A New Distributed Scheduling Scheme for guaranteeing quality of service (QoS) in Wireless Sensor Networks

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Abstract—We propose a new distributed scheduling scheme for guaranteeing quality of service (QoS) in WSNs. We first introduce the two multi-hop delay factors which can be caused by conventional TDMA scheduling: queueing delay and the delay by random link schedule. Next, this paper drives average end-to-end delay of the proposed scheduling scheme that sequentially schedules the slots on the path and the conventional random scheduling scheme that randomly schedules slots on the path. Finally, we simulate the TDMA network with the proposed link scheduling scheme and compare it with that of conventional random link scheduling scheme. From the analysis results, the more the average hop distance increases, the more the difference of the delay performance of both scheduling schemes increases. When the average number of hops is 2.66, 4.1, 4.75, and 6.3, the proposed sequential scheduling scheme reduces the average end-to-end delay by about 22%, 36%, 48%, and 55% respectively compared to the random scheduling scheme.

I. INTRODUCTION

A wireless sensor network (WSN) is a collection of spatially distributed sensors, each of which has computing power and can transmit and receive packets over wireless communication links. Scheduling of medium access plays an important role in the performance of WSNs, where carrier sensing multiple access (CSMA) and time division multiple access (TDMA) are two major medium access methods. In general, it has been known that CSMA consumes more energy than TDMA protocols because they waste energy in collisions and idle listening. Moreover, they do not give delay guarantees [1][2]. Therefore, this paper only focuses on the TDMA scheduling. Especially, we focus on time slot assignment to edges, called link scheduling, rather than nodes because of the two following reasons. First, if a time slot is assigned to a node then none of the two-hop neighbors of the node can be assigned the same slot. Thus, assigning time slots to edges increases the number of concurrent transmissions. Next, when time slots are assigned to nodes, each neighbor of the transmitting node has to switch on its transceiver, irrespective of whether it is the intended receiver or not. Consequently, nodes waste energy in receiving frames not intended for them. On the other hand, if each edge is assigned a slot, only the intended receiver switches on its transceiver [3].

In general, WSNs are application-specific. Therefore, each design (quality of service : QoS) requirement may be different for each application. In the literature, almost all the works [3]-[6] have focused on how to determine the smallest length conflict-free assignment of slots in which each link is activated at least once. For convenience of presentation, we refer to the conventional schedules employing minimum length slot assignment as random link schedule in the rest of this paper. However, they have some drawbacks in terms of delay. First, although such works reduce the frame size, they may bring about queueing delay, which can increase end-to-end delay in WSNs. Next, they did not consider the order of time slots being allocated on the path. Therefore, they also may experience the extra delay. On the other hand, in the field of wireless mesh networks, [7] proposed the scheduling scheme that considers the sequential link schedule. However, it necessarily needs a centralized base station so as to find the minimum length schedule, with the assumption that transmission order, i.e., priority of each node, is already known prior to scheduling. [8] that is a multi-channel extension of [7] still needs the centralized station. Therefore, we first introduces these two delay factors and propose a new distributed sequential link scheduling scheme jointly combined with routing in order to obtain a TDMA schedule with the minimum end-to-end delay, not the least frame length. Finally, we simulate a TDMA network for the performance comparison of the proposed scheduling scheme with the random link schedule.

The rest of this paper is organized as follows. Section II describes system model for the proposed sequential link schedule. Two delay factors and random/sequential link schedules in WSNs are introduced in section III. Section IV describes the proposed scheduling scheme. The performance evaluation via simulation is presented and discussed in Section V. Finally, conclusions and future works are drawn in Section VI and VII, respectively.
II. System Model

In this paper, we model WSNs with a topology graph connecting the nodes in the wireless range of each other. The network can be represented with a directed connectivity graph \( G(B, E) \), where \( B = \{ b_1, ..., b_m \} \) is the set of nodes and \( E = \{ e_1, ..., e_q \} \) is the set of directed links, and it is said that two nodes and are neighbors if \((u, v) \in E\). In the network, there is a set \( F \) of flows, and flow \( f(\in F) \) is specified by a node set \( R(f) = \{ p_1, ..., p_q \} \), where \( p_k \) is the \( k \)th node on the path(2 \( \leq q; \ k = 1 \): the source node, 1 \( < k < q \): the intermediate node(s), and \( k = q \): the destination node). Two channels are used in the network. One is for transmitting data, called data channel(DCH), and the other is for signaling by carrier sensing multiple access(CSMA), called control channel(CCH). Fig 1. shows the TDMA frame structure in DCH. DCH consists of \( L \) frames and a frame consists of \( N \) slots. Here, \( L \) and \( N \) are fixed numbers. The first parts(slots) in each frame is reserved for each node to transmit a beacon. A beacon contains the following information where \( n(1 \leq n \leq N) \) denotes the slot in the frame.

\[
\begin{align*}
ST_m(n) & : if \ node\ transmits\ data\ packets\ to\ its\ neighbors\ in\ slot\ n; 0: otherwise. \\
SR_m(n) & : if \ node\ receives\ data\ packets\ from\ one\ of\ its\ neighbors\ in\ slot\ n; 0: otherwise. \\
NT_m(n) & : if \ node\ has\ neighbors\ which\ transmit\ data\ packet\ to\ their\ neighbors\ in\ slot\ n; 0: otherwise.
\end{align*}
\]

By exchanging this information, each node in the network is aware of unassigned slots in each other’s frame and updates such information every time it receives the beacon from its neighbors. Each node gets the opportunity to transmit its beacon every frame, which is called a cycle.

III. Multi-hop Delay Factors

In this section, we describe two main factors that cause the end-to-end delay to increase in WSNs. We first introduce the queueing delay. And then, we show that random link schedule may increase the end-to-end delay and analyze the delay caused by the random link schedule.

A. Queueing delay

In previous works[3]-[6], TDMA scheduling generally is to find the optimal length schedules. However, such schedules may cause extra queueing delay, only to have a bad influence on delay-sensitive networks;i.e. not guaranteeing QoS of mission-critical events in WSNs. Fig. 2 presents a simple WSN where queueing delay occurs. Queueing delay in WSNs occurs when a relay node has multiple inbound links and only one outbound link. In Fig. 2, Node 3 and Node 8 have multiple inbound links, and Node 4, Node 6, Node 7, and Node SINK have one inbound link. Assume that a network employs the minimum link schedule. It is also assumed that Node 1 and Node 2 is supposed to send a packet to Node 3 in 1st slot and 2nd slot, respectively. And, Node 3 is scheduled with Node 4 in 3rd slot. It is also assumed that, in each node, a packet arrives from application layer concurrently with the start of a frame. In 3rd slot, Node 3 has two packets to send; one from Node 1 and the other from Node 2. However, Node 3 transfers the packet from Node 1 in 1st frame and does the packet from Node 2 in 2nd frame because it can transfer only one packet per frame. Intuitively, this kind of queueing delay may be avoided if the arrival of the packet from Node 1 is with the start of 1st frame and the arrival of the packet from Node 2 is with the start of 2nd frame; i.e. the queueing delay may be avoided if there is no concurrent packet arrival within one frame. In this case, Node 1 and Node 2 can transfer its own packet within one frame after each packet arrival. However, such a queueing avoidance may cause packets to experience another queueing delay in the middle of flows as shown in Fig. 2(queueing point 2). Accordingly, optimal length schedules have a merit that they have minimum frame length. However, such a merit may not be a demerit for the multi-hop transmission of delay-sensitive events in WSNs.

In order to evaluate the effect by the queueing delay in WSNs, this letter simulates the network as shown in Fig. 2. For the TDMA scheduling, distance-1 coloring is employed. We define node activation ratio as the ratio of the activated

![Fig. 1. Frame structure of the system.](image1)

![Fig. 2. Queueing points in WSNs.](image2)
number of nodes to the total number of nodes. If the total number of nodes is 10 and the node activation ratio is 0.4, only 4 nodes are activated during the simulation. Each activated node generates one packet during the simulation. Table I shows the average number of frames elapsed for transmitting one packet to the destination node in the network. From the simulation result, the average number of frames increases as the node activation ratio increases. That is, the more the packet generation nodes per frame is, the more the total queueing delay increases. This is because a relay node assigns only one slot for the outbound link although they have multiple flows in inbound link.

B. Delay by Random Link Schedules.

In this section, we briefly introduce random and sequential link schedule, and explain and analyze the delay by random link schedule. In addition to the queueing delay mentioned in previous section, WSNs may experience the delay by random link schedule. As mentioned before, conventional TDMA scheduling schemes were designed to find the minimum-length schedules. Such schemes do not take sequential link schedule into account, where “sequential” means that the outbound link is always scheduled to transmit after the inbound link on the path. Fig. 3 shows an example of random and sequential link schedules where the number of nodes, $q$, is 4 and the hop distance, $h$, is 3. It is assumed that the source node, $p_1$, is supposed to transfer packet $z_1$ from $i^{th}$ frame. If the slot allocation is performed randomly $(e_2 e_1 e_3)$, the destination, $p_4$, will receive the packet $z_1$ in $(i+1)^{th}$ frame(Fig. 3(b)). Let frame delay be the number of frames required to transfer a packet from a source to a destination. In this case, the frame delay of the random link schedule is 2-frame long. However, as in Fig. 3(c), the packet $z_1$ will be transferred to the destination, $p_4$, in $i^{th}$ frame because the slots on the path are sequentially allocated($e_1 e_2 e_3$). This case has frame delay that is 1-frame long. Therefore, if the sequential link schedule is not considered, the end-to-end delay may be quite large as the number of hop increases.

For the end-to-end delay analysis of random link schedule, this paper assumes that the traffic flow between all node pairs in the network is uniform and the processes of new packet arrival to the different nodes are independent. Therefore, we now concentrate on the characteristics of one node, and thus it is assumed that the node transmits a packet at the first slot of every frame. Consider a typical packet generated by the node. Because we assume the stop-and-go queuing system[9], the total packet transmission delay suffered by a packet, $D$, can be obtained by the following three components(Fig. 4); (1) the time between its generation and the end of the current frame, (2) the average frame delay that means the number of frames required to transfer a packet from the source to the destination, (3) the time between the start of the last frame and its reception by the destination. Since all frames are of equal length, the average time between the packet generation time and the end of the current frame is $0.5T_M$. Next, assuming that the slot for destination is randomly allocated in a frame, the time between the start of the last frame and packet reception by the destination is $0.5T_M + T$. Finally, the average frame delay $F_h (h \geq 2)$, can be calculated by

$$F_h = \frac{1}{h} \sum_{k=3}^{h+1} k! \left(\frac{h+1}{2}\right).$$

Proof : Now, we prove the above equation. It is assumed that a node is supposed to transfer the packet $z_1$ from $i^{th}$ frame in Fig. 3. If the slot allocation is randomly completed and $h = 3$, then such cases are as many as 3!; And, for each case, the frame delay is $T_M(e_1 e_2 e_3)$, $2T_M(e_1 e_2 e_2, e_2 e_1 e_3, e_2 e_3 e_1, e_3 e_1 e_2)$, and $3T_M(e_1 e_2 e_1)$ long. Thus, $F_3$ is $12T_M/3! = 2T_M$. If we consider each $h(\geq 2)$, we obtain

$$F_2 = 3T_M/2!, F_3 = 12T_M/3!, F_4 = 60T_M/4!, \ldots$$

Accordingly, the total end-to-end delay suffered by a packet, $D_r$, is given by

$$D_r = [0.5T_M + (F_h - 1) T_M + 0.5T_M + T] = F_h T_M + T.$$
A. Multi-hop Slot Assignment Process

First of all, this paper assumes that each node keeps global slot synchronization. Thus, all nodes know the starting time of every frame. As mentioned before, there are two main factors which cause end-to-end delay to increase in WSNs. In this section, we introduce a new sequential link scheduling scheme that resolves these two factors. First, the proposed scheduling scheme allocates one slot per each flow in the outbound link of an intermediate node in order to get rid of queueing delay. Second, the proposed scheduling scheme allocates the slots as jointly combined with routing in order to sequentially schedule the slots on the path. That is, when the routing protocol is operated, the multi-hop slot assignment process allocates the slots as jointly combined with routing in order to sequentially schedule the slots on the path. When the node transfers a SA_REQ packet as in [10]. A SA_RES packet includes the forwarding information composed of Assigned Slot Index and Next Node Address. Fig. 6 shows an example of multi-hop slot assignment process when a destination node, p3, receives a SA_REQ packet destined to itself. In Fig. 6, p1, p2, and p3 means the source node, the relay node, and the destination node in a flow, respectively. In this example, it is assumed that each node has four empty slots(1 to 4). First of all, p3 assigns the 3rd slot as a RN, and then sends SA_RES[Next Node address, Assigned Slot Index] to p2. When p2 receives SA_RES[p2,3] from p3, then it assigns the same 3rd slot as a T N. Next, for the communication between p1 and p2, p2 assigns 1st slot as a RN, and sends SA_RES[p3,1] to p2. Finally, the source node, p1 assigns 1st slot as a T N. When an intermediate node allocates a slot as a RN, it is important for the node to assign the left-side slot in comparison with the Assigned Slot Index within the SA_RES packet received, such that multi-hop links can be sequentially scheduled on the path.

B. Reducing frame size

We have assumed that initially the network has enough slots for scheduling, called Max_slot that is a network input parameter. To reduce the frame size, we employ a similar scheme with that proposed by [11]. The proposed scheduling scheme first starts to allocate the slots from the destination side. Therefore, the slot index reserved by the source node is the smallest slot index in a flow. After the multi-hop slot assignment process, all source nodes broadcast that slot index. If a source node has multiple flows, the smallest slot

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**Fig. 5.** Delay effect by random link schedule

Fig. 5 shows the delay effect by random link schedule when the frame length is 1- and 10-second. As the number of hops increases, the average end-to-end delay linearly increases.

**Fig. 6.** An example of the multi-hop slot assignment process.

- **Next Node**: A neighbor peer node on the path to the source/destination node.
- **Previous Node**: A neighbor peer node on the path to the source node.

If a source node has packets to be transmitted, then it broadcasts a SA_REQ packet. The SA_REQ packet propagation follows the path request (PREQ) packet propagation rules in [10]. If a node receives the SA_REQ packet broadcast through the network, then it creates a reverse path table. The reverse path table consists of Source Node Address, Destination Node Address, and Previous Node Address. This Previous Node Address will be set to Next Node Address when the node transfers a SA_RES packet as in [10]. A SA_RES packet includes the forwarding information composed of Assigned Slot Index and Next Node Address.
C. End-to-end Delay Analysis

Similar to the analysis in the random link schedule, the delay suffered by a packet, $D_s$, can be obtained by the following three components (Fig. 7): (1) the time between its generation and the end of the current frame, (2) the distance between the first slot and the slot assigned for the multi-hop away destination node, (3) packet transmission time in both the source node and destination node. The first component is the same as that in the case of the random link schedule, whose value is $0.5 T_M$, and the packet transmission time in both the source node and destination node is $2 T$. On the other hand, the second component, the distance between the first slot and the slot assigned for the multi-hop generation and the end of the current frame, is the same as that in the case of the random link schedule, this paper simulates a TDMA network with 100 nodes randomly distributed in a square area of 200 x 200 meter. It is assumed that the overhead by beacons in each frame is neglected. We change the network density by each node’s varying the communication range from 60 to 25 meters. If the communication range of a node decreases, the frame size decreases because the number of interfering nodes increases. As soon as all source nodes complete the multi-hop slot assignment process successfully, they generate one packet before transmitting it in the allocated slot. If the intermediate nodes receives packets from the previous node on the path, they transmit the received packet in the allocated slot for each flow. The reason why each source node generates only one packet is that this paper tries to compare the delay performance by both sequential and none-sequential schedules. Different traffic patterns or multiple packet generation may show the different results. However, the results under those environments also show the delay effect by both scheduling schemes. We consider different network density, which causes the average number of hops to vary in the simulated TDMA network. The more communication range increases in the TDMA network, the more network density increases. This paper considers 10 different random topologies and their simulation results are averaged. Some results such as average degrees of nodes, average number of hops, and the frame size in the simulated networks are shown in Table II.

V. PERFORMANCE EVALUATION

In this section, we explain the simulation scenario for the performance evaluation of random/sequential scheduling schemes. Next, we discuss the simulation result and compare it with that of the analytical result.

A. Simulation Scenario

To compare the proposed scheduling scheme with the conventional random link schedule, this paper simulates a TDMA network with 100 nodes randomly distributed in a square area of 200 x 200 meter. It is assumed that the overhead by beacons in each frame is neglected. We change the network density by each node’s varying the communication range from 60 to 25 meters. If the communication range of a node decreases, the frame size decreases because the number of interfering nodes increases. As soon as all source nodes complete the multi-hop slot assignment process successfully, they generate one packet before transmitting it in the allocated slot. If the intermediate nodes receives packets from the previous node on the path, they transmit the received packet in the allocated slot for each flow. The reason why each source node generates only one packet is that this paper tries to compare the delay performance by both sequential and none-sequential schedules. Different traffic patterns or multiple packet generation may show the different results. However, the results under those environments also show the delay effect by both scheduling schemes. We consider different network density, which causes the average number of hops to vary in the simulated TDMA network. The more communication range increases in the TDMA network, the more network density increases. This paper considers 10 different random topologies and their simulation results are averaged. Some results such as average degrees of nodes, average number of hops, and the frame size in the simulated networks are shown in Table II.

B. Simulation Results

Fig. 9 shows the average end-to-end delay (slots) vs. average number of hops in both random and proposed scheduling schemes. When $h = 2.02$, the average end-to-end delay of the proposed scheduling scheme is larger than that of the random scheduling scheme. This is because each destination node in the proposed scheduling scheme preferentially selects the slot assigning point in the latter half part of the frame when performing the slot allocation process. However, as the number of hops increases, such a effect decreases because of the increase of the delay by the random schedule. Meanwhile, the average end-to-end delay of the proposed scheduling scheme is bounded in $1.5 T_M(0.5 T_M + T_M)$, for it
sequentially schedules the slots on the path such that it gets rid of both the queueing delay and the delay by random link schedule. $0.5T_M$ means that a packet randomly arrives in a frame (refer to Fig. 7). In Fig. 9, the average end-to-end delay of the proposed scheduling scheme decreases as the frame size decreases due to the decrement of the average degree. This is because the number of hops increases (i.e., the decrement of the communication range), resulting in the decrease of the frame size. On the other hand, the average end-to-end delay of the random link scheduling scheme increases as the number of hops increases. This is because the frame delay of the random link scheduling scheme increases linearly as shown in Fig. 5. When the average number of hops is 2.66, 4.1, 4.75, and 6.3, the proposed sequential scheduling scheme reduces the average end-to-end delay by about 22%, 36%, 48%, and 55% respectively when compared to the random scheduling scheme.

VI. Conclusions

This paper proposed a new distributed link scheduling scheme combined with routing, which sequentially schedules the slots on the path, in order to get rid of the queueing delay and the extra delay by the random link schedule; ultimately to support QoS of mission-critical events in WSNs. According to the simulation results, the more the average hop distance increases, the more the differential of the delay performance of both scheduling schemes increases. The first reason for this is the queueing delay by the least frame scheduling policy of the conventional scheduling schemes. The second one is because of the increase of the frame delay due to the none-sequential characteristic of the random link schedule. From this result, it is said that either the larger the frame length is or the more the number of hops increases, the more important the sequential link schedule becomes.

VII. Future Works

For the future works, we are interested in extending the proposed scheduling scheme to an autonomous environment where either new nodes can efficiently assign time slots or existing nodes can release their slots on the path in a distributed manner.

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