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확률모형을 이용한 무선센서망 수명 최대화에 관한 분석*

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A Stochastic Model for Maximizing the Lifetime of Wireless Sensor Networks

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■ Abstract ■

Reduction of power consumption has been a major issue and an interesting challenge to maximize the lifetime of wireless sensor networks. We investigate the practical meaning of *N*-policy in queues as a power saving technique in a WSN. We consider the N-policy of a finite M/M/1 queue. We formulate the optimization problem of power consumption considering the packet loss probability. We analyze the trade-off between power consumption and the packet loss probability and demonstrate the operational characteristics of *N*-policy as a power saving technique in a WSN with various numerical examples.

Keyword : Wireless Sensor Networks, Sensor Node, Power Consumption, Queue, *N*-policy

1. Introduction

A wireless sensor network (WSN) consists of distributed sensor nodes and a sink node. Sensor nodes capture events in the surrounding environment. Sensor nodes transmit and relay the sensing data packets to a sink node for further processing. A sensor node is typically equipped

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with a sensing unit, a radio transceiver, and batteries. Sensor nodes are deployed in large quantities in remote or hostile environments. It is difficult or impossible to replace or recharge their batteries. To prolong the lifetime of a WSN, it is therefore necessary to reduce the power consumption of its nodes. Hence, power saving techniques have been extensively studied over the past several years. Yang et al. [17] invented a method that takes advantage of sensor node mobility to balance the uneven power consumption. In another attempt to achieve power consumption balance, Ok [12] proposed an ant-based routing algorithm, in which sensor nodes can spread data packets over the whole network. Zhao and Zhao [18] studied optimal sensor node scheduling and proposed a data packet routing scheme considering the impacts of the network geometry and power consumption in communications. Matamoros and Anton-Haro [11] proposed the SNR-constrained power saving technique, which aims to decrease the transmission power. Chang and Tassiulas [2] proposed a cross-layer design over routing and power control that only considers minimum transmission power routing. Madan et al. [9] considered the joint optimal design of the physical, medium access control (MAC) and routing layers in energy-constrained WSNs. For other power saving techniques, readers refer to [1, 4, 6, 10] and references therein.

On the other hand, the transitional energy that occurs when a sensor node switches from one mode to another, for example, from idle mode to busy mode, has a significant effect on the power consumption [13]. To conserve energy, the sensor node turns off its radio transceiver whenever the buffer system becomes empty. Therefore, at any instant in time, it can be either in idle mode or in busy mode. In idle mode, the sensor node itself generates packets and cannot relay packets toward other nodes; in busy mode, the sensor node both generates and relays packets. According to [13], the transitional energy when switching from idle mode to busy mode has a significant effect on the power consumption. Compared with other types of energy wastes, mode alternations incur much more energy waste. For this reason, it is desirable to reduce the number of the mode alternations.

Recently, Jiang et al. [3] first applied the N-policy of M/M/1 queueing systems to a WSN. When the number of data packets in a sensor node reaches a predetermined threshold N, the radio transceiver in the sensor node starts transmitting the buffered data packets to other sensor nodes or the sink node. They showed that the N-policy is effective for reducing power consumption in a WSN. N-policy is an energy efficient operation since it reduces the switching times of a sensor node between idle mode and busy mode.

In [3], sensor nodes are modeled as queueing systems with an infinite buffer. In the real operation of a WSN, however, the sensor nodes are equipped with a finite buffer for packets [8]. The objective of buffer management is to store incoming packets and schedule them for future transmission. In a typical sensor node, there is a queue to buffer locally generated packets from the sensing unit and packets received from other sensor nodes that need to be relayed to the next sensor node along the way to the sink node. The size of the buffer is limited due to the power consumption and cost constraints in building and deploying sensor nodes. Hence, all packets cannot be queued in the buffer and some of them must be lost. The packet loss probability should be considered as a quality of service (QoS) requirement for guaranteeing the packet delivery. As a result, in a WSN, not only the power consumption but also the packet loss probability becomes a significant practical issue. In addition, the tradeoff between the power consumption and QoS is inherent since QoS could be improved at the cost of the power consumption, and vice versa [15]. A trade-off exists between power consumption in sensor nodes and the packet loss probability when we operate the N-policy in a WSN. A large N could save the power consumption since it reduces the number of the switches from the idle mode to the busy mode. On the other hand, it results in a high packet loss probability since it causes fewer waiting spaces to be available when the transceiver starts working. Accordingly, when we apply the N-policy to a WSN, it is necessary to consider a finite queue and analyze the power consumption and the QoS together.

We extend the research in [3] to a finite M/M/1 queue. N-policy was first introduced by Yadin and Naor [16] and has been studied extensively (see the references in [5]). For N-policy of finite queues, Takagi [14] analyzed M/G/1 queues and Ke and Wang [5] examined GI/M/1 queues. Therefore, the N-policy of M/M/1 finite queues considered in this paper is mathematically solved. We focus on the operational aspects of the N-policy of finite queues rather than a mathematical queueing analysis. We formulate the optimization problem of power consumption subject to the QoS and packet loss probability. We analyze the operational characteristics of N-policy as a power saving technique in a WSN and demonstrate the trade-off between the power consumption and the packet loss probability with numerical examples.

The remainder of this paper is structured as follows. Section 2 describes the queueing model, summarizes the main performance measures in N-policy of M/M/1 finite queues, and formulates the optimization problem. Section 3 investigates the operational characteristics with numerical works. Finally, Section 4 concludes with a brief summary.

2. Queueing Model and Problem Formulation

We model the sensor node as a finite buffer M/M/1/K queueing system with N-policy. The arrival of packets follows a Poisson process with a rate λ. Packets are served (transmitted or processed) by a single radio transceiver in the order of their arrival, i.e. on a first-come first-served (FCFS) basis. The service time of the radio transceiver follows an exponential distribution with a rate μ. We define $\rho = \lambda/\mu$ as the offered load of the sensor node. We assume that the arrival process of packets and the service time of the radio transceiver are mutually independent. The radio transceiver is turned off whenever all present packets are transmitted. When the radio transceiver stays idle and the buffered packet size builds up to N packets, the sensor node triggers its transmitting function of a radio transceiver and starts transmission of the queued packets. In addition, the sensor node has a finite number of buffer spaces K ($\geq N$). When the sensor node is full of K packets, any new incoming packet is rejected and lost (queue overflow). The WSN should satisfy a maximum allowable packet loss probability as a QoS requirement for guaranteeing the packet delivery.

Let $p_{n,1}$ and $p_{n,0}$ denote the queue length distribution when the radio server is busy and idle, respectively. It is straightforward to obtain $p_{n,1}$ and $p_{n,0}$ from the balance equations in Appendix 1. Let $q(N)$ denote the packet loss probability that is the QoS measure of a WSN. Then we have

$$q(N)=p_{K,1}=\frac{\rho^{K+2}(1-\rho)(1-\rho^{N})}{N\rho^{N}(1-\rho)-\rho^{k+2}(1-\rho^{N})}. \qquad (1)$$

We consider the same power consumption structure in [3]. Let C_S, C_H, C_I, and C_B denote the setup energy per busy cycle, the holding power for each data packet present in the system, the power consumption for keeping the server in idle period, and the power consumption while the radio server is in the busy period, respectively. Let $F(N)$ be the average power consumption function per unit time. Then $F(N)$ can be expressed as

$$F(N)=C_H L+C_I P_I+C_B P_B+C_S/E[T_N^K], \qquad (2)$$

where the performance measures P_I, P_B, L, and T_N^K in (2) respectively denote the probability that the radio transceiver is idle, the probability that the radio transceiver is busy, the mean queue length, and the length of time between two consecutive epochs at which the radio transceiver becomes idle. They are given by

$$P_I=\sum_{n=0}^{N-1}p_{n,0}=Np_{0,0}=\frac{N\rho^{N}(1-\rho)^2}{N\rho^{N}(1-\rho)-\rho^{K+2}(1-\rho^{N})}, \qquad (3)$$

$$P_B=\sum_{n=1}^{K}p_{n,1}=1-P_I=\frac{N\rho^{N+1}(1-\rho)-\rho^{K+2}(1-\rho^{N})}{N\rho^{N}(1-\rho)-\rho^{K+2}(1-\rho^{N})}, \qquad (4)$$

$$L=\frac{\begin{array}{l}2\rho^{K+2}(1-\rho^{N})(K\rho-K-1)\\ \quad -N\rho^{N}(1-\rho)[(N-3)\rho-N+1]\end{array}}{2(1-\rho)[N\rho^{N}(1-\rho)-\rho^{K+2}(1-\rho^{N})}, \text{ and} \qquad (5)$$

$$E[T_N^K]=\frac{N\rho^{N}(1-\rho)-\rho^{K+2}(1-\rho^{N})}{\lambda\rho^{N}(1-\rho)^2}. \qquad (6)$$

Let $\tilde{q}$ denote the QoS requirement, that is, the maximum allowable packet loss probability in a WSN. Then, the problem can be characterized by the following optimization

$$\textit{minimize } F(N), \qquad (7)$$

subject to the QoS reqirement

$$q(N)=\frac{\rho^{K+2}(1-\rho)(1-\rho^{N})}{N\rho^{N}(1-\rho)-\rho^{K+2}(1-\rho^{N})}\le\tilde{q}. \qquad (8)$$

3. Operational Characteristics with Numerical Examples

We investigate the characteristics of the packet loss probability $q(N)$ in (1). For $0<\rho<1$ and $N\ge 1$, we have

$$\frac{d}{dN}q(N)=\frac{\rho^{K+N+1}(1-\rho)^2(\rho^{N}-N\ln\rho-1)}{(\rho^{K+2}-N\rho^{N}+N\rho^{N+1}-\rho^{K+N+2})}>0, \qquad (9)$$

since $\rho^{N}-N\ln\rho-1$ in the numerator of (9) is always positive. Then, it concludes that $q(N)$ is an increasing function of N and $q(N)$ is minimized when $N=1$. Hence, from the viewpoint of QoS, the N-policy is not effective in finite buffer systems.

Remark 1 : As N increases and approaches K, there are few waiting spaces available when the transceiver starts working. In this case, succeedingly arriving packets have few chances to enter the sensor node and most arriving packets are blocked. Therefore, the blocking probability $q(N)$ becomes high as N increases.

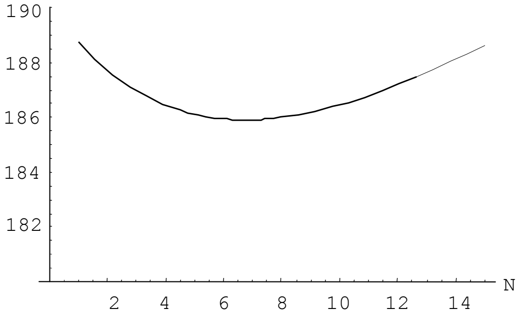
Let $\tilde{N}$ denote the maximum integer that satisfies $q(N) \le \tilde{q}$. Then, $\tilde{N}$ becomes the integer part of the solution in the equation $q(N) = \tilde{q}$. Since $q(N)$ is an increasing function of N, the QoS constraint in (9) can be simplified

$$N \le \tilde{N}. \tag{10}$$

Next, we examine the characteristics of the power consumption function $F(N)$ in (2). Let N_Q^* and N_0^* denote N that minimizes $F(N)$ with and without the QoS constraint (8), respectively. In Appendix 2, we summarized numerical examples of P_I, P_B, L, and $E[T_N^K]$, including their graphs and a discussion about their meanings. Although P_I increases and P_B decreases as N increases, for a sufficiently large K, P_I and P_B quickly converge to $1-\rho$ and ρ, as seen in (A1). Therefore, $C_I P_I + C_B P_B$ might be regarded as a constant value, and the impact of $C_I P_I + C_B P_B$ on $F(N)$ in (2) is negligible. Meanwhile, the mean queue length L increases over N and the expression $1/E[T_N^K]$ shows a decreasing and convex function of N. It is expected that $F(N)$ including $C_H L + C_S/E[T_N^K]$ is convex. Since N_0^* can be greater than 1, the N-policy can be effective to save battery power in a sensor node. This implies that there exists a trade-off between the QoS and power consumption.

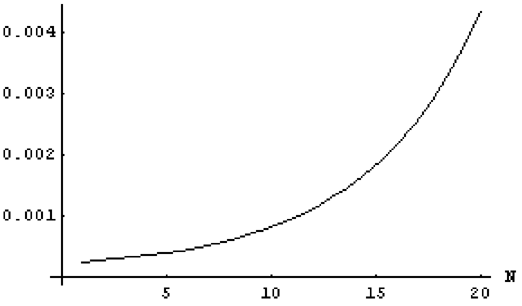
We demonstrate the abovementioned operational characteristics with some specific numerical examples. We apply the same values of the power consumption elements in [3] as follows : $C_S = 20$, $C_H = 2$, $C_I = 4$, and $C_B = 200$. In addition, it is assumed that $\rho = 0.8$, $K = 30$, and $\lambda = 1$.

[Figure 1] shows that $F(N)$ is convex and is minimzed when $N = 7$. That is, $N_0^* = 7$. The N-policy should be effective for reducing the power consumption in the sensor node.



[Figure 1] Average power consumption $F(N)$ over N

[Figure 2] shows that $q(N)$ increases over N. [Figure 1] and [Figure 2] demonstrate the trade-off between the QoS and power consumption.



[Figure 2] Packet loss probability $q(N)$ over N

First, let us consider that $\tilde{q} = 0.001$. Solving the equation $q(N) = 0.001$ numerically gives that $N = 11.2528$. Thus we have $\tilde{N} = 11$. From (11), the QoS constraint for $q(N) \le \tilde{q}$ is simplified as $N \le 11$. Note that $q(11) =$ 0.000961764 and $q(12) =$ 0.00112346. Finally, it is concluded that

$$N_Q^* = N_0^* = 7 \text{ for } \tilde{q} = 0.001. \tag{12}$$

Now, let us assume that the QoS requirement chanages to $\tilde{q} = 0.0003$. Calculating $q(N)$ gives that

$q(12)=0.000278847$ and $q(3)=0.00031504$. Then,

$$N_Q^*=2 \text{ and } N_Q^*\neq N_0^* \text{ for } \tilde{q}=0.0003. \quad (13)$$

The analysis in (12) and (13) concludes that the optimal operation of N-policy for reducing power consumption is affected by the QoS. The optimal operation obtained from infinte queues must be adjusted.

4. Conclusion

In this paper, we have proposed a queue-based power saving technique for a WSN. We modeled the sensor node as a finite buffer M/M/1/K queueing system with N-policy. Based on the queueing results, we formulated an optimization problem that minimizes the average power consumption function of a sensor node subject to the QoS constraint such as the packet loss probability. We showed that a trade-off exists between power consumption and the packet loss probability in the operation of N-policy in a WSN. We presented numerical examples and demonstrated that the QoS affected the optimal operation for reducing power consumption. We expect that our results can be useful to guarantee packet-level QoS, design an admission control scheme, and efficiently allocate energy resources.

In relation to this work, further studies on the following cases are needed. First, we need to model a sensor node as a discrete-time queueing system. It is widely known that the discrete-time queue is more suitable for analyzing digital communication systems because its protocols are operated by a unit of slots which are equal time intervals. Therefore, the discrete-time queue is more realistic and practical for modeling a sensor node. Secondly, in this paper, we presented a power saving technique for a single sensor node without considering the network topology. It is recommended that a WSN be modeled as a fork-and-joint type queueing network, and the optimality for the power consumption of such a queueing network should be extensively investigated.

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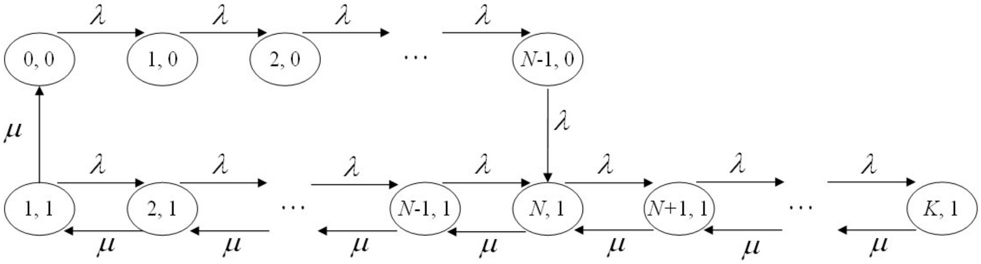
⟨Appendix 1⟩ Transition Diagram and Balance Equations of M/M/1/K Queues with N-policy

The transition diagram which governs our model is depicted below.



[Figure A1] Transition Diagram in the M/M/1/*K* Queue with the *N*-policy

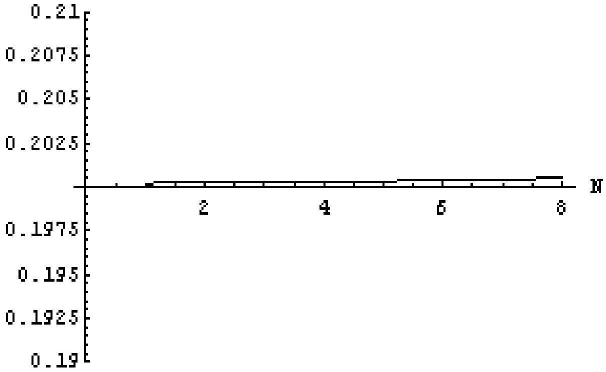
Using [Figure A1], we obtain the following balance equations :

$$\lambda p_{0,0} = \mu p_{1,1}$$
$$\lambda p_{n,0} = \lambda p_{n-1,0}, \text{ for } 1 \le n \le N-1,$$
$$\{(1-\delta_{n,K})\lambda + \mu\} p_{n,1} = (1-\delta_{n,1})\lambda p_{n-1,1} + (1-\delta_{n,K})\mu p_{n+1,1} + \delta_{n,N}\lambda p_{N-1,0}, \text{ for } 1 \le n \le K,$$

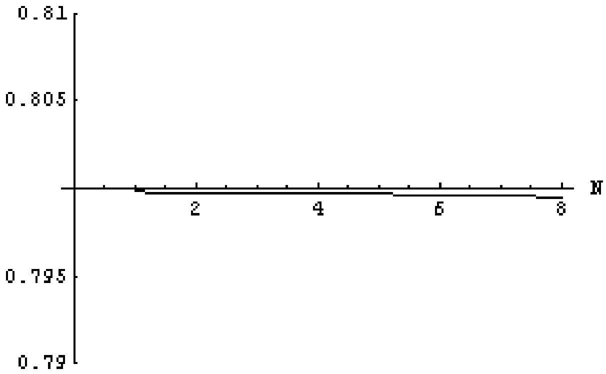
where $\delta_{i,j}$ is the Kronecker's delta.

⟨Appendix 2⟩ Numerical Examples of P_I, P_B, L, $E[T_N^K]$ over N

We demonstrate numerical examples when $\rho = 0.8$, $K = 30$, and $\lambda = 1$. [Figure A2] and [Figure A3] show that P_I increases and P_B decreases over N, respectively.



[Figure A2] P_I over N



[Figure A3] P_B over N

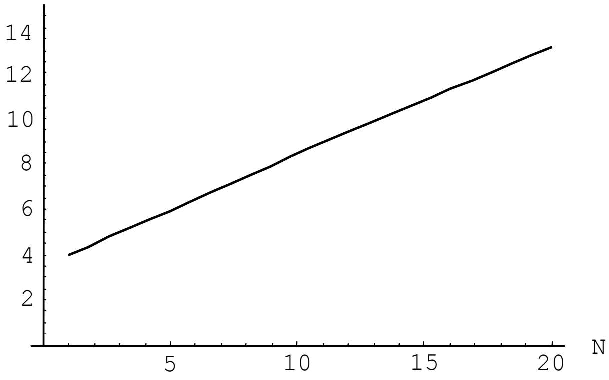
P_I in (3) can be expressed

$$P_I = (1-\rho)/\left[1-\rho^{K+2}\frac{(1-\rho^N)}{N\rho^N(1-\rho)}\right]. \tag{A1}$$

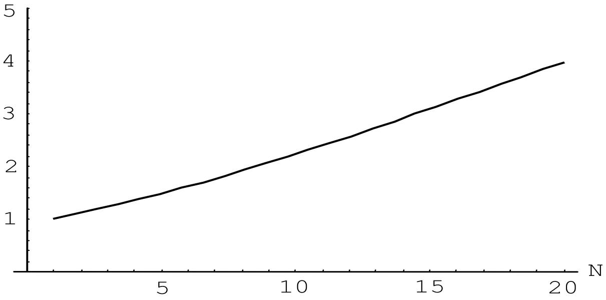
Note that $(1-\rho^N)/\{N\rho^N(1-\rho)\}$ in the denominator in (A1) increases over N. Consequently, P_I is an increasing function of N. P_B is a decreasing function of N since $P_B = 1-P_I$.

Remark A1 : It is easily expected that P_I increases with N increasing. As N is increasing, the idle period relatively lengthens and P_I increases.

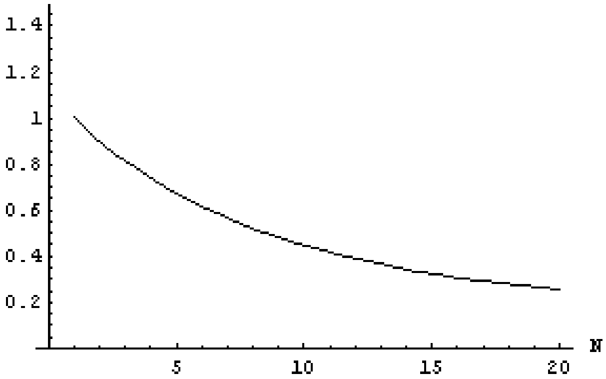
[Figure A4] and [Figure A5] respectively show that L and $E[T_N^K]$ increases over N. [Figure A6] shows that $1/E[T_N^K]$ is convex and decreases over N.



[Figure A4] L over N



[Figure A5] $E[T_N^K]$ over *N*



[Figure A6] $1/E[T_N^K]$ over *N*

Remark A2 : With larger N, more packets are queued during the longer idle period and that makes the queue length longer. Therefore, L is the increasing function of N.

Remark A3 : The initial delay consists of N separate service times. Hence, larger N also leads to longer initial delay. Since the initial delay is known to be proportional to the delay cycle [7], the mean delay cycle $E[T_N^K]$ is also proportional to N.