Dynamic Traffic Prioritization and TXOP Allocation in 802.11e Based Multihop Wireless Networks

Dongho Lee, Kwangsung Ju, and Kwangsue Chung

Communications Engineering Department, Kwangwoon University, Seoul, Korea

Summary
Multihop wireless network applications require that mission-critical data should be guaranteed to be delivered to their corresponding targets in time. However, end-to-end QoS (Quality of Service) assurance in multihop networks is a very challenging topic. Several schemes have been proposed to provide end-to-end delay assurance for multihop wireless network environment. However, these schemes do not consider the situation that the network is overloaded and burst collision is occurred. In this paper, we propose the dynamic traffic prioritization scheme for multihop wireless networks. The proposed scheme dynamically assigns priorities to traffic according to network status in order to achieve guaranteed end-to-end QoS in multihop wireless networks. In addition, we propose a dynamic TXOP (Transmission Opportunity) allocation scheme to support QoS for wireless networks, which assign the variable length of TXOPs to different traffics based on the precise channel condition prediction.

Key words:
Multihop wireless networks, MAC protocols, E-to-end QoS, Dynamic traffic prioritization

1. Introduction

The multihop wireless environment is characterized by harsh propagation channels, interference, frequent and rapid changes in network topology, a lack of centralized network control, and the requirement of multihop communication from source to destination. Many of present wireless network applications will require that mission-critical data should be guaranteed to be delivered to their corresponding targets in time. However, end-to-end QoS (Quality of Service) assurance in multihop networks is a very challenging topic [1][2].

In order to provide QoS in a wireless network, the IEEE 802.11e MAC (Medium Access Control) protocol [3] is proposed. The IEEE 802.11e MAC protocol introduces the HCF (Hybrid Coordination Function), which defines two new MAC mechanisms namely, HCCA (HCF Controlled Channel Access) and EDCA (Enhanced Distributed Channel Access). EDCA achieves service differentiation by introducing different ACs (Access Categories) and their associated backoff entities. Although EDCA is designed to provide QoS assurance, it does not fit into multihop wireless environment because it has no notion of end-to-end QoS guarantee.

The APHD (Adaptive Per Hop Differentiation) scheme [4] is designed to extend and incorporate EDCA technique into multihop wireless network environment, aiming at provide end-to-end delay assurance for time sensitive application. APHD attempts to utilize adaptive service differentiation at each intermediate hop to achieve an end-to-end delay requirement. However, APHD scheme does not consider the situation that the network is overloaded and burst collision is occurred. In this situation, APHD scheme adjusts priority of most packets to the highest level because the scheme only takes account of satisfying the end-to-end delay requirement. It leads to more collisions and failure of end-to-end delay guarantee even if the packet is originally mission-critical.

In this paper, we propose the dynamic traffic prioritization scheme for multihop wireless networks. The proposed scheme dynamically assigns priorities to traffic according to network status and the newly defined traffic categories in order to achieve guaranteed end-to-end QoS in multihop wireless networks. In order to calculate available network resources more accurate than previous schemes, the scheme adjusts priority by considering the link reliability. In addition, the proposed scheme performs priority resetting when the burst collision is occurred. In addition, we propose a dynamic TXOP (Transmission Opportunities) allocation scheme based on the precise channel condition prediction. The TXOP is a novel mechanism, proposed by IEEE 802.11e, for burst packet transmission within wireless networks. However, its use is not optimized. Our proposed scheme utilizes dynamic bandwidth allocation rather than the default TXOPs, which improves the network reliability by allowing more failure recovery times, such as the retransmission time required to recover packet losses.

The rest of this paper is organized as follows. In Section II, we provide a summary of mechanisms for QoS support defined in IEEE 802.11e networks and present research works related to the dynamic traffic prioritization schemes for multihop wireless networks. The details of the proposed schemes are then presented in Section III. In Section IV, the simulation results are described. Finally, Section V presents the conclusion and discusses our future work.

Manuscript received February 5, 2012
Manuscript revised February 20, 2012

2. Related Work

In this section, IEEE 802.11e MAC protocol and the EDCA mechanism are described. In addition, the existing research works on dynamic traffic prioritization schemes in multihop wireless networks are discussed.

2.1 IEEE 802.11e EDCA Mechanism

IEEE 802.11e [3] was proposed to supplement IEEE 802.11 MAC [5] by providing service differentiation in WLAN. The IEEE 802.11e defines a set of QoS enhancements for WLAN applications through modifications to the MAC layer. The standard is considered of critical importance for delay sensitive applications, such as voice over WLAN and streaming multimedia. The IEEE 802.11e MAC protocol introduces the HCF, which defines two new MAC mechanisms namely, HCCA and EDCA. EDCA achieves service differentiation by introducing different ACs (Access Categories) and their associated backoff entities.

	AC_VO [0]	AC_VI [1]	AC_BE [2]	AC_BK [3]
AIFSN	2	2	3	7
CWmin	3	7	15	15
CWmax	7	15	1023	1023

Fig. 1 Prioritized channel access category with the QoS parameters

In EDCA mechanism, traffic prioritization is based on the four ACs, i.e., voice, video, best effort, and background, listed in Fig. 1. A station with high priority traffic waits a little less before it sends its packet than a station with low priority traffic. Applications map each data frame onto a given AC, and add the frame to one of four independent transmit queues. Each AC has different queue, different AIFS (Arbitration Interframe Space), and different contention window parameters (CWmin, CWmax). Frames with the highest priority tend to have the lowest AIFS and backoff values, so they have a better chance of getting a TXOP earlier. The differentiation of these contention parameters allows all traffic categories to have different probabilities of winning the channel contention. For each AC, the AIFS duration is derived from the AIFSN (AIFS Number). The AIFSN indicates the number of slots after an SIFS (Short Interframe Space) that a station should wait before either invoking a backoff or starting a transmission. For each AC, the backoff duration is computed as the sum of the AIFSN and a random value from zero to the CW. The CW is initially set to a CWmin value that depends on the AC, and it is doubled following each collision until a maximum value CWmax is reached. Fig. 2 shows the differentiated channel access mechanism of the 802.11e EDCA scheme.

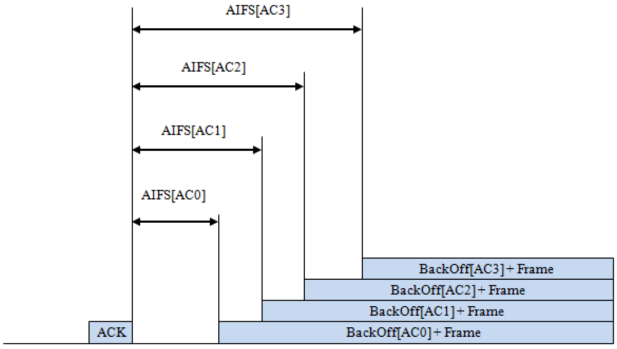


Fig. 2 The channel access mechanism of the 802.11e EDCA scheme

To mitigate the impact of the overheads and improve the system efficiency, the TXOP scheme has been proposed in the IEEE 802.11e protocol. Different from IEEE 802.11 where a station can transmit only one frame after winning the channel, the TXOP scheme allows a station gaining the channel to transmit the frames available in its buffer successively provided that the duration of transmission does not exceed a certain threshold, namely the TXOP limit. As shown in Fig. 3, each frame is acknowledged by an ACK after a SIFS interval. The next frame is transmitted immediately after it waits for an SIFS upon receiving this ACK. If the transmission of any frame fails the burst is terminated and the station contends again for the channel to retransmit the failed frame. The TXOP scheme is an efficient way to improve the channel utilization because the contention overhead is shared among all the frames transmitted in a burst. Moreover, it enables service differentiation between multiple traffic classes by virtue of various TXOP limits.

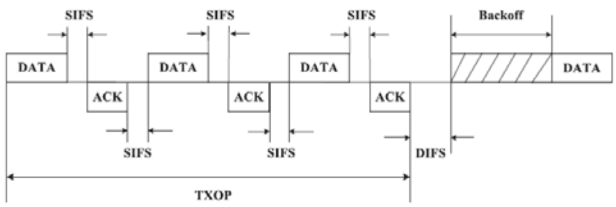


Fig. 3 Procedure of the burst transmission during a TXOP

2.2 Dynamic Traffic Prioritization Schemes

There are several studies of dynamic traffic prioritization to provide end-to-end delay assurance based on EDCA scheme for multihop wireless networks. Iera et al. [6][7] proposed schemes to improve QoS and throughput in single and multi-hop WLAN through a dynamic priority assignment where traffic priorities are determined dynamically at each hop, which is distinguishable from the fixed traffic categorization in EDCA. The main concepts of these schemes are to dynamically assign priorities to each application, rather than to a certain traffic class as indicated by IEEE 802.11e, when accessing the channel. The objective of assigning priorities is guaranteeing all connections a minimum average throughput according to the applications' requirements.

The APHD (Adaptive Per Hop Differentiation) scheme [4] is designed to extend and incorporate EDCA technique into multihop wireless network environment, aiming at provide end-to-end delay assurance for time sensitive application. APHD computes a per-hop delay budget at each participating node for the packet based on end-to-end delay requirement supplied by the application. The per-hop delay budget is the amount of time a packet is allowed to spend at one node such that it can meet the total delay requirement. When a node is aware that the budget is low, it speeds up the transmission by raising the priority level of such packets over those that have higher budget. In addition, APHD scheme only raises priority level at places where it is needed, allowing more efficient network utilization.

In ReAP (Reallocative Priority) scheme [8], each packet has a deadline based on which the laxity is computed at each hop. The priority is then recomputed as a ratio of current laxity to the remaining hops, giving higher priority to those that have high laxity and longer hops to traverse.

Above-mentioned EDCA based dynamic traffic prioritization schemes do not consider the situation that the network is overloaded and burst collision is occurred. It leads to more collisions and failure of end-to-end delay guarantee.

3. Proposed Schemes

In order to achieve guaranteed end-to-end QoS in multihop wireless networks, we propose the dynamic traffic prioritization scheme for multihop wireless networks. The proposed scheme dynamically assigns priorities to traffic according to network status. In addition, we propose a dynamic TXOP allocation scheme to support QoS for wireless networks, which assign the variable length of TXOPs to different traffics based on the precise channel condition prediction.

3.1 Traffic Prioritization Scheme

The proposed traffic prioritization scheme dynamically assigns priorities to traffic according to network status and delay requirement, in order to achieve guaranteed end-to-end QoS in multihop wireless networks. Process of the scheme is similar to another dynamic traffic prioritization scheme. The scheme is categorized into node state monitoring and priority adaptation. In node state monitoring, each node calculates per class delay. In priority adaptation, nodes assign traffic category to packet using per class delay.

In order to calculate per class delay more accurate than previous schemes, MTM (Medium Time Metric) [9] is considered. Due to the shared nature of wireless networks, not only individual links may interfere but transmissions compete for the medium with each other in the same geographical domain. Therefore, the MTM assigns a weight to each link in the network that is proportional to the amount of medium time used by sending a packet on that link and measuring transfer rate or link reliability. Our scheme also uses link reliability in a similar way in order to calculate the accurate medium access time. Equation (1) shows the per class delay of priority level i. *l* is the link between nodes that transmit and receive current packet *p*. *r(l)* is the reliability of link *l* is calculated by successful delivery ratio of data packets and ACK packets.

$$per\_class\_delay(i) = \frac{size(p)/rate(l)}{r(l)} \tag{1}$$

In priority adaptation, nodes assign traffic category to packet using application requirements and per class delay. In application layer, a packet with originally assigned priority is delivered to MAC layer. In QoS mapping module of MAC layer, the packet is queued in different queue according to packet priority. If the packet priority is AC[1] or AC[2], the packet is enabled to use multiple queues by considering of multihop transmission delay. Queuing is determined by delay budget and priority index. Equation (2) shows the delay budget.

$$delay\_budget(i) = \frac{(deadline - current)}{remain\_hops} \tag{2}$$

Priority index is calculated through comparison delay budget to per class delay. The dynamic priority adaptation mechanism is shown in fig. 4.

The proposed scheme performs priority resetting when the burst collision is occurred. Through priority resetting, it can satisfy the end-to-end delay requirement of mission-critical data by sacrificing QoS for non-mission-critical data along the path for the delivery of those mission-critical data. The priority adaptation algorithm including priority resetting is shown in fig. 5.

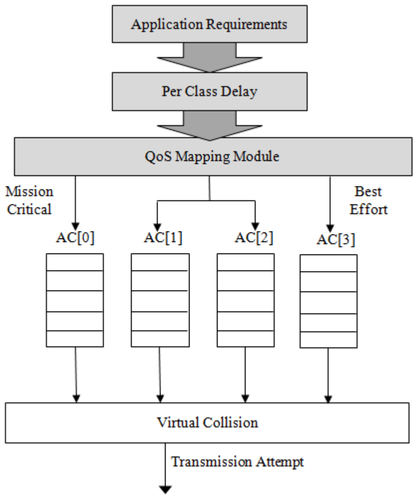


Fig. 4 Dynamic priority adaptation mechanism

Algorithm : Priority adaptation

```
MAC receives packet p :
if p.service == SLS1 then
   priority = 0;
else if p.service is in(SLS2, SLS3, SLS4) then
   delay_buget = deadline(p)-cur_time/remain_hops(p)
   for (i = adapt_prio_max ; i >= adapt_prio_min ; i--)
      if delay_buget < class_delay(i) then
         priority = i;
      end if
   endfor
   if buffer_overflow == true then
      priority = p.original_prioity;
   endif
else
   priority = 3;
endif
```

Fig. 5 Priority adaptation algorithm

3.2 Dynamic TXOP Allocation Scheme

Many studies have shown that the wireless channel exhibits time varying characteristics; namely, the quality of received signals changes dramatically even over short time intervals due to multiple causes such as multi-path, user mobility, and fading signals [10]. In order to estimate channel condition, the CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) process that creates well-defined times at which packet transmissions is observed. [11]. When the medium is idle, where a transmission could begin; when the medium is busy because one or more transmissions are taking place, the CSMA/CA countdown is halted until DIFS/EIFS (Distributed Interframe Space/Extended Interframe Space) after the medium becomes idle.

To specify the admissible transmission times, the following four different time slot are defined. At first, a station has seen the medium as idle and, if backoff is in progress, has decremented its backoff counter. We call these idle slots. Secondly, a station has detected the medium as busy due to one or more nodes are transmitting, and have suspended its backoff during NAV (Network Allocation Vector), AIFS/SIFS indicate when the backoff can resume. We call these slots other transmissions. Thirdly, a station has transmitted and received an ACK and is about to resume backoff. We call these slot successful transmissions. Fourthly, a station has transmitted and timed out while waiting for an ACK and is about to resume its backoff. We call these slots unsuccessful transmissions.

Transmission by a station is only permitted at event boundaries. We also make the following assumptions. At first, the probability of a collision by a station is then precisely the probability that at a slot boundary the channel is busy due to a transmission by one or more other stations. We note that first assumption is reasonable in a distributed random access MAC scheme such as CSMA/CA. This assumption is central to well-established models of 802.11 operations such as that of Bianchi [12] and the non-saturated heterogeneous model [13]. Secondly, the collision probability is independent of the backoff stage of a station. This assumption can be relaxed at the cost of increased book-keeping in our estimator.

We use the notation P_c for the collision error probability and P_e for the channel error probability. Suppose that a station transmits T times and A of these is successful because ACKs are received. Suppose there are also R slots in which a station does not transmit and I of these are idle. The likelihood of particular P_c and P_e is shown in (3).

$$L(P_c, P_e) = \binom{T}{A}((1-P_c)(1-P_e))^A \times \\ (1-(1-P_c)(1-P_e))^{T-A}\binom{R}{I}(1-P_c)^I P_c^{R-I} \quad (3)$$

Hence, the maximum likelihood estimators for the collision probability and the channel error probability are providing that $0 \le P_e \le 1$. Equation (4) shows the collision probability, P_c and Equation (5) shows the error probability, P_e.

$$P_c = \frac{R-I}{R} = \frac{\#OtherTransmits}{\#Idle + \#OtherTransmits} \quad (4)$$

$$P_e = 1 - \frac{1 - \frac{T-A}{T}}{1-P_c} \quad (5)$$

The collision probability is estimated as the proportion of busy slots due to other transmissions by other stations. To determine P_s, one needs to determine the successful transmission probability, P_s, that a station can transmit a packet successfully. Equation (6) shows that P_s can be calculated using P_c and P_e.

$$P_s = \frac{\#\,Successful\ Transmits}{\#\,AttemptedT\ ransmis} = (1-P_c)(1-P_e) \qquad (6)$$

The proposed dynamic TXOP allocation is performed at each station based on the channel condition measurements. Upon the arrival of a new flow at a QSTA (QoS Station), the station begins by estimating the value of the successful transmission probability, P_s. Afterwards, the QSTA compares the estimated probability P_s with the threshold, δ. The threshold δ is a value to determine the channel condition, which is decided by experiments. The optimal value of 0.54 is obtained by comprehensive simulations. If the probability P_s is larger than the threshold, the TXOP value will be increased. On the other hand, if the probability P_s is smaller than the threshold, we will decrease the TXOP value. Fig. 6 shows the pseudo code of our dynamic TXOP allocation scheme.

$$
\begin{aligned}
& if\,(P_s > \delta) \\
& \qquad TXOP_i = (1 + P_s) \times TXOP_i \\
& esle\ if\,(i \le \delta) \\
& \qquad TXOP_i = (P_s) \times TXOP_i \\
& \\
& New\ TXOP = (1-\alpha) \times Past\ TXOP_i + \alpha \times TXOP_i
\end{aligned}
$$

Fig. 6 Pseudo code for dynamic TXOP allocation scheme

Each time a new TXOP calculated according to P_s and the previous TXOP value. α represents a smoothing factor. The optimal value of α, 0.83, is obtained by comprehensive simulations on various traffics and channel conditions. The QSTA with our dynamic TXOP allocation will have a relatively fair channel access, since the dynamically assigned TXOPs provide a better chance in recovering the failed transmission comparing with the fixed TXOPs in the existing 802.11e EDCA.

4. Performance Evaluation

4.1 Dynamic Traffic Prioritization

In this section, the evaluation of the proposed dynamic traffic prioritization scheme in terms of per hop delay and packet delivery ratio is described. Simulations have been conducted using OPNET modeler 16.0. We compare the proposed scheme with APHD scheme. In order to implement proposed dynamic traffic prioritization scheme, we modify IEEE 802.11e EDCA scheme in OPNET modeler. The simulation parameters are summarized in TABLE I. In simulation environment, multiple source nodes transmit packets to a destination node through multihop topology. The network topology is shown in Fig. 7.

TABLE I. SUMMARY OF SIMULATION PARAMETERS

Parameters	***Value***
Data rate	1 Mbps
Transmission power	0.005 W
Retry limit	4
Buffer size	256 Kbits
AP beacon interval	0.02 s
Ad-hoc routing protocol	AODV

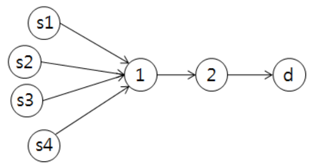


Fig. 7 Network topology

Fig. 8 shows the comparisons between estimated and actual per hop delay of each scheme. In order to calculate per class delay more accurate, the proposed scheme employs reliability of the link. On the other hand, the APHD scheme only considers packet size and transmission rate of the node to calculate per class delay. Therefore, the proposed scheme is more similar to actual delay than APHD.

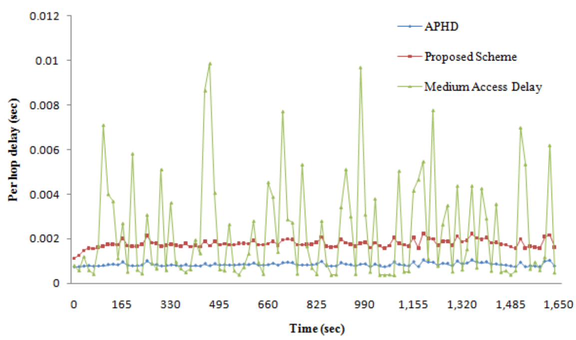


Fig. 8 The comparisons between estimated and actual per hop delay

Fig. 9 compares the packet delivery ratio of the proposed scheme and APHD scheme during the simulation. The proposed scheme can avoid concentration of high priority through by more accurate estimation of per hop delay. Concentration of high priority causes buffer overflow and thus packet loss. Consequently, APHD scheme results in lower packet delivery ratio than the proposed scheme.

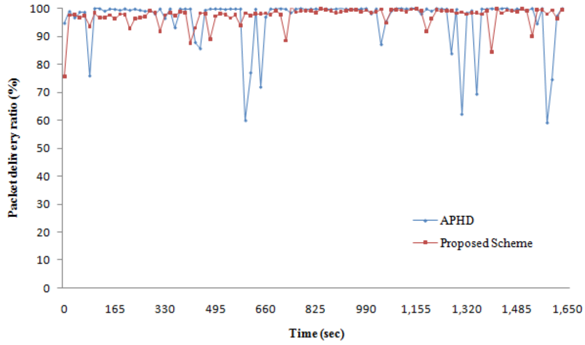


Fig. 9 Packet delivery ratio of each scheme

4.2 Dynamic TXOP Allocation

We evaluate the proposed dynamic TXOP allocation scheme in terms of throughput and average end-to-end delay. Simulations using a real MPEG-1 encoded VBR movie “Jurassic Park” are conducted.
We consider 4 QSTAs, 30 meters initially far from the QAP, in a Ricean fading channel with K factor 10-4, and Doppler frequency of 20Hz; we compare the proposed scheme with 802.11e EDCA scheme. We note that a TXOP limit of 0 values for background and best effort traffic types indicates that only a single frame may be transmitted during a TXOP period. We run the simulation for 300 seconds. The simulation results are then measured while four QSTAs are located 30m, 45m and 60m away from the QAP.

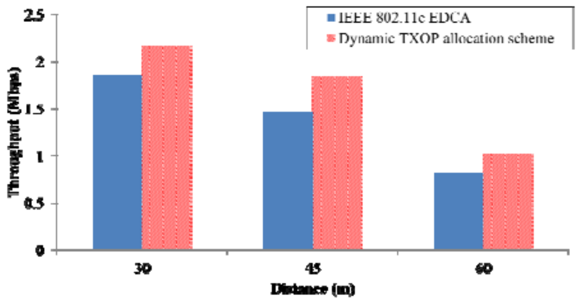


Fig. 10 Throughput comparison of VBR video using EDCA and dynamic TXOP allocation scheme

Fig. 10 compares the throughput of VBR video using EDCA and dynamic TXOP allocation scheme. Our dynamic TXOP allocation scheme is capable of measuring the collision and channel error probability and it also allocate the TXOP dynamically so that it has a better performance which improves the network throughput.
Fig. 11 compares the average end-to-end delay of VBR video using EDCA and dynamic TXOP allocation scheme. Our dynamic TXOP allocation scheme has a low average end-to-end delay because it can reduce the number of retransmissions caused by collisions and channel errors, and accordingly lower the overhead caused by retransmissions.

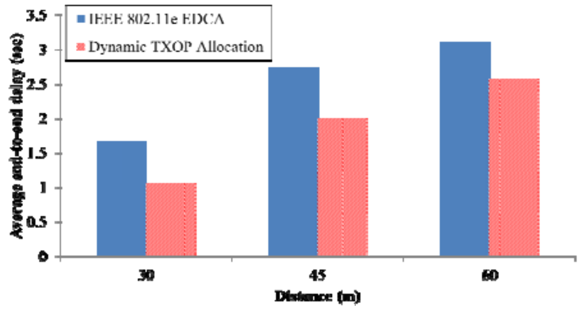


Fig. 11 Average end-to-end delay comparison of VBR video using EDCA and dynamic TXOP allocation scheme

5. Conclusion

In this paper, we propose the dynamic traffic prioritization scheme for multihop wireless networks. First, we propose traffic prioritization scheme that dynamically assigns priorities to traffic according to network status and delay requirement, in order to achieve guaranteed end-to-end QoS in multihop wireless networks. In order to calculate per class delay more accurately, the proposed scheme employs reliability of the link. In addition, the proposed scheme performs priority resetting when the burst collision is occurred. Through priority resetting, it can satisfy the end-to-end delay requirement of mission-critical data by sacrificing QoS for non-mission-critical data along the path for the delivery of those mission-critical data.

We also propose a dynamic TXOP allocation scheme based on the precise channel condition prediction. Our proposed scheme utilizes dynamic bandwidth allocation rather than the default TXOPs, which improves the network reliability by allowing more failure recovery times, such as the retransmission time required to recover packet losses.

In order to evaluate the performance of the proposed traffic prioritization scheme, we compare the performance of proposed scheme with APHD scheme and EDCA scheme. The results have shown the proposed scheme estimates per hop delay more similar to actual delay than APHD scheme and achieves high packet delivery ratio. In addition, the proposed scheme reduces end-to-end delay and increases throughput compared to the previous schemes.

Our future work includes the evaluation of the proposed dynamic TXOP allocation in various network topologies. We also plan to study of enhanced TXOP allocation scheme in mobile ad-hoc networks.

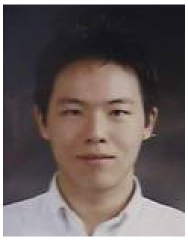
Acknowledgments

This work was supported by Agency for Defense Development under the contact UD100023ID.

References

[1] J. Jung, K. Ryu, and B. Roh, “Mission-critical packet transfer with explicit path selection in WMN-based wireless networks,” Proceedings of the 9th conference on Wireless telecommunications symposium, pp. 1-5, April 2010.
[2] R. Hall and J. Auzins, “A two-level quality of service scheme for collision based mobile ad hoc networks,” Proceedings of the Military Communications Conference, pp. 1-8, October 2007.
[3] IEEE 802.11 WG. “IEEE 802.11e/D8.0, draft amendment to 802.11: medium access control (MAC) quality of service (QoS) enhancement, “ February 2004.
[4] J. Li, Z. Li, and P. Mohapatra, “Adaptive per hop differentiation for end-to-end delay assurance in multihop wireless networks,” Ad hoc Networks, vol. 7, no. 6, pp. 1169-1182, August 2009.
[5] IEEE 802.11 WG, “IEEE standard for information technology telecommunication and information exchange between systems LAN/MAN specific requirements Part 11: wireless LAN medium access control (MAC) and physical layer (PHY) specifications,” 1999.
[6] A. Iera, A. Molinaro, G. Ruggeri, and D. Tripodi, “Improving QoS and throughput in single- and multihop WLANs through dynamic traffic prioritization,” IEEE Network, vol. 19, no. 4, pp. 35-44, August 2005.
[7] A. Iera, A. Molinaro, S. Polito, and G. Ruggeri, “Coordinated multihop scheduling in IEEE802.11e wireless ad hoc networks,” Proceedings of the IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications, September 2006.
[8] T. Reddy, J. John, and C. Murthy, “Providing MAC QoS for multimedia traffic in 802.11e based multi-hop ad hoc wireless networks,” The International Journal of Computer and Telecommunications Networking, vol. 51, no. 1, pp. 153-176, January 2007.
[9] B. Awerbuch, D. Holmer, and H. Rubens, “High throughput route selection in multi-rate ad hoc wireless networks,” Proceedings of the IEEE 1st Working Conference on Wireless On-demand Nework Systems, vol. 2928, pp. 253-270, January 2004.
[10] A. Miu, G. Tan, H. Balakrishnan, and J. Apostolopoulos, “Divert: fine-grained path selection for wireless LANs,” Proceedings of the Second International Conference on Mobile Systems, Applications, and Services, pp. 203–216, June 2004.
[11] D. Malone, P. Clifford, and D. J. Leith, “MAC layer channel quality measurement in 802.11,” IEEE Communications Latters, vol. 11, issue. 2, pp. 143-145, February 2007.
[12] G. Bianchi, “Performance analysis of IEEE 802.11 distributed coordination function,” IEEE Journal on Selected Areas in Communications, vol. 18, issue, 3. pp. 535-547, March 2000.
[13] D. Malone, K. Duffy, and D.J. Leith, “Modeling the 802.11 distributed coordination function in non-saturated heterogeneous condition,” IEEE Communications Latters, vol. 9, issue. 8, pp. 715-717, August 2005.

Dongho Lee received the B.S. degree from Kwangwoon University, Seoul, Korea, from Computer Science Department in 2006. Currently he is pursuing Ph.D. degree in Communications Engineering Department at Kwangwoon University. His research interests include MANET, wireless sensor networks, and ubiquitous computing.



Kwangsung Ju received the B.S. degree from Kwangwoon University, Seoul, Korea, from Communications Engineering Department in 2010. Currently he is pursuing Ph.D. degree in Communications Engineering Department at Kwangwoon University. His research interests include MANET, QoS mechanism, and video streaming.

Kwangsue Chung received the B.S. degree from Hanyang University, Seoul, Korea, M.S. degree from KAIST (Korea Advanced Institute of Science and Technology), Seoul, Korea, Ph.D. degree from University of Florida, Gainesville, Florida, USA, all from Electrical Engineering Department. Before joining the Kwangwoon University in 1993, he spent 10 years with ETRI (Electronics and Telecommunications Research Institute) as a research staff. He was also an adjunct professor of KAIST from 1991 to 1992 and a visiting scholar at the University of California, Irvine from 2003 to 2004. His research interests include communication protocols and networks, QoS mechanism, and video streaming.