Analysis of Throughput Achieved by Contention-based MAC Scheme in Wireless Passive Sensor Networks: Case Study

Heewon Seo[1], Jun Ha[2], Jin Kyung Park[3], and Cheon Won Choi[4]✉
[1 2 3 4] Department of Applied Computer Engineering, Dankook University
152 Jukjeon Ro, Suji Gu, Yongin Si, Gyeonggi Do, Korea
E-mail: [1]hwseo10@gmail.com, [2]ftword@dku.edu, [3]pjk9466@dku.edu, [4]cchoi@dku.edu

Abstract: Different from a conventional wireless sensor network, a wireless passive sensor network distinctively has RF sources, which feed energy to sensor nodes by radiating RF waves. Against theoretical expectations about an eternal life, 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 resource. Perceiving such difficulties, we consider a contention-based MAC scheme, which is rooted in framed and slotted ALOHA, for sensor nodes to transmit packets to a sink node. Then, we analytically investigate the network-wide throughput attained by the MAC scheme when the sensor nodes are randomly scattered in the initial phase and the transmitted packets experience path losses. Especially, in a network consisting of 3 sensor nodes, we derive the exact throughput formula in a closed form. The numerical examples produced by the throughput formula confirm that the contention-based MAC scheme can be optimized as to achieve maximum throughput by properly deciding the length of an acting interval.

Keywords – **Wireless passive sensor network, MAC scheme, Framed and slotted ALOHA, Throughput formula, Path loss, Capture**

1. Introduction

Different from a conventional wireless sensor network, a wireless passive sensor network distinctively has separate radio frequency (RF) sources besides sink and sensor nodes. In the network, an RF source transfers energy to sensor nodes by radiating RF waves. Then, a sensor node receives the RF waves and converts them to direct current (DC). By using the DC, the sensor node senses the environment, gathers information and transmits data to a sink node [1][2]. Theoretically, an RF source is able to continuously transfer abundant energy to sensor nodes. In practice, however, there are some practical difficulties in a wireless passive sensor network. First, energy is scarce due to high propagation loss of RF wave and low efficiency of rectenna. Secondly, a sensor node is usually unable to receive energy from an RF source and transmit data to a sink node simultaneously. Thirdly, receiving energy up to a level that a sensor node can communicate with a sink node takes much longer time compared with transmitting a segment of data to a sink node. As a result, a sensor node has to store the received energy at its capacitor rather than it consumes the energy to directly run itself. Furthermore, a sensor node has to transmit data in a sporadic fashion between two successive long intervals for charging its capacitor. In such a wireless passive sensor network, a sensor node is not able to directly exchange information with a nearby sensor node and even a sink node is able to easily neither collect information about sensor nodes nor distribute it to them. Therefore, a sophisticated or intelligent medium access control (MAC) scheme is practically inadequate for supporting sensor nodes to transmit data to a sink node.

Perceiving such difficulties, we consider a contention-based MAC scheme, which is rooted in framed and slotted ALOHA [3], for sensor nodes to transmit packets to a sink node. Next, we analyze the throughput achieved by the contention-based MAC scheme when the sensor nodes are randomly scattered in the initial phase and the packets transmitted by sensor nodes experience path losses. Especially, we derive the exact throughput formula in a closed form when 3 sensor nodes are scattered around a sink node.

In section 2, we describe the contention-based MAC scheme for wireless passive sensor networks. In section 3, we exactly derive the network-wide throughput in a closed form for 3 sensor node network. Section 4 is devoted to numerical examples demonstrating the effect of parameters on the network-wide throughput.

2. Contention-based MAC Scheme

Consider a wireless passive sensor network in which a single sink node coexists with an RF source and many sensor nodes are scattered around the sink node. The sensor nodes are initially deployed in a random fashion and never moves afterwards. In the network, the RF source transfers energy to the sensor nodes by radiating RF waves using an omni-directional antenna. Using an omni-directional antenna, a sensor node receives RF waves, extracts energy and charges its internal capacitor. Consuming the energy at the capacitor, the sensor node senses the environment, gathers information, encapsulates it into a packet, and transmits the packet to the sink node.

Two or more sensor nodes may transmit packets almost simultaneously, which incurs a collision among the transmitted packets and interferes with the sink node's receiving a packet correctly. Intending to arbitrate among the contending sensor nodes, we consider a contention-based MAC scheme as follows:

Time is divided into frames and each frame is again divided into a charging interval and an acting interval. An acting interval is also partitioned into a number of slots of fixed length.

During a charging interval, the RF source transfers energy to sensor nodes. A sensor node then receives the energy and charges its capacitor. As a charging interval is over, a sensor node detects a change in received power and recognizes that an acting interval starts. Then, each sensor node senses the environment, gathers information and encapsulates it into a packet. Next, the sensor node equally likely chooses a single slot among the slots belonging to the acting interval. Hoping to avoid a collision with the packets from other sensor nodes, the sensor node finally transmits the packet to the sink node during the selected slot.

Considering the difficulties inherent in a wireless passive sensor network, the sink node returns no acknowledgement for the correct reception of a packet. Hence, any sensor node never retransmits a packet, which invokes a degree of packet losses.

3. Throughput Analysis: Case Study

In a wireless passive sensor network, suppose that a single RF source coexists with a single sink node and M sensor nodes, denoted by $\sigma_1, \cdots, \sigma_M$, reside around the sink node. In the network, sensor nodes are initially deployed in a random fashion and never move afterwards. Let (D_m, Θ_m) represent the location of the sensor node σ_m in the polar coordinate system. Assume that $(D_1, \Theta_1), \cdots, (D_M, \Theta_M)$ are mutually independent and identically distributed for all $m \in \{1, \cdots, M\}$.

A frame consists of a charging interval and an acting interval. The lengths of charging and acting intervals are set to be equal to c and a slots, respectively.

Every sensor node transmits a packet with power U. Let V_m denote the power received by the sink node when the sensor node σ_m transmits a packet. Then, V_m is related to U as follows [4]:

$$V_m = UK(\frac{D_0}{D_m})^\gamma \tag{1}$$

where K is the path loss constant, D_0 is the reference distance and γ is the path loss exponent. Suppose that n sensor nodes, denoted by $\sigma_{\pi_1}, \cdots, \sigma_{\pi_n}$, simultaneously transmit their packets in a same slot of an acting interval, and hence a collision. Then, the signal-to-interference ratio (SIR) that the packet from the sensor node σ_{π_k} experiences is defined by

$$R_{\pi_k}(\pi_1, \cdots, \pi_n) = \frac{V_{\pi_k}}{\sum\limits_{m \in \{1,\cdots,n\} \setminus \{k\}} V_{\pi_m}}. \tag{2}$$

We set that the sink node is able to correctly receive the packet from sensor node σ_{π_k} as far as the SIR $R_{\pi_k}(\pi_1, \cdots, \pi_n)$ is greater than or equal to a threshold τ.

Let X_n denote the number of packets that the sink node correctly receives in the nth frame. Note that $X_1, X_2, \cdots$ are independent and identically distributed. Let η denote the network-wide throughput in packets/slot. Then, from the strong law of large numbers [5], we have

$$\eta = \frac{1}{c+a} \lim_{n \to \infty} \frac{X_1 + \cdots + X_n}{n} = \frac{E(X_n)}{c+a}. \tag{3}$$

Suppose that there are only 3 nodes in the wireless passive sensor network. In the initial phase, assume that these sensor nodes are identically distributed on an annulus in which radii of smaller and larger circles are r_1 and r_2, respectively. Set

$$Y_m \triangleq (\frac{r_2}{D_m})^\gamma \tag{4}$$

for $m \in \{1, 2, 3\}$. Then, $Y_m \in [1, \varepsilon]$, where $\varepsilon = (\frac{r_2}{r_1})^\gamma$. For example, suppose that the sensor nodes σ_1, σ_2 and σ_3 transmit their packets in a same slot. If the SIR $R_1(1,2,3) \geq \tau$, then the sink node is able to correctly receive the packet from the sensor node σ_1 even though a collision occurred among the packets. Note that the event $\{\omega \in \Omega : R_1(1,2,3)(\omega) \geq \tau\}$ is equivalent to the event $\{\omega \in \Omega : Y_1(\omega) \geq \tau Y_2(\omega) + \tau Y_3(\omega)\}$. As shown in the example, regarding the sink node's correct reception of a packet, the sample space Ω, which is equivalent to $\{\omega \in \Omega : (Y_1(\omega), Y_2(\omega), Y_3(\omega)) \in [1, \varepsilon]^3\}$, is partitioned into mutually exclusive 6 events, denoted by $\mathsf{F}_1, \cdots, \mathsf{F}_6$, as follows:

$$\begin{aligned}
\mathsf{F}_1 &= \{\omega \in \Omega : 1 \leq Y_3(\omega) \leq Y_2(\omega) \leq Y_1(\omega) \leq \varepsilon\} \\
\mathsf{F}_2 &= \{\omega \in \Omega : 1 \leq Y_2(\omega) \leq Y_3(\omega) \leq Y_1(\omega) \leq \varepsilon\} \\
\mathsf{F}_3 &= \{\omega \in \Omega : 1 \leq Y_3(\omega) \leq Y_1(\omega) \leq Y_2(\omega) \leq \varepsilon\} \\
\mathsf{F}_4 &= \{\omega \in \Omega : 1 \leq Y_1(\omega) \leq Y_3(\omega) \leq Y_2(\omega) \leq \varepsilon\} \\
\mathsf{F}_5 &= \{\omega \in \Omega : 1 \leq Y_2(\omega) \leq Y_1(\omega) \leq Y_3(\omega) \leq \varepsilon\} \\
\mathsf{F}_6 &= \{\omega \in \Omega : 1 \leq Y_1(\omega) \leq Y_2(\omega) \leq Y_3(\omega) \leq \varepsilon\}.
\end{aligned} \tag{5}$$

Then, the expected number of the packets that the sink node correctly receives in a frame is calculated by

$$E(X_n) = \sum_{k=1}^{6} E(X_n \mid \mathsf{F}_k) P(\mathsf{F}_k). \tag{6}$$

Note that

$$E(X_n \mid \mathsf{F}_1) = \cdots = E(X_n \mid \mathsf{F}_6) \tag{7}$$

and

$$P(\mathsf{F}_k) = \frac{1}{6} \tag{8}$$

for all $k \in \{1, \cdots, 6\}$ by symmetry. Thus

$$E(X_n) = E(X_n \mid \mathsf{F}_1). \tag{9}$$

In (5), the event F_1 is further partitioned into mutually exclusive 7 events as follows:

$$\begin{aligned}
\mathsf{E}_1 &= \{\omega \in \Omega : Y_3 \leq \tau Y_3 \leq Y_2 \leq \tau Y_2 + \tau Y_3 \leq Y_1\} \\
\mathsf{E}_2 &= \{\omega \in \Omega : Y_3 \leq Y_2 \leq \tau Y_3 \leq \tau Y_2 + \tau Y_3 \leq Y_1\} \\
\mathsf{E}_3 &= \{\omega \in \Omega : Y_3 \leq \tau Y_3 \leq Y_2 \leq \tau Y_2 \leq Y_1 \leq \tau Y_2 + \tau Y_3\} \\
\mathsf{E}_4 &= \{\omega \in \Omega : Y_3 \leq Y_2 \leq \tau Y_3 \leq \tau Y_2 \leq Y_1 \leq \tau Y_2 + \tau Y_3\} \\
\mathsf{E}_5 &= \{\omega \in \Omega : Y_3 \leq \tau Y_3 \leq Y_2 \leq Y_1 \leq \tau Y_2\} \\
\mathsf{E}_6 &= \{\omega \in \Omega : Y_3 \leq Y_2 \leq \tau Y_3 \leq Y_1 \leq \tau Y_2\} \\
\mathsf{E}_7 &= \{\omega \in \Omega : Y_3 \leq Y_2 \leq Y_1 \leq \tau Y_3\}.
\end{aligned} \tag{10}$$

Then, the expected number of the packets that the sink node correctly receives in a frame is expressed by

$$E(X_n \mid \mathsf{F}_1) = \sum_{k=1}^{7} E(X_n \mid \mathsf{E}_k) \frac{P(\mathsf{E}_k)}{P(\mathsf{F}_1)}. \tag{11}$$

In order to calculate $E(X_n)$, we need $E(X_n|E_k)$ and $P(\mathsf{E}_k)$.

Suppose that E_1 takes place. Then, the sink node is able to correctly receive a packet from the sensor node σ_1 even if it collides with two packets from the sensor nodes σ_2 as well as σ_3. Moreover, the sink node can correctly receive a packet from the sensor node σ_2 when it collides with a packet from the sensor node σ_3. Since each sensor node equally likely choose a slot with probability $\frac{1}{a}$, we thus have

$$E(X_n|\mathsf{E}_1) = \frac{3a^2 - 3a + 1}{a^2}. \tag{12}$$

By the same way, we obtain $E(X_n|E_k)$ for all $k \in \{2, \cdots, 7\}$.

In order to calculate $P(\mathsf{E}_k)$ for $k \in \{1, \cdots, 7\}$, suppose that Y_1, Y_2 and Y_3 identically have the uniform distribution in $[1, \varepsilon]$. As a result of massive calculation, we then obtain

$$P(\mathsf{E}_1) = \frac{1}{6\tau^2(\tau+1)}\varepsilon^3 - \frac{1}{2\tau}\varepsilon^2 + \frac{\tau+1}{2}\varepsilon - \frac{\tau(\tau+1)^2}{6} \tag{13}$$

if $\varepsilon > \tau(\tau+1)$ and $P(\mathsf{E}_1) = 0$ otherwise. In addition, for all $k \in \{2, \cdots, 7\}$, we obtain $P(\mathsf{E}_k)$ after massive calculation.

From (3), (8), (9), (11), and (11), the exact network-wide throughput achieved by the contention MAC scheme is expressed by

$$\eta = \frac{6}{c+a} \sum_{k=1}^{7} E(X_n|\mathsf{E}_k) P(\mathsf{E}_k) \tag{14}$$

where $E(X_n|\mathsf{E}_k)$ and $P(\mathsf{E}_k)$ are given in (12) and (13), respectively.

4. Numerical Examples

Table 1. Parameter values used in numerical examples.

Parameters	Values
Radius of smaller circle (r_1)	0.5 m
Radius of larger circle (r_2)	2.5 m [6]
Path loss exponent (γ)	2
SIR threshold (τ)	5
Length of charging interval (c)	40 slots [6]
Length of acting interval (a)	5 slots

Using the throughput formula obtained in section 3, we investigate the effect of the parameters (including path loss exponent, SIR threshold and length of acting interval) on the network-wide throughput. In the numerical examples, we assume the environment summarized in table 1.

Figure 1 shows the network-wide throughput with respect to the path loss exponent. In this figure, we observe that the network-wide throughput increases as the path loss exponent increases. When two sensor nodes transmit packets, a higher path loss exponent invokes a wider difference between two levels of received power and results in higher throughput.

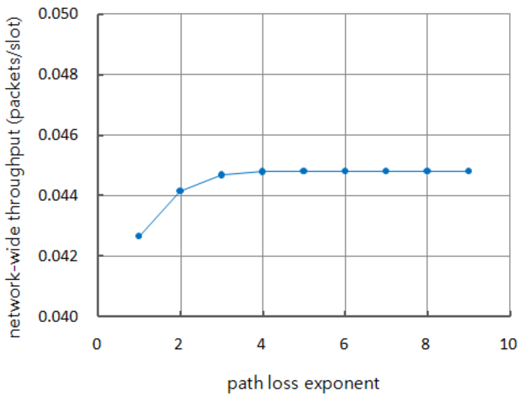

Figure 1. Network-wide throughput vs. path loss exponent.

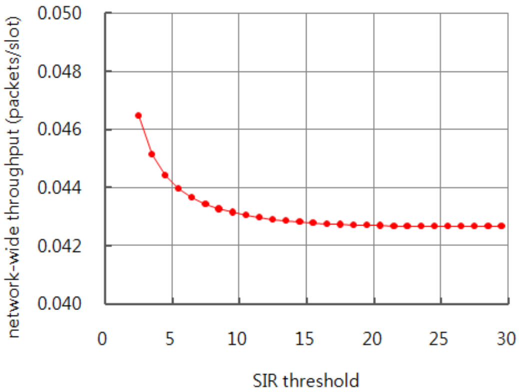

Figure 2. Network-wide throughput vs. SIR threshold.

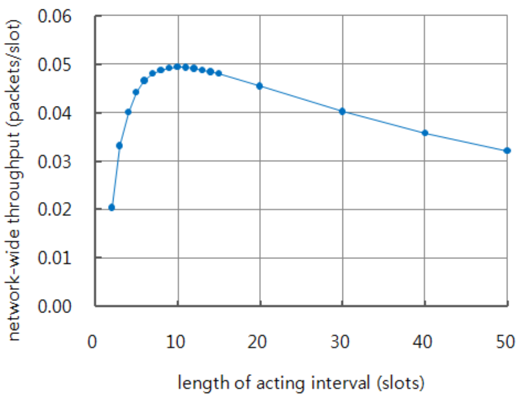

Figure 3. Network-wide throughput vs. length of acting interval.

Figure 2 shows the network-wide throughput with respect to the SIR threshold. In this figure, we notice that the network-wide throughput decreases as the SIR threshold increases. Also, we observe that the network-wide throughput converges to a throughput value which is attained when the sink node is not able to correctly receive any packet once a collision happens.

Figure 3 shows the network-wide throughput with respect to the length of acting interval. In this figure, we observe that there is an optimal length of acting interval which maximizes the network-wide throughput.

5. Conclusions

A wireless passive sensor network is a network in which an RF source transfers energy to sensor nodes by radiating RF wave and a sensor node transmits sensed data to a sink node by consuming the energy received from an RF source. Against theoretical expectations about an eternal life, however, a wireless passive sensor network suffers from many practical difficulties. Perceiving such difficulties, we considered a contention-based MAC scheme for sensor nodes to transmit packets to a sink node. We analytically investigated the network-wide throughput achieved by the MAC scheme when the sensor nodes are randomly scattered in the initial phase and the transmitted packets experience path losses. Especially, we exactly derived the network-wide throughput in a closed form in case that 3 sensor nodes reside in the network. The numerical examples produced by the throughput formula confirmed that the contention-based MAC scheme can be optimized as to achieve the maximum throughput by properly deciding the length of acting interval.

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