Modifying the IEEE 802.11 MAC protocol for Multi-hop Reservation in MIMC Tactical Ad Hoc Networks

Youn-Chul Cho*, Sun-Joong Yoon** and Young-Bae Ko*
Department of Computer Engineering*, Department of NCW Engineering **
Graduate School of Ajou University, Suwon, Republic of Korea
younchul@uns.ajou.ac.kr, {sun2015, youngko}@ajou.ac.kr

***Abstract*— In multi-interface multi-channel (MIMC) based tactical ad hoc networks, QoS support is one of the main challenging issues for multi-hop transmissions. To support QoS in such a harsh environment, we propose a novel MAC scheme to minimize multi-hop as well as per-hop delay. The current IEEE 802.11 MAC protocols should contend to reserve the channel resource at every hop by each sender. The every-hop channel contention results in a degradation of end-to-end delay for multi-hop transmissions. The basic idea of our scheme is to make a "multi-hop reservation" at the MAC layer by using the modified RTS frame. It contains additional information such as destination information, packet priority, and hop count, etc. Our scheme can minimize the multi-hop delay and support the QoS of the critical data in real time (i.e., VoIP, sensing video data, Video conference between commanders). Our simulation study and numerical analysis show that the proposed scheme outperforms the IEEE 802.11 MAC.**

Keywords-component; Tactical ad hoc networks, Multi-hop MAC, Multiple Interface and Multiple Channel (MIMC)

I. INTRODUCTION

Tactical ad hoc networks, a collection of mobile nodes forming wireless multi-hop networks in battlefields, play a critical role in the network-centric warfare. Quick deployment, self-configuration, and maximizing mesh connectivity are key benefits of these disruptive networks. The available capacity of such a tactical ad hoc network can also be increased by having mobile nodes equipped with multiple interfaces and multiple channels (MIMC). For instance, the DARPA (Defense Advanced Research Project Agency) program called WNaN (Wireless Networks After Next) aims to develop large-scale, mobile ad hoc networks consisting of low-cost cognitive radios with multiple interfaces[1].

There are many challenging issues faced by tactical ad hoc networks as well, such as security, QoS (Quality of Service) support, and reliable communication. Especially, providing QoS service for multimedia streaming applications is challenging in harsh tactical environments, due to error-prone shared radio channels, insecure wireless medium with jamming threat, and fast node mobility. One simple observation to solve this problem of QoS support in multi-hop wireless networks is the fact that the end-to-end delay between a source and destination and thus per-hop delay should be minimized.

In this paper, we propose a novel scheme to minimize per-hop delay in MIMC based tactical ad hoc networks. The basic idea behind our scheme is to make a "multi-hop reservation" at the MAC layer, for which the existing RTS (Request-to-Send) frame needs to be modified. Note that the current IEEE 802.11 MAC protocol requires an every-hop channel contention by each sender (i.e., a single-hop reservation only), resulting in a degradation of end-to-end delay for multi-hop transmissions [2].

The remainder of the paper is organized as follows. Section II reviews some related work and Section III describes an overview of the IEEE 802.11 MAC protocol with a problem definition of possibly a long end-to-end delay. In Section IV, we explain the proposed MAC scheme and show how the 802.11 MAC is modified for a multi-hop reservation. Performance evaluation via not only numerical analysis but also simulation studies using the QualNet simulator [9] is presented in Section V. Finally, we conclude our work in Section VI.

II. RELATED WORK

There has been an effort in minimizing the end-to-end delay and enhancing the network throughput for multi-hop transmissions in mobile ad hoc networks. In [3], Arup et al. proposed the data driven cut-through multiple access (DCMA) protocol. DCMA uses Multi-Protocol Label Switching (MPLS) and labels which are assigned when a packet enters a network. DCMA is based on the enhancement of IEEE 802.11 with 4-way handshaking. While the 802.11 sends RTS, CTS (Clear-to-Send), DATA, and ACK frame separately, the DCMA protocol sends a unified ACK/RTS frame for a multi-hop transmission. The ACK/RTS frame, containing the receiver node's MAC addresses of ACK and RTS, will process two frames simultaneously. Therefore, the end-to-end delay and throughput become improved. However this scheme is operated in a single channel and exposed terminal problem may still exist in multi-hop transmission environments.

Ram et al. [4, 5] propose an access protocol called Channel Access over Path Segments (CAPS) using four orthogonal channels with a single transmitter. Among the four orthogonal channels, one channel is dedicated as a control channel. Using this method, CAPS is capable of reserving different channels for a single route having multiple hops. reservation at each hop is termed as

978-0-7695-4338-3/11 $26.00 © 2011 IEEE
DOI 10.1109/WAINA.2011.113

"segment", which is defined as a Segment Request-To-Send (S-RTS). The S-RTS created by the source node and transmitted multi-hop until it meets an existing flow. The modified S-RTS contains hop count, relay address, source address etc. The duration field in the original RTS and ACK are removed in Segment control fields. In this scheme, a control packet is relayed by the non-pipelined mode, whereas DATA frames are sent by the pipelined mode. The channels for multi-hops are allocated orthogonally in their scheme. The forwarding table for routing control is stored at the physical layer. It is based on a cross layer design, but not compatible with the existing IEEE 802.11 MAC.

Bononi et al. [6] propose a scheme of channel allocation and fast multi-hop MAC (FMH – MAC) protocol. It is also based on multi-channels and multi-interfaces environment but it divides a common control channel and data channels. FMH – MAC has two types: a fast-forward negotiation mode (FFNM) and a basic negotiation mode (BNM). FFNM provides a fast data relaying on multi-hop topologies and it applies a cut- through mechanism. FMH-MAC uses RCTS frames which combine the functionalities of RTS and CTS with flow identifier, data channel number and reservation period as additional fields. If the selected data channel is busy, the receiver node delivers the NCTS frame, which contains the time information about when the channel is going to be free. However, in tactical environments if a common control channel is jammed or have interference of any means, then the data channels are useless.

III. BACKGROUND AND PROBLEM DEFINITION

In this section we describe an overview of the IEEE 802.11 MAC protocol with its potential problem of multi-hop transmission. Fig. 1 shows one example of IEEE 802.11 MAC. We assume that node A has some packets to send to node D. If node B is currently transmitting a packet to node C, node A and D cannot transmit nor receive any packets at this moment owing to the NAV (Network Allocation Vector) generated from node B and C. First, node B sends a RTS frame to node C including the time information for NAV. The NAV operates via a virtual carrier-sensing. Most of the IEEE 802.11 frames have a duration field for NAV [8]. The duration is used to reserve the medium for a predefined time period. For example, the NAV by RTS and CTS frames are calculated by equation (1) and (2) respectively.

$$RTS\_NAV = 3 \times SIFS + CTS + DATA + ACK \quad (1)$$

$$CTS\_NAV = 2 \times SIFS + DATA + ACK \quad (2)$$

These NAVs cause long delay, resulting in poor QoS and throughput in multi-hop transmission. In order to support our argument, we performed a simulation study using the QualNet simulation [9].

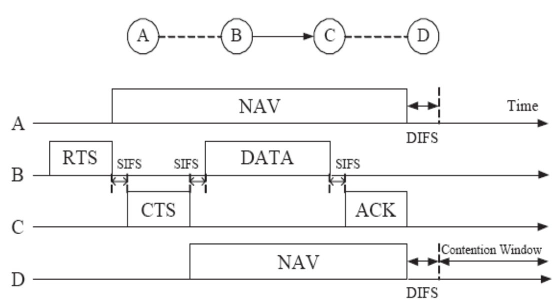

Figure 1. Example of IEEE 802.11 MAC

Table1. Simulation Results using QualNet
(End-to-end delay measurement for 4 nodes topology)

	Single channel/ interface	Two channels/ interfaces	Three channels/ interfaces
End-to-end delay (ms)	11.88	11.11	10.69

Table 1 shows the simulation results by varying the number of channels and interfaces in a linear topology of four nodes. Data rate of tactical ad hoc networks is not high, so we set the data rate to 2 Mbps and packet size is set to 512 bytes. Packet arrival interval is set to 10*ms* and the source node is set to node A and the destination node is set to node D. Here, there is no common channel. The average one hop delay is 3.43*ms*. The delay of a single channel / interface is the longest, because of intra-interference like the exposed node problem.

In case of 2 channels and 2 interfaces, node A and C send packets with the same channel and node B send packets with the other orthogonal channel. In case of 3 interfaces and 3 channels, node A, B and C send packets using orthogonal channels. Here, we can know that as the number of interfaces and channels increases, the end-to-end delay decreases in multi-hop transmission. The delay at 3 MIMC is the shortest because there is not intra-interference between the hops. Even though 3 multiple interfaces and channels are applied, the end-to-end delay can still be large because the IEEE 802.11 based MAC has to contend at each hop using back-off and exchange RTS and CTS frame before transmitting data. Every hop contention and exchange of control packets cause the increasing delay.

IV. MODIFIED 802.11 MAC PROTOCOL WITH MULTI-HOP RESERVATION

To minimize the end-to-end delay of the IEEE 802.11 based MAC using multiple interfaces and channels, we propose a multi-hop reservation scheme for multi-hop transmission. Our scheme modifies the RTS frame by adding some information. The *modified RTS* frame contains the destination IP address, hop counts, priorities, sequence numbers. These are enable to reserve multi-hop resource in advance.

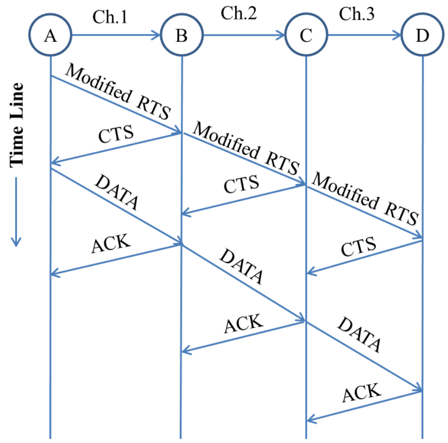

Figure 2. The concept of the proposed Scheme

Fig. 2 shows the concept of the proposed scheme. If node B receives the modified RTS frame, it sends CTS frame back to node A and sends the modified RTS frame to node C right away after checking the next hop node. Node C also forwards the modified RTS frame to node D before receiving the DATA. Later, when node C receives DATA from node B, it can send DATA to node D immediately without any delay of a contention and exchange of control packets. We assume that orthogonal channels are allocated for nodes within 3 hops (at minimum) to avoid intra-interference.

A. Modified RTS Frame and NAV setup

Fig. 3 depicts the modified RTS frame for multi-hop transmission. RTS in IEEE 802.11 MAC contains control frame, duration, receiver MAC address, transmitter MAC address, and FCS (Frame Check Sequence). Here, we add some information to send RTS frame to the destination node in advance. The destination IP address represents the destination address received from The Network Layer. The hop count is the multi-hop value which increments at every hop. The priority is divided into 2 types (High priority (0), Low priority (1)). For example, if we set the sensing data from UAV (Unmanned Aerial Vehicle) as high priority, our scheme applies the modified RTS frame to minimize end-to-end delay. Sequence control contains the sequence number of the DATA to identify RTS and the corresponding data packet. FCS is added one more for additional RTS frame size.

In case of our proposed scheme, the NAV of RTS frame is set as shown in equation (3) in case of (RTS + CTS + SIFS) < DATA. In case of (RTS + CTS + SIFS) ≥ DATA, the NAV of RTS is equivalent to equation (1). N is the number of hops. The number of hops indicates the distance

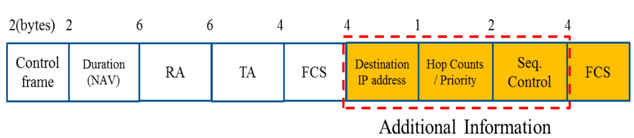

Figure 3. Modified RTS frame

of the current node from the source node. The NAV of CTS is calculated by equation (4).

$$\text{ModifiedRTS\_NAV} = (2 \times \text{SIFS} + \text{CTS} + \text{ACK}) + \text{N} \times \text{DATA} - (\text{N} - 1) \times \text{RTS} \quad (3)$$

$$\text{ModifiedCTS\_NAV} = (\text{SIFS} + \text{ACK}) + \text{N} \times \text{DATA} - (\text{N} - 1) \times \text{RTS} \quad (4)$$

B. The operation of the proposed scheme

Generally, if a node receives a RTS frame in 802.11 MAC, it sends back a CTS frame to the sender node. If a node receives the modified RTS frame, first, it sends back a CTS frame to the sender node. After that, the node received the modified RTS forwards the additional information as shown in Fig. 3 to the network layer. When the network layer receives the additional information, first, it compares the destination IP address with its own node address. If the destination IP address equals its own node address, it means this node is the destination node. In this case, the additional information is dropped and the node waits the data packet. If the destination IP address is not equal to its own node address, this node refers to the routing table to acquire the address of the next hop node. After acquiring the IP address of next hop node, it accesses the ARP (Address Resolution Protocol) table to get the MAC address of the next hop node. If the ARP table does not have the MAC address of the next hop node, this node acquires the MAC address by broadcasting a ARP request packet before the data packet is arrived. When the data packet arrives in the network layer later, it only needs to refer from the ARP table to acquire the MAC address. After checking the information of the next hop node, the network layer sends the updated additional information to the data link layer.

If the data link layer receives the additional information from the network layer, the number of hops is added by one. After that, the data link layer sends the updated modified RTS frame including updated information such as the next hop MAC address and hop counts etc. The modified RTS frame will be stored in the queue if the node is currently using all the channels and interfaces. When the channel and interface become available, the node transmits the modified RTS frame to the next hop node.

V. PERFORMANCE EVALUATION

A. Numerical Analysis

In this section, we numerically compare the end-to-end delay of the conventional IEEE 802.11 MAC with our proposed scheme. We assume that both schemes use multiple channels and multiple interfaces and assign orthogonal channels at minimum three consecutive hops. In here, we do not consider the propagation delay. We set R as the data rate (bits/sec) of link and d as the end-to-end delay. C means the number of hops. The end-to-end delay of node D using conventional IEEE 802.11 MAC is calculated by equation (5).

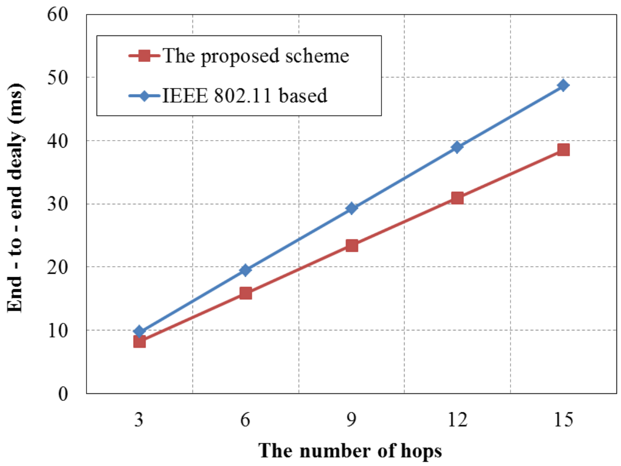

Figure 4. End-to-End Delay Analysis by varying Number of Hops

$$D_{conv} = C \times (T_{rts} + T_{cts} + T_{data} + 2 \times SIFS + backoff) \quad (5)$$

Where T_{rts}, T_{cts}, T_{data} and T_{ack} are the time for RTS, CTS, DATA and ACK respectively including the PLCP (Physical Layer Convergence Procedure) header. The PLCP header is 34 bytes and RTS is 20 bytes, CTS and ACK are 14 bytes in [8]. We set the data rate to 2Mbps. We set SIFS to 10*us* and slot time of backoff as 20*us*. We assume the number of backoff slots is 31. The end-to-end delay of the proposed scheme is shown in equation (6) and (7).

$$D_{prop} = (T_{modifiedrts} + T_{cts} + T_{data} + 2 \times SIFS + backoff) + (C - 1) \times (T_{data} + 2 \times SIFS)$$
$$T_{data} > T_{modifiedrts} + T_{cts} + SIFS \quad (6)$$

$$D_{prop} = C \times (T_{modifiedrts} + backoff) + 2 \times SIFS + (C - 1) \times T_{data}$$
$$T_{data} \leq T_{modifiedrts} + T_{cts} + SIFS, C \geq 2 \quad (7)$$

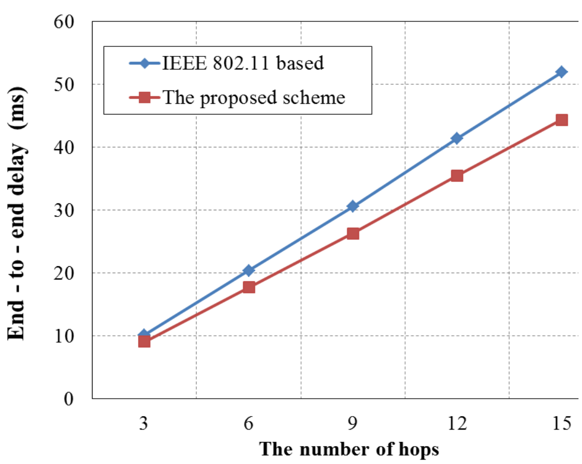

Figure 5. End-to-End Delay by varying Number of Hops

The results of end-to-end delay can be varied according to the number of hops. Fig. 4 shows the numerical analysis when data size is 512 bytes. We can know that end-to-end delay increases proportionally as the number of hops increases. The gap of end-to-end delay between the two schemes also increases according to the increasing number of hops.

B. Simulation Setting

Using QualNet 4.5[9], we have performed simulation to compare the proposed scheme with IEEE 802.11 based MAC in three channel and interface environment. The data rate is set to 2 Mbps considering SRW (soldier radio waveform) in [10] and we use CBR traffic over UDP. The packet arrival interval sets from 1*ms* to 100*ms*. The simulation time is 100 seconds. We evaluate the proposed scheme using following four metrics: *throughput, end-to-end delay, control packet overhead, and successful hit ratio*. The successful hit ratio represents the ratio of the delivered packets in the predefined end-to-end delay time among all received packets.

C. Simulation results

1) Linear Topology

First, we simulate the two protocols, IEEE 802.11 and the proposed scheme, in a linear topology. Fig. 5 shows the end-to-end delay when the number of hops increases from 3 to 15 for a single flow. The proposed scheme outperforms IEEE 802.11 based MAC as the number of hops increases. It is similar with numerical analysis. The end-to-end delay of the proposed scheme is enhanced nearly 16% at 15 hops.

Fig. 6 shows the successful hit ratio in case that the requirement of end-to-end delay is 10, 20, and 30*ms* respectively when the number of hops is three, six, and nine. Our scheme almost satisfies the requirement of end-to-end delay. However, IEEE 802.11 based MAC satisfies only 61% on average. As the number of hops increases, the deference of ratio is larger.

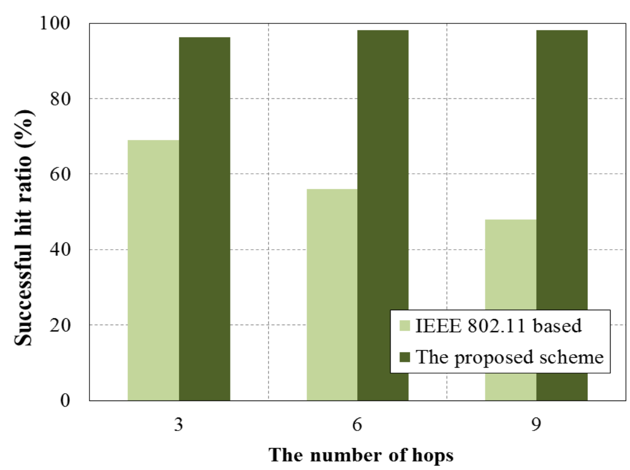

Figure 6. Successful Hit Ratio by varying Number of Hops

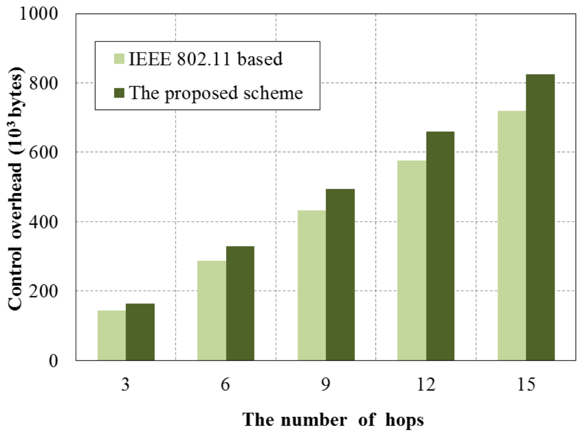

Figure 7. Control Packet overhead by varying Number of Hops

The control packet overhead means the sum of RTS, CTS, ACK frame. The RTS frame size of our scheme increases nearly 150 %. However, this is not much increase in terms of total control packets. Fig. 7 shows the control packet overhead when the packet arrival interval is 100*ms*. The control packet overhead approximately increases by 113% on average.

2) Grid Topology

We further simulate the end-to-end delay in a grid topology**.** 36 nodes are deployed in a 6x6 square area. Nodes are immobile and are placed in a grid. The number of flows varies from 2 to 5. Each flow has average 6 hops from the source to the destination. Each flow dissects through other flows. This kind of deployment is used for generating more transmission collisions in the network. The packet size is configured to 512 bytes, and high priority is given to the time critical message such as command control message, attack alarm message etc. Fig. 8 shows the end-to-end delay. As the number of the flows increases, end-to-end delay also grows. The main reason of increasing delay is resource constraints of the cross points between the flows. The orthogonal channels are not always guaranteed when several flows are operated at a time. However, the end-to-end delay of the proposed scheme is little better than that of the IEEE 802.11 based MAC by reducing the delay time when the orthogonal channels are partially guaranteed in a few hops. Fig. 9 illustrates the throughput. The performance of our scheme is little higher than that of IEEE 802.11 based. When the orthogonal channels and interfaces are partially guaranteed in a few hops, our scheme has shorter delay. By reducing partial delay time in a few hop at every flow, the proposed scheme enables to improve the throughput slightly.

3) Compatibility with legacy nodes

To apply the proposed scheme in real tactical environment, compatibility should be considered with the IEEE 802.11 MAC standards. Control frame (2 bytes) in IEEE 802.11 MAC frames has the type and sub-type information to distinguish the frame type. For example, if the type is 01 and the sub-type is 1011, this frame becomes the RTS frame [7]. We set the type and sub-type to 01, 1011 for identifying the modified RTS frame. If a legacy node using conventional IEEE 802.11 based MAC receives the modified RTS frame, it uses only general information of the RTS frame and ignores the additional information of backside. And then, it obeys the existing 802.11 MAC standard process. If a node receives the DATA frame from a legacy node and is not the destination node, this node sends the modified RTS frame to the next hop node after adding additional information.

Fig. 10 shows the end-to-end delay by varying the number of legacy nodes. The legacy node increases from 1 to 3 in a 15 hop linear topology. The delay of the proposed scheme is still better than that of the IEEE 802.11 based MAC, although it contains legacy nodes as the intermediate nodes.

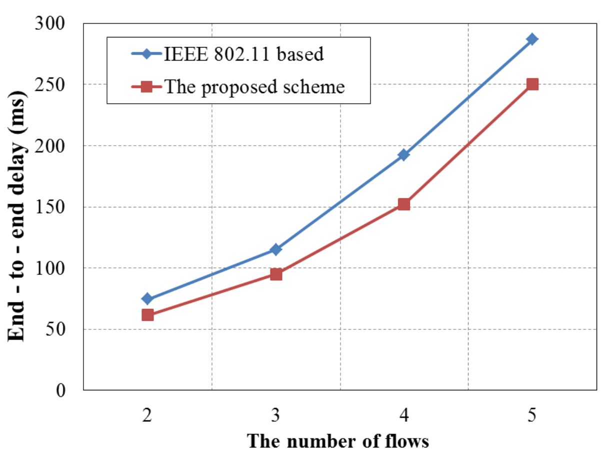

Figure 8. End-to-End Delay by varying Number of Traffic Flows in a Grid Topology

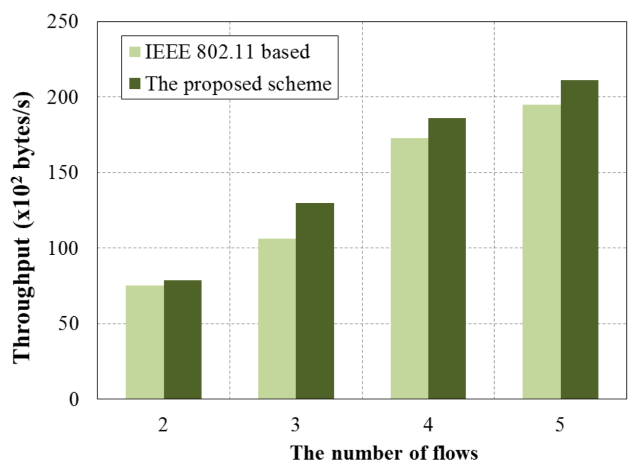

Figure 9. Throughput by varying Number of Traffic Flows in a Grid Topology

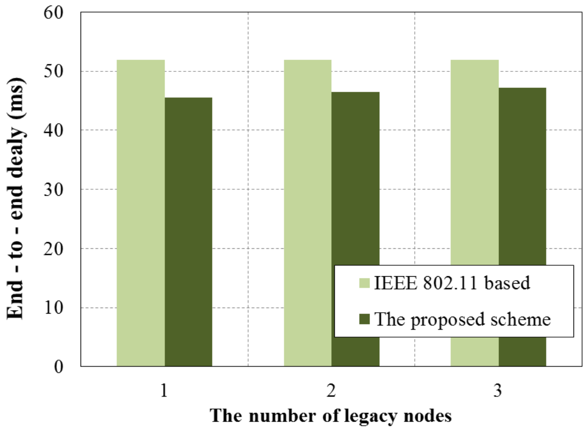

Figure 10. End-To-End Delay by varying Number of Legacy nodes

However, as the number of legacy nodes increases in our scheme, the end-to-end delay becomes similar to that of the IEEE 802.11 based MAC.

VI. CONCLUSION

There are various types of tactical messages that require high QoS services. In this paper, we propose the IEEE 802.11 based multi-hop MAC protocol in MIMC tactical ad hoc networks to support QoS and minimize the end-to-end delay. We modified the current RTS frame in IEEE 802.11 MAC by adding some additional information to send this RTS frame to the multi-hop destination node in advance. The modified RTS frame operates like an advance guard. The modified RTS frame is enable to reserve the resource to multiple hops before the DATA frame arrives. If an intermediate node receives the DATA frame, this frame can be delivered without contention and control packet exchange delay We compared our proposed scheme with general IEEE 802.11 MAC in several scenarios. As the number of hops increases, the gain of end-to-end delay of our scheme gets larger. In future work, we will enhance the general back-off scheme according to the priority of tactical messages and improve the NAV policy for sending large tactical files at once with minimum end-to-end delay.

ACKNOWLEDGMENT

This research was supported by the MKE(The Ministry of Knowledge Economy), Korea, under the ITRC(Information Technology Research Center) support program supervised by the NIPA(National IT Industry Promotion Agency" (NIPA-2010-(C1090-1021-0011))

REFERENCES

[1] P. Marshall, “DARPA Progress Towards Affordable, Dense, and Content focused Tactical Edge Networks,” in proc. IEEE MILCOM 2008.

[2] S. Xu T. Saadawi, “Does the IEEE 802. 11 MAC protocol work well in multihop wireless ad hoc networks?,” IEEE communication magazine, June, 2001.

[3] A. Acharya, A. Misra, and S. Bansal, “A Label-switching Packet Forwarding Architecture for Multi-hop Wireless LANs,” in proc. WoWMoM 2002.

[4] R. Ramanathan, F. Tchakountio, “Ultra Low Latency MANETs”, BBN Technical Memorandum No. TM-2023, available at http://www.ir.bbn.com/ ramanath/pdf/ull-techreport.pdf

[5] R. Ramanathan, F. Tchakountio, “Channel access over path segments for ultra low latency MANETs,” in proc. MILCOM 2007.

[6] L. Bononi, M.D. Felice, A. Molinaro, S. Pizzi, “A cross-layer architecture for efficient multi hop communication in multi-channel multi-radio wireless mesh networks,” in proc. Sensor, Mesh and Ad Hoc Communication and Networks workshop 2009.

[7] M. S. Cast, 802.11 Wireless Netwrok: The Definitive Guide, O’Reilly and Assocites, 1st Edition, 2002

[8] B. H. Walke, S. Mangold, L.Berlemann, IEEE 802 Wireless Sytems, John Wiley & Sons, Ltd, 2006.

[9] QualNet Simulator version 4.5, Scalable Network Technologies, www.scalable-networks.com.

[10] BG Jeffrey, W. Foley, “WIN-T incrasing the power of battlefield communications,” Army Communicator, Summer 2008 vol 33(3).