Simple Contending-type MAC Scheme for Wireless Passive Sensor Networks: Throughput Analysis and Optimization

Jin Kyung Park, Heewon Seo, and Cheon Won Choi

Department of Applied Computer Engineering, Dankook University / Yongin, Korea

* Corresponding Author: Cheon Won Choi, cchoi@dku.edu

Received April 18, 2017; Accepted May 29, 2017; Published August 30, 2017

** Regular Paper*

** Extended from a Conference: Preliminary results of this paper were presented at ICEIC 2016. This paper has been accepted by the editorial board through the regular review process that confirms the original contribution.*

***Abstract*:** A wireless passive sensor network is a network consisting of sink nodes, sensor nodes, and radio frequency (RF) sources, where an RF source transfers energy to sensor nodes by radiating RF waves, and a sensor node transmits data by consuming the received energy. Against theoretical expectations, a wireless passive sensor network suffers from many practical difficulties: scarcity of energy, non-simultaneity of energy reception and data transmission, and inefficiency in allocating time resources. Perceiving such difficulties, we propose a simple contending-type medium access control (MAC) scheme for many sensor nodes to deliver packets to a sink node. Then, we derive an approximate expression for the network-wide throughput attained by the proposed MAC scheme. Also, we present an approximate expression for the optimal partition, which maximizes the saturated network-wide throughput. Numerical examples confirm that each of the approximate expressions yields a highly precise value for network-wide throughput and finds an exactly optimal partition.

***Keywords*:** Wireless passive sensor networks, Contending-type MAC scheme, Network-wide throughput, Approximate expression, Optimization

1. Introduction

A wireless passive sensor network is a network consisting of sink nodes, sensor nodes, and radio frequency (RF) sources. In the network, an RF source transfers energy to neighboring sensor nodes by radiating RF waves towards them. Upon reception of the RF waves, a sensor node rectifies them to direct current (DC) and then drives itself to sense the environment, gather information, and transmit data to a sink node [1].

Theoretically, a sensor node is able to continuously receive abundant energy from an RF source. Against theoretical expectations, however, a sensor node suffers from many difficulties in practice [2-4]. The first difficulty is a scarcity of energy. RF waves experience severe path loss during propagation. Also, conversion of RF waves to DC incurs a heavy loss of power. Moreover, the level of power that an RF source can transmit is often legally limited. Thus, energy is insufficient at the sensor nodes. The second difficulty is the non-simultaneity of energy reception and data transmission. Since RF waves transmitted by an RF source can interfere with a signal transmitted by a sensor node, a sensor node is hardly ever able to receive energy from an RF source and transmit data to a sink node simultaneously. The third difficulty is inefficiency in allocating time resources. Receiving energy from an RF source up to a level where the sensor node can communicate with a sink node takes a much longer time than transmitting a piece of data to a sink node. As a result, a sensor node has to store the received energy at its internal capacitor rather than consume the energy to directly run itself. Furthermore, a sensor node has to sporadically transmit data between two successive long periods for charging its capacitor.

In this paper, we consider a wireless passive sensor network in which a single sink node stands in the center of the network coverage, a single RF source coexists with the sink node, and many sensor nodes are scattered around the sink node. Supporting sensor nodes to deliver packets to the sink node needs a medium access control (MAC) scheme that must meet two requirements. First, two or more sensor nodes may transmit packets simultaneously. If they do, one packet interferes with other packets and hence a collision among the transmitted packets. As a result, the sink node may not receive any packets at all. Thus, the MAC scheme must be able to arbitrate among the sensor nodes contending to deliver packets. Secondly, under the strong constraints mentioned above, a sensor node is not able to directly exchange information with neighboring sensor nodes. Even a sink node is not able to easily collect information from sensor nodes, or distribute it to them. Thus, neither complicated nor intelligent MAC schemes are adequate.

Perceiving such requirements, we propose a simple contending-type MAC scheme, based on ALOHA [5], which supports sensor nodes to deliver packets to a single sink node while arbitrating among the contending sensor nodes. Even though the proposed MAC scheme fulfills the two requirements, the naïveté of the proposed MAC scheme may degrade throughput performance. To investigate the effect of design parameters on throughput, we derive an approximate expression for the throughput that can be attained under the proposed MAC scheme. Furthermore, we obtain expressions for the optimal values that the design parameters should take to maximize throughput.

In Section 2, we propose and describe a simple contending-type MAC scheme for supporting sensor nodes to deliver packets to a single sink node. In Section 3, we present an approximate expression for the throughput that the proposed MAC scheme can achieve. Also, we present expressions for the optimal values that the design parameters should take to maximize throughput. Section 4 is devoted to numerical examples that demonstrate the precision and optimality of the approximate expressions.

2. Contending-type MAC Scheme

Consider a wireless passive sensor network in which a single sink node stands in the center, a single RF source coexists with the sink node, and a number of sensor nodes reside around the sink node (as shown in Fig. 1). In the network, the RF source, using an omni-directional antenna, radiates RF waves, and thus, transfers energy to all the sensor nodes. Then, a sensor node, using an omni-directional antenna, receives energy and charges its internal capacitor. Next, consuming the energy accumulated in the capacitor, the sensor node does the triplet; sensing the environment, gathering information, and encapsulating it into packets. Finally, the sensor node transmits the packets to the sink node.

In the network, two or more sensor nodes may transmit packets simultaneously, which incurs collisions among the packets. Thus, a MAC scheme that supports sensor nodes to deliver packets to the sink node must be able to arbitrate among the contending sensor nodes. Furthermore, such a

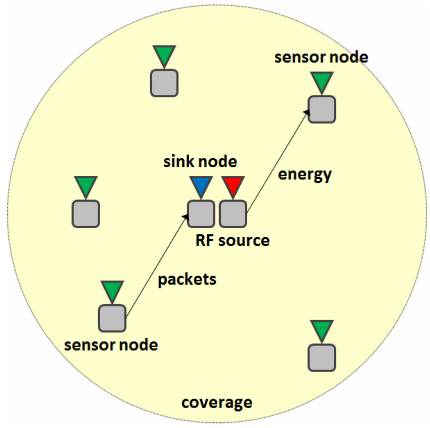

Fig. 1. Configuration of wireless passive sensor network.

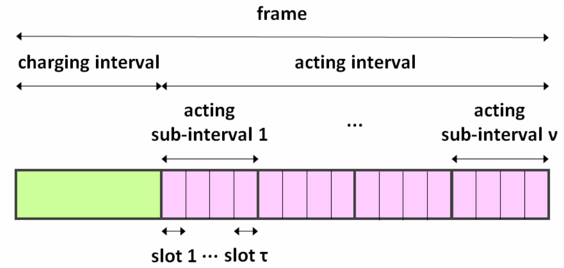

Fig. 2. Time structure in proposed MAC scheme.

MAC scheme must preserve naïveté so as to overcome practical difficulties inherent in wireless passive sensor networks.

Taking these constraints into account, we propose a MAC scheme as follows. At a sensor node, time is divided into frames and frames are again divided into charging and acting intervals. During a charging interval, the RF source transfers energy to the sensor nodes, and each sensor node charges its capacitor. Alternately, an acting interval is partitioned into a number of acting sub-intervals, which consist of the same number of slots. (See Fig. 2.)

At the start of each acting sub-interval, a sensor node decides whether to do the triplet (i.e., sensing the environment, gathering information and encapsulating it into packets) or not with probability $p \in [0,1]$. Once the sensor node decides to do, it immediately generates a packet and temporarily stores the packet in its internal buffer. If the buffer is not empty, the sensor node picks up a packet in the buffer according to the first come first served (FCFS) discipline. Then, the sensor node equally likely select a single slot among the slots that belong to the acting sub-interval. Finally, hoping to avoid a collision, the sensor node transmits the packet during the selected slot via the reverse channel. During every acting interval, the sink node always listens to the reverse channel. If the sink node correctly receives a packet in a slot, the sink node broadcasts an acknowledgement of correct reception of the packet at the end of the slot. If a sensor node receives an acknowledgement corresponding to its packet, the sensor node immediately removes the packet from the buffer. Fig. 3 shows a flow chart which illustrates the behavior of a

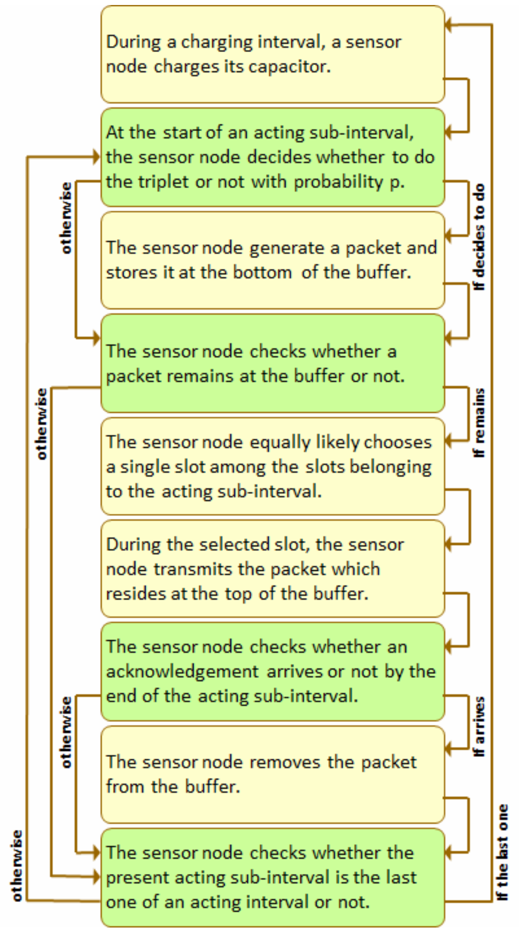

Fig. 3. Behavior of sensor node.

sensor node.

3. Throughput Analysis and Optimization

Consider a wireless passive sensor network that consists of a single sink node, a single RF source, and M sensor nodes identified as $s_1, \cdots, s_M$. (See Fig. 1.) In this section, we derive an approximate expression for the throughput that the proposed MAC scheme can attain in such a network.

As described in Section 2, time is divided into frames, and each frame is divided into charging and acting intervals. In this time structure, a charging interval is made up of σ slots. Meanwhile, an acting interval is partitioned into ν acting sub-intervals, which are identically comprised of τ slots. (See Fig. 2.) Before an acting sub-interval starts, a sensor node decides whether to do the triplet (i.e., sensing the environment, gathering information and encapsulating it into a packet) or not with probability $p \in [0,1]$. Once the sensor node decides to do, it instantly generates a packet and temporarily stores the packet at the bottom of its infinite buffer.

For $m \in \{1, \cdots, M\}$, let $X_n^{(m)}$ denote the number of packets remaining in the buffer of sensor node s_m just before the n th acting sub-interval starts. (Note that the j th acting sub-interval of the i th frame is called the $(i(\nu-1)+j)$ th acting sub-interval.) For $m \in \{1, \cdots, M\}$ and $n \in \mathbb{N}$, let $U_n^{(m)}$ denote the number of packets arriving at the buffer of sensor node s_m right before the n th acting sub-interval starts. Also, let $V_n^{(m)}$ be the number of packets departing from the buffer of sensor node s_m during the n th acting sub-interval. Then, the sequence $\{X_n^{(m)}, n = 1, 2, \cdots\}$ is related as follows:

$$X_{n+1}^{(m)} = X_n^{(m)} + U_n^{(m)} - V_n^{(m)} \tag{1}$$

for $m \in \{1, \cdots, M\}$ and $n \in \mathbb{N}$. Thus, $\{X_n^{(m)}, n = 1, 2, \cdots\}$ forms a sequence for the number of packets remaining in the buffer of a single-server queueing system [6].

In the following, we let $X_n^{(m)}$ be approximated by a number of packets residing in a Geom/Geom/1 queueing system [7] with arrival rate p and service rate q. Since a sensor node generates a packet with probability p at the start of each acting sub-interval, we have

$$\begin{aligned})P(U_n^{(m)} = \quad &= p \\ P(U_n^{(m)} = 0) &= 1 - p. \end{aligned} \tag{2}$$

First, assume that there exists a proper random vector $\left(Y^{(1)}, \cdots, Y^{(M)}\right)$ such that

$$(X_n^{(1)}, \cdots, X_n^{(M)}) \xrightarrow{d} \left(Y^{(1)}, \cdots, Y^{(M)}\right) \tag{3}$$

as $n \to \infty$. Let $h^{(m)}$ denote the marginal mass of $Y^{(m)}$ for $m \in \{1 \cdots M\}$. Then, by symmetry, there exists a number, r, such that

$$r = 1 - h^{(m)}(0) \tag{4}$$

for all $m \in \{1, \cdots, M\}$. Secondly, assume that $X_n^{(m)} = Y^{(m)}$ in distribution and $Y^{(1)}, \cdots, Y^{(M)}$ are mutually independent. Then, we have

$$\begin{aligned} P(V_n^{(m)} = 1 \mid X_n^{(m)} \in \mathbb{N}) &= q \\ P(V_n^{(m)} = 0 \mid X_n^{(m)} \in \mathbb{N}) &= 1 - q \end{aligned} \tag{5}$$

where

$$q = (1 - \frac{r}{\tau})^{M-1} \tag{6}$$

Thus, under the two assumptions, the sequence

$\left\{X_n^{(m)}, n=1,2,\cdots\right\}$ becomes a birth and death Markov chain [8] on state space $\mathcal{S}=\{0,1,\cdots\}$ which has a transition probability function $g:\mathcal{S}\times\mathcal{S}\rightarrow[0,1]$ as follows:

$$\begin{aligned} g(0,1) &= p \\ g(0,0) &= 1-p \end{aligned}$$

and

$$\begin{aligned} g(x,x+1) &= p(1-q) \\ g(x,x) &= pq+(1-p)(1-q) \\ g(x,x-1) &= (1-p)q \end{aligned} \tag{7}$$

for $x\in\mathbb{N}$. Hence, $\left\{X_n^{(m)}, n=1,2,\cdots\right\}$ also becomes the sequence of the numbers of packets remaining in a Geom/Geom/1 queueing system, where the arrival rate is p and the service rate is q.

Note that there exists a steady state distribution for the sequence $\left\{X_n^{(m)}, n=1,2,\cdots\right\}$ if and only if $p<q$. Let $\tilde{h}^{(m)}$ denote the steady state mass of $\left\{X_n^{(m)}, n=1,2,\cdots\right\}$. Then, we have

$$\begin{aligned} \tilde{h}^{(m)}(0) &= 1-\frac{p}{q} \\ \tilde{h}^{(m)}(x) &= \frac{p}{q}\left[1-\frac{p(1-q)}{(1-p)q}\right]\left[\frac{p(1-q)}{(1-p)q}\right]^{x-1} \end{aligned} \tag{8}$$

for $x\in\mathbb{N}$. Since $\tilde{h}^{(m)}(x)$ must be equal to $h^{(m)}(x)$ for all $x\in\{0,1,\cdots\}$, we have an equation which yields an implicit solution for r as follows:

$$p=r\left(1-\frac{r}{\tau}\right)^{M-1} \tag{9}$$

From (6) and (9), we can get the service rate q.

In the Geom/Geom/1 queueing system with arrival rate p and service rate q, the departure rate

$$\delta=\min\{p,q\}. \tag{10}$$

Note that there are ν chances per frame for a packet to depart from the queueing system. Also, at every chance, a packet departs from the queueing system with probability δ. Since the length of a frame is equal to $\sigma+\nu\tau$, we thus have an approximate expression for the network-wide throughput that the proposed MAC scheme can achieve as follows:

$$\eta=M\frac{\nu}{\sigma+\nu\tau}\delta=M\frac{\nu}{\sigma+\nu\tau}\min\{p,q\} \tag{11}$$

As far as a proper $r\in[0,1]$ exists, we note that

$$p=r\left(1-\frac{r}{\tau}\right)^{M-1}\le\left(1-\frac{r}{\tau}\right)^{M-1}=q \tag{12}$$

from (6) and (9), where the equality holds when $r=1$. Let the pair (ν,τ) denote the partition which divides an acting interval into ν acting sub-intervals consisting of τ slots. Given partition (ν,τ), we then have the saturated network-wide throughput, i.e., the maximum network-wide throughput with respect to the acting probability, as follows:

$$\tilde{\eta}=M\frac{\nu}{\sigma+\nu\tau}\left(1-\frac{1}{\tau}\right)^{M-1} \tag{13}$$

Suppose that the length of an acting interval is fixed to γ, i.e., $\nu\tau=\gamma$. Then, the saturated network-wide throughput in (13) can be rewritten by

$$\tilde{\eta}=M\frac{\nu}{\sigma+\gamma}\left(1-\frac{\nu}{\gamma}\right)^{M-1}. \tag{14}$$

Note that the saturated network-wide throughput in (14) is maximized by setting ν to be $\frac{\gamma}{M}$. Since the number of acting sub-intervals must be an integer, we thus have an optimal partition (ν^*,τ^*) which maximizes the saturated network-wide throughput in (13) as follows:

$$\nu^*=\begin{cases} \left\lfloor\frac{\gamma}{M}\right\rfloor & \text{if } \tilde{\eta}|_{\nu=\lfloor\frac{\gamma}{M}\rfloor}\ge\tilde{\eta}|_{\nu=\lceil\frac{\gamma}{M}\rceil} \\ \left\lceil\frac{\gamma}{M}\right\rceil & \text{if } \tilde{\eta}|_{\nu=\lfloor\frac{\gamma}{M}\rfloor}\le\tilde{\eta}|_{\nu=\lceil\frac{\gamma}{M}\rceil} \end{cases} \tag{15}$$

and

$$\tau^*=\frac{\gamma}{\nu^*}.$$

4. Numerical Examples

Through numerical examples in this section, we show the impact of the acting probability as well as the partition of an acting interval on the network-wide throughput achieved by the proposed scheme. Also, we demonstrate the existence of an optimal partition (which maximizes the saturated network-wide throughput) and we find the optimal partition itself.

In the following numerical examples, we set an acting interval to be made up of 24 slots. Note that there are 8 partitions, which divide such an acting interval into sub-intervals of the same length. Also, we set the length of a charging interval to be 480 slots [9]. During such a

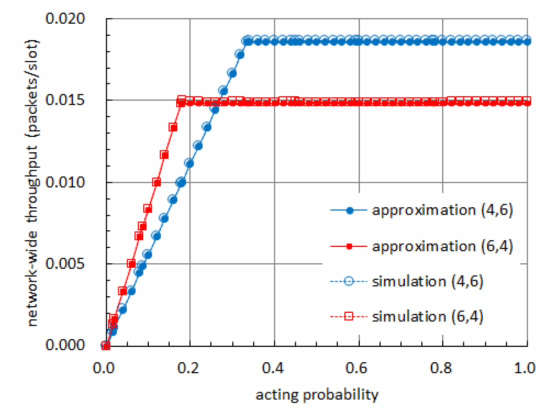

Fig. 4. Network-wide throughput vs. acting probability.

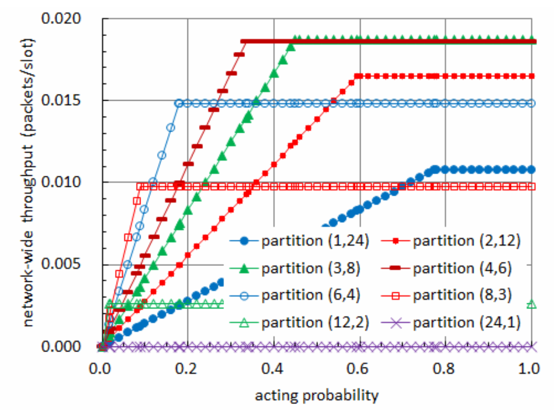

Fig. 5. Network-wide throughput vs. acting probability.

charging interval, a sensor node is then able to collect enough energy to transmit packets 24 times, even if it lies on the boundary of network coverage.

Fig. 4 shows the network-wide throughput with respect to the acting probability. In this figure, the number of sensor nodes is 7. Either partition (4,6) or (6,4) is employed; we observe that the approximate expression yields a highly precise value for network-wide throughput in comparison with a simulation result.

For every possible partition, Fig. 5 shows the network-wide throughput, which is yielded by the approximate throughput formula in (11), with respect to the acting probability. In this figure, the number of sensor nodes is 7. In Fig. 5, we notice that the network-wide throughput linearly increases until the acting probability reaches a threshold value, i.e., as long as the sensor nodes stay in an underloaded state. Then, the network-wide throughput remains unchanged while the sensor nodes lie in an overloaded state. Such a threshold value increases as an acting interval is partitioned into fewer sub-intervals. However, the saturated network-wide throughput, i.e., the network-wide throughput obtained by adopting the threshold value, does not exhibit monotonicity according to the number of acting sub-intervals. This phenomenon gives a glimpse of the existence of an optimal partition of an acting interval.

With respect to the number of acting sub-intervals, Fig. 6 shows the saturated network-wide throughput, i.e., the

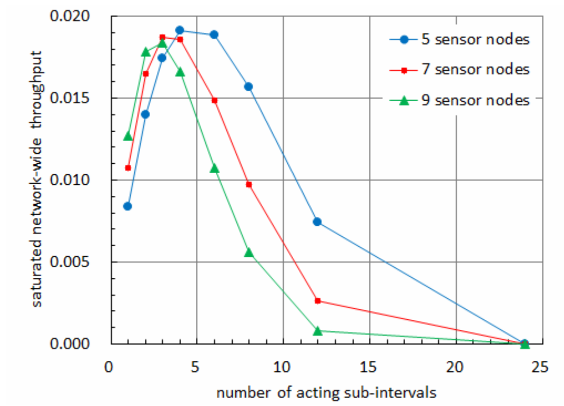

Fig. 6. Saturated network-wide throughput vs. number of acting sub-intervals.

network-wide throughput obtained by adopting the threshold value for the acting probability. In this figure, we observe that there exists an optimal partition that maximizes the saturated network-wide throughput. Such an existence is explained by noting that the probability of a packet collision increases while the number of slots unused for packet transmission decreases as the acting interval is divided into more sub-intervals. In addition, we notice that an exactly optimal partition is yielded by Eq. (15).

5. Conclusion

A wireless passive sensor network is a network in which an RF source transfers energy to sensor nodes by radiating RF waves, and sensor nodes transmit data to a sink node by consuming the received energy. Against theoretical expectations, a wireless passive sensor network suffers from many practical difficulties. Perceiving such difficulties, we proposed a simple contending-type MAC scheme for sensor nodes to deliver packets to the sink node. Then, we developed an approximate expression for the network-wide throughput that can be achieved by the proposed scheme. In comparison with simulation results, an approximate expression was confirmed to yield a highly precise value for throughput over the whole range of acting probability. Also, we found an approximate expression for the optimal partition which maximizes the saturated network-wide throughput. Numerical examples verified that the approximate expression yields an exactly optimal partition.

References

[1] O. Akan, M. Isik and B. Baykal, "Wireless Passive Sensor Networks," *IEEE Communications Magazine*, vol. 47, no. 8, pp. 92-99, August 2009. Article (CrossRef Link)

[2] P. Ghang, I. Jun, H. Seo, J. Ha, J. Park, and C. Choi, "Basic MAC Scheme Based on ALOHA for Wireless Passive Sensor Networks: Performance Analysis," *Proceedings of IEIE/IEEE International Conference on Electronics, Information and Communication*

2016, Da Nang, Vietnam, pp. 855-857, January 2016.

[3] C. Choi and H. Seo, "Elementary MAC Scheme Based on Slotted ALOHA for Wireless Passive Sensor Networks," *Journal of IEIE*, vol. 53, no. 4, pp. 20-26, April 2016. Article (CrossRef Link)

[4] C. Choi and H. Seo, "Optimal Design of Contending-type MAC Scheme for Wireless Passive Sensor Networks," *Journal of IEIE*, vol. 53, no. 6, pp. 29-36, June 2016. Article (CrossRef Link)

[5] R. Rom and M. Sidi, *Multiple Access Protocols: Performance and Analysis*. Springer-Verlag, 1990. Article (CrossRef Link)

[6] J. Cohen, *The Single Server Queue*. 2nd edition, North-Holland, 1982.

[7] H. Takagi, *Queueing Analysis - A Foundation of Performance Analysis, Volume 3: Discrete-time Systems*. North-Holland, 1993.

[8] P. Hoel, S. Port and C. Stone, *Introduction to Stochastic Processes*. Houghton Mifflin, 1972.

[9] H. Seo, J. Park, J. Ha, and C. Choi, "Method for Approximately Calculating Charging and Acting times in Wireless Passive Sensor Networks," *Proceedings of IEIE Conference Fall 2015*, Wonju, Korea, pp. 863-865, November 2015.

Jin Kyung Park received the B.A. degree in economics and the M.S. degree in information and communications, and the Ph.D. degree in electronics and computer engineering from Dankook University, Korea, in 1998, 2002, and 2009, respectively. From 2009 to 2010, Dr. Park was a post-doctorate researcher at the electrical engineering department of the University of California at Los Angeles, U.S.A. In 2017, she joined the faculty of Dankook University, Korea, where she is presently an invited professor at the department of applied computer engineering. Her research interests include design and performance analysis of medium access control schemes for wireless networks, especially wireless MANs, wireless sensor networks, and RFID networks. She is a member of IEIE and IEEE.

Heewon Seo received the B.S. degree in electronics and computer engineering and the M.S. degree in computer engineering and science from Dankook University, Korea, in 2010 and 2012, respectively. Currently, he is a Ph.D. candidate at the department of computer engineering and science, Dankook University, Korea. His research interests include energy-harvesting wireless sensor networks, and wireless passive sensor networks. He is a member of IEIE and IEEE.

Cheon Won Choi received the B.S. degree and the M.S. degree in electronics engineering from Seoul National University, Korea, and the Ph.D. degree in electrical engineering from the University of California at Los Angeles, U.S.A. in 1986, 1988, and 1996, respectively. From 1996 to 1997, Dr. Choi was an engineer at IRI Computer Communications Corporation. Since 1997, he has been on the faculty of Dankook University, Korea, where he is presently a professor at the department of applied computer engineering. From 2006 to 2008, he served as the chief information officer at Dankook University. In 2011, he was appointed as the chair of the research institute for convergence of information and telecommunications technologies at Dankook University and led the institute for four years. His research interests include medium access control and resource allocation in wireless networks, and application of queueing theory and game theory to performance analysis. He is a life member of IEIE, and a senior member of IEEE.