

A Distributed Sequential Link Schedule Combined with Routing in Wireless Mesh Networks

Jae-Ryong Cha and Jae-Hyun Kim

This letter proposes a new distributed scheduling scheme combined with routing to support the quality of service of real-time applications in wireless mesh networks. Next, this letter drives average end-to-end delay of the proposed scheduling scheme that sequentially schedules the slots on a path. Finally, this letter simulates the time division multiple access network for performance comparison. From the simulation results, when the average number of hops is 2.02, 2.66, 4.1, 4.75, and 6.3, the proposed sequential scheduling scheme reduces the average end-to-end delay by about 28%, 10%, 17%, 27%, and 30%, respectively, compared to the conventional random scheduling scheme.

Keywords: Multi-hop, link schedule, QoS, real-time, WMN.

I. Introduction

Wireless mesh network (WMN) technology is a key technology for next-generation wireless networking. Previous works on WMNs were largely based on 802.11 wireless local area networks (WLANs). One of the major drawbacks of WLANs is that it is difficult for them to support the quality of service (QoS) required to sustain real-time applications, especially in multi-hop wireless networks. This is because packet transmission delay accumulates at every hop in multi-hop wireless networks. This letter proposes a new distributed scheduling scheme based on time division multiple access (TDMA), combined with routing to support the QoS of real-time applications in WMNs.

In a TDMA-based multi-hop environment, routing and time scheduling are key factors for guaranteeing the QoS. In [1]-[3], the QoS routing algorithms were proposed based on bandwidth reservation, which maintains the QoS information by exchanging control packets. The main concern of this letter is to address how to schedule the slots on a path. Therefore, this letter focuses on the scheduling scheme rather than the QoS routing. In [4]-[6], TDMA-based scheduling schemes were proposed for WMN. Most TDMA-based scheduling schemes for WMN were proposed to find the optimal length schedules. However, they do not take the sequential link schedule into account. If the sequential link schedule is not considered, then the end-to-end delay may be quite long. The scheduling scheme proposed by Djukic and Valaee considered the sequential link schedule [7]. However, it needs a centralized base station so as to find the minimum length schedule. Trung and Mo proposed a scheme, which is a multi-channel extension of [7] but still needs a centralized station [8]. In the field of wireless sensor networks, Gandham and others proposed a scheduling scheme that became the best-known distributed edge coloring scheme [9]. However, that scheme also experiences the delay by the random link schedule, ultimately increasing the end-to-end packet transmission delay.

II. System Descriptions

1. Network Model

In this letter, we focus on the wireless mesh backbone network. For the convenience of presentation, we refer to the wireless mesh backbone network as the WMN in the rest of this letter. We model the WMN with a topology graph connecting the nodes in the wireless range of each other. The

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network can be represented with a directed connectivity graph $G(B, E)$, where $B=\{b_1, \dots, b_m\}$ is the set of nodes and $E=\{e_1, \dots, e_g\}$ is the set of directed links, and it is said that two nodes u and v 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 $R(f)=\{P_1, \dots, P_q\}$, where P_k is the k -th node on the path. Two channels are used in the network. One is for transmitting data, called the data channel (DCH), and the other is for signaling by carrier sensing multiple access, called the control channel (CCH). The DCH consists of L frames and a frame consists of N slots. The first parts (slots) in each frame are reserved for each node to transmit a beacon. It is assumed that each node in the network is aware of unassigned slots in each other's frame by exchanging each beacon every frame and updates such information every time it receives the beacon from its neighbors.

2. Random/Sequential Link Schedules

Figure 1 shows an example of a random/sequential link schedule where $q=4$ and the hop distance, h , is 3. It is assumed that the source node, p_1 , is supposed to transfer packet z_1 from the i -th frame. In Fig. 1, e_1, e_2 , and e_3 are edges between p_1 and p_2 , between p_2 and p_3 , and between p_3 and p_4 , respectively. In Fig. 1(b), if the slot allocation is performed randomly ($e_2e_1e_3$), the destination will receive the packet z_1 in the $(i+1)$ th frame. Let frame delay be the number of frames required to transfer a packet from a source to a destination. Then, in this case, the frame delay of the random link schedule is two frames long. However, in Fig. 1(c), the packet z_1 will be transferred to the destination in the i -th frame because the slots on the path are sequentially allocated ($e_1e_2e_3$). This case has the frame delay that is one frame long. Therefore, if the sequential link schedule is not considered, then the end-to-end delay may be quite long.

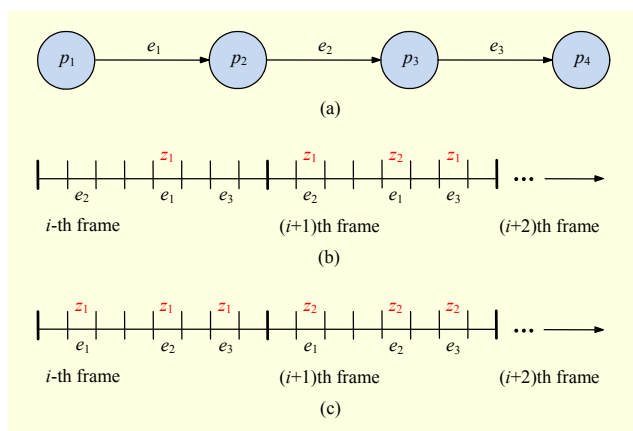


Fig. 1. (a) Topology of four-node network and example of (b) random link schedule and (c) sequential link schedule.

III. Proposed Sequential Scheduling Scheme

1. Multi-hop Slot Assignment Process

It is assumed that all nodes have enough slots for all the flows needed in the network. The multi-hop slot assignment process is simultaneously performed by using the routing table information while the routing protocol is executed. The following terminologies are used in the multi-hop slot allocation process.

- *Next Node*. A neighbor peer node on the path to the source/destination node.
- *Next Node Address*. The MAC address of *Next Node*.
- *Previous Node*. A neighbor peer node on the path to the source node.
- *Previous Node Address*. The MAC address of *Previous Node*.
- *Assigned Slot Index*. The slot index assigned for a flow in the DCH.

To accomplish the multi-hop slot assignment, two control packets, slot assignment request (SA-REQ) and slot assignment response (SA-RES), are used in the CCH. If a source node has packets to be transmitted, then it broadcasts an SA-REQ packet. The SA-REQ packet propagation follows the path request packet propagation rules in [10]. If a node receives the SA-REQ packet, then it creates a reverse path table. The reverse path means the path to the source node. The routing table for reverse paths includes *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 an SA-RES packet to the source node. In the proposed scheme, the actual multi-hop slot assignment is performed while the SA-RES packet is transferred. An SA-RES packet includes the forwarding information composed of *Assigned Slot Index* and *Next Node Address*. Figure 2 shows an example of the multi-hop slot assignment process when a destination node receives an SA-REQ packet destined for itself. In this example, p_1, p_2 , and p_3 mean the source node, the relay node, and the destination node in a flow, respectively. In this

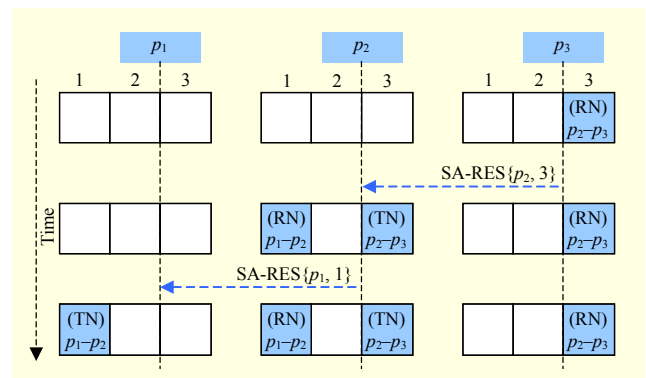


Fig. 2. Example of slot assignment process.

example, it is assumed that each node has three empty slots (1 to 3). First of all, p_3 reserves the 3rd slot as a receiving node (RN) and then sends an SA-RES{Next Node address, Assigned Slot Index} to p_2 . When p_2 receives an SA-RES{ $p_2, 3$ } from p_3 , then it reserves the 3rd slot as a transmitting node (TN). Next, for the communication between p_1 and p_2 , p_2 reserves the 1st slot as an RN, and sends an SA-RES{ $p_1, 1$ } to p_1 . Finally, the source node, p_1 , reserves the 1st slot as a TN. When an intermediate node allocates a slot as an 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.

2. Multi-hop Packet Delay Analysis

It is assumed that nodes are synchronized so that each node knows exactly when it can transmit. This letter also 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. Then, the total end-to-end delay suffered by a packet, D , can be obtained by the following three components (Fig. 3): i) the time between its generation and the end of the current frame, ii) the distance between the first slot and the slot assigned to the destination node, and iii) 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 $0.5T_M$, and the packet transmission time in both the source node and destination node is $2T$. On the other hand, the second

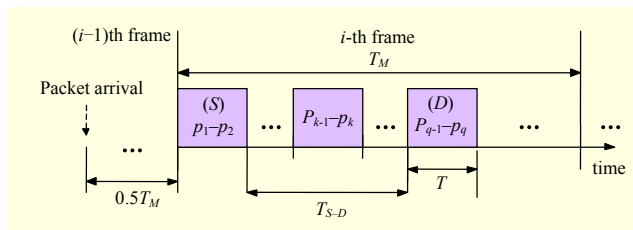


Fig. 3. Delay components in proposed scheme.

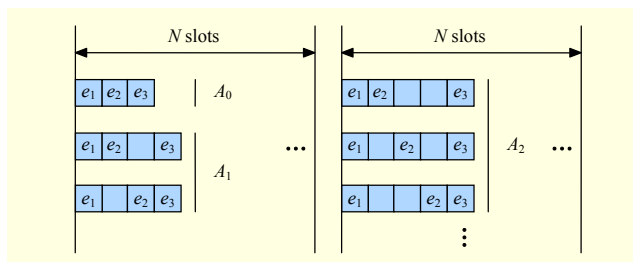


Fig. 4. Example of T_{S-D} calculation when $h=3$.

component, the distance between the first slot and the slot assigned for the destination node, T_{S-D} , can be calculated by averaging all possible combinations. Figure 4 shows an example of the T_{S-D} calculation when $h=3$. First of all, when there is no vacant slot (A_0), T_{S-D} is T , and such a case is only one (${}_{3-2}C_{3-2}$), where ${}_aC_b$ means the combination of a things taken b at a time. Secondly, when there is one vacant slot (A_1), T_{S-D} is $2T$ and there are two such cases (${}_{4-2}C_{3-2}$). Thirdly, when there are two vacant slots (A_2), T_{S-D} is $3T$ and there are three such cases (${}_{5-2}C_{3-2}$). Therefore, for all N , T_{S-D} can be calculated by

$$T_{S-D} = \left[\left(\sum_{j=h}^N {}_{j-2}C_{h-2} \times (j-2) \right) / \left(\sum_{j=h}^N {}_{j-2}C_{h-2} \right) \right] \times T, \quad (1)$$

where $N=T_M/T$. Accordingly, the total end-to-end delay suffered by a packet, D , is given by

$$D = 0.5T_M + T_{S-D} + 2T. \quad (2)$$

IV. Performance Evaluation

1. Simulation Scenarios

This letter simulates a TDMA network with 100 nodes randomly distributed in a square area of 200×200 meters. It is assumed that the overhead by beacons in each frame is neglected and the unit slot time (T) is set to 0.0002 s. As soon as all source nodes complete the multi-hop slot assignment process successfully, each source node generates one packet and then all source nodes simultaneously transmit these packets to their allocated slots. If the intermediate nodes receive packets from the previous nodes on the path, each such node transmits the received packet to the allocated slot for the flow. We consider a difference in network density, which causes the average number of hops to vary in the simulated TDMA network. We change the network density by varying each node's communication range from 60 m to 25 m. The more the communication range increases in the TDMA network, the more the network density increases. This letter considers 10 different random topologies, and their simulation results are averaged.

2. Numerical and Simulation Results

Table 1 shows the frame size as the communication range increases. We refer to the scheduling scheme proposed in [9] as REVISITED from this section on. This letter employs REVISITED for the performance comparison because REVISITED is the best-known distributed edge coloring scheme in the literature. In Table 1, the frame size of both scheduling schemes decreases as the communication range

Table 1. Frame size vs. communication range.

Communication range (m)	60	50	40	30	25
Average number of hops	2.02	2.66	4.1	4.75	6.3
Average one-hop degree	22.56	16.79	11.49	6.6	4.47
Frame size (proposed)	164	156	136	122	115
Frame size (REVISITED)	101	65	42	37	28

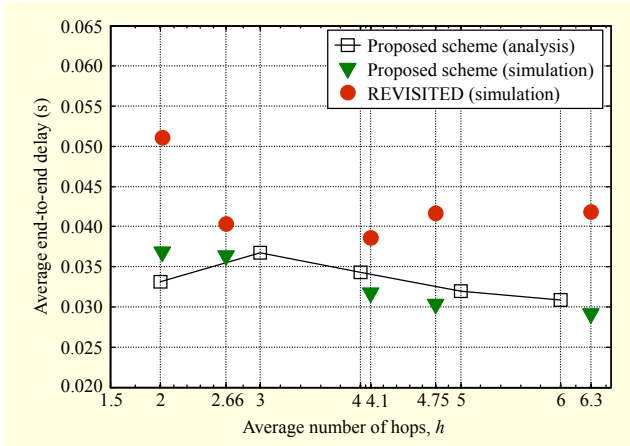


Fig. 5. Average end-to-end delay vs. average number of hops.

decreases. If the communication range decreases, the average hop distance increases. This causes the frame size to decrease because the number of interfering nodes per node decreases. Also, the frame size of the proposed scheduling scheme is relatively larger than REVISITED. REVISITED, which uses the smallest frame length policy, allocates only one common slot for all the flows going through an intermediate node. However, the proposed scheduling scheme allocates a different slot to each flow in an intermediate node. Figure 5 shows the average end-to-end delay of the proposed scheduling scheme and REVISITED as the number of hops increases. The analysis result is similar to the simulation result of the proposed scheduling scheme. In Fig. 5, the average end-to-end delay of the proposed scheduling scheme is bounded in $0.5T_M + T_M$ for it sequentially schedules the slots on the path, such that it gets rid of the delay by a random link schedule. That is, the average end-to-end delay mainly depends on the frame size. However, in REVISITED, the frame size and the hop distance have an influence on the average end-to-end delay. The greater the hop distance becomes or the longer the frame length is, the less delay performance REVISITED shows. Therefore, the delay performance of REVISITED is proportional to $h \cdot T_M$. When the average number of hops is 2.02, 2.66, 4.1, 4.75, and 6.3, the proposed sequential scheduling scheme reduces the average end-to-end delay by about 28%, 10%, 17%, 27%, and 30%,

respectively, compared to REVISITED.

V. Conclusion and Future Works

This letter proposed and analyzed a new distributed scheduling scheme combined with routing, which sequentially schedules the slots on a path to support the QoS of real-time applications in WMNs. According to the analysis results, the delay performance of the proposed sequential link scheduling scheme is better than the conventional link scheduling scheme. This is because the frame delay of the random link schedule increases due to the non-sequential scheduling characteristic of it.

For 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 a path in a distributed manner.

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