Distributed TDMA MAC Protocol with Source-Driven Combined Resource Allocation in Ad Hoc Networks

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***Abstract*—MAC protocols for multimedia traffic transmission in mobile ad hoc networks have been studied steadily. It is still challenging to design an efficient protocol due to limited resource and multi-hop transmission property. CSMA-based MAC protocol is not suitable for multimedia traffic transmission due to hop-by-hop contention and collision. TDMA-based MAC protocol is appropriate to transmit time-sensitive traffic but slot allocation and sharing of slot information mechanism is essential. In this paper we propose a novel TDMA MAC protocol for mobile ad hoc networks, which includes distributed resource reservation and resource state sharing mechanism. In addition, we present an efficient collision resolution method. We show that our proposed TDMA MAC is suitable for delay-sensitive data transmission via simulations.**

***Keywords*-ad hoc networks, MAC protocol, TDMA, QoS.**

I. INTRODUCTION

In the next generation wireless communication systems, it is likely that there will be an increasing demand for fast deployment of independent mobile devices, e.g., establishing decentralized and dynamic communication links for emergency operations, industrial process monitoring, and military networks. A mobile ad hoc network (MANET) is an autonomous collection of mobile nodes connected by wireless links. Since a MANET is a self-configuring network of mobile nodes, it does not have/need any centralized coordinator such as base stations (BSs) or access points (APs). Typically, routing functionality is incorporated into each mobile node in MANET, so that mobile nodes can communicate with one another over wide range of distance. In MANET, it is required to setup multi-hop paths in a proactive or reactive manner, and the routing functionality relies on Medium Access Control (MAC) layer. So it has the same problem as that in conventional wireless networks, e.g., hidden/exposed terminal problem. Moreover, it might be challenging to meet end-to-end performance requirements due to limited radio resource, path set up/management overhead or mobility.

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To control the access to the medium for MANET, contention-based MAC protocol, i.e., IEEE 802.11 Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocol, has been typically considered [1], [2]. In this approach, every mobile node has a fair chance to transmit data by the Binary Exponential Backoff (BEB) algorithm to avoid collisions with mobile nodes in a network. When the network traffic becomes heavy, overall network throughput might be degraded due to frequent collisions. Moreover, end-to-end delay may increase when information is transmitted over multiple mobile nodes along a path.

Time Division Multiple Access (TDMA) MAC protocol is an alternative way to resolve shortcomings of contention-based MAC protocol [3]. In this approach, time resource is slotted and these time slots are assigned to mobile nodes in an orthogonal way, which results in contention-free medium access. A main challenge of TDMA MAC is how to assign/schedule specific time slots to mobile nodes. In MANET, since there is no centralized coordinator, time slots should be reserved in advance or assigned in a distributed manner. In addition, all mobile nodes have to be time-synchronized to utilize regular time slots. If delay-sensitive and real-time data are to be communicated over multi-hop links, MANET has to support quality of service (QoS).

There have been some research work to design distributed TDMA-based MAC protocol for ad hoc networks [4]–[9]. In [4], Unifying Slot Assignment Protocol Multiple Access (USAP-MA) is proposed. It provides broadcast and unicast transmission of datagram and high capacity or low latency streams, sparse and dense neighborhood optimization, and the ability to scale up to large networks. However, explicit method to resolve collision during slot reservation is not provided. The node activation multiple access protocol (NAMA) [5], assigns time slots to mobile nodes based on their priorities. Although NAMA allows collision-free broadcast transmissions, it may not be able to control the number of

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time slot allocations. In [9], Max Spatial Reuse Scheduling Algorithm (MARSA) is proposed. MARSA allows 1-hop distance neighbor nodes to communicate with other nodes in the same slot using directional antenna. In [8], cross layer design is provided for video streaming over wireless ad hoc networks using multichannels. The authors define Maximum Latency Rate (MLR) to provide differentiated traffic for TDMA structure. And congestion-aware routing protocol with congestion-aware metrics (MAC utilization and queue length of MAC) is proposed. GMAC [6] exploits the geographic positions of neighbors to construct a TDMA schedule. Although no negotiation phase is needed to assign time slots to nodes, GMAC relies on accurate location awareness, e.g., devices equipped with position awareness via a system such as Global Positioning System (GPS). In TDMA based multi-channel MAC (TMMAC) [7], every node negotiates which channel and time slot to use for data communications using IEEE 802.11 DCF, which results in frequent collisions when traffic becomes heavy.

In this paper, we propose a novel TDMA MAC protocol for MANET, which supports QoS and assigns time slots to mobile nodes in a distributed way. In the proposed MAC, each mobile node exchanges its routing information and resource allocation information to neighbors periodically in a pre-assigned time slot so that they can transmit network information without collisions. Using the resource allocation information from neighbors, each mobile node can reserve time slots for data transmissions without additional contention. In case of a reservation slot collision, our proposed MAC resolves the collision quickly by the preemption value without exchanging additional information. When a collision occurs, each node evaluates its own preemption value using neighbor information, and the node with higher preemption value occupies the collided time slot and the node with lower value tries reservation in another slot. The proposed MAC assigns priority to each node or traffic flow so that the node or the traffic flow with higher priority can reserve time slots before those with lower priority to support QoS.

The organization of the paper is as follows. The proposed MAC protocol including collision resolution mechanism is described in Section II. We simulate our proposed MAC in Section III. Finally, we make a conclusion in Section IV.

II. PROPOSED TDMA MAC

A. TDMA MAC Frame Structure

Our proposed TDMA MAC frame is composed of Network Information Broadcast (NIB), Resource Reservation (RR), and user data slots (see Fig. 1). We assume that the TDMA frame synchronization is provided by GPS, and that an NIB slot and an RR slot are pre-assigned to a specific node. So the number of NIB slot and an RR in a cycle are same as the number of nodes and NIB slot and an RR slot allocation relate to a node ID. These assumption is suitable for military, emergency, and private ad hoc network which

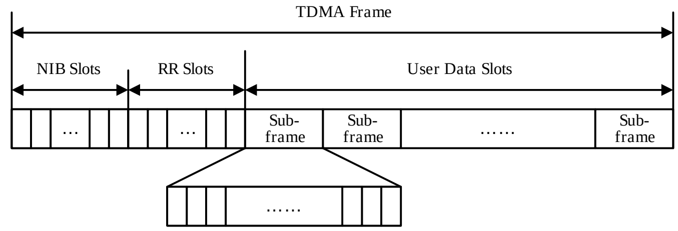

Figure 1. Proposed TDMA frame structure.

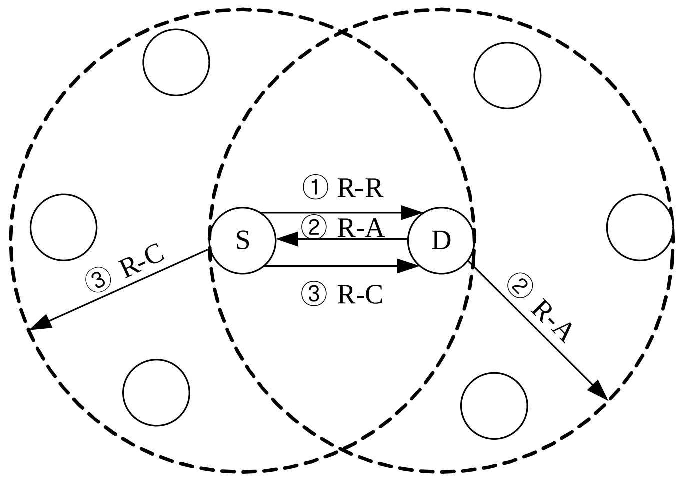

Figure 2. Resource reservation procedure during an R-R slot.

do not require self-organizing function. The NIB slots are used for broadcasting of routing information and resource allocation information. The broadcast message in an NIB slot is utilized to maintain the information of an ad hoc network. The routing information message can be different depending on an ad hoc routing protocol. If a reactive ad hoc routing protocol is used, the routing information may be route request or route reply. If a proactive ad hoc routing protocol is used, the routing information may be a hello message. In the NIB slots, resource allocation information is also broadcast too. The resource allocation information denotes the occupation status of user data slots. Each node in a network maintains the Resource Allocation Table (RAT). A node creates a resource allocation information message by referring to its own RAT. When neighbor nodes receive a resource allocation information message from a node it updates its own RAT. The RAT includes the resource allocation information for 3-hop neighbors to maintain user data slot occupation information of neighbors. The nodes over 3 hops do not interfere with one another, so they can use the same user data slot simultaneously.

In the RR slots, reservation messages are exchanged. The reservation is performed in a 3-way hand shake way. The source node who wants to send data transmits a Resource Request (R-R) message in the pre-defined RR slot. The R-

R message includes source ID, destination ID, sub-frame index, number of slots to use, and duration of slots to use in a sub-frame. A source node tries to reserve as many slots as the hop count of a path for source-driven combined multi-hop reservation. So hop-by-hop user data slot reservation is not necessary, which results in low end-to-end delay. When a node receives an R-R message, the node checks its own RAT and decides the requested user data slots are available. If the requested slots are available, the node transmits a Resource ACK (R-A) message including the information of the original R-R message. If they are not available, the node does not transmit anything. The source node waits for the R-A message before the R-A timer expires. If the source node receives the R-A message, the source node transmits a Resource Confirm (R-C) message including the information of the original R-R message. If the source node does not receive the R-A message before the R-A timer expires, the source node tries reservation again in the next TDMA frame. The nodes which overhear the R-A and/or R-C messages update their own RATs. The resource reservation procedure is depicted in Fig. 2.

A user data slot is composed of sub-frames. A user data slot is identified by a sub-frame index and a slot index in a R-R message. The slot index may be indicated by a bitmap of slots. So the sub-frame structure reduces the overhead of resource allocation information messages and resource reservation procedure. A node can request user data slots only in a sub-frame to prevent monopolization of user data slots. If a node wants to transmit best effort traffic, it requests slots in a sub-frame first, and if more slots are needed, the node requests slots in another sub-frame at the next TDMA frame. As a result, allocated slots for best effort traffic are slowly increasing.

The cycles for the transmission of NIB and RR messages can be defined appropriately. For example, if there are 8 nodes and the NIB cycle is 4 frames, node 1 and 2 use the NIB slots in the ith frame, and node 3 and 4 use the NIB slots in the $(i + 1)$th frame. The cycles of NIB and RR messages have to be defined carefully by considering network characteristics.

B. Collision Resolution

Our proposed TDMA MAC protocol provides collision-free access unless 2-hop neighbors use the same time slot (user data slot). In the proposed TDMA MAC, reservation is made based on RATs containing resource allocation information from 3-hop neighbors to avoid duplicate use of the same time slot. However, RATs cannot immediately reflect dynamically changing topologies. So collisions may happen, and network throughput might be degraded due to simultaneous transmission in the same time slot. For instance, at the initial stage of network, nodes have little knowledge about their neighbors, and the time slots which seem to be unoccupied may already be in use. In order to resolve such collision,

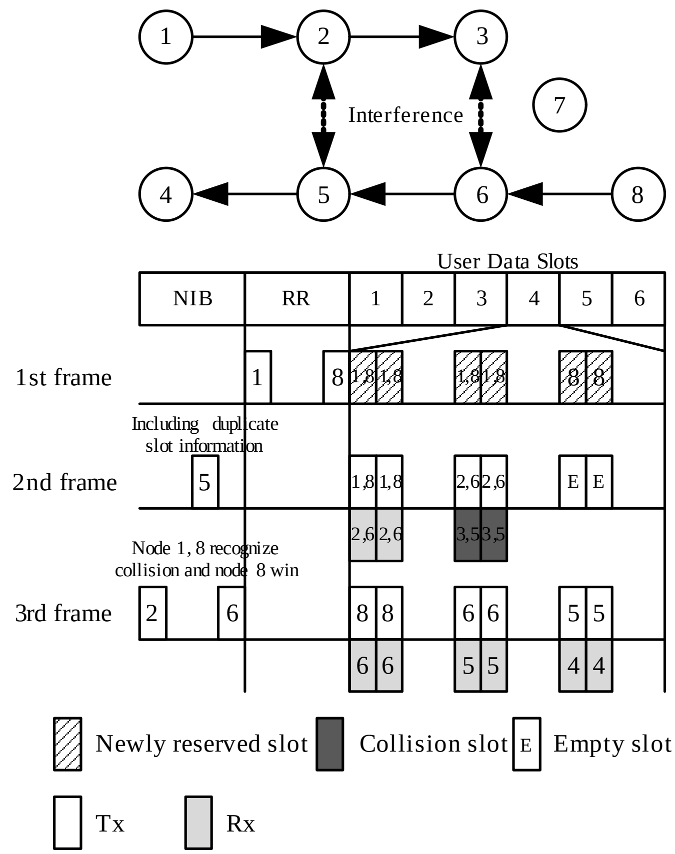

Figure 3. An example of collision resolution.

we present a simple and distributed method with minimum protocol overhead. It does not require any additional control message or negotiation between nodes. It refers to RATs exchanged in the NIB duration, which contains time slot schedule for upcoming user data slots.

A preemption value (V_{pre}) represents a priority for a certain time slot and a given node. A node with the highest V_{pre} value is allowed to use the collided time slot, and everyone else give up and look for another time slot which seems to be idle. So a node with the most important traffic is given a higher transmission priority. Providing fair transmission opportunity to the nodes with the same priority is also important. Thus we define V_{pre} as follows.

$V_{pre} = priority \& class \& \{(ID + T_{collision}) \% n\} \& ID$

where $\&$ and $\%$ denote bit level concatenation and modulo operation, respectively. $priority$ is the traffic priority, $class$ is the user priority, and ID is a uniquely identifiable address of a node. $T_{collision}$ is the time offset in microseconds from the beginning of a TDMA frame to the current time slot, and n is the number of nodes in the entire network. $T_{collision}$ can prevent a node or traffic from having relatively higher V_{pre} than any other node all the time, compensating unfairness in the transmission opportunity.

Tx ID	Sub-frame index	Slot index bitmap	Duration
1	4	110011000000	20
8	4	110011001100	15

Figure 4. An example of RAT at node 5.

On receiving RATs, each node in a network checks for duplicate reservations. If duplicate reservations are found, G_{col}, a group of nodes which are involved in a collision, can be defined. Each node in G_{col} calculates the preemption values V_{pre} of every nodes in G_{col}. Only one node with the highest V_{pre} in G_{col} is eligible to use the collided time slot, and other nodes are supposed to make reservation on other time slots in the next frame.

Fig. 3 shows how collision resolution works. Assume that there are voice traffic demands from node 1 to node 3 and from node 8 to node 4, respectively. Since it is voice traffic, a source node manages reservation not only for one-hop neighbor but also for all the nodes in the route. Node 1 makes a reservation on the slots at the 4th sub-frame. On successful reservation, neighbors of node 1 (node 4 and 5 in this case) can overhear R-A or R-C message and update their RATs. At the same time, node 8 makes another reservation on the slots at the 4th sub-frame, and unfortunately both reservations use the same slots in the same sub-frame. Nevertheless, reservation request from node 8 is acknowledged because messages from node 1 and 2 are not heard to node 6. However data transmission from node 2 to node 3 interferes with data transmission from node 6 to node 5 (collision). It is not possible for node 5 and node 2 to realize collision immediately, because RATs for both traffic has not been distributed yet. In the NIB duration of the next frame, RATs are flooded one-hop further, and while updating RAT at node 5, node 5 can find the source of collision (An example of RAT records for node 5 is given in Fig. 4). In the third NIB duration, node 2 and node 6 transmit RATs to node 1 and 8, respectively. Then node 1 and node 8 finally recognize collision.

Now node 1 calculates V_{pre}s of node 1 and node 8, and so does node 8. By comparing the values they can decide which node wins the collided time slot. For example, assume that $priority = 3$, $class = 3$, $n = 8$, ID of Node 1 is 8453, and that of node 8 is 1584. And assume that $T_{collision}$ is 100μs. Then, V_{pre} is calculated as follows.
V_{pre}(Node 1)=3&3&$\{(8453 + 100)\%8)\}$&$8453 = 3318453$
V_{pre}(Node 8)=3&3&$\{(1584 + 100)\%8)\}$&$1584 = 3341584$
Since V_{pre}(Node 1) $\leq$ V_{pre}(Node 8), node 8 wins the slot and node 1 should find idle slots at the next frame.

This collision resolution method can also be used to apply priority. If there is not enough slots to transmit a traffic flow, the node who wants to transmit checks its own RAT and tries to reserve the slots which are already used by a node or a traffic with lower priority (e.g., best effort traffic). Then the node with the already used slot recognizes that the slot collides and computes V_{pre}. The node will give up the slots due to lower priority.

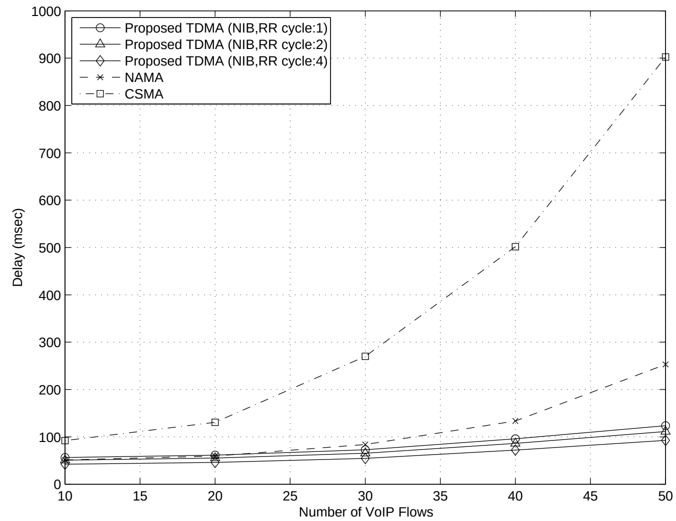

Figure 5. Delay of proposed TDMA, NAMA and CSMA.

III. PERFORMANCE EVALUATION

In this section, we present simulation results of the proposed TDMA MAC protocol, the existing NAMA [5] and the CSMA protocol. 100 nodes are distributed uniformly in 500mx500m space. The transmission range of a node is 200m. The PHY transmission rate is assumed to be 2Mbps. The Optimized Link State Routing (OLSR) is used for ad hoc routing protocol. The CSMA parameters are the same as those of IEEE 802.11b. The frame size of NAMA is 250ms and the data slot size is 0.4ms. The length of contention period to construct a contender set is 50ms. So there are 500 data slots in a frame. The frame size of the proposed TDMA MAC is 250ms when NIB and RR cycle is 1. The size of user data slots is 0.25ms. And the number of user data slots is 800. We consider Voice over IP (VoIP) traffic as delay-sensitive traffic. The rate of a VoIP flow is 6.4Kbps and the interval of VoIP packets is 30ms. And we use one FTP traffic for as background traffic. We vary the number of VoIP traffics from 10 to 50 and the NIB and RR cycle is 1, 2 or 4. The frame size of proposed TDMA MAC is changed with change of the NIB and RR cycle.

Fig. 5 shows the delay of VoIP traffic. The delay of the proposed TDMA MAC is slightly increased with the growth of VoIP traffics. The delay of the proposed TDMA MAC is below 150ms. As NIB and RR cycle becomes larger, the number of NIB and RR transmissions becomes smaller. So the delay of VoIP traffic improves. When defining NIB and RR cycle, mobility and traffic characteristics must be considered. The routing information and resource allocation

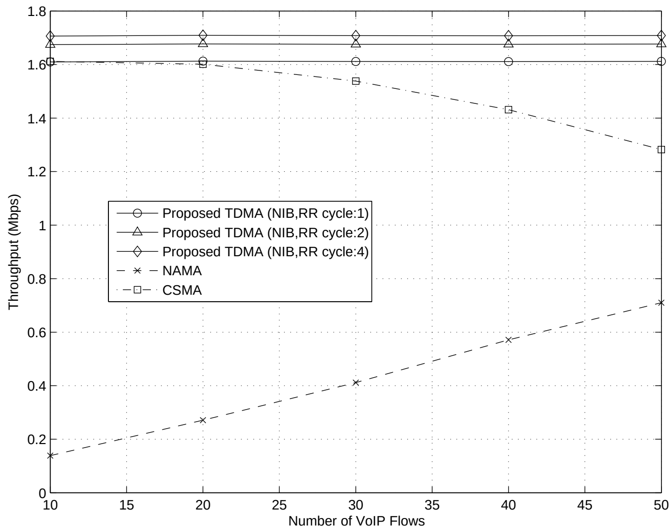

Figure 6. Total throughput of proposed TDMA, NAMA and CSMA.

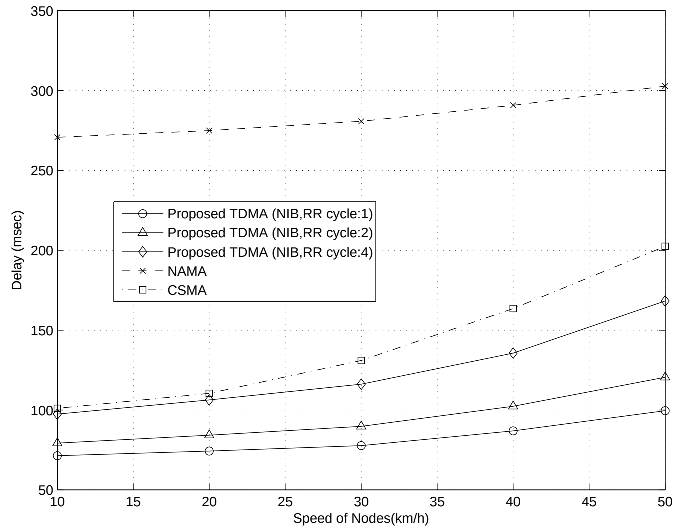

Figure 7. Delay of proposed TDMA, NAMA and CSMA with Mobility.

information in NIB is needed more frequently in the high mobility condition, and RR depends on traffic arrivals. The delay of NAMA is similar to the proposed TDMA protocol in low traffic load. However the delay of NAMA becomes larger than that of proposed TDMA as the number of VoIP traffics increases. The NAMA protocol may not schedule slots in parallel with traffic load, so the intermediate nodes in a routing path act as bottleneck nodes. The delay of CSMA increased rapidly with the growth of VoIP traffics. The CSMA can only accept less than 30 VoIP traffics if delay requirement is 300ms.

Fig. 6 shows total throughput of VoIP traffics and ftp traffic. The throughput of the proposed TDMA MAC is almost constant, which achieves the maximum throughput. As NIB and RR cycle increases, the throughput of the proposed TDMA MAC increases due to the relative growth of user data slots. The throughput of NAMA is relatively lower than other protocols. The NAMA protocol may not be able to differentiate traffic characteristics. So it allocates many slots to ftp traffic as well as VoIP traffics. The throughput of CSMA decreases rapidly as VoIP traffic increases. When there are many VoIP traffics, collision probability becomes high in CSMA.

Fig. 7 shows the delay of VoIP traffic with varying speed of nodes. We use random way point mobility model. The speed of nodes varies from 10 to 50Km/h. If a node reaches its destination, it waits a random time (0-30sec) and moves again. As NIB and RR cycle becomes larger, the routing information and slot allocation information are broadcast with long interval in the proposed TDMA protocol. The delay increase of the proposed TDMA protocol inherits from route change and collisions due to mobility. The delay of NAMA also increases as mobility increases. The main factor of delay increase is that the contender set becomes incorrect due to mobility. If the contender set is not perfect, there may be collisions. The delay of CSMA is influenced by routing protocol. Increasing delay of CSMA is caused by route failure.

IV. Conclusion

In this paper, we have proposed a new TDMA MAC protocol for MANET. In the proposed TDMA MAC, each mobile node broadcasts its routing information and resource allocation information to neighbors periodically in a pre-assigned time slot so that it can transmit network information without collision. Using the resource allocation information from neighbors, each mobile node can reserve time slots for data transmission without collision. In the proposed slot reservation procedure, three way hand shake mechanism lessens the hidden node problem. Although there might be reservation collision because of over 3-hop nodes, our proposed MAC resolves the collision by the preemption value without exchanging additional information. The simulation results show that our proposed TDMA MAC protocol is suitable for delay-sensitive data transmission in ad hoc networks.

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