Dynamic TDMA Slot Assignment in Ad Hoc Networks

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Abstract

In this paper, we propose a TDMA slot assignment protocol to improve the channel utilization, which controls the excessive increase of unassigned slots by changing the frame length dynamically. Our proposed protocol assigns one of the unassigned slots to a node which joins the network. If there is no unassigned slots available, our proposed protocol generates unassigned slots by depriving one of the multiple slots assigned to a node, or enlarging frame length of nodes which can cause collision with each other. Moreover, by setting frame length as a power of 2 slots, our proposed protocol provides the collision-free packet transmission among nodes with different frame length. The simulation results show that our proposed protocol improves the channel utilization dramatically as compared with the conventional protocols.

1 Introduction

Recent advances in hardware and wireless communication technologies have led to an increasing interest in ad hoc networks which are temporarily constructed by only mobile hosts. TDMA (Time Division Multiple Access), which is a conventional wireless communication technique, has the ability to provide the collision-free packet transmission regardless of the traffic load. There has been many studies for applying TDMA to an ad hoc network. However, most of them do not take into consideration autonomous behaviors of mobile hosts, and thus they cannot assign time slots for new coming mobile hosts. A few conventional protocols [7, 8] that assign time slots for new coming mobile hosts show poor channel utilization because they must provide enough time slots for new coming mobile hosts and this causes a large number of unassigned slots.

In this paper, we propose a new TDMA slot assignment protocol to improve the channel utilization. Our proposed protocol changes the frame length dynamically according to the number of mobile hosts in the *contention area* and controls the excessive increase of unassigned slots. Here, the contention area is defined for each mobile host as the set of mobile hosts that can cause collisions of sending packets with each other, i.e., mobile hosts within two hops from the host.

The remainder of the paper is organized as follows. In section 2, we explain conventional TDMA protocols for ad hoc networks. In section 3, we explain the proposed slot assignment protocol which improves the channel utilization. In section 4, we show the results of simulation experiments. Finally, in section 5, we conclude this paper.

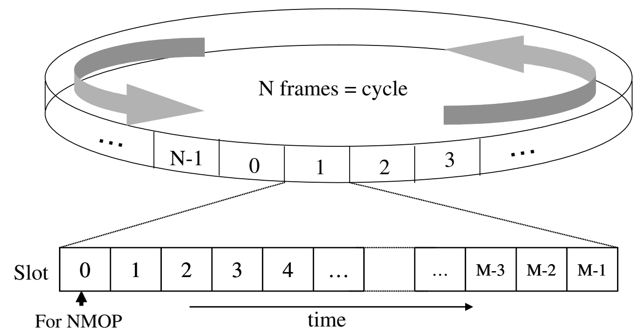

Figure 1. TDMA format in USAP

2 Related Work

Young [9, 10] has proposed TDMA slot assignment protocols in ad hoc networks, called *Unifying Slot Assignment Protocol (USAP)* and *USAP-Multiple Access (USAP-MA)*, that take into account autonomous behaviors of mobile hosts. In this section, we explain these protocols.

2.1 Unifying Slot Assignment Protocol (USAP)

Figure 1 shows the TDMA format in USAP, which consists of N frames and a frame consists of M slots. Here, N and M are fixed numbers. The first slot in each frame is reserved for a particular node to transmit a control packet, called NMOP (Net Manager Operational Packet). Thus, USAP allows N nodes to exist in the network, and each node gets the opportunity to transmit NMOP every N

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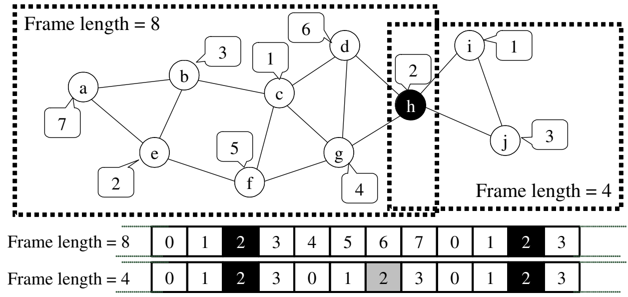

Figure 2. ABC (Adaptive Broadcast Cycle)

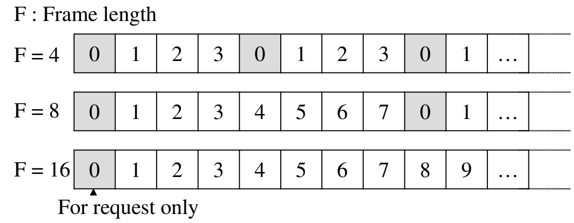

Figure 3. TDMA format in our protocol

frames, which is called a cycle. NMOP contains the following information. Here, suffix i denotes the node that transmits the NMOP and s $(0 < s < M)$ denotes a slot in the frame:

$STi(s)$: 1: if node i transmits a data packet to its neighbors in slot s, 0: otherwise.

$SRi(s)$: 1: if node i receives a data packet from one of its neighbors in slot s, 0: otherwise.

$NTi(s)$: 1: if node i has neighbors which transmit data packets to their neighbors in slot s, 0: otherwise.

By exchanging these information among neighbors, each node in the network knows unassigned slots in the frame and can assign one of the slots to itself. Because each node updates its own USAP information every time when it receives a new NMOP, USAP copes with the topology change of the network caused by movement of nodes.

In this paper, we call a node which newly joins the network as a *new node*. In USAP, at the moment when a new node joins the network, it is not assigned any slots and does not have information about neighbors. Thus, it firstly collects NMOPs by listening the network channel for a cycle and recognizes the slot assignments in its contention area. Then, the new node selects an unassigned slot and assigns it to itself. Finally, the new node announces the selected slot to its neighbors.

Since USAP needs to provide enough slots to assign to all nodes in the network, N and M should be large enough considering the case of existing the maximum number of nodes. As a result, the channel utilization usually becomes low due to a large number of unassigned slots.

2.2 USAP Multiple Access (USAP-MA)

To solve the problem of USAP, USAP-MA, which is an extension of USAP, introduces *ABC (Adaptive Broadcast Cycle)*. Figure 2 shows the outline of ABC. In ABC, the frame length and the frame cycle can be changed dynamically depending on the number of mobile hosts and the network topology. They can also be changed in parts in the network. Since it is not necessary to provide enough slots for new nodes in advance, the channel utilization of USAP-MA becomes higher than that of USAP. In addition, by setting the frame length as a power of 2, ABC can avoid packet collision at a node that is a boundary between subnetworks with different frame lengths. For example, in Figure 2, node h, which belongs to two subnetworks whose frame lengths are 8 and 4, respectively, can transmit packets without collision in both subnetworks by setting its frame length as 8.

USAP-MA improves the channel utilization by reducing unassigned slots with consideration of the number of nodes and the network topology. However, USAP-MA does not offer neither when and how to change the frame length nor how to select a slot assigned to a new node. Moreover, because unassigned slots appear in the latter part of the frame when the frame length is doubled, the channel utilization is still low.

3 Proposed Protocol

In this section, we explain our TDMA slot assignment protocol. Our protocol sets the frame length for a new node based on the number of nodes in its contention area and minimizes the number of unassigned slots to improve the channel utilization.

3.1 Frame Format

Figure 3 shows the TDMA format in our protocol. Similar to ABC, the frame length in our protocol is set as a power of 2. The first slot in the frame is reserved for new nodes to transmit control packets for requesting a slot assignment. Thus, no data packets are transmitted in this slot.

3.2 Packet Format

There are two modes, *transmit mode* and *control mode*, and each node behaves differently in different modes. Packets transmitted in each mode are as follows:

1. Transmit mode

   Data packet (DAT) contains the information on the frame length and slots assigned to the sender, and the maximum frame length of the sender and its neighbors. Of cource, data is also contained in DAT.

2. Control mode

   Request packet (REQ) is transmitted by only a new node. By sending this packet to neighbors, a new node requests the information on the frame length and assigned slots of all nodes in its contention area.

   Information packet (INF) contains the information on the frame length of the sender and slots assigned to the sender and its neighbors.

   Suggestion packet (SUG) is transmitted by only a new node similar to REQ. By sending this packet to the neighbors, the new node announces the frame length and its assigned slot.

   Reply packet (REP) is transmitted for the confirmation of a receiving SUG.

3.3 Slot Assignment

A new node selects a slot assigned to itself by the following four steps.

(1) Requesting the information on slot assignment in the contention area

At the moment when a new node joins the network, it knows neither the information on network topology nor slots assigned to other nodes in its contention area. To get these information, the new node listens the network channel and checks packets transmitted from the neighbors for a certain period. A DAT from a neighbor contains the information on its frame length, assigned slots, and the maximum frame length among itself and its neighbors. From these information, the new node knows the position of the first slot in a frame and the maximum frame length among all nodes in its contention area. Then, the new node sends a REQ in the first slot of the next frame.

Neighbors that have received the REQ transmitted from the new node transit to the control mode. Then, each neighbor of the new node gives information on its frame length and slots assigned to itself and its neighbors by transmitting an INF in its assigned slot. The transmission of the INF also has the meaning of declaring to its neighbors that the node has transited to the control mode. After all neighbors of the new node have transmitted INFs, all nodes in the contention area of the new node can recognize its appearance.

(2) Setting the frame length and grasping slot assignment

After collecting INFs from all neighbors, the new node sets its frame length. If all nodes in its contention area have the same frame length, the new node sets its own frame length to this length. Otherwise, the new node adopts the maximum frame length among all nodes in the contention area. Then, from the received INFs, the new node knows the

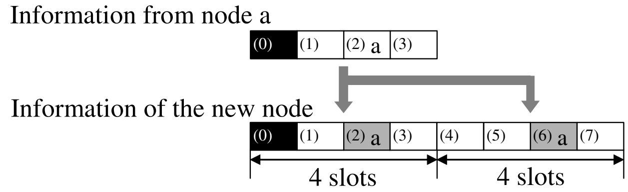

Figure 4. Copying information of node a

information on the slot assignment in the contention area. In the former case, this is done by only merging the information of all received INFs. In the latter case, the following process is required to get the slot assignment information. First, the new node creates its own slot assignment information of frame length, M_o, Here, M_o denotes the frame length that is set to the new node. Then, if the frame length of a neighbor is same as M_o, the slot assignment information of the neighbor in the received INF is copied to that of the new node. Otherwise, when $M_o = \alpha M_i$, the slot assignment information of the neighbor is copied repeatedly to every M_o/α slots from the first entry in that of the new node. Here, M_i is the frame length of the neighbor and α is an integer of a power of 2. In this way, the new node merges the information from all neighbors and creates its own slot assignment information. For example, when the new node sets its frame length as 8, the slot assignment information in the INF received from node a whose frame length and assigned slot is 8 and 4 respectively, is copied repeatedly to every 4 slots in that of the new node, as shown in Figure 4.

(3) Selecting an assigned slot

Based on the slot assignment information created at the new node, it selects a slot assigned to itself by the following three procedures. In Figure 5, Figure 6 and Figure 7, black and white slots denote the first slot and unassigned slots, respectively, and shaded slots denote slots assigned to other nodes in the contention area. Moreover, the number and the letter in each slot denote the slot number and the node to which the slot is assigned, respectively.

1. *Getting an unassigned slot (GU)*

   If some unassigned slots are found in the slot assignment information, the new node assigns one of them to itself. For example, as shown in Figure 5, when unassined slots 3 and 7 are found, the new node assigns a slot either 3 or 7 to itself.

2. *Releasing multiple assigned slots (RMA)*

   If no unassigned slot is found, the new node checks whether some nodes in the contention area are assigned multiple slots. If such nodes are found, the new node releases one of these slots and assigns it to itself. If there are more than one node to which multiple slots

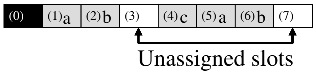

Figure 5. Getting an unassigned slots

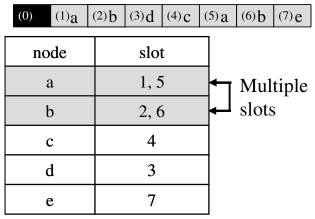

Figure 6. Releasing multiple assigned slots

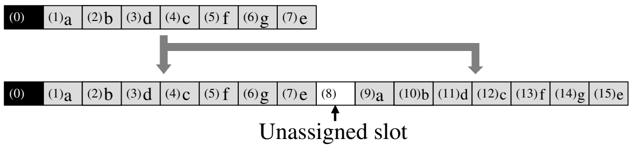

Figure 7. Doubling the frame

are assigned, the node with the largest number of assigned slots among them is chosen to release a slot. For example, as shown in Figure 6, when node a and b are assigned multiple slots, the new node selects a slot from slots 1,2,5, and 6 which are assigned to a and b, and assigns the selected slot to itself.

3. *Doubling the frame (DF)*

   If no unassigned slot is found and no node has multiple assigned slots which are able to be assigned to the new node, the new node doubles the frame length of the slot assignment information and copies the assignment information to both of the former half and the latter half of the doubled frame. As described above, the first slot in the frame is not assigned to any nodes. Therefore, after doubling the frame length, the first slot in the latter half becomes an unassigned slot. The new node assigns this slot to itself. For example, as shown in Figure 7, when the new node doubles the frame length (i.e., 16), slot 8 is assigned to itself.

(4) Announcement and Confirmation

After selecting a slot assigned to itself, the new node sends a SUG to its neighbors which contains information on the frame length and the assigned slot. When a neighbor receives this packet, it updates its slot assignment information. If the frame length of the neighbor is different from that in SUG, its frame length is changed in the same way in *(2) Setting the frame length and grasping slot assignment*.

After updating the information based on the received SUG, each neighbor sends a REP to its neighbors. Sending the REP implies the confirmation of the SUG for the new node and the announcement of updating the slot assignment information and exiting from the control mode for all neighbors of the sender. The sender and receivers of the REP adopt the new slot assignment and restart data transmission from the next frame. After receiving the REPs from all neighbors, the new node transits to the transmit mode.

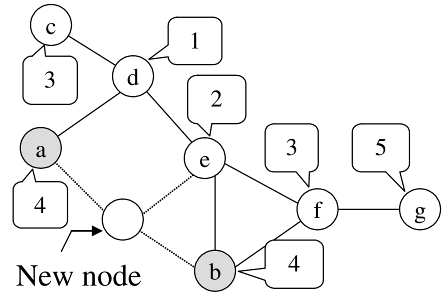

Figure 8. Example of conflicting an assigned slot

3.4 Detection of Conflict and its Solution

In our protocol, a conflict of slot assignment occurs when a new node connects to two or more nodes to which the same slots are assigned. In the example shown in Figure 8, a conflict occurs at a new node between node a and b in slot 4. When a new node detects the conflict, it solves the conflict in the following procedure:

1. Deleting a conflicting slot

   If there are some un-conflicting slots assigned to nodes causing the conflict, the conflicting slot is released from all the nodes except for that with the smallest number of assigned nodes. For example, as shown in Figure 9, when nodes a and b are assigned un-conflicting slots 7,11, and 15, conflicting slot 3 is released from node a to which more slots are assigned than node b.

2. Dividing the assignment

   If multiple slots are conflicting at the new node, these slots are divided to the nodes which have caused the conflict. For example, as shown in Figure 10, conflicting slot 3 and 11 are divided to nodes a and b, respectively.

3. Doubling the frame and dividing the assignment

   If a conflict occurs among nodes to which only one slot is assigned, the conflict cannot be solved with the current frame length. In this case, the frame length of these nodes is doubled and the slot assignment is divided in the doubled frame. For example, as shown in Figure 11, the space for conflicting slot is doubled by doubling the frame length, and it is divided to nodes a and b.

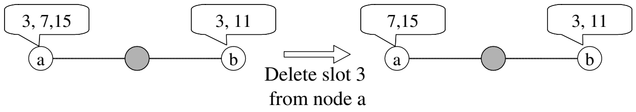

Figure 9. Deleting a conflicting slot

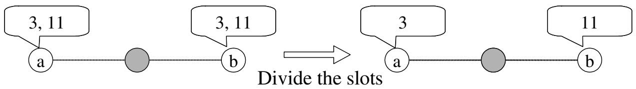

Figure 10. Dividing the assignment

After reconfigurating the slot assignment, the new node sends a SUG with the information on the reconfigured slot assignment and the selected slot. Neighbors which have received the SUG also reconfigure their slot assignment and send REPs with the reconfigured information. However, in this situation, the new node may fail to collect the information on the slot assignments correctly due to the collisions of INFs. If such a case occurs, the new node sends the information on the slot in which collisions have occured to all neighbors instead of the SUG. Neighbors of the new node, which have sent the INFs in the conflicting slot, retransmit the INFs after waiting for certain frames determined at random. This operation is repeated until the new node completes the collection of INFs from all neighbors.

3.5 Releasing Slot Assignment

When a node exits from the network, it releases slots assigned to itself and stops transmitting DATs. Neighbor nodes detect the exit of the node when no packets from the exited node have been received during the time of the frame length of the exited node. Then, they release the slots assigned to the exited node from their slot assignment information. In addition, they also release the slots assigned to nodes that have gone out of their contention areas due to the node's exit. After reconfiguring the slot assignment, neighbors of the exited node send the updated information to their neighbors. The nodes which have received this information reconfigure the slot assignment by releasing the slots assigned to the exited node.

4 Performance Evaluation

In this section, we show simulation results regarding performance evaluation of our proposed protocol. In the simulation experiments, we compare the performance of our protocol with USAP.

4.1 Simulation Environment

For simplicity, it is assumed that each node in the network does not move. A new node appears at a random posi-

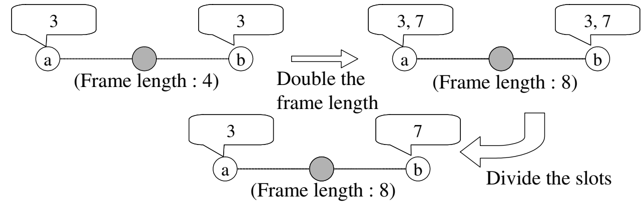

Figure 11. Doubling the frame and dividing the assignment

tion within the area in which the node can connect to at least one node. After the new node has appeared, no other node appears or exits from the network until the slot assignment to the new node is completed and all nodes transit back to the transmit mode. The number of nodes is initially 2, and increases one by one until the whole number of nodes in the network becomes 50.

For USAP, we set the frame length 50, in order to enable all nodes to be assigned slots certainly. Based on the slot assignment information made from the received NMOPs, the unassigned slot with the smallest slot number among all unassigned slots is assigned to the new node. On the other hand, in our protocol, the new node is assigned the slot with the smallest slot number among all unassigned slots when using GU. When using RMA, a new node is assigned the slot with the smallest slot number among the possible candidates.

4.2 Evaluation Criteria

In the simulation experiments, we evaluate the average *channel utilization* [7] of each protocol. The channel utilization of node i, ρ_i, represents the frequency that node i can transmit packets and is expressed by the following equation:

$$\rho_i = \frac{\text{the number of slots assigned to node } i}{\text{the frame length of node } i}. \quad (1)$$

The average channel utilization is the average of channel utilization in whole network. The higher the channel utilization of a node is, the more frequent the node can transmit packets. However, even if the average channel utilization of the entire network is high, the end-to-end communication throughput may not be high due to some intermediate nodes with low channel utulizations. This is because a packet transmission between the source and the destination is delayed at such intermediate nodes. Therefore, we also evaluate the fairness of slot assignment by comparing the variance of the channel utilization of all nodes.

4.3 Simulation Results

Figure 12 and Figure 13 show the simulation results. The vertical axis in the graph indicates the average channel uti-

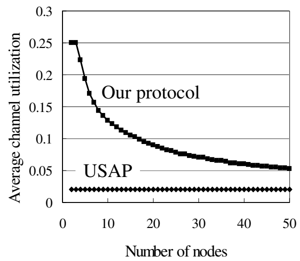

Figure 12. Average channel utilization

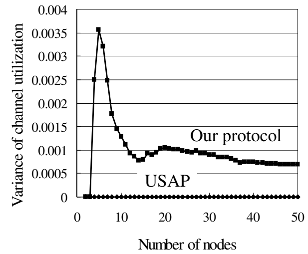

Figure 13. Variance of channel utilization

lization in Figure 12 and the variance of the channel utilization in Figure 13. The horizontal axis in both graphs indicates the number of nodes in the network.

From the result in Figure 12, the average channel utilization in USAP is very low because the fixed frame length causes many unassigned slots. On the other hand, the average channel utilization in our protocol is always higher than that in USAP. This result shows that the channel utilization is much improved by our protocol. Although the channel utilization decreases as the number of nodes increases, it is converging to a certain value (almost 0.05). Therefore, it can be concluded that our protocol acquires stablely high channel utilization. However, as shown in Figure 13, the variance of the channel utilization of our protocol is high, contrary to that of USAP being always zero. As mentioned above, such unfairness of slot assignment may cause the deterioration of end-to-end communication throuput. Thus, addressing this problem is a significant issue open to our future work.

5 Conclusion

In this paper, we have proposed a TDMA slot assignment protocol to improve the channel utilization. Our protocol avoids the increase of unassigned slots by minimizing the frame length of each node. Moreover, it provides the collision-free packet transmission among mobile hosts with different frame lengths by using the frame length of a power of 2. We also have conducted simulation experiments to evaluate the performance of our protocol. The results show that our protocol improves the channel utilization.

Our protocol can enlarge the frame length, but cannot minify it. Thus, as part of our future work, we plan to extend our protocol to have a facility of minifying the frame length effectively when a node exits from the network. We will also extend our protocol to have a facility of reassigning the slot for eliminating the unfairness of the channel utilization. In addition, we consider how to accommodate the movement of nodes.

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