traffic QoS is recent challenging work. However, the mechanisms of protocols that can guarantee multimedia traffic QoS have several problems in multihop wireless sensor networks. There are a lot of reasons, including limited end-to-end delay and high throughput. In this paper, we propose ascalable MAC protocol that guarantees multimedia traffic, still images, and scalar sensor data QoS in multi-hop wireless sensor networks. The MAC protocol has made it possible to transmit multimedia streaming traffic without a great change of the end-to-end delay for a specific time. And if there are the some link failures in multi-hop transmission, the protocol can recover the links quickly. Using this algorithm, the proposed MAC protocol outperforms the IEEE 802.11e EDCF and the IEEE 802.15.4 MAC protocol in terms of the end-to-end delay and stable transmission of multimedia streaming data.

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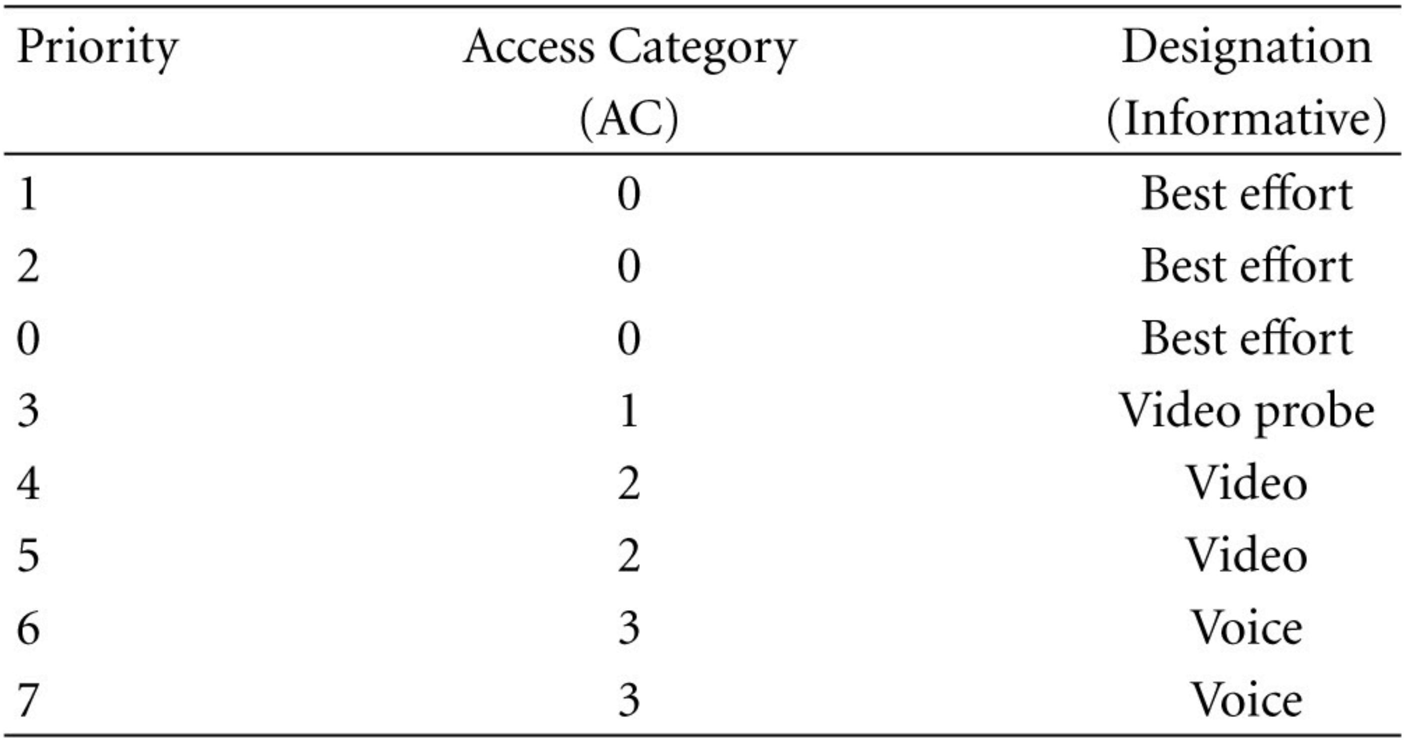
1. Introduction

Social concern about applications using multimedia traffic has been growing for the last several years. Research papers concerning applications that generate multimedia traffic, namely, video and audio streaming, still images, and scalar sensor data, are being carried out to implement a communication protocol in the real world. These applications need mostly high throughput and low delay. Networks that connect wireless devices to obtain multimedia traffic are defined as wireless multimedia sensor networks (WMSNs) [1]. In WMSNs, MAC protocols supporting multimedia traffic QoS are divided into three types. The first is contention-based MAC protocols. The typical contention-based MAC protocol is IEEE 802.11e enhanced distributed coordination function (EDCF) that gives the differential priorities according to types of traffic. In EDCF protocol, nodes should participate in contention for channel acquisition through CSMA/CA technique. However, this scheme cannot guarantee multimedia traffic QoS, because the EDCF results in high collision rate at high multimedia traffic load. Most contention-based schemes [2, 3] cannot guarantee multimedia traffic QoS due to collisions of control packets. The second is time division multiple access (TDMA) MAC protocols. TDMA MAC protocols have been studied for supporting multimedia traffic QoS in WSNs. However, the centralized system is used to assign time slots in most TDMA MAC protocols. Due to the centralized system, TDMA MAC protocols [4] are not suitable in WMSNs in terms of the scalability. The third is hybrid MAC protocols. Hybrid MAC protocols [5] using the merit of contention-based and contention-free MAC protocols have been brought to public attention. Due to these features, hybrid MAC protocols can solve the high collisions of packets and scalability problems. Almost all of hybrid MAC protocols are operated in two periods, which are contention period and contention-free period. Hybrid MAC protocols reserve time slots in contention period and nodes transmit data during an assigned slot time in contention-free period. In this protocol, an important factor is the methods that reserve time slots and maintain reservation table in all nodes. If the neighbor nodes do not maintain the same reservation table, collisions of control packets can occur. There have been a few studies that try to support multimedia traffic QoS and maintain reservation table in WMSNs.

2. Related Works

First, we will examine a representative contention-based MAC protocol, namely, IEEE 802.11e EDCF [6, 7]. IEEE 802.11e EDCF uses a priority method to support multimedia traffic QoS. The QoS supporting is realized through the introduction of traffic categories (TCs). In Figure 1, differential arbitration inter frame space (AIFS) is applied to every packet according to the access category (AC) of packets. The nodes independently start a backoff after detecting the channel being idle for an AIFS. After waiting for AIFS, each backoff sets a counter to a random number drawn from the interval $[1, \mathrm{CW}+1]$. CWmin refers to the minimum size of the CW. The maximum size of CW is CWmax. EDCF protocol allocates differential values at CWmin and CWmax in accordance with the priority of packets. Each frame from the higher layer arrives at MAC layer along with a specific priority value. Then, each QoS data frame carries its priority value in the MAC frame header. An 802.11e stations shall implement four access categories (ACs), where an AC is an enhanced variant of the DCF 0. Each frame arrives at MAC layer with a priority is mapped into an AC as shown in Table 1. The values of AIFS, CWmin, and CWmax, which are referred to as the EDCF parameters, are announced by the access point (AP) via beacon frames. The AP can adapt these parameters dynamically depending on network conditions Basically, the smaller, AIFS and CWmin, the shorter the channel access delay for the corresponding priority, and hence the more capacity share for a given traffic condition. However, the probability of collisions increases when nodes are operating with smaller CWmin. After all, EDCF is not suitable in multimedia traffic because of high collision rate at high multimedia traffic load.

TABLE 1: EDCF priority to Access Category Mappings.



Priority	Access Category (AC)	Designation (Informative)
1	0	Best effort
2	0	Best effort
0	0	Best effort
3	1	Video probe
4	2	Video
5	2	Video
6	3	Voice
7	3	Voice

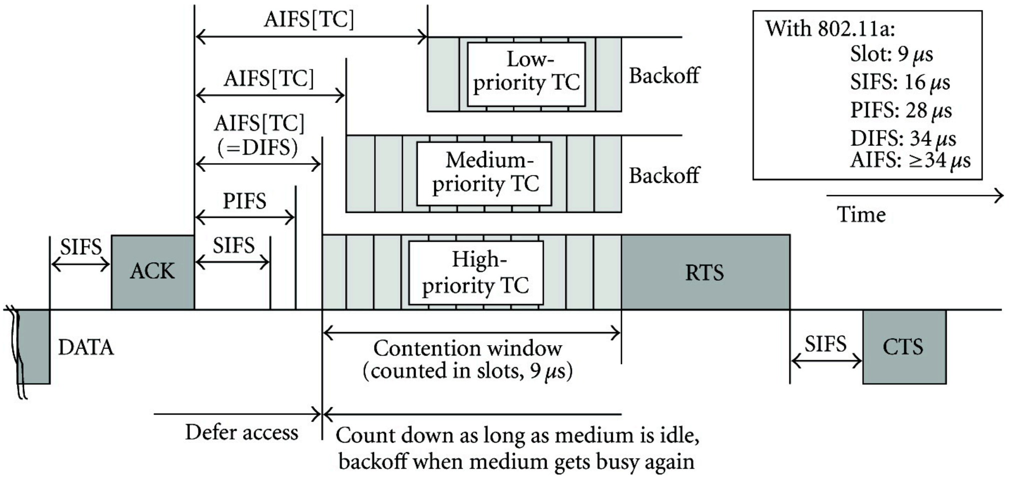


Figure 1 Multiple backoff of EDCF with different priorities.

Second, we will introduce a PARMAC (power-aware reservation-based MAC) [8] that is a major hybrid MAC protocol. This protocol assumes that all stations are synchronized, using a global synchronization scheme, and time is divided in frames of fixed length. Each frame is divided as shown in Figure 2 into the reservation period (RP), during which nodes contend to establish new reservations or cancel reservations, and the contention-free period (CFP), during which they send data packets without contention during the reserved transmission windows and sleep when they do not have packets to send or receive. The lengths of a frame, CFP and RP, are prespecified in the network. Each node operates distributed reservations scheme, namely, each node only attains the link information of 2-hop neighbor nodes. Because of this mode, the scalability of the network can be guaranteed. Basically, PARMAC is appropriate for the transmission of multimedia streaming traffic. However, PARMAC is not suitable for transmission of a periodic scalar sensor data. Besides, correct reservation tables should be maintained by the neighbor nodes. Otherwise, the data that is sent by the reserved nodes might have collisions with several sending data in CFP. Specially, because wireless condition has frequent channel errors, the new reservations do not notice the neighbor nodes exactly due to collision of control packets in the RP period. Finally, even if one node among nodes on the multihop routing path has problem with the data transmission, a source node cannot transmit the data to a destination node. PARMAC does not ensure multimedia streaming traffic QoS when wireless link is broken in certain region during the multimedia traffic transmission.

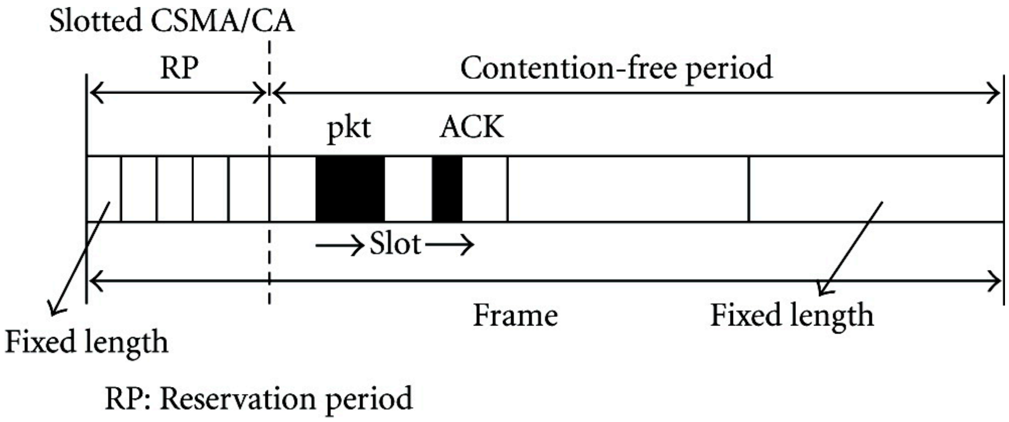


Figure 2 Operation of the PARMAC.

We also introduce a representative hybrid MAC protocol. The MAC protocol is IEEE 802.15.4 MAC [9] protocol. Most of the pertinent features of IEEE 802.15.4 are in the beacon-enabled mode. The beacon-enabled mode uses a superframe structure where the MAC frame is split in an active and an inactive period; tuning the length of each of them allows to adjust the duty cycle dynamically. The active period consists of (1) the beacon, (2) a contention access period (CAP), and (3) a collision-free period (CFP). The CFP is only available if guaranteed time slots (GTSs) are allocated by the coordinator; each GTS can occupy multiple timeslots among the 16 available, but only 7 GTSs are allowed in the CFP. A node therefore listens to the beacon first to understand whether a GTS has been reserved by the coordinator or not. If it has, then it remains powered off until its GTS is scheduled to transmit the data. If no GTS is reserved, then it uses CSMA/CA during CAP where the typical backoff procedures are applied.

3. Proposed Schemes

We assume that sensor nodes are high-end devices and all nodes are synchronized at initial stage. High-end devices have the camera that generates multimedia streaming data and still images. All nodes share the location information of the neighbor nodes despite the hello messages. Reservation table is empty initially and routing path is established later. In the following subsection, we will discuss the frame structure of a Scalable QoS (SQ) MAC protocol.

3.1. Frame Structure

The proposed MAC protocol is divided into four periods. As shown in Figure 3, the first is the synchronization period. The second is the random access period. The third is the switching period. Finally, the fourth is the adaptive scheduled access period. These periods will be examined later in detail. We will discuss the way how three traffics are transmitted. We investigate the case that multimedia streaming traffic is generated. In this case, a node operates the reservation set procedure at the random access period and reserves a time slot in the adaptive scheduled access period. All the neighbor nodes of the sender and receiver must record the reservation in their own reservation tables. Once reserved, the sender transmits data and receives ACK message at the adaptive scheduled access period until the reservation cancel procedure is operated. The reservation set procedures occur in nodes along the routing path. As a result, nodes reserve the time slots successively in multi-hop. Nodes operate the reservation cancel procedure when multimedia streaming traffic generation is over. The procedure changes the reserved slots of the nodes' reservation table into free slots at the random access period. Afterward all neighbor nodes can use the time slots for packet transmission.

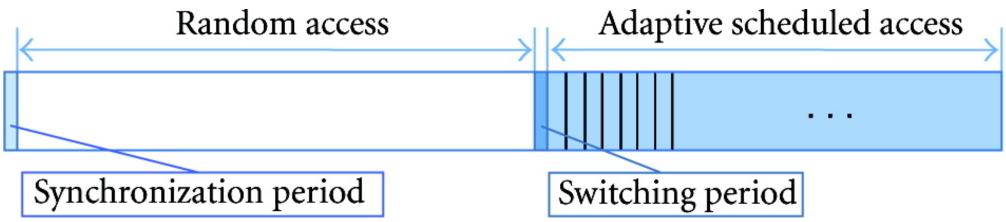


Figure 3 Frame structure of SQ-MAC.

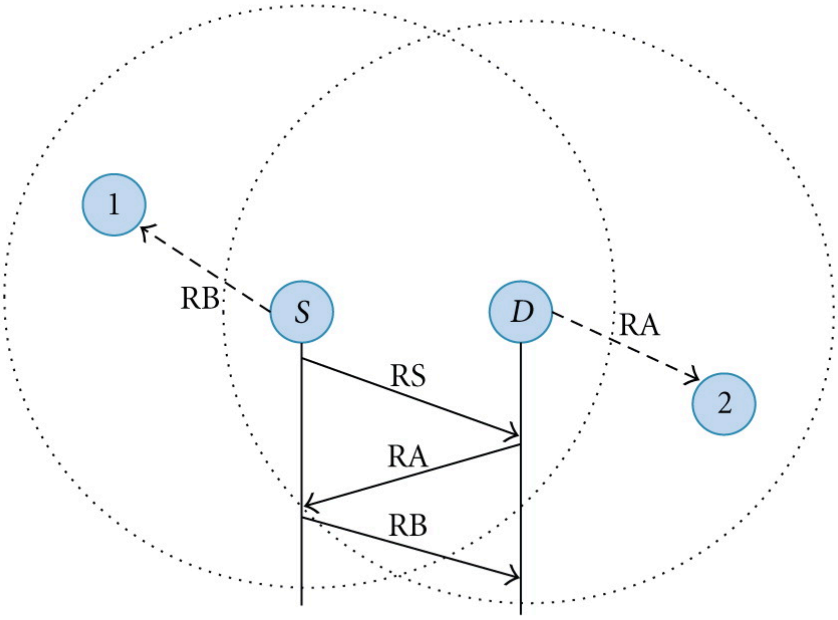
Next, we will discuss the case of still images and scalar sensor data. These traffics are transmitted in the procedure of RTS/CTS/DATA/ACK at the random access period through the CSMA/CA technique. Moreover the traffic scan be transmitted in the way as slotted CSMA/CA if there are free slots in the adaptive scheduled access period.

3.1.1. Operation in Frame Structure. We will briefly review the operation of each period. First of all, every node is synchronized by the efficient flooding scheme at the synchronization period. In the random access period, nodes must utilize CSMA/CA technique as IEEE 802.11 MAC for channel acquisition. Two kinds of packets are transmitted in this period. The first one is reservation control packets. These packets are used for updating reservation table of each node. We will discuss the reservation control packets and the recording method of reservation table in the following chapter. The other is packets for still images and scalar sensor data which are transmitted by the way of RTS/CTS/DATA/ACK. More important packets, such as reservation control packets, are allocated in differential interface space and small contention window size because the packets are transmitted through contention. This will be presented later in detail. In the switching period, the designated nodes must broadcast the slot information of the adaptive scheduled access period. The slot information represents whether the time slot is reserved. If the adaptive scheduled access period is divided into 16 time slots, the information can be represented as 16 bits. In the adaptive scheduled access period, each sending node sends the data and receives ACK message according to the order in the reservation table. If there are free slots in reservation table, all nodes can contend to acquire the slots by slotted CSMA/CA technique. The winner node operates the reservation procedures or sends still images and scalar sensor data. Channel throughput is improved in this way.

3.2. Reservation Procedures

In this section, we will discuss the reservation procedures in detail. The procedures start by the node that generates multimedia streaming traffic. These procedures are operated in the random access period.

3.2.1. Reservation Set Procedure. Reservation procedures can be classified into three operations. The first is the reservation set procedure. This operation starts once when multimedia streaming traffic is generated. Reservation will be maintained until reservation cancel procedure is done. As shown in Figure 4(a), a source node transmits a reservation set (RS) packet to a destination node. The type represents the reservation set packet and the following two fields indicate the addresses of the source and destination node. The slot information field expresses whether each time slot of the sender is reserved. If the adaptive scheduled access period consists of 16 time slots, the slot information field is represented as 16 bits and each bit expresses the reservation information of each time slot. The bit 0 indicates a free slot and the bit 1 manifests a reserved slot. Finally, the deadline field represents the remaining time left to reach the destination node. The destination node that receives the reservation set packet compares its own slot information with the reservation table of the source node. If the first 0 match is found in the binary strings in both of these slot information fields, that matching bit slot must be reserved. As an example, if the slot information of the source node is 01110111 and the slot information of the destination node is 11000000, the fifth slot will be reserved. The reservation is corresponded by the destination node with reservation ACK (RA) packet. The reserved slot information field represents 00001000 bits in this case and informs the source node that the fifth slot is reserved. The timeout field indicates the initial value of counter. This field will be examined in detail further in the next subsection. The source node that receives the reservation ACK packet has to broadcast the reservation broadcast (RB) packet. Both the reservation ACK and reservation broadcast packets will inform all neighbor nodes of the related information: the reserved slot, the source address, and the destination address. All nodes have to record the information in their own reservation table.



(a)

Type	SourceAddr	Dest.Addr.	Slot infor.	Deadline

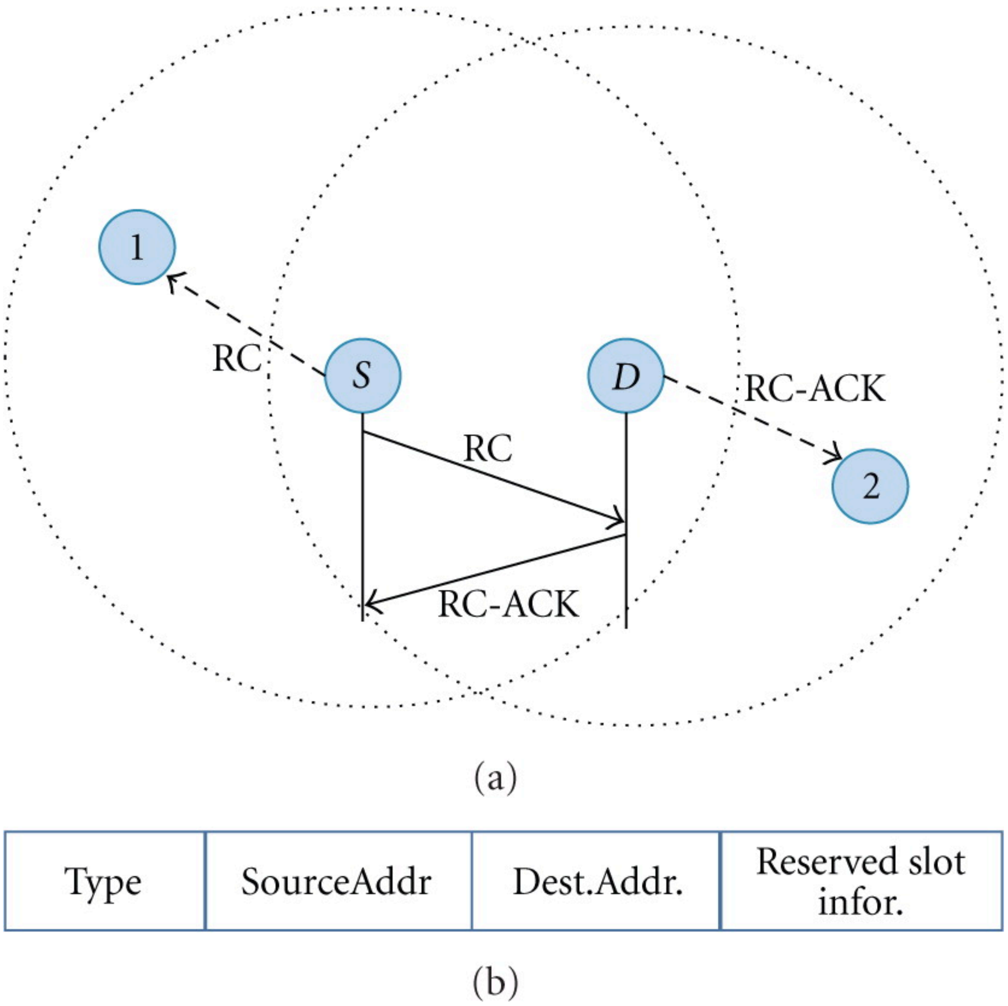
(b)

Type	SourceAddr	Dest.Addr.	Reserved slot infor.	Time out

(c)

Figure 4 (a) Reservation set procedure. (b) Reservation set format. (c) Reservation ACK and broadcast formats.

3.2.2. Reservation Cancel Procedure. The reservation cancel procedure cancels the reservation of the reserved slot in reservation table of the relevant nodes. This procedure will be initiated by the source node that has no data left to be sent or the node that has expired the timeout of the reservation table. Figure 5(a) expresses the procedure. The source node sends the reservation cancel packet and receives the reservation cancel ACK packet from the destination node. Figure 5(b) indicates the format of the packet. All nodes that receive the packets compare the information of the packet with the information of their own reservation table. If the information includes address of the nodes in their reservation table, the nodes will cancel the reservation in their own reservation table.

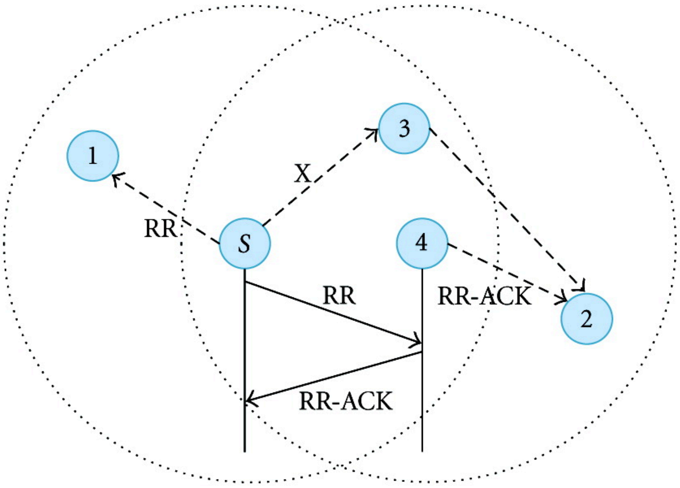


Type	SourceAddr	Dest.Addr.	Reserved slot infor.

Figure 5 (a) Reservation cancel procedure. (b) Reservation cancel and reservation cancel ACK formats.

3.2.3. Reservation Recovery Procedure. It is necessary to resolve the problem when the multimedia streaming traffic QoS cannot be guaranteed, in such cases when at least one node is dead or the channel condition is bad in the special region. The reason is that the transmission is accomplished through multihop transmission. In order to recover this problem quickly, we will need the reservation recovery procedure. Once the reservation set procedure has been completed, the source node sends data and receives the ACK message during the reserved slot time in the adaptive scheduled access period. If the source node does not receive the ACK message during the reserved slot time, the source node will recognize connection failure. Then the source node will find the other destination node. As a general rule, the selected node will be located close to the original node. Then the reservation recovery procedure will proceed. The source node has to transmit the reservation recovery packet to the selected node and receive the reservation recovery ACK packet. The packet fields indicate the address of the original node in the lost address field and address of the selected node in the destination address field. All nodes that overhear the packets have to change the lost address to destination address in reservation table.

Owing to this procedure, the problem can be recovered rapidly. For example, as shown in Figure 6(a), the multimedia traffic flow is 1 →*S*→ 3 → 2 and the situation is that the reservations have been completed. When the connection between the nodes *S* and 3 breaks down, the node *S* must operate the reservation recovery procedure. The node *S* selects a node 4 as a forwarding node instead of the node 3. The connection can be recovered rapidly. Figures 6(c) and 6(d) show the reservation table of nodes before and after the reservation recovery procedure.



(a)

Type	SourceAddr	Dest.Addr.	Lost Addr.	Reserved slot infor.	Time out

(b)

Slot number	Source node	Dest. node	Timeout (ms)	Slot infor.
1	*S*	3	12	1
2	3	2	10	1

(c)

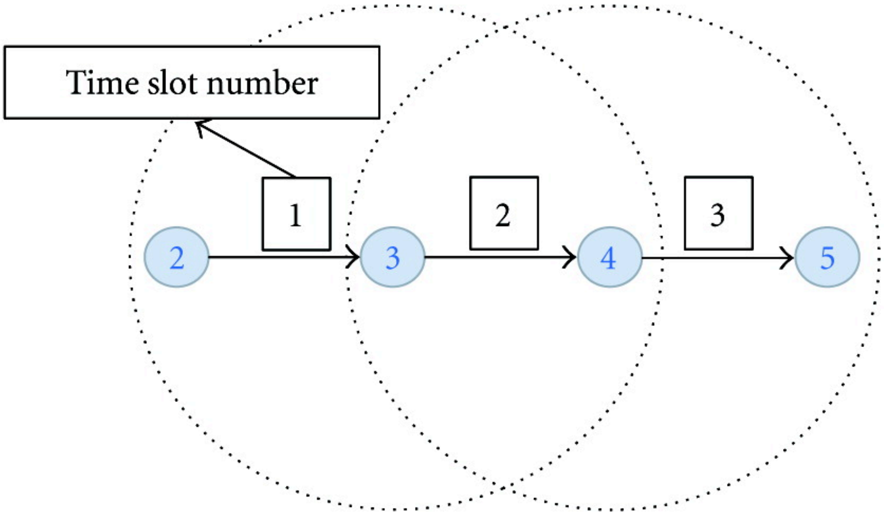
Slot number	Source node	Dest. node	Timeout (ms)	Slot infor.
1	*S*	4	20	1
2	4	2	20	1

(d)

Figure 6 (a) Reservation recovery procedure. (b) Reservation recovery and reservation recovery ACK formats. (c) Reservation table of all nodes before the reservation recovery procedure. (d) Reservation table of all nodes after the reservation recovery procedure.

3.3. Reservation Table

The reservation table can be updated by listening and overhearing the reservation control packets in the random access period. All the nodes that listen to the reservation ACK or reservation broadcast have to register the address of the source and destination node and the reserved slot number in their reservation tables. The timeout counter is also initiated by the predetermined value. Consider Figures 7(a) and 7(b) for example. The routing path is 2 → 3 → 4 → 5. The reservations have been completed during the random access period through the reservation set procedure. The value between the nodes indicates the number of the reserved slot. Figure 7(b) shows the reservation table of the node 3. The slot information consists of 0 and 1 bits, and the bit 1 represents a reserved slot and the bit 0 indicates a free slot. Figure 8 describes the slot information in detail.



(a)

Slot number	Source node	Dest. node	Timeout (ms)	Slot infor.
1	2	3	10	1
2	3	4	15	1
3	4	5	20	1
4				0

(b)

Figure 7 (a) Network topology. (b) Reservation table of node 3.

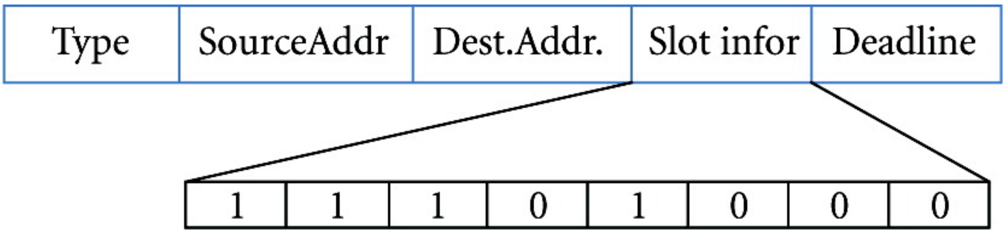


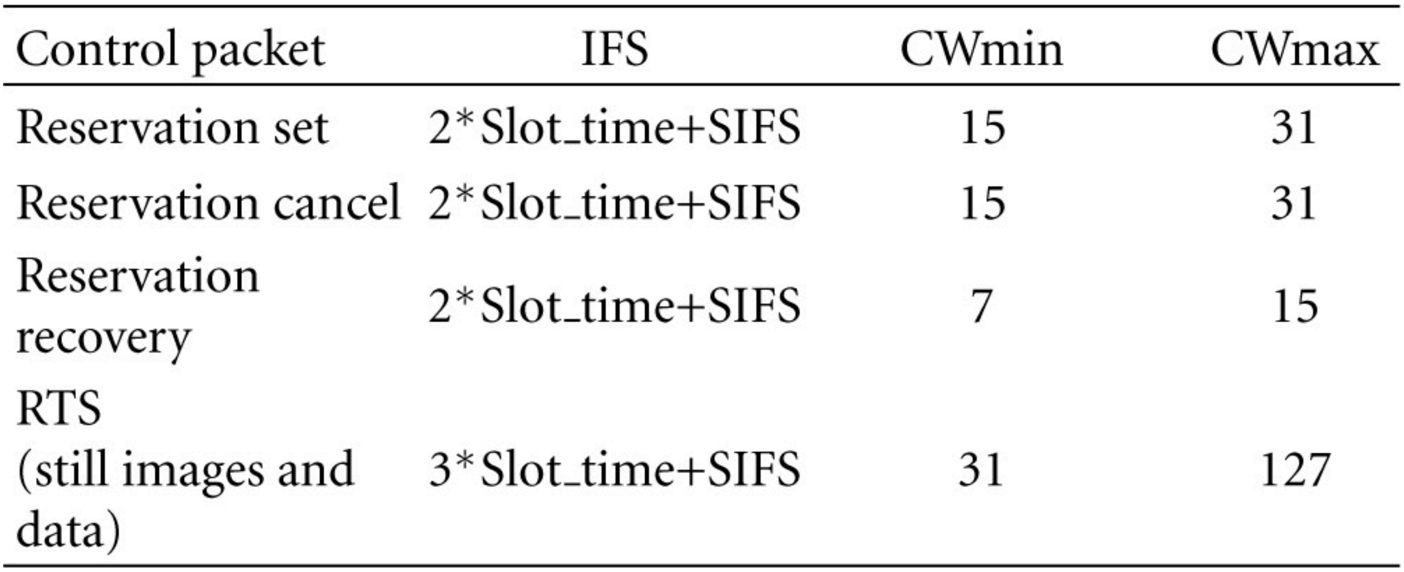
Figure 8 Slot information field.

The slot information is very important for the reservation among the nodes and escaping collision. This slot information is utilized in the switching period. In the next subsection, we will describe the switching period.

3.4. Contention Method of the Random Access Period

In the random access period, reservation control packets and the RTS packets for sending still images and scalar sensor data will contend for channel acquisition. We will give priority to the reservation control packets than the RTS packet. The method that gives priority to the reservation control packets sets up the differential interface space (IFS) and contention window size. Table 2 shows the parameters of interface space and contention window size of the control packets.

TABLE 2: Parameters of interface space and contention window.



Control packet	IFS	CWmin	CWmax
Reservation set	2*Slot_time+SIFS	15	31
Reservation cancel	2*Slot_time+SIFS	15	31
Reservation recovery	2*Slot_time+SIFS	7	15
RTS (still images and data)	3*Slot_time+SIFS	31	127

3.5. Description of the Switching Period

Due to unstable wireless channel and collision among the reservation control packets, the reservation table of a node and the neighbor nodes cannot coincide. In this case the multimedia traffic transmission can generate collision with each other. As a result, multimedia traffic QoS cannot be guaranteed. In order to solve this problem, the specific nodes broadcast the slot information during the switching period. The specific nodes that send or receive the reservation control packets during the prior random access period should broadcast the slot information according to the random backoff scheme. The exact reservation table will be maintained among the neighbor nodes (Figure 9).

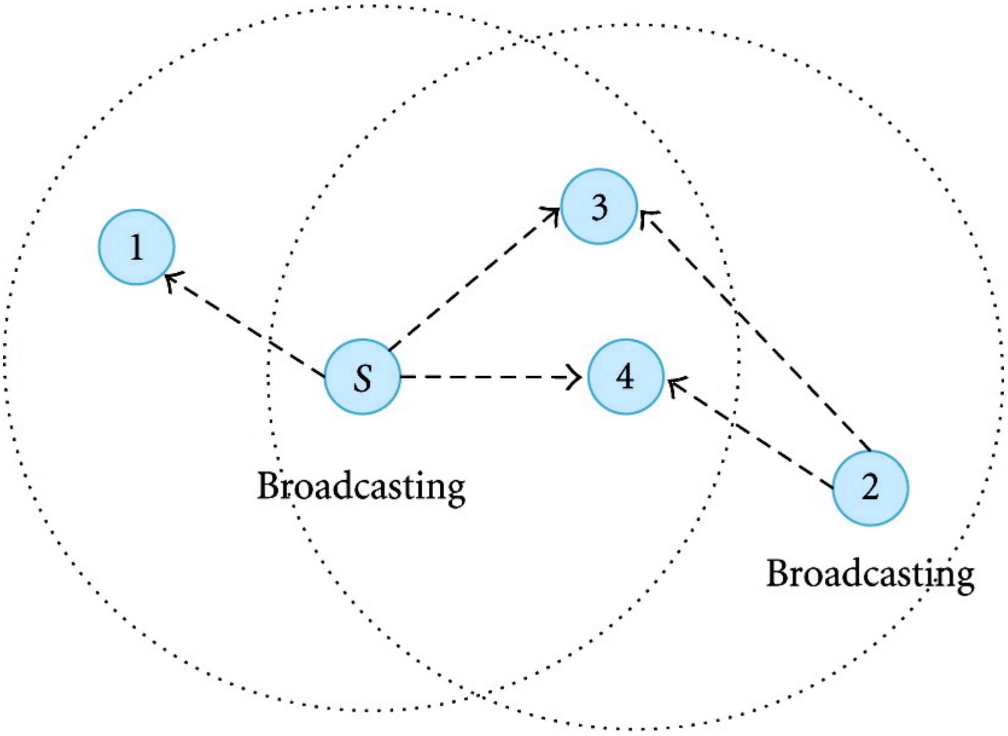
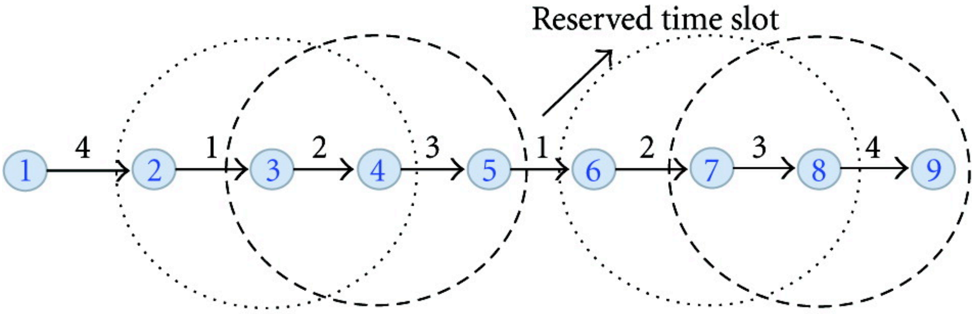


Figure 9 Broadcasting slot information.

3.6. Description of the Adaptive Scheduled Access Period

The adaptive access period consists of several fixed time slots. The length of a time slot is determined by the network manager. If data is transmitted successfully during each time slot, the nodes will reset the timeout value in the reservation table.

In case when the timeout value is 0, the node shall perform the reservation cancel procedure. The number of time slots should be limited according to the volume of the traffic. During the free time slots, all forwarding nodes can transmit data through a slotted CSMA/CA technique. Nodes without sending or receiving data can sleep during the time slots. Figure 10 shows an example of multihop transmission for multimedia traffic.



(a)

Slot number	Source node	Dest. node	Timeout (ms)	Slot infor.
1	2	3	10	1
2	3	4	15	1
3	4	5	20	1
4	1	2	10	1

(b)

Slot number	Source node	Dest. node	Timeout (ms)	Slot infor.
1				0
2	6	7	10	1
3	7	8	8	1
4	8	9	15	1

(c)

Figure 10 (a) Network topology for simulation. (b) Reservation table of node 3. (c) Reservation table of node 8.

4. Performance Analysis

We will examine the performance analysis under the N-hop linear topology. Figure 11 shows the topology. We will find both the optimal random access period and adaptive scheduled access period for minimum end-to-end delay according to the multimedia streaming data rate. In Figure 11, node S is a source node that generates multimedia streaming traffic. Node S delivers multimedia streaming traffic to a destination node through multihop transmission for a while. The objective function refers to the expected time of the end-to-end delay from node S to node D. Variables of the optimization problem indicate the number of time slots in the adaptive scheduled access period and the length of the random access period:

$$\begin{aligned} \text{minimize} \quad & E\left[\text{Delay}_{e2e}\right] \\ \text{subject to} \quad & T_R \geq 0, \\ & n \geq 0, \ \text{integer}. \end{aligned} \tag{1}$$

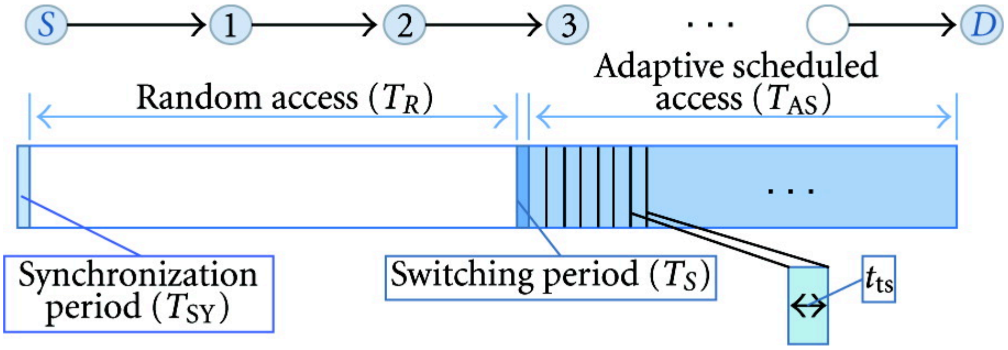


Figure 11 Network topology and analysis variables.

We assume no processing delay of CPU, no queueing delay, and no propagation delay. The synchronization period and switching period are constant values.

Table 3 shows the analysis parameters for the performance evaluation.

Table 3: Analysis parameters.

Random access period	T_{R}
Synchronization period	T_{SY}
Adaptive scheduled access period	T_{AS}
Switching period	T_{S}
The hop number	N_{h}
The number of the time slots	n
The multimedia streaming data rate	r_{data}
The data length	L_{data}
Time to Tx/Rx a byte	t_{B}
The time of a time slot	t_{ts}
The time of a ACK packet	t_{ACK}
The time of the contention window	t_{CW}
The time of the RS	t_{RS}
The time of the RA	t_{RA}
The time of the RB	t_{RB}
The time of the IFS	t_{IFS}
The time of the SIFS	t_{SIFS}
The time of RS procedure	t_{RSP}

We defined a frame time as the sum of the four periods, which are the synchronization period, random access period, switching period, and adaptive scheduled access period. The following equation expresses a frame time:

$$T_{\text{frame}} = T_{SY} + T_R + T_S + T_{AS}. \tag{2}$$

The adaptive scheduled access period is divided into *n* time slots. Therefore, the adaptive scheduled access period is expressed as the product of *n* and a time slot. The following equation shows the numerical formula:

$$T_{AS} = n \cdot t_{\text{ts}}. \tag{3}$$

One time slot should be enough time to receive and send a data packet. As shown in (4), a time slot indicates the sum of the data transmission time, ACK receiving time, three times of short interframe space time, and guard time:

$$t_{ts} = \frac{L_{\text{data}}}{t_B} + t_{\text{ACK}} + 3 \cdot t_{\text{SIFS}} + \text{guard\_time}. \tag{4}$$

Now, we will examine the expected time of a reservation set procedure. This procedure proceeds in the random access period. In other words, the CSMA/CA technique is used for channel acquisition. First, we wait for the IFS time after the preceding transmission. The IFS time for the reservation set procedure appears at Table 2. Then, the random backoff time for contention follows the IFS time. The average value of the random backoff time is half of contention window size. After sending the reservation set, reservation ACK and reservation broadcast packets are transmitted by the source and destination nodes. Two short interframe spaces are among these packets. The following equation indicates the expected time of a reservation set procedure:

$$E\left[t_{\text{RSP}}\right] = t_{\text{IFS}} + \frac{t_{\text{CW}}}{2} + t_{\text{RS}} + t_{\text{RA}} + t_{\text{RB}} + 2 \cdot t_{\text{SIFS}}. \tag{5}$$

The maximum number of the completed reservation set procedure in a frame period, MN_{RSP}, is expressed in (6). Reservation set procedures must be performed in the random access period. So the maximum number of the completed reservation set procedures is the value of random access period divided by the expected time of a reservation set procedure. Because this value is integer, the decimal fraction is erased:

$$\text{MN}_{\text{RSP}} = \left\lfloor \frac{T_R}{E[t_{\text{RSP}}]} \right\rfloor. \tag{6}$$

Now, we find the probability of one more hops' transmission during a frame period. It is possible that the sending node reserves a preceding time slot than a time slot of the relay node in the adaptive scheduled access period. The probability, P_r, is expressed in (7). We assume that the number of the unreserved time slots is *k*. If the sending node selects a time slot, the relay node chooses one of the following time slots than the selected time slot. The probability is independent of the value of *k*. The value of *k* is an invariable in

$$P_r = \frac{1}{k}\left(\frac{k-1}{k-1} + \frac{k-2}{k-1} + \cdots + \frac{2}{k-1} + \frac{1}{k-1}\right) = \frac{1}{2}, \quad 0 \le k \le n. \tag{7}$$

We will use the probability of one more hops' transmission to find the average hop count of the relayed packets during a frame period. Because the probability of one more hops' transmission is the same regardless of the value of *k*, the average hop count of the relayed packets is expressed as the sum of the probability from one hop transmission to the maximum hops transmission during a frame period:

$$E\left[M_h\right] = 1 \cdot 1 + 2 \cdot P_r + \cdots + \text{MN}_{\text{RSP}} \cdot \left(P_r\right)^{\text{MN}_{\text{RSP}}-1}. \tag{8}$$

We now examine the average end-to-end delay in the multihop transmission condition. First, we find the average number of a frame period spent for multihop transmission. The value is that the hop number from a source node to a destination node is divided by the average hop count of the relayed packets. The average end-to-end delay equals the product of the average number of a frame period and a frame time. The following equation shows the average end-to-end delay:

$$E\left[\text{Delay}_{e2e}\right] = \left\lfloor \frac{N_h}{E[M_h]} + 1 \right\rfloor \cdot T_{\text{frame}}. \tag{9}$$

We assume no queueing delay. For this we apply $D/D/1$ queueing model in sensor nodes. Both the arrival and the service rate are constant value. The arrival rate is smaller than the service rate. However, there is waiting delay due to channel contention. If a sensor node transmits data, the two forwarding nodes cannot send the data in Figure 10. The constraint function of the random access period is indicated in (10). The minimum random access period is the product of the expected time of a reservation set procedure and the three times the number of the generated data during a frame time:

$$T_R \geq 3E\left[t_{\mathrm{RSP}}\right] \cdot \left(r_{\mathrm{data}} \cdot T_{\mathrm{frame}}\right). \tag{10}$$

The number of the time slots is expressed as (10). The minimum number of the time slots is three times the number of the generated data during a frame time. The number is integer:

$$n \geq \left[3r_{\mathrm{data}} \cdot T_{\mathrm{frame}} + 1\right]. \tag{11}$$

Now, we define the end-to-end delay as an optimization problem through the previous equations. The following equation indicates the optimization problem:

$$\begin{aligned} \text{minimize} \quad & E\left[\mathrm{Delay}_{e2e}\right] \\ \text{subject to} \quad & T_R \geq 3E\left[t_{\mathrm{RSP}}\right] \cdot \left(r_{\mathrm{data}} \cdot T_{\mathrm{frame}}\right), \\ & n \geq \left[3r_{\mathrm{data}} \cdot T_{\mathrm{frame}} + 1\right], \\ & T_R \geq 0, \\ & n \geq 0, \ \text{integer}. \end{aligned} \tag{12}$$

We will find the optimal random access period and the number of time slots in each senor node according to the data rate from the source node. Therefore, we arrange (12) for the math problem in terms of a random access period and the number of time slots. The following equation shows the final optimization problem of the end-to-end delay:

$$\begin{aligned} \text{minimize} \quad & E\left[\mathrm{Delay}_{e2e}\right] = \left[\frac{N_h}{E[M_h]} + 1\right] \\ & \qquad \cdot \left(T_{SY} + T_R + T_S + n \cdot t_{ts}\right) \\ \text{subject to} \quad & \left(\frac{1}{3E[t_{\mathrm{RSP}}] \cdot r_{\mathrm{data}}} - 1\right) \cdot T_R - t_{ts} \cdot n \geq T_{SY} + T_S, \\ & \left(\frac{1}{3r_{\mathrm{data}}} - t_{ts}\right) \cdot n - T_R \geq T_{SY} + T_S, \\ & T_R \geq 0, \\ & n \geq 0, \ \text{integer}. \end{aligned} \tag{13}$$

We solved (13) using mathematical program and found the optimal values as the data rate varies. The parameters except three variables use the values of Table 4. The distance from a source node to a destination node is ten hops apart. When data rate is one unit per second, the graph of end-to-end delay is convex function as the random access period varies as shown in Figure 12. Even though the data rate varies, the graph of the end-to-end delay is almost the same pattern in terms of the random access period. Therefore the random access period that satisfies the constraints and minimum end-to-end delay is a global optimization value.

Table 4: Simulation parameters.

Simulation parameter	
The number of source nodes	k
Channel throughput	3 Mbytes/s
Packet Length	
All control packets	10 bytes
DATA	2.5 kbytes
Traffic Classification	
Multimedia streaming data	CPR 10 units/s
Still image and data	CPR 1 units/s
Interface Space and Contention Window Size	
DIFS	0.022 ms
SIFS	0.016 ms
A contention window slots	0.009 ms
A time slot	2 ms
IEEE 802.15.4 MAC	
Frame period	20 ms
Contention access period	6 ms
Contention free period	14 ms
The number of guaranteed time slots	7
SQ-MAC	
Frame period	20 ms
Random access period	4 ms
Adaptive scheduled period	16 ms
The number of adaptive scheduled slots	8

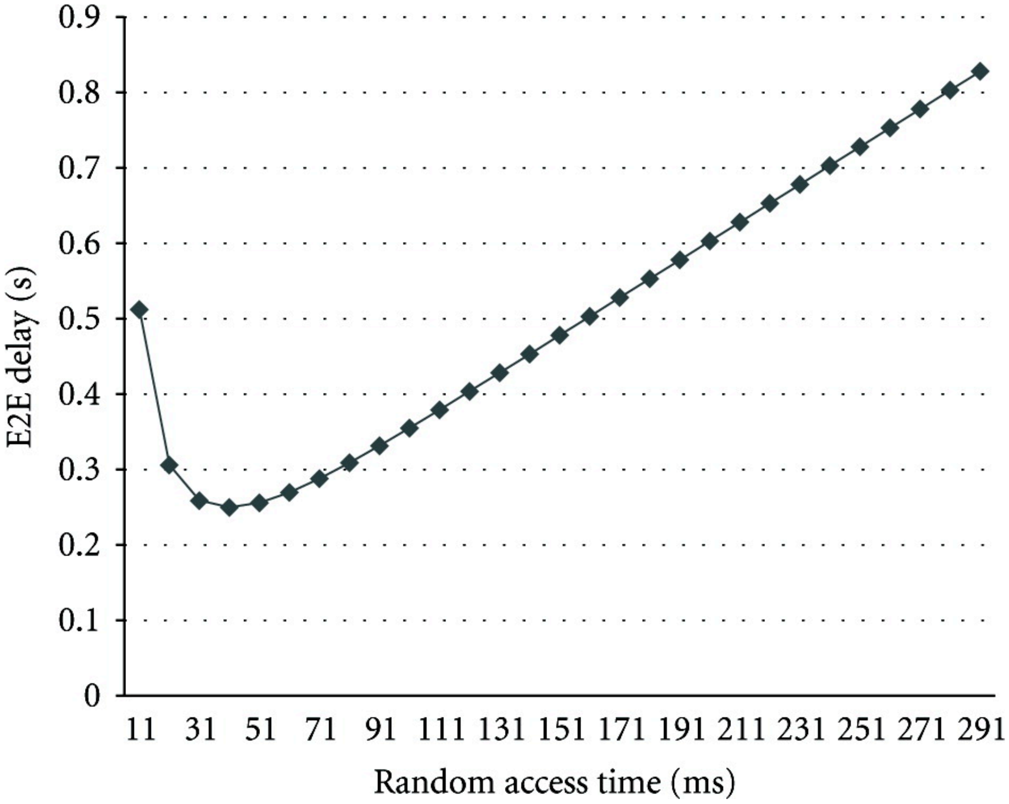


Figure 12 E2E delay when the data rate is one.

Figure 13 shows the end-to-end delay as the number of the time slots varies when the data rate is ten. More the number of the time slots than optimal number of those result in increasement of the end-to-end delay. Therefore the optimal number of the time slots in adaptive scheduled access period is important for multimedia traffic QoS.

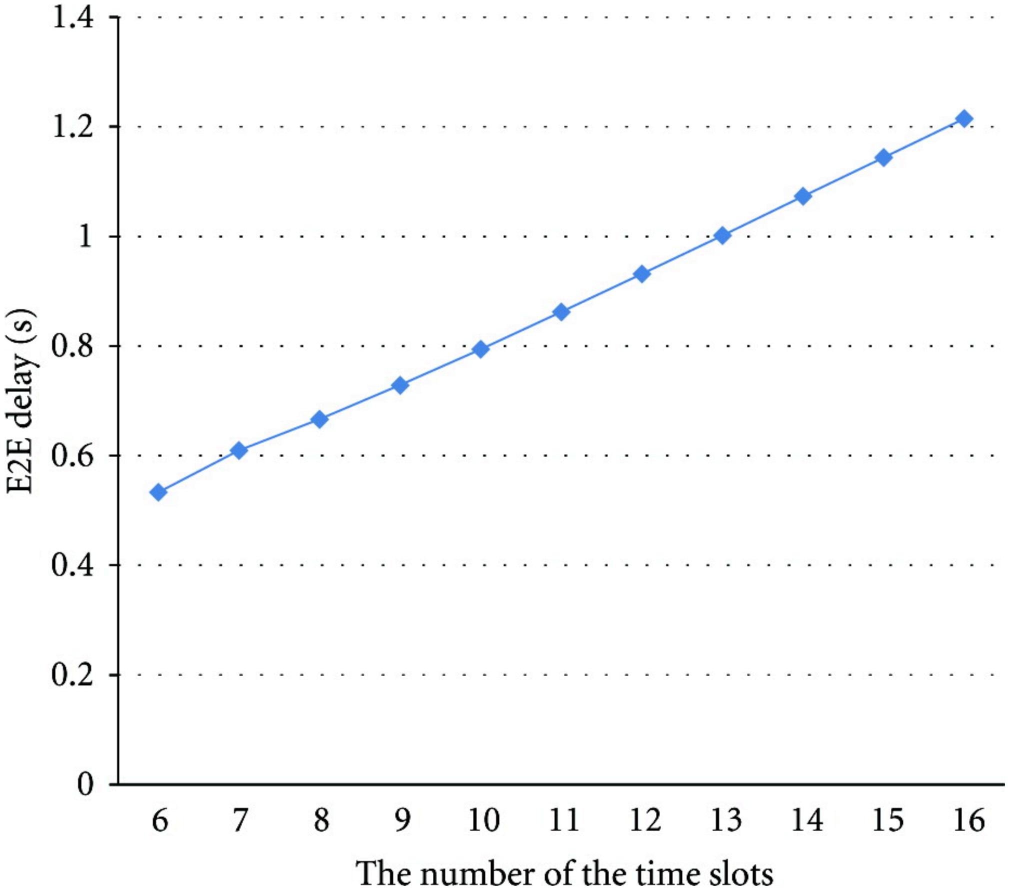


Figure 13 E2E delay as the number of the time slots varies when the data rate is ten.

As shown in Figure 14, the end-to-end delay of multimedia streaming traffic increases linearly as the data rate rises. The reasons of the linear delay increasement are that both the number of time slots in the adaptive scheduled access period and the random access period have to increase according to the data rate. Once the reservation set procedure has completed in nodes on multihop path from a source node to a destination node, the reserved slots will be used to guarantee the multimedia streaming traffic QoS until the reservation cancel procedures have been operated by the node. As a result, the number of the control packets for several reservations in each node is much less than those of other protocols. The collisions of the control packets have hardly occured in SQ-MAC as we expected.

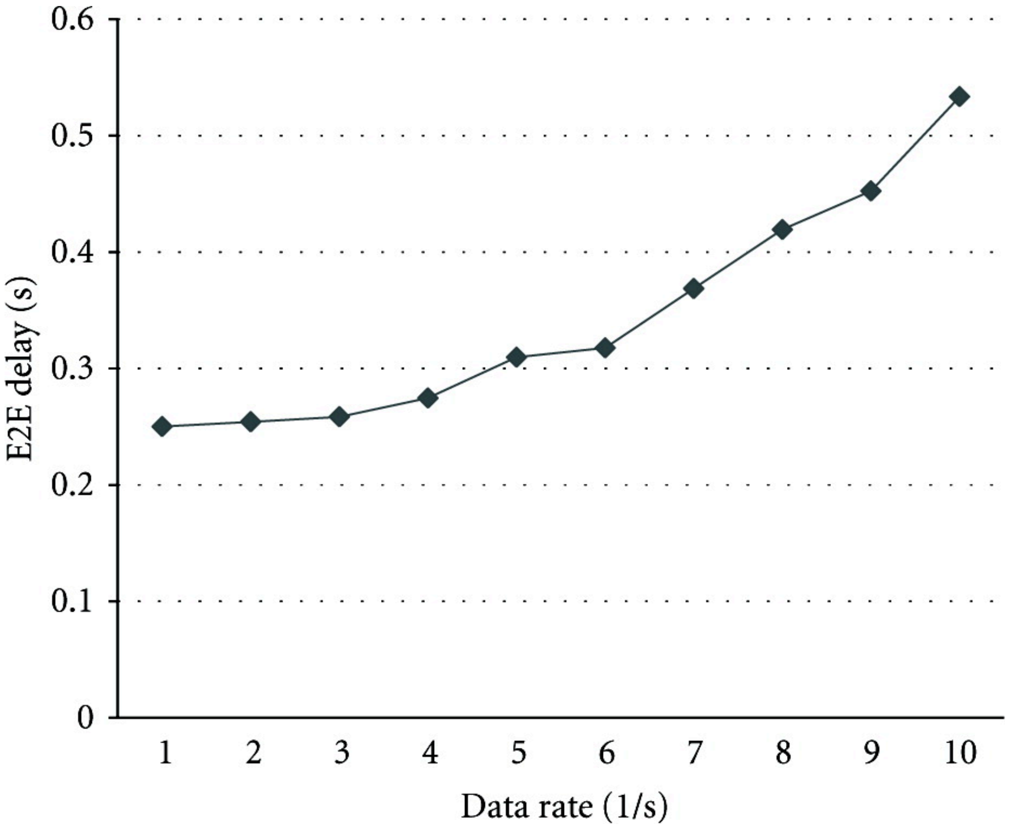


Figure 14 Optimal E2E delay as the data rate varies.

5. Simulation Results

The network topology for the simulation is represented in Figure 11. The simulation parameters are summarized in Tables 2 and 4. We used the MaTLAB simulator for the simulation. The distance from node *S* to node *D* is 10 hops away in the network topology. We assume that both the synchronization period and the switching period are one millisecond, respectively. The beacon period is also one millisecond in IEEE 802.15.4 MAC protocol. The environment condition is that multimedia streaming traffic and still images are generated at the constant packet rate (CPR). The number of the source nodes on routing path increases from one to nine. In this case we examined the expected packet delay from node *S* to node *D* until the transmission of one thousand packets from node *S* has been completed. We will compare the SQ-MAC with IEEE 802.11e EDCF and IEEE 802.15.4 MAC protocols in terms of the several variables. IEEE 802.15.4 MAC protocol operates in beacon-enabled mode. The coordinator nodes are 1, 4, 7 and destination nodes. Throughout the nodes, guaranteed time slots is reserved for multimedia streaming traffic. In beacon period, the coordinator nodes notice the reserved time slots.

First, we observed the collision probability of the control packets for data transmission in three protocols as the source node increases from one to nine nodes. The control packets include RTS, reservation set, and polling packets. The collision probability of the control packets increases rapidly because of the exponential growth of control packets for transmission of burst multimedia traffic in EDCF protocol (see Figure 15). The probability almost approaches 80 percent in the case of nine source nodes. Thus, most of the RTS packets must be retransmitted by source nodes in order to utilize wireless channel. On the other hand, the collision probability of the control packets increases slowly in the IEEE 802.15.4 MAC and SQ-MAC protocols. The reason is that the protocols hardly use control packets for multimedia traffic transmission.

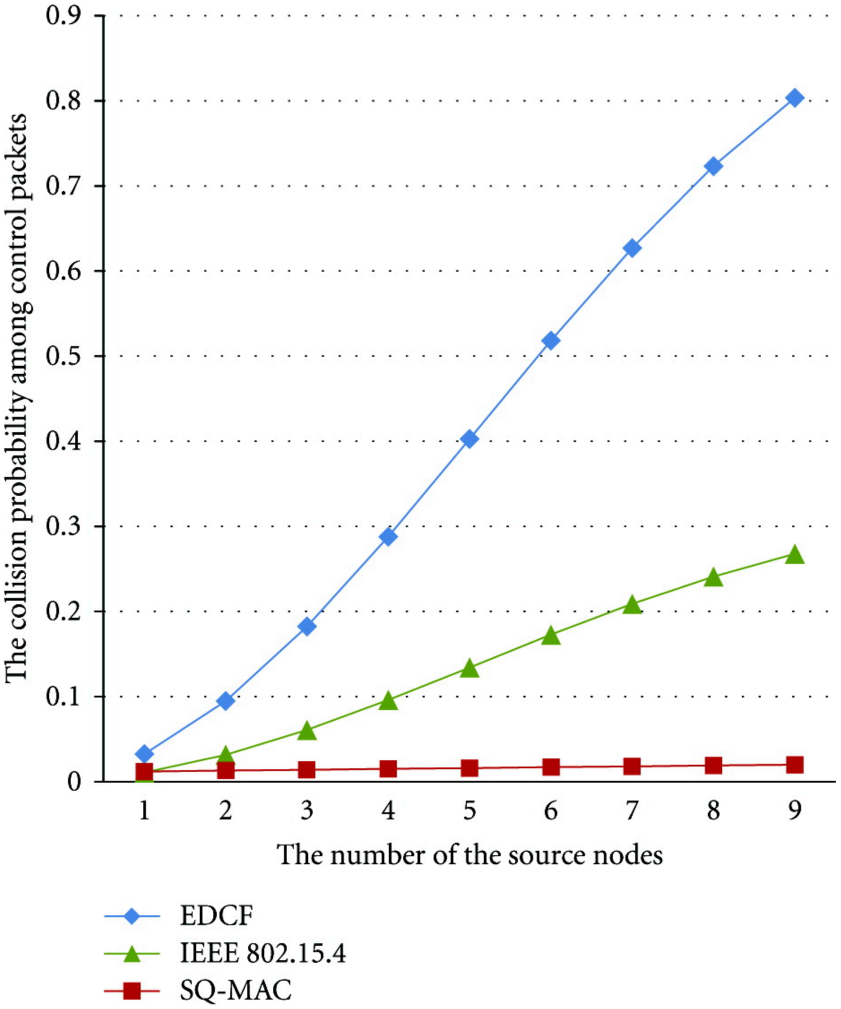


Figure 15 The collision probability among control packets as the number of the source nodes increases from one to nine.

After the successful control packet transmission, the data packet is transmitted by the node. Therefore the expected transmission time of a data packet has relevance to the retransmission number of the control packets. We define the reservation set packets as the control packets in SQ-MAC. There is almost no increase in the number of the control packets as multimedia streaming traffic increases in SQ-MAC. The reason is that only one control packet is transmitted to reserve a time slot when the node starts to transmit multimedia streaming traffic. Therefore, the collision probability of the reservation set packets is much lower than that of the RTS packets in EDCF protocol. In EDCF protocol, the expected time of a successful packet transmission has increased rapidly as the number of the source nodes increases due to the exponential collision growth of the RTS packets as shown in Figure 15. As a result, the channel utilization is very low in EDCF protocol. In IEEE 802.15.4 MAC, the control packets are polling packets for GTS reservation and RTS packets using slotted CSMA/CA in CAP. The coordinator nodes cannot use the GTS reservation packets unlike the other nodes. Therefore, IEEE 802.15.4 protocol shows better performance than EDCF protocol (Figure 16).

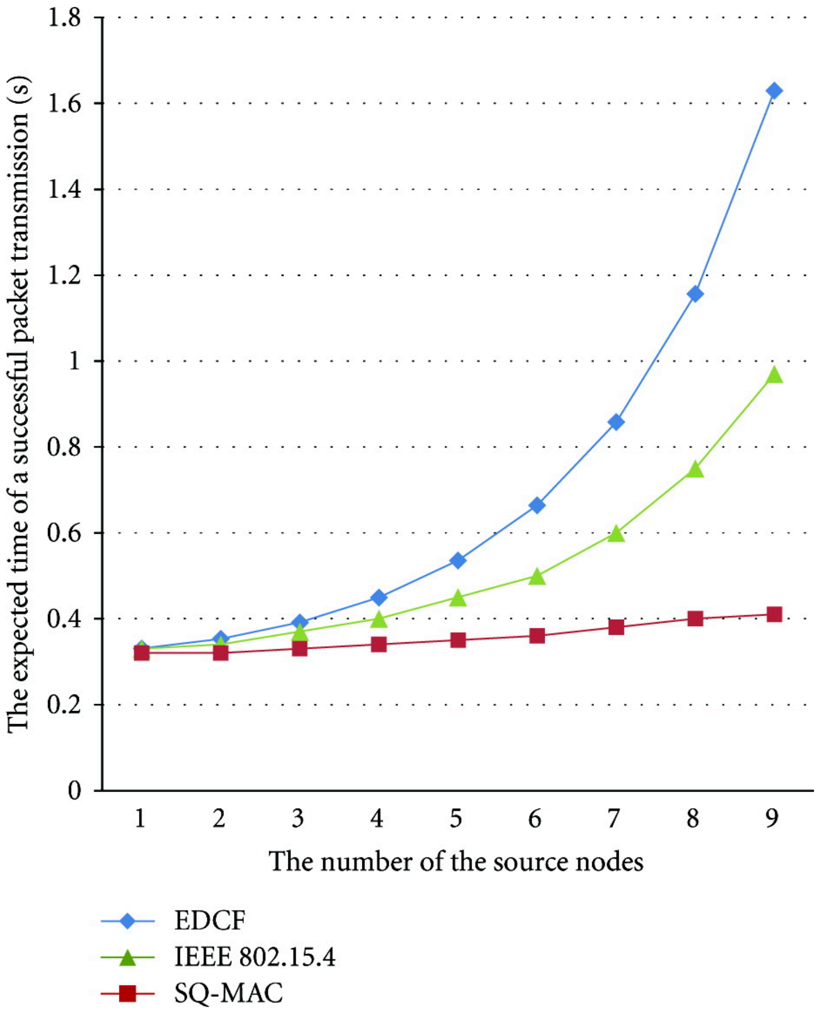


Figure 16 The expected time of a successful packet transmission as the number of the source nodes increases from one to nine.

Finally, we will examine the end-to-end delay from node *S* to node *D* as the number of the source nodes increases. In EDCF protocol, the delay increases geometrically because of the retransmission of the RTS packets. For the retransmission of the RTS packets, the node waits for the random backoff time in order to avoid collision. As the number of the retransmission increases, the backoff time grows, which results in the increasement of the end-to-end delay in network topology. Besides, there are wide variations in the end-to-end delay of packets. In other words, EDCF protocol cannot guarantee a stable transmission supporting multimedia traffic QoS. In IEEE 802.15.4 MAC protocol, the delay increases geometrically because of the collision among the RTS and GTS reservation packets. On the other hand, SQ-MAC not only makes shorter end-to-end delay due to the low collision rate of the control packets but also stable multimedia traffic transmission through the reservation of time slots (Figure 17).

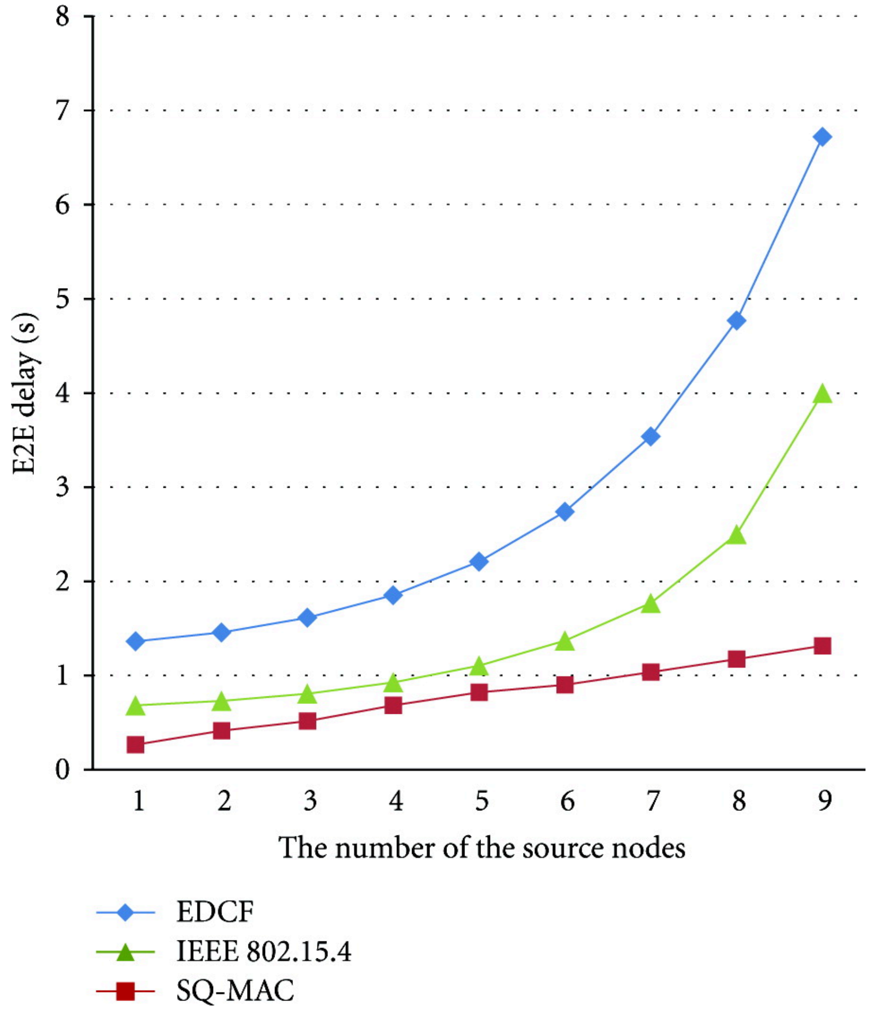


Figure 17 E2E delay as the number of the source nodes increases from one to nine.

6. Conclusion

We proposed SQ-MAC supporting several kinds of multimedia traffic. Owing to the protocol operation in a distributed fashion, SQ-MAC is scalable in WMSNs. In this condition, multimedia traffic packets are transmitted through multihop path. Therefore, we should resolve several problems in order to support multimedia traffic QoS. Even if one node on the routing path is not capable of transmitting multimedia packets, the end-to-end delay increases rapidly. To solve this problem, we propose the reservation recovery procedure. The second problem is that EDCF and IEEE 802.15.4 MAC protocols cannot guarantee multimedia traffic QoS due to the collisions among the control packets. To tackle this problem, we suggest the reservation set procedure that reduces the number of the control packets. It is possible that data packets are transmitted from a source node to a destination at constant intervals by allocating the time slots to multimedia traffic packets. Due to unstable wireless channel or collision among the reservation control packets, the reservation table of a node and the neighbor nodes cannot coincide. To resolve this matter, the designated nodes broadcast the slot information during the switching period.

SQ-MAC protocol contributes to the performance improvement in terms of the end-to-end delay, jitter, and throughput in WMSNs. In the future, we will analyze energy consumption in the proposed scheme and more simulations will be operated.

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