A Real-Time MAC Protocol with Extended Backoff Scheme for Wireless Sensor Networks

Zhang Teng, Ki-Il Kim, *Member, KIMICS*

***Abstract*—Wireless sensor networks (WSNs) are formed by a great quantity of sensor nodes, which are consisted of battery-powered and some tiny devices. In WSN, both efficient energy management and Quality of Service (QoS) are important issues for some applications. Real-time services are usually employed to satisfy QoS requirements in critical environment. This paper proposes a real-time MAC (Medium Access Control) protocol with extended backoff scheme for wireless sensor networks. The basic idea of the proposed protocol employs (*m*,*k*)-firm constraint scheduling which is to adjust the contention window (CW) around the optimal value for decreasing the dynamic failure and reducing collisions DBP (Distant Based Priority). In the proposed protocol, the scheduling algorithm dynamically assigns uniform transmitting opportunities to each node. Numerical results reveal the effect of the proposed backoff mechanism.**

***Index Terms*— Real-Time, Wireless Sensor Networks, Routing Protocol**

I. INTRODUCTION

IN this current decade, WSN (Wireless Sensor Networks) [1] have a significant attention in application such as monitoring physical phenomena and manmade environmental phenomena and events. In virtue of the limitative battery-powered on sensor node, a large challenge of sensor network is the limited energy which is used for monitoring information from environment and transmitting the information to us. For the sake of the energy constrained application, the design model to decrease energy consumption is often selected in MAC (Medium Access Control) protocol [2]. Therefore, substantial number of the MAC protocols [3-7] for wireless sensor networks are designed in the literature for the traditional challenge: energy-efficiency. However, in several special cases, a fundamental requirement is timely message transmission. During the time critical applications, the largest challenge is that how to guarantee the alarm information meet their deadline for providing security of events in the environment. In addition to those applications, the energy consumption is the secondary importance such as WSN is employed in natural disaster monitor system. In modern times, wireless sensor network are increasingly used for time critical applications. For sensor networks, the research which guarantees bounded delay is often proposed in MAC (Medium Access Control) layer. Hence the real-time communication system is often employed for wireless sensor MAC protocol in the literature [8-11].

In real-time communication system packets that do not reach the destination before deadline contain stale information that cannot be used. For wireless sensor networks, as the natural condition and other factors, the packet loss is unavoidable. In order to adopt the limited natural conditions, the (*m*,*k*)-firm guarantee model can be employed in WSN. A real-time stream with an (*m*,*k*)-firm guarantee requirement states that m out of any k consecutive packets in the stream must meet their respective deadlines [12]. If less than m packets meet deadline in any consecutive k packets, it is called the application experiences a dynamic failure and the current state is called failure state.

Traditional MAC protocols, such as IEEE 802.11, are not suitable for data delivery of wireless sensors with real-time. In this paper we proposed a real-time MAC for sensor network protocol by extending backoff algorithm with (*m*,*k*)-firm constraint. This real-time MAC protocol is based on unscheduled MAC protocol by enhancing the backoff algorithm in IEEE 802.11. For contention mode, an unscheduled MAC protocol may consume fewer processing resources, have a smaller memory footprint, and decrease the number of messages that a sensor node must transmit. However, the biggest issue of contention-based protocol is a higher rate of collision, idle listening, and overhearing because the sensor nodes do not coordinate transmissions. Most protocol in contention-based wireless sensor networks can be achieved by controlling the behaviors of the backoff algorithm. Before transmitting packets, a node first checks the channel. If no nodes use the medium, the node transmits a packet to its neighboring node. When the medium is used, the node backoff their counters and wait a random amount of time for the next transmitting attempt. The novel mechanism employs (*m*,*k*)-firm to perform a backoff action, the different state of (*m*,*k*)-firm for data streams have various waiting time. This algorithm dynamic assigns waiting time for guaranteeing one data stream with higher priority has higher probability to transmit packet earlier for breaking away from the failure state of (*m*,*k*)-firm.

Manuscript received April 20, 2011; revised May 11, 2011; accepted May 27, 2011.

The authors are with the Department of Informatics, Engineering Research Institute, Gyeongsang National University, Jinju, 660-701, Korea (Tel: +82-55-772-1373, Fax: +82-55-772-1370, Email: kikim@gnu.ac.kr). Ki-Il Kim is corresponding author.

The remainder of this paper is organized as follows. In section **II** we discuss the related works. Section **III** describes the algorithm of the proposed protocol. Section **IV** shows the simulation results and performance evaluation of the proposed protocol. Section **V** concludes this paper and also includes the further work.

II. RELATED WORKS

In message transmission networks the real-time communication system is increasingly being employed for advancing Quality of Service (QoS) requirements. In wireless sensor networks, QoS for real-time communications are often defined at the MAC and Network Layers [13]. Some solutions with (m,k)-firm guarantee model are proposed to support QoS for real-time communication requirements.

Supporting components for real time sensors (SUPORTS) [14] based hard real-time at MAC layer for supporting real-time flows in highly unpredictable sensor network environments. The goal of SUPORTS is to consider the delay requirement of each arriving packet to maximize the probability of meeting its deadline. SUPORTS implements a least-laxity based scheduler component at each sensor node that determines the order with which each individual packet will be delivered by the MAC service. The protocol compute the laxity value L of a packet as the difference between the deadline and the end-to-end time to transmit the packet from the source to the sink:

$$\mathrm{L} = \mathrm{Deadline} - (\mathrm{t_{el}} + \mathrm{t_{snk}} + \mathrm{D})$$

In the equation above mentioned, t_{el} is the elapsed time since the packet was initiated at the source. The t_{snk} is delay that the downstream node estimates that will be required until the packet reaches the sink. The D is the local estimation of the projected sojourn time.

In delay sensitive sensor systems the goal of traffic regulation is two parts. First, in cases of congestion, packets need to be dropped to decrease contention and relief overflowing queues in an attempt to reduce delays. Secondly, when a packet is overly delayed, it should not be further forwarded since that would be a waste of transmission energy. Even if the deadline of a packet is large, the packet may still miss its deadline because it might be dropped due to congestion.

As a traditional MAC protocol, IEEE 802.11 is not suitable for message delivery of wireless sensors network with real-time. The IEEE 802.11 standard provides both the medium access control (MAC) and the physical (PHY) layers. We focus on the discussion and extending the performance of MAC layer with backoff algorithm. One of the most important functions of the MAC layer of IEEE 802.11 is coordinating the wireless medium access procedure [15]. The IEEE 802.11 consists two parts: the fundamental access approach is the distributed coordination function (DCF), it is based on the CSMA/CA MAC protocol; another is an alternative access, which is called point coordination function (PCF).

Our main discussion focused on the DCF. The DCF is composed two modes: the basic CSMA access mode and the RTS/CTS based CSMA modes. In the RTS/CTS based modes, after getting an opportunity to access the channel, the source node will send a RTS (Request-to-Send) message prior to data transmission to announce the upcoming transmission. When the destination node receives the RTS message, it will reply a CTS (Clear-to-Send) message to source node. Then the source node is allowed to transmit its packet to destination node. In the RTS/CTS based CSMA modes, a binary exponential backoff algorithm is employed to resolve contentions. We will explain the backoff algorithm detail in chapter III.

In addition, we show the algorithm of DBP (*m*,*k*)-firm scheduling. Distance-based Priority (DBP) [16] is based on (*m*,*k*)-firm real-time approach, which is a dynamic priority assignment mechanism. DBP scheduling is proposed to research the efficiently serve multiple streams based on (*m*,*k*)-firm constraints sharing a single server. The priority assignment algorithm is described as follows. Let 0 and 1 represent a deadline miss and meet, respectively, $s_j = (\delta^j_{i-k_j+1}, \ldots, \delta^j_{i-1}, \delta^j_i)$ is the current state s_j of stream R_j, $l_j(n,s)$ denote the position (from the right side) of the n^{th} meet (or 1) in the state s_j of stream R_j. then the priority of the next packet is designed by:

$$\varphi^j_{i+1} = k_j - l_j(m_j, s) + 1 \qquad (1)$$

By calculate from (1), the lower value has higher priority. If there are less than n 1's in s_j, then $l_j(n,s) = k_j + 1$, that mean the current state s_j is failure (*priority* = 0), compare with successful state, the highest priority will be assigned. There is example, a stream R_j with (2,4)-firm constraint, current k-sequence state is 1110, then $l_j(n,s) = l_j(2,s) = 3$ and the $\varphi^j_{i+1} = 2$.

III. ALGORITHM DESCRIPTION

The proposed real-time MAC protocol is proposed for multi streams communication. It is employed on backoff algorithm which is based on IEEE 802.11 DCF with CSMA/CA MAC protocol. In this work we use the (*m*,*k*)-firm for RTS/CTS based CSMA networks.

In this algorithm, the proposed mechanism based on CSMA with RTS/CTS networks. In the RTS/CTS based CSMA networks, a binary exponential backoff algorithm is used to resolve contentions [17].

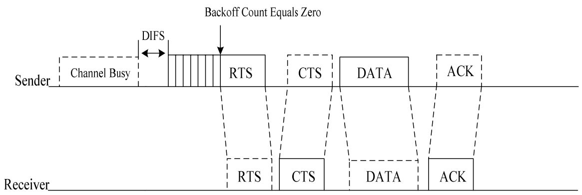

Fig. 1. IEEE 802.11 DCF backoff algorithm and message transfer.

A node desiring to initiate data transmission shall invoke the carrier-sense mechanism to determine the busy/idle state of the channel. As shown in fig. 1, if the channel is busy, the node shall transmit until the channel is determined to be idle without interruption for a period of time equal to DIFS when the last frame detected on the medium was received correctly. After the DIFS time, the node will generate a random waiting time for an additional deferral time before transmitting. This process minimizes collisions during contention between multiple nodes that have been transmitting to the same destination.

For designing the waiting time, a node performs the backoff algorithm by randomly selecting a number of timeslots to wait and storing this value in a backoff counter [18]. As show in fig. 2, for each timeslot where the node senses no activity on the channel, it decrements its backoff counter and transmits data packet when the count reaches zero. If the node detects activity on the channel before the backoff counter reaches zero, it halts the countdown, defers access to the current transmission, and continues the countdown after the channel becomes idle for a DIFS.

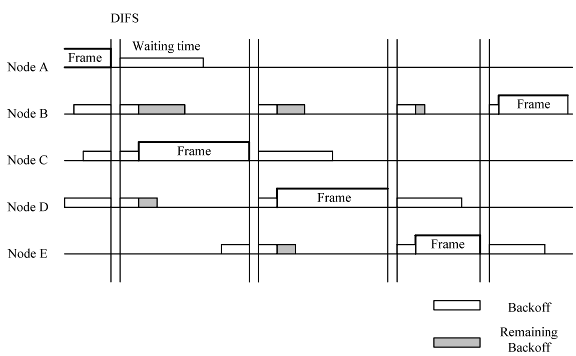

Fig. 2. The backoff procedure.

In the RTS/CTS based CSMA networks, the pseudorandom integer of backoff counter is drawn from a uniform distribution over the interval [0,CW], where CW (contention window) is an integer within the range of values between CWmin and CWmax, CWmin ≤ CW ≤ CWmax. The set of CW values is sequentially ascending integer powers of 2, minus 1, beginning with a specific CWmin value:

$$CW = \min(2^n - 1, CWmax) \qquad (2)$$

In (2), the value of n is from 3 to 8, whenever a CTS is not received after an RTS, the node shall retransmit the RTS, then the value of n will increase, the CW of the node will continue increase if retransmit again until it reach the CWmax. When a CTS is received after a RTS, the CW will be reset to the CWmin. By the value of backoff counter CW, the waiting time is calculated as shown in the following:

$$wtime = \{ (rand() \bmod CW) \} * timeslot \qquad (3)$$

To provide real-time service in a contention-based wireless sensor network, the (*m*,*k*)-firm constraint is proposed to use in contention-based mode. We modify the mechanism by applying a priority assignment algorithm which is DBP scheduling. The DBP value φ_{i+1}^{j} is used for dividing priority of data streams. The value φ_{i+1}^{j} means the priority of next packet with data stream *j*. In this mechanism when a node generates the CW value, the following equation is applied:

$$CW_{i+1}^{j} = \min(2^{\varphi_{i+1}^{j}+n} - 1, CWmax) \qquad (4)$$

Then the waiting time is calculated as shown in the following equation:

$$Wtime_{i+1}^{j} = (rand() \bmod CW_{i+1}^{j}) * timeslot \qquad (5)$$

In DBP scheduling algorithm, the lower (*m*,*k*)-firm value φ_{i+1}^{j} has higher priority for transmitting the next packet. Thus, as shown in equation (4), if one node gets a lower φ_{i+1}^{j} value, it shall get a lower CW_{i+1}^{j} value. Then the node has a higher probability to get a short waiting time by equation (5) for transmitting the next packet earlier to meet deadline. Thus the node shall break away from a lower (*m*,*k*)-firm value state earlier.

Fig. 3 presents the algorithm of the proposed backoff method. If one data packet which is stored in the buffer of one sensor node needs to be transmitted to destination node, the source node first checks if the data packet meets its deadline. If the data packet misses deadline, the packet will be dropped since the information of the packet is only late but wrong. If the data packet meets its deadline, the node will calculate the DBP value by the equation (1). Then we can get the value of CW from the equation (4). By the equation (5), we can calculate the waiting time and the waiting time is decreasing by time. If the medium is sensed to be busy, the backoff procedure is suspended, when the medium is idle, through a DIFS, the backoff procedure will resume. When waiting time is exhausted, the node will transmit the RTS message and wait the CTS message from the destination. If the node does not receive the CTS message, it thinks that there is collision on the channel, then the node will check if the data packet meet deadline and experience the process which is mentioned above again. If the node receive CTS message successfully, the node will transmit the data packet to destination.

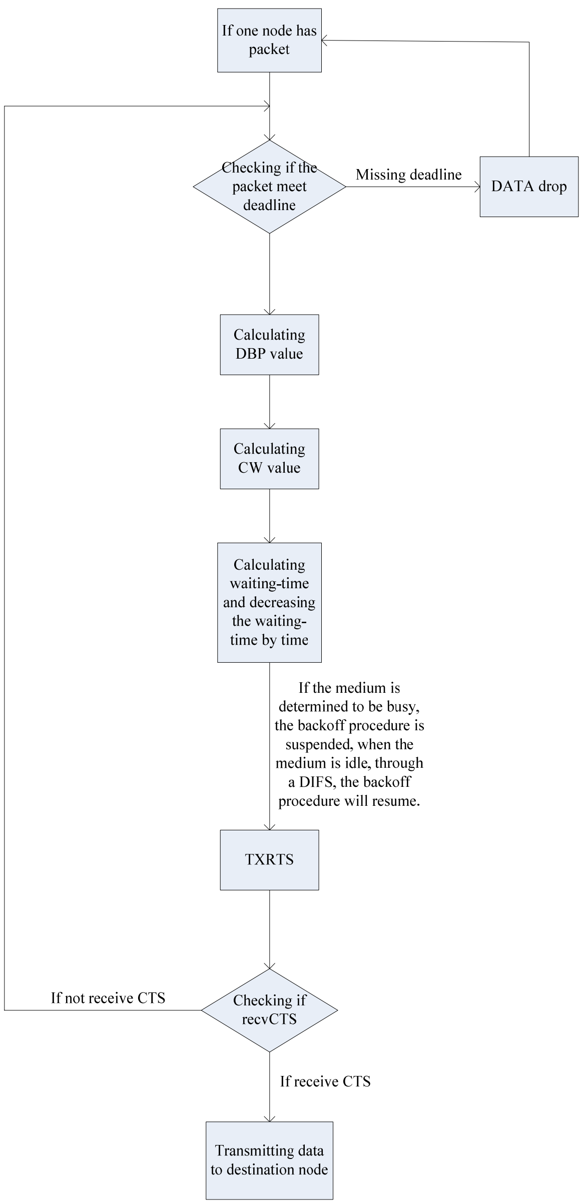

Fig. 3. The proposed backoff algorithm with (m,k)-firm constraint.

IV. PERFORMANCE EVALUATION

We have developed a simulation tool for the proposed protocol using C program as the simulator. By the simulator we compared performance between the proposed protocol and the previous protocol. In this simulation we compared the probability of dynamic failure between the proposed protocol and IEEE 802.11 with CSMA/CA. The inputs to the simulator include scheduling policy, stream parameters, and simulator directives. The scheduling policies which are RTS/CTS based CSMA IEEE 802.11 standard and the proposed protocol we chose for evaluating their performance.

For this simulation, we consider a multi-sources one-destination topology for transmitting as shown in Fig. 4. In this simulation we assume the deadline of data packets which are generated from the multi-sources is same. The message inter-arrival period is 1 second.

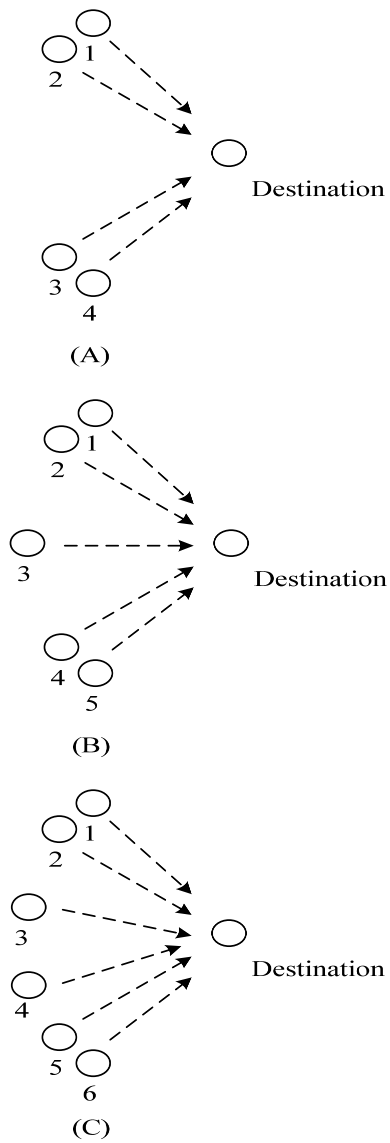

Fig. 4. Transmission between multi-sources to one destination.

Fig. 5 shows the comparison of the probability of dynamic failure between basic CSMA/CA in IEEE 802.11 and the proposed protocol which employs (*m*,*k*)-firm constraints on backoff algorithm based on CSMA/CA. As shown in this figure, most nodes have lower probability of dynamic failure in proposed protocol. Especially on node 4, the probability of dynamic failure of the proposed protocol lower than basic CSMA/CA by 24 percentage point. For the node 5, the probability of dynamic failure of the proposed protocol a little higher than basic CSMA/CA because the backoff algorithm randomly selects a number of timeslots to wait, the probability of dynamic failure of basic CSMA/CA is still lower than the proposed protocol.

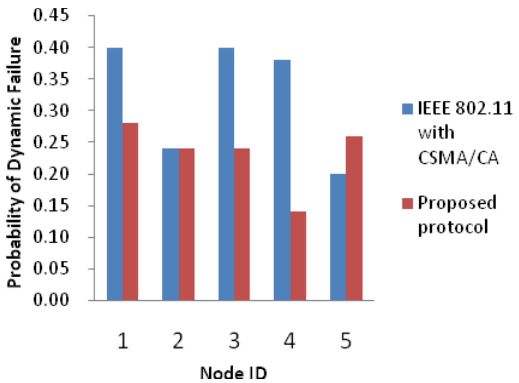

Fig. 5. Comparison of the probability of dynamic failure with (3,5)-firm in contention-based mode.

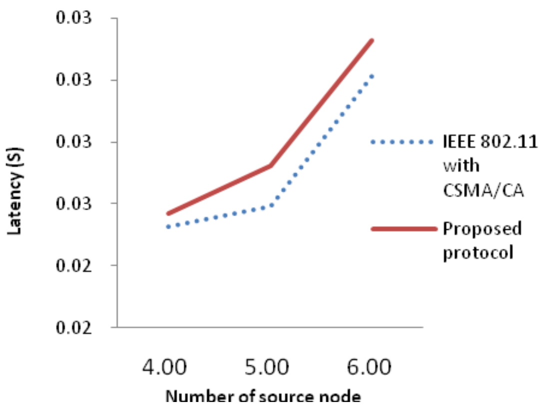

Fig. 6. Average latency of each packet by different amount of source nodes.

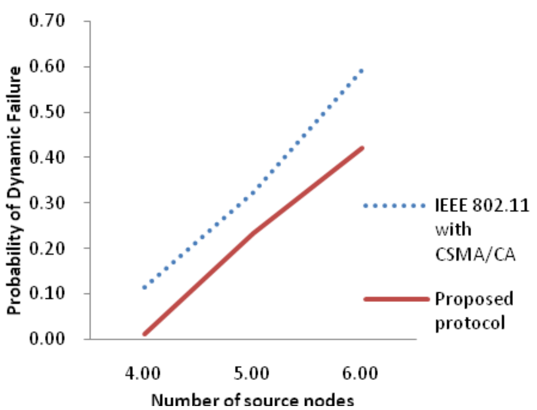

Fig. 7. Comparison of the average probability of dynamic failure with (3,5)-firm with different source nodes in contention-based mode.

As shown in Fig. 6, the latency of the proposed protocol is similar, even a little higher than basic CSMA/CA in IEEE 802.11. This is because in order to dynamic divide different waiting time by different priority which is designed from DBP value, the nodes with lower priority get longer waiting time in the proposed protocol. However, proposed protocol is better to ensure QoS. For topology in Fig. 4, we increased the amount of source nodes from A to C for compare the average probability of dynamic failure. As shown in Fig. 7, for the proposed protocol, the probability of dynamic failure is 0.012 when the number source nodes are 4, representing an 89.6% improvement over the basic CSMA/CA. We observe that the probability of dynamic failure is increasing when the number of source nodes is raise. It is due to fact that the deadline of every source node is same, when the number of source nodes increase, because of the more collision, more packets are dropped by missing deadline.

V. CONCLUSION AND FUTURE WORK

In this paper, we proposed a real-time Medium Access Control (MAC) protocol which adopt the (*m*,*k*)-firm constraint to guarantee QoS of real-time transmission in wireless sensor networks. In this paper, the proposed protocol applies a priority assignment algorithm which is DBP scheduling, the algorithm can dynamic divide different waiting time by different priority which is designed from DBP value in CSMA/CA. The proposed protocol is based on a dynamic priority assignment which can ensure each node sent enough valid information to sink node. The simulation results show that previous mechanism cannot guarantee each node provides enough valid information to customer, the novel protocol is a good solution for this problem.

In the further work, we will consider to research the energy constraint in the propose protocol and attempt apply real-time with (*m*,*k*)-firm constraint on multi-hop wireless sensor networks.

ACKNOWLEDGMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011-0004102).

REFERENCES

[1] I.-F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “A Survey on Sensor Networks,” IEEE Communications Magazine, Vol. 40, August 2002, pp. 102–114.

[2] Y. Bashir and B.-O. Jalel, “Towards a Classification of Energy Aware MAC Protocols for Wireless Sensor Networks,” Wireless Communications and Mobile Computing, Vol. 9, February 2009, pp. 1572-1607.

[3] W. Ye, J. Heidemann, and D. Estrin, “An Energy-Efficient MAC Protocol for Wireless Sensor Networks," in Proc. IEEE INFOCOM, June 2002, pp. 1567‐1576.
[4] W. Ye, J. Heidemann, D. Estrin, “Medium Access Control with Coordinated Adaptive Sleeping for Wireless Sensor Networks,” IEEE/ACM Transactions on Networking, Vol. 12, June 2004, pp. 493‐506.
[5] T.-H. Hsu, J.-S. Wu, “An Application-Specific Duty Cycle Adjustment MAC Protocol for Energy Conserving over Wireless Sensor Networks,” Computer Communications, Vol. 31, November 2008, pp. 4081-4088.
[6] P. Lin, C. Qiao, X. Wang, “Medium Access Control with a Dynamic Duty Cycle for Sensor Networks,” in Proc. IEEE WCNC, Vol. 3, March 2004, pp. 1534‐1539.
[7] S. Du, A.-K. Saha, and D.-B. Johnson, “RMAC: a routing-enhanced duty-cycle MAC protocol for wireless sensor networks,” in Proc. INFOCOM, 2007, pp. 1478–1486.
[8] J. Kim, J. Lim, C. Pelczar, and B. Jang, “RRMAC: A Sensor Network MAC for Real Time and Reliable Packet Transmission,” in Proc. IEEE International Symposium on Consumer Electronics (ISCE), April 2008, pp. 1-4.
[9] T. Watteyne, I. AUGÉ-BLUM , and S. UBÉDA, “Dual-Mode Real-Time MAC Protocol for Wireless Sensor Networks: a Validation/Simulation Approach,” in Proc. International Conference on Integrated Internet Ad Hoc and Sensor Networks (InterSense), May 2006.
[10] T. Watteyne and I. AUGÉ-BLUM, “Proposition of a Hard Real-Time MAC Protocol for Wireless Sensor Networks,” in Proc. IEEE MASCOTS, September 2005, pp. 533 – 536.
[11] A. Krohn, M. Beigl, C, Decker, and T. Zimmer, “TOMAC – Real-Time Message Ordering in Wireless Sensor Networks Using the MAC layer,” in Proc. International Workshop on Networked Sensing Systems (INSS), 2005.
[12] A. Striegel and G. Manimaran, “Best-Effort Scheduling of (m,k)-firm Real-Time Streams in Multihop Networks,” Computer Communications, Vol. 23, July 2000, pp. 1292-1300.
[13] J.-M. Chen, Z. Wang, Y.-Q Song, and Y.-X. Sun, “Extended DBP for (m,k)-firm Based QoS,” in Proc. International Federation for Information Processing (IFIP), 2004, pp. 357-365.
[14] K. Karenos and V. Kalogeraki, “Real-Time Traffic Management in Sensor Networks,” in Proc. IEEE RTSS, 2006, pp. 422-434.
[15] W.-K. Kuo and C.-C. Jay Kuo, “Enhanced Backoff Scheme in CSMA/CA for IEEE 802.11,” in Proc. VTC, 2003.
[16] M. Hamdaoui and P. Ramanathan, “A Dynamic Priority Assignment Technique for Streams with (m,k)-Firm Deadlines,” IEEE Transactions on Computers, Vol. 44, December 1995, pp. 1443-1451.
[17] K. Kredo Ⅱ and P. Mohapatra, “Medium Access Control in Wireless Sensor Networks,” Computer Networks (elsevier), March 2007, pp. 961-994.
[18] IEEE Computer Society LAN MAN Standard Committee, “Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications”, IEEE Standard 802.11 – 1997, The Institute of Electrical and Electronics Engineers, 1997.

Zhang Teng received M.S. degree from the Gyeongsang National University, Jinju, Korea. His research interests include sensor networks, and MAC protocol.

Ki-Il Kim received the M.S. and Ph.D. degrees in computer science from the ChungNam National University, Daejeon, Korea, in 2002 and 2005, respectively. He is currently with the Department of Informatics at Gyeongsang National University. His research interests include routing for MANET, QoS in wireless network, multicast, and sensor networks.