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Lifetime elongation for wireless sensor network using queue-based approaches

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Abstract A wireless sensor network (WSN) is envisioned as a cluster of tiny power-constrained devices with functions of sensing and communications. Sensors closer to a sink node have a larger forwarding traffic burden and consume more energy than nodes further away from the sink. The whole lifetime of WSN is deteriorated because of such an uneven node power consumption patterns, leading to what is known as an energy hole problem (EHP). From open literatures, most research works have focused on how to optimally increase the probability of sleeping states using various wake-up strategies. In this article, we propose a novel power-saving scheme to alleviate the EHP based on the N-policy M/M/1 queuing theory. With little or no extra management cost, the proposed queue-based power-saving technique can be applied to prolong the lifetime of the WSN economically and effectively. A mathematical analysis on the optimal control parameter has been made in detail. Focusing on many-to-one WSN, numerical and network simulation results validate that the proposed approach indeed provides a feasibly cost-effective approach for lifetime elongation of WSN.

Keywords Wireless sensor networks · Energy hole problem · Sink node · Queuing theory · Many-to-one network · Optimal policy

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1 Introduction

The wireless sensor networks (WSN) has emerged as a promising research domain for a wide range of potential applications, such as habit or environmental monitoring, wildlife tracking, danger alarm, disaster managing, patient monitoring and security surveillance, and so on [1–3]. A typical WSN is comprised of a large number of distributed sensor nodes with an information collector, referred to as the sink node. These sensor nodes may consist of nothing more than a sensing unit, a battery and a radio server. Typically the sensor nodes may be deployed in distant, unattended, and hostile environment with large quantities, and the physical size of a sensor node is made as small as possible for stealthy missions and saving cost. Most of sensor nodes in WSN are equipped with non-rechargeable batteries that have limited lifetime. Thus it is usually difficult to recharge or replace their batteries. As long as the on-board power supply is exhausted, the sensor node is expired. Hence, one of major design issues for WSN is to manage power consumption and to increase the operational lifetime of sensor nodes as much as possible [4, 5].

Power consumption is an essentially important issue and also an interesting challenge to prolong the lifetime of wireless sensor networks. The sensor node usually behaves as both data packets originator and packets router. All of the data that is generated must eventually reach a single sink node in sensor network. The traffic follows a many-to-one pattern, where nodes nearer to the sink carry heavier traffic loads. Therefore, the nodes around the sink would deplete their energy faster, leading to what is known as an *energy hole problem* (EHP) around the sink [6]. No more data packets can be delivered to the sink in case of an energy hole appears. Consequently, a considerable amount of energy is wasted, and the network lifetime ends prematurely. For large WSN in the single static sink model, the simulated experiments [7] show that up to 90% of total initial energy can be left unused when the network lifetime is over. And also with analytical results, [8] argue that by the time the sensor one hop away from the sink exhaust their energy budget, sensors farther away (e.g. in the seventh shell) still have up to 93% of their initial energy budget.

The lifetime of the whole WSN is dominated by sensor nodes in the innermost shell of sensor network. The power consumption dominates the lifetime of these sensor nodes. To gain deeper insight upon the power consumption on a generic sensor node, as described in [9], four main sources of energy waste are identified as: collision, overhearing, control packet overhead, and idle listening. Both overhearing and idle listening incur energy waste by keeping the radio receiver in operation without getting useful information. When the packet collision happens, several packets competing for medium are corrupted and they have to be discarded wholly. Moreover, the follow-on competing process for medium would introduce uncertain numbers of packets retransmissions among those competing sensor nodes, which definitely increase energy consumption for the WSN. Compared with other three types of energy wastes for a generic node, packet collisions incur much more energy waste including operations of both radio transmitter and receiver.

The major cause of packet collisions among sensor nodes arises from the contention of medium under the assumption of contention-based protocol. How to mitigate the total average times of contending the medium among sensor nodes? This is the first challenge to our research goal. Besides, Shih et al. [10] have shown that the transitional energy when switching from one mode to another significantly impacts the total power consumption. How to alleviate the total average times of switching between idle mode and busy mode of radio server as well? Reduction of transitional energy waste is the second research goal. Hence, for each generic sensor node, we present a novel and economical approach to alleviate total average times of both medium contention and mode switching of radio server. The proposed power-saving technique may meet these two research goals in an economical and feasible manner. This approach is based on the theory of N-policy M/M/1 queuing model. Queuing theory has provided numerous applications on production systems, transportation systems, telecommunication networks and other scientific/engineering fields for its solid mathematical frameworks. It attracts us to expand the applicability for queuing theory into the wireless sensor network as well.

The inner-shell nodes have a larger forwarding burden and consume more energy than nodes further away from the sink node. The nodes near the sink take more traffic loads and would die earlier. From the basic queuing theory, the higher relay traffic loads imply that the average arrival rate of the inner-shell nodes is large than that of the outer-shell nodes. Hence, for nodes in each shell, we can adopt the corresponding optimal N criterion for them using the proposed queue-based scheme. A queue threshold, N, is specified for the concept of "queued wake-up". This threshold could be used to control the total average times of turning on the transmitting function of radio server for the buffered data packets. In the "queued wake-up" scheme, when the queue holds N packets, the sensor node triggers its transmitting function of radio server, and starts the transmission process for the queued packets in a burst. The proposed scheme can also balance the energy expenditure through tuning the optimal N value for each shell, especially for nodes in the innermost shell. To the best of our knowledge, this appears to be the first time that such an approach has been proposed to prolong the lifetime of WSN.

The key contributions of this paper are threefold: (i) with little or no management cost, we provide the sensor network administrator with a feasible and economical power-saving technique to prolong lifetime of WSN (ii) mathematical expressions are derived in detail and we establish theoretical background for the proposed approach. And also data simulations with MATLAB tool on optimal queued values for mitigating power consumption are conducted (iii) we analyze the average traffic load per node on regular planar sensor network, and conduct NS-2-based network simulation on lifetime elongation metric. The simulated results indicate that the proposed approach may provide a feasibly cost-effective approach to prolong the lifetime for the sensor network. Moreover, because the perturbation on experimental parameters for different hardware seems to be inevitable, the sensitivity analysis is also conducted to visualize the impacts incurred by different parameter settings.

The rest of the paper is organized as follows. Sect. 2 describes related work and the motivation behind this research. In Sect. 3, an N-policy M/M/1 queuing model is adopted and elaborated, and we derive the relevant system performance measures like the expected length of busy period, idle period, etc. Following this, in Sect. 4, the optimal N-policy is further addressed in terms of total average power consumption, which data simulations are conducted as well for the feasibility of the proposed scheme. In Sect. 5, focusing on many-to-one WSN, the average traffic load per node is analyzed on regular planar sensor network, and the network experiments with NS-2 simulator are also conducted. Finally, some concluding remarks are made in Sect. 6.

2 Related works

A number of research issues for mitigating the power consumption of WSN have been explored in recent years. To minimize the energy consumption of the communication unit, major power-saving techniques can basically be categorized in two groups: power saving through duty cycling and in-network processing. In-network processing [11] takes advantage of compression or aggregation technique to reduce the number of information to be sent. Duty cycling schemes defines coordinated sleep/wake-up schedules among nodes in WSN. Wake-up strategy determines the time point when to wake up a node from a idle state to the busy state. The wake-up action is basically a process of turning on the radio server and applies to any MAC protocol for a sensor node. It performs initial configuration of the radio, starts the radio and its oscillator, then switches the radio to receive or/and transmit modes, and finally performs the necessary actions. From the viewpoint of power consumption, the cost for powering up the radio is almost the same for all protocols. The difference between various MAC protocols is how long the radio is on after it has been started and how many times the radio is re-started. The latter issue, how to decrease the total average times of triggering radio transmission throughout node's lifetime, is the target for this research.

IEEE 802.11 standard [12] is the standard widely used by commercial wireless local area network (WLAN) cards. It specifies a CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) protocol designed for reducing the collision probability between multiple stations accessing a medium in active mode, at the point where collisions would most likely occur. The adopted exponential backoff mechanism can effectively provide the basic function of collision avoidance. But this backoff procedure can only reduce the collision probability among competing nodes, but it cannot alleviate the total numbers of medium contention needed for each sensor node throughout the lifetime. We try to study the feasible approach how to optimize the threshold value (N) based on the power consumption.

The S-MAC [13] protocol also periodically sleeps, wakes up, and listens to the channel, and then returns to sleep. Each active period is of fixed size, 115 ms, with a variable sleep period. The length of the sleep period dictates the duty cycle of S-MAC. In the follow up article, Ye et al. [9] add adaptive listening in case of the node overhears a neighbor's RTS (request to send) or CTS (clear to send) packets, it wakes up for short period of time at the end of their neighbor's transmission to immediately transmit its own data. S-MAC is designed to save energy on single radio architecture. While this approach does allow packets to be buffered, it provides no mechanism to communicate with the receiver on-demand. The S-MAC uses a fixed sleep interval regardless of traffic. Also the S-MAC does not address any approach how to mitigate the total average times of medium contention at all. B-MAC [14] is a lightweight, configurable MAC that is used as the default MAC for Mica2 motes. It is unscheduled, and it adopts CSMA with duty cycles to conserve energy. It uses clear channel

Table 1 Taxonomy of wake-up strategies for sensor node

Basic characteristics	In-band or Out-band signaling	Clock synchronization	Mechanism for checking incoming packets	Using queued wake-up for sending data
IEEE 802.11 [12]	In-band	Synchronous	Periodical wake-up	None ($N = 1$)
S-MAC [9, 13]	In-band	synchronous	Adaptive listen	None ($N = 1$)
B-MAC [14]	In-band	asynchronous	Periodic channel sampling	None ($N = 1$)
STEM [15]	Out-band	asynchronous	Receiver node is notified by beacon packets via additional wake-up band	None ($N = 1$)
Miller [16]	Out-band	asynchronous	Triggered wake-up via additional wake-up band	use a fixed $N = 2$

assessment and packet backoffs for channel arbitration, link layer acknowledgement for reliability, and low power listening for low power communication.

STEM [15] is a two-radio architecture that achieves power savings by keeping the data radio sleep until communication is desired while the wake-up radio periodically listens using a low duty cycle, which reducing idle listening energy. STEM uses asynchronous beacon packets in special wake-up channel to wake up intended receivers. When a possible event is detected, the main processor is woken up to analyze the data in more detail. The radio server, which is normally turned off, is only woken up if the processor decides that the information needs to be forwarded to the data sink. Generally, the STEM protocol can be used in conjunction with any MAC layer transmission scheduling scheme. But, however, the STEM protocol does not address issues regarding how to reduce the total expected times of medium contention in data radio whenever the sensor node itself has incoming data packets to send out.

A queue threshold, N, is specified in the concept of "queued wake-up." This threshold could be used to control the average times of turning on the data radio and the latency delay for the buffered data packets. In the "queued wake-up" scheme, a sensor node triggers the data radio, only when the queue holds N packets, and conducts the medium-contention process. Then it transmits the queued packets in a burst as soon as it obtains the access right of air medium. From the viewpoint of queued wake-up, the abovementioned MAC protocols, like IEEE 802.11, S-MAC, B-MAC, or STEM can be regarded as taking $N = 1$. Using the similar concept, Miller et al. [16] adopt a queue threshold with $N = 2$ to reduce the energy consumption compared to the STEM protocol. Table 1 roughly summarizes the taxonomy of the some wake-up strategies for sensor nodes. The last column in Table 1 reveals that most of existing MAC protocols does not incorporate the queued wake-up scheme in case of sending data packets. Inspired by their research, we would ask questions: Is it possible to choose an optimal N value based on queuing theory? How to find optimal N in terms of system parameters, like power consumption, or expected arrival rate of packets? These issues would be explored further in this article.

To minimize the total energy expended by the WSN to locate the desired resource, Mann et al. [20] characterized the performance of random-walk WSN search algorithms when both agents and queries are assigned expiration times. Similarly, they utilized a queuing approach in their work in which an event table was modeled as an M/M/∞ queue. Their research showed that resource replication levels must be carefully managed in order to gain a proper balance between energy efficiency and query failures. A feasible approach to obtain appropriate replica level was also provided by their work.

3 Mathematical preliminaries

3.1 Overview of proposed N-policy queue-based scheme

In our application, a "customer" arriving and queued in the queuing system for the server's service represents a "data packet" arriving and queued in the sensor node for the radio server's transmission. The data packets arriving at the sensor node in each shell, except the outermost shell, are composed of two sources from both the sensed data and relay data. The nodes in the outermost shell only needs to forward their own sensed data without any relay data from neighboring shells. The size of queue buffer is assumed to be large enough to be regarded as infinity. The buffer is modeled as a centralized FCFS queue. The wireless channel is assumed to be error-free. The communication pattern is assumed to be many-to-one, in which a group of sensor nodes only communicate to a specific sensor in a one-hop environment. The destination node could be a cluster head, a data fusion, or a base station.

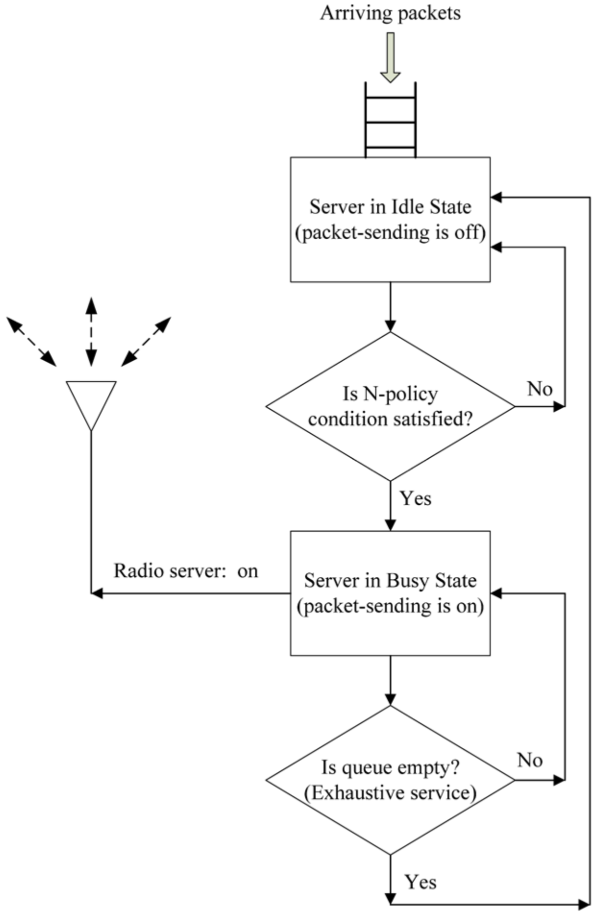
In this article, we study the optimal operation of radio server in an N-policy M/M/1 queuing system under steady-state conditions. The sensor node can turn on the transmission function of radio at packet's arrival and off at service completion epochs. It is assumed that packets arrive following a Poisson process with mean arrival rate λ for a generic sensor node. The radio service times are exponentially distributed with mean $1/\mu$. The transmission function of radio server is configured to be on/off and applies the N-policy discipline: turn on the transmission function of server whenever N ($N \geqq 1$) or more packets are present; turn off the transmission function of server when no packets are present. The states of the system are assumed to have two major operational states for the radio server of the sensor node: idle and busy states. The system may be in any of the following two states:

Idle state: the function of packet transmission in the radio server is turned off and the number of packets waiting in the queue is less than or equal to $N - 1$ ($N \geqq 1$).

Busy state: the radio server is busy in offering data packets transmission service, the queue length being greater than or equal to zero.

As soon as the radio server is switched into the busy state from the idle state, the packets queued in the buffer will be sent out until the system is empty (exhaustive service). In general, the idle state corresponds to the lowest value of the radio server power consumption, which can be viewed as the state of turning off the function of packet transmission in the radio server; while being busy state, energy is spent in the front-end amplifier that supplies the power for actual RF transmission for the standard process of medium contention and the subsequent phase of sending packets. We study

Fig. 1 Proposed operational model for a generic sensor node



the behavior of a single sensor of applying the N-policy M/M/1 queuing model, in which the operating flow for the sensor node can be modeled as shown in Fig. 1. In Fig. 1, before accumulating N data packets in the queue buffer, the function of transmitter in radio server is turned off (Sever in Idle State). At the instant of the Nth packet arrival, the transmitter is turned on, and begins delivery service for queued data packets in an exhaustive manner (Server in Busy State).

3.2 Steady-state results in an N-policy M/M/1 queuing model

We first state mathematical background for the N-policy Markovian queuing system [17]. The analytic steady-state results are developed for a generic sensor node. The states of the system are described by the pair (i, n), $i = 0$ and 1, $n = 0, 1, 2, \ldots,$ where $i = 0$ and $i = 1$ represents the radio server is in idle state and busy state, respectively. The value n is the number of data packets queued in the sensor node. In steady-state, the following notations are used:

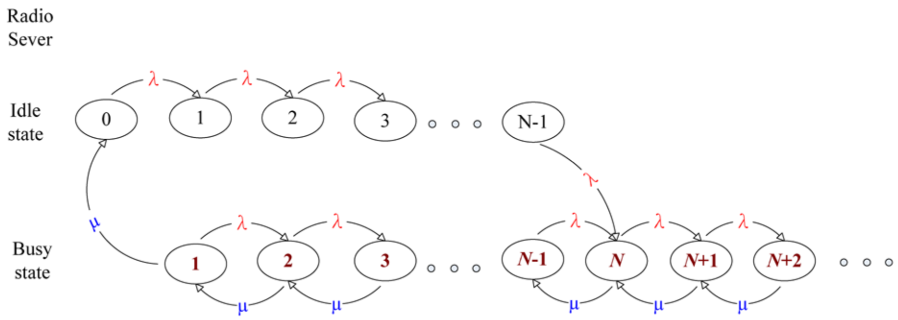


Fig. 2 State-transition-rate diagrams for the N-policy M/M/1 queuing system

$P_0(0) =$ the probability that there is no data packets in the node when the transmission function of radio server is turned off (idle state).

$P_0(n) =$ the probability that there are n data packets in the node when the transmission function of radio server is turned off (idle state), where $n = 1, 2, \ldots, N-1$,

$P_1(n) =$ the probability that there are n data packets in the node when the transmission function of radio server is turned on (busy state), where $n = 1, 2, \ldots$

The state-transition-rate diagram for the N-policy M/M/1 queuing system is shown in Fig. 2. In Fig. 2, there are two chains of horizontal circles associated with the state of the radio server. The upper and lower chains represent the idle state and the busy state of the radio server, respectively. Each circle with number in it denotes that the number of data packets queued in the sensor node for that state. The value λ is the mean arrival rate of data packets into the sensor node, and the value μ is the mean service rate of radio server. The steady-state equations for $P_0(n)$ and $P_1(n)$ are as follows:

$$\lambda P_0(0) = \mu P_1(1), \tag{1}$$

$$\lambda P_0(n) = \lambda P_0(n-1), \quad 1 \le n \le N-1, \tag{2}$$

$$(\lambda + \mu) P_1(1) = \mu P_1(2), \tag{3}$$

$$(\lambda + \mu) P_1(n) = \lambda P_1(n-1) + \mu P_1(n+1), \quad 2 \le n \le N-1, \tag{4}$$

$$(\lambda + \mu) P_1(N) = \lambda P_0(N-1) + \lambda P_1(N-1) + \mu P_1(N+1), \tag{5}$$

$$(\lambda + \mu) P_1(n) = \lambda P_1(n-1) + \mu P_1(n+1), \quad n \ge N+1 \tag{6}$$

The probability generating function (PGF) may be used to obtain analytic solution $P_0(0)$ in neat closed-form expressions since solving (1)–(6) using a recursive method is difficult. We define the following three PGFs as follows:

$G_I(z) \equiv$ PGF of the number of packets in the node when the radio server is in idle state

$G_B(z) \equiv$ PGF of the number of packets in the node when the radio server is in busy state

$G_N(z) \equiv$ PGF of the number of packets in the node under N-policy

The expressions for $G_I(z)$, $G_B(z)$ and $G(z)$ are given by

$$G_I(z) = \sum_{n=0}^{N-1} z^n P_0(n), \quad |z| \le 1,$$

$$G_B(z) = \sum_{n=1}^{\infty} z^n P_1(n), \quad |z| \le 1,$$

$$G_N(z) = G_I(z) + G_B(z)$$

From (1) and (2), we have $P_0(n) = P_0(0)$. Hence $G_I(z)$ can be expressed in terms of $P_0(0)$, and is given as follows:

$$G_I(z) = \sum_{n=0}^{N-1} z^n P_0(n) = P_0(0) \cdot \sum_{n=0}^{N-1} z^N = \frac{1-z^N}{1-z} P_0(0) \tag{7}$$

In (2)–(6), (2) is multiplied by z, (3)–(6) are multiplied by z^{n+1} $(n = 2, 3, \ldots)$ and all the equations are added term by term for all possible values of n. We obtain

$$\begin{aligned} &\lambda z P_0(0) + (\lambda + \mu) z G_B(z) = \mu G_B(z) + \lambda z^2 G_B(z) + \lambda P_0(N-1) z^{N+1}, \\ &[\lambda z^2 - (\lambda + \mu) z + \mu] \cdot G_B(z) = \lambda z (1 - z^N) \cdot P_0(0), \\ &G_B(z) = \frac{\lambda z (1 - z^N)}{\lambda z^2 - (\lambda + \mu) z + \mu} \cdot P_0(0) = \frac{\rho z (1 - z^N)}{\rho z^2 - (1 + \rho) z + 1} \cdot P_0(0) \end{aligned} \tag{8}$$

Here the utilization $\rho = \lambda/\mu$. Combining (7) and (8). The $G_N(z)$ can be derived in terms of $P_0(0)$ as follows:

$$G_N(z) = G_I(z) + G_B(z) = \frac{1-z^N}{(1-\rho z)(1-z)} \cdot P_0(0) \tag{9}$$

In order to obtain $P_0(0)$, we use the normalization condition: $\sum_{n=0}^{N-1} P_0(n) + \sum_{n=1}^{\infty} P_1(n) = 1$. From definition of PGF, we have

$$G_N(z) = G_I(z) + G_B(z) = \sum_{n=0}^{N-1} z^n P(0) + \sum_{n=1}^{\infty} z^n P_1(n), \quad \text{let } z = 1 \text{ and yields}$$

$$G_N(1) = \sum_{n=0}^{N-1} P_0(0) + \sum_{n=1}^{\infty} P_1(n) = 1$$

Since the denominator and numerator are both 0 from (9), we use L'Hôspital's rule and find that

$$\begin{aligned} &1 = G_N(1) = \lim_{z \to 1} G_N(z) = \lim_{z \to 1} \frac{1-z^N}{(1-\rho z)(1-z)} \cdot P_0(0) = \frac{N}{1-\rho} \cdot P_0(0), \\ &P_0(0) = \frac{1-\rho}{N} \end{aligned} \tag{10}$$

Let P_I and P_B denote the probabilities that the radio server is in the idle state and in the busy state, respectively. The expressions for P_I and P_B are given by $P_I = \sum_{n=0}^{N-1} P_0(n) = G_I(1)$ and $P_B = \sum_{n=1}^{\infty} P_0(n) = G_B(1)$, respectively. Then it is evident from (2) and (10) that $P_I = NP_0(0) = 1 - \rho$. Also P_I can be derived from PGF where $P_I = G_I(1) = \lim_{z\to 1} \frac{1-z^N}{1-z} P_0(0) = NP_0(0) = 1 - \rho$. Similarly $P_B(z)$ can be derived from PGF where $P_B = G_B(1) = \lim_{z\to 1} \frac{\rho z(1-z^N)}{(1-\rho)(1-z)} P_0(0) = \rho$. From total probability concept, the probability that radio server is in busy state can be also obtained by $P_B = 1 - P_I = \rho$. It is noted that for N policy M/M/1 queuing model, the steady-state probability that the radio server is busy is equal to ρ which is termed as "traffic intensity" or "utilization" of the system in a generic sensor node.

The expected number of data packets in a generic sensor node when the radio server is in the idle and busy states are denoted by L_I and L_B, respectively. The expected number of data packets in a one-node system under N-policy is denoted by L_N. The expressions for L_I, L_B, and L_N are given by

$$\begin{aligned} L_I &= \sum_{n=0}^{N-1} n \cdot P_0(n) = P_0(0) \sum_{n=0}^{N-1} n = \frac{1-\rho}{N} \cdot \frac{N(N-1)}{2} = \frac{(N-1)(1-\rho)}{2}, \\ L_B &= \sum_{n=1}^{\infty} n \cdot P_1(n) = G'_B(1) = \lim_{z\to 1} G'_B(z) \end{aligned} \tag{11}$$

To find L_B, we compute $\lim_{z\to 1} G'_B(z)$ in (8) by using L'Hôspital's rule twice to obtain

$$L_B = G'_B(1) = \frac{N\rho(1-\rho) + \rho(1+\rho)}{2(1-\rho)} \tag{12}$$

And hence,

$$L_N = L_I + L_B = \frac{(N-1)(1-\rho)}{2} + \frac{N\rho(1-\rho) + \rho(1+\rho)}{2(1-\rho)} = \frac{N-1}{2} + \frac{\rho}{1-\rho} \tag{13}$$

To formulate the expressions regarding system performance metrics, it is necessary to construct period-related functions such as idle period, busy period and busy cycle. The idle period, the busy period and the busy cycle are defined as follows:

(1) Idle period denoted by I_N: This is the length of time per cycle when the radio server is idle and the numbers of packets waiting in the queue is less than N.
(2) Busy period denoted by B_N: This is the length of time per cycle when the radio server is busy and data packets are being transmitted.
(3) Busy cycle denoted by T_N: This is the length of time from the beginning of the last period to the beginning of the next idle period.

The expected length of the idle period, the busy period and the busy cycle, are denoted by $E[I_N]$, $E[B_N]$, and $E[T_N]$, respectively. Since the busy cycle is the sum of the idle period and the busy period, we obtain $E[T_N] = E[I_N] + E[B_N]$. Applying the memoryless property for the exponential distribution, the length of the idle period is the sum of N exponential random variables each having mean $1/\lambda$. Thus, the expected length of the idle period is given by $E[I_N] = N/\lambda$. The long-run fraction of time the radio server is idle and busy are given by $\frac{E[I_N]}{E[T_N]} = P_I = 1 - \rho$ and $\frac{E[B_N]}{E[T_N]} = P_B = 1 - P_I = \rho$, respectively. Thus we have

$$E[T_N] = \frac{N}{\lambda(1-\rho)}, \tag{14}$$

$$E[B_N] = \frac{N}{\mu(1-\rho)} \tag{15}$$

Based on the aforementioned model and equations, performance metrics are developed. The metrics include multifarious expected length of system parameters, and their relationships with the power consumption of the one-node system. These performance metrics are needed for built up the evaluation function like the total expected power consumption.

4 Optimal N policy

The strategy to minimize the total cost of the operating horizon is referred to as the optimal policy. The cost can be regarded as the power consumption for the sensor node. In this section, we develop an expected cost function for the proposed queue-based approach. The cost function $F(N)$ is called "total expected power consumption function" which contains the major power consumption elements and the control parameter N.

4.1 Power consumption function

In this subsection, we develop the total expected power consumption function, $F(N)$, in which N is the queue-based parameter. Without loss of generality, our objective is to establish the closed form of power consumption function $F(N)$ in terms of relevant system parameters. Since there is only one radio server setup for each busy cycle, it is reasonably assumed that fixed energy consumption is incurred per busy cycle by switching from idle mode to busy mode and vice versa. The sum of these two types of energy waste, called the setup energy consumption element, is given by C_{s}. Let

C_{s} = setup energy for per busy cycle
C_{h} = holding power for each data packet present in the system
C_{id} = power consumption for keeping the server in idle period
C_{b} = power consumption while the radio server is in the busy period

Using the definitions of each power consumption element and its corresponding performances, the power consumption function is given by

$$F(N) = C_{\mathrm{h}} L_N + \frac{C_{\mathrm{s}}}{E[T_N]} + C_{\mathrm{id}} \frac{E[I_N]}{E[T_N]} + C_{\mathrm{b}} \frac{E[B_N]}{E[T_N]} \tag{16}$$

Where L_N, $E[T_N]$, and $E[B_N]$ are given in (13), (14), and (15), respectively. It is noted that the expected length of the idle period is given by $E[I_N] = N/\lambda$. Putting these relevant expressions into (16) yields

$$F(N)=C_{\mathrm{h}}\left(\frac{N-1}{2}+\frac{\rho}{1-\rho}\right)+C_{\mathrm{s}}\frac{\lambda(1-\rho)}{N}+C_{\mathrm{id}}(1-\rho)+C_{\mathrm{b}}\rho \tag{17}$$

By differentiating $F(N)$ with respect to N, we have

$$\frac{dF(N)}{dN}=\frac{C_{\mathrm{h}}}{2}-\frac{C_{\mathrm{s}}\lambda(1-\rho)}{N^2}$$

Setting $dF(N)/dN=0$ yields

$$N^*=\sqrt{\frac{2C_{\mathrm{s}}\lambda(1-\rho)}{C_{\mathrm{h}}}} \tag{18}$$

Differentiating $F(N)$ with respect to N twice and using (17), we get

$$\frac{d^2F(N)}{dN^2}=\frac{2C_{\mathrm{s}}\lambda(1-\rho)}{N^3}>0 \quad (\rho<1) \tag{19}$$

The graph of total expected power consumption function $F(N)$ is concave upward since $F''(N)>0$. Hence N^* is the minimum of $F(N)$. If N^* is not an integer, the optimal positive integer value of N is one of the integers surrounding N^*. The upward-cavity characteristic in (19) provides us with that the optimality can be reached by the proposed queue-based scheme.

4.2 Data simulation and performance improvements

To demonstrate the application of the proposed queue-based models, data simulations are presented. We assume that packets arrive by a Poisson process with mean arrival rate (λ). The radio service times are exponentially distributed with mean $1/\mu$. All data simulations are performed with MATLAB 7.6 on Intel Core 2 Quad CPU (2.4 GHz clock, 2 G RAM). Custom MATLAB scripts are written to simulate the proposed power-saving scheme. Simulations are compared with ordinary M/M/1 queuing case (i.e., $N=1$). In other words, the power consumption in $N=1$ is regarded as a baseline value.

Data Simulation 1:

The system parameters are assumed as follows:

- mean arrival rate (mar) of packets: λ (range from 1.0 to 5.0)
- mean service rate: $\mu=10$.
- power consumption elements: $C_{\mathrm{s}}=20$, $C_{\mathrm{h}}=2$, $C_{\mathrm{id}}=4$, and $C_{\mathrm{b}}=200$

In this data simulation, we first study the effect of varying different mean arrival rate (from 1.0 to 3.0) to obtain the corresponding optimal N value while keeping other parameters constant. Based on (17), each value of the total expected power consumption function $F(N)$ can be computed. Since contour plots provide the best graphical representation of the optimization profile, and also possess a powerful visualization that permits the solutions of the optimization problem by inspection. The simulated

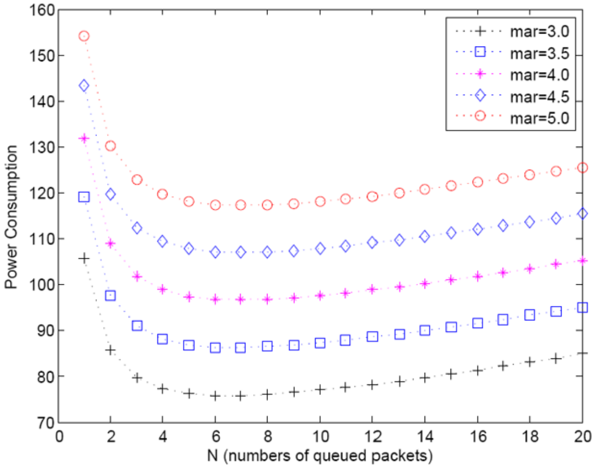


Fig. 3 Power consumption, λ: 1.0 ∼ 3.0

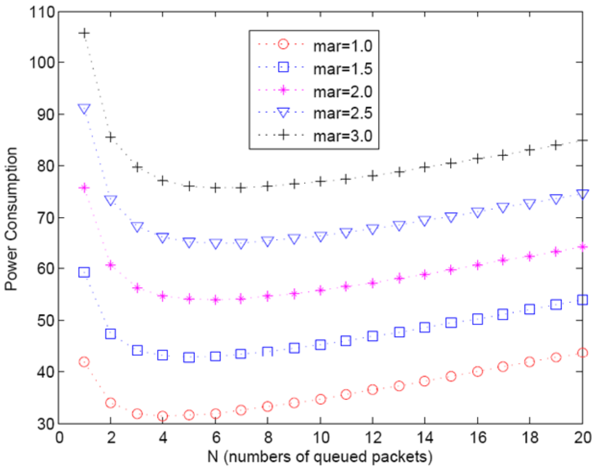


Fig. 4 Power consumption, λ: 3.0 ∼ 5.0

results are shown in Figs. 3 and 4 with mar (λ) set from 1.0 to 3.0 and from 3.0 to 5.0, respectively.

These two graphs of $F(N)$ are all concave upward, which would be in agreement with the geometrical implication of (19). The location of optimal N value (i.e., the bottom point of each curve) shifts right accordingly as the mean arrival rate (mar) is tuned larger gradually. For instance, observing curves for mar $(\lambda) = [1.0, 2.0, 3.0, 4.0, 5.0]$ in Figs. 3 and 4, we can find that the corresponding bottom points are located at $N^* = [4, 6, 6, 7, 7]$. Moreover, how about the power consumption reduction incurred by the proposed approach? We take λ to be 3.0 as an example, the power consumption reduction can be observed by calculating the expression: $F(N = 1.0) - F(N = 3.0) = 30$. Because the total expected power consumption function $F(N)$ is a multivariate function in mathematical view, it would be proper to evaluate the relative improvement degree on power consumption instead of the absolute quantity. To provide the sensor administrator the relative improvement level

Table 2 Power consumption improvement factor (PCIF in %)

N	2	3	4	5	6	7	8	9	10	11	12
$\lambda = 1.0$	19.13	23.91	25.11*	24.87	23.91	22.54	20.92	19.13	17.22	15.22	13.15
$\lambda = 1.5$	19.83	25.32	27.21	27.68*	27.42	26.76	25.84	24.75	23.54	22.25	20.89
$\lambda = 2.0$	19.82	25.54	27.74	28.53	28.62*	28.31	27.74	27.01	26.16	22.25	20.89
$\lambda = 2.5$	19.47	25.83	27.56	28.52	28.79*	28.68	28.31	27.79	27.15	26.43	25.64
$\lambda = 3.0$	18.93	24.61	26.97	28.02	28.39*	28.39	28.16	27.76	27.26	26.43	25.63
$\lambda = 3.5$	18.25	23.77	26.12	27.19	27.62	27.69*	27.53	27.22	26.81	26.32	25.77
$\lambda = 4.0$	17.46	22.77	25.05	26.11	26.57	26.68*	26.59	26.32	25.96	25.53	25.05
$\lambda = 4.5$	16.57	21.63	23.81	24.84	25.29	25.41*	25.33	25.12	24.80	24.42	23.98
$\lambda = 5.0$	15.58	20.35	22.40	23.38	23.91	23.93*	23.86	23.67	23.38	23.02	22.62

on power consumption with various (N, λ) pairs, we present the Power Consumption Improvement Factor, PCIF for short, in the next subsection.

4.3 Improvement of power consumption

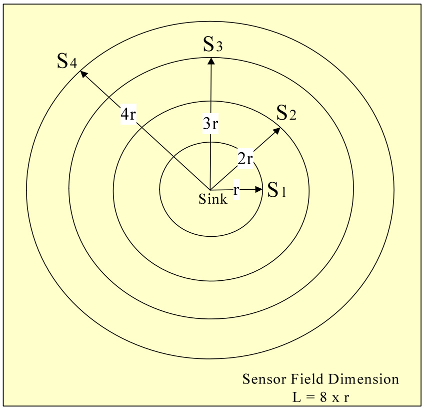
To mitigate the direct perturbation from different system parameters settings, relative improvement level is introduced for power consumption evaluation. The improvement degree of power consumption due to the proposed queuing approach may be evaluated by the following equation:

$$\text{Power Consumption Improvement Factor (PCIF)} = \frac{F_{\text{ord}} - F(N)}{F_{\text{ord}}} \times 100\% \qquad (20)$$

where F_{ord} represents the power consumption of an ordinary M/M/1 system without the N-policy (i.e., $N = 1$). In other words, the term F_{ord} can be regarded as the power consumption of general MAC-based mechanisms as discussed in Sect. 2. Based on the numerical data in Figs. 3 and 4, the PCIFs (in percentage) are calculated and summarized in Table 2. In Table 2, each row represents a specific contour as shown in Figs. 3 and 4. Each cell indicates the PCIF value in percentage for a specific (N, λ) pair. For instance, in the 1st row for $\lambda = 1.0$, the cell having asterisk mark (25.11*) is the largest value of PCIF for that row. The largest value of PCIF for the 2nd row ($\lambda = 1.5$) is the cell having asterisk mark (27.68*). Since the $F(N)$ is concave upward, the function PCIF(N) is thus concave downward.

Table 2 revealed that the PCIF for each assigned λ can reach from 25.11% to 28.79% for the chosen optimal N values. Such a significant improvement level on power consumption for a generic sensor node has strengthened the effectiveness and feasibility of applying the proposed N-policy M/M/1 queued approach into the MAC-based scheme. Consequently, a considerable amount of energy can be saved, and the lifetime of the sensor node can be prolonged.

Fig. 5 A sensor field consisting of four shells



5 Design approach for lifetime elongation in WSN

The proposed design approach to prolong the lifetime in WSN is composed of threefold process. Firstly, for a given shell, the per-node average traffic load in each shell is analyzed and the neat closed-form mathematical expression is derived as well. Secondly, based upon different average traffic load in each shell, we model the power consumption pattern of each sensor node in each shell with the proposed N-policy M/M/1 queuing model. Then the lifetime elongation in WSN can be reached by alleviating the EHP by focusing on the improvement of power consumption in sensor nodes of the innermost shell, i.e., the dominant shell. Finally the network simulations are conducted using NS-2 simulator [18] to verify and evaluate the proposed scheme.

5.1 Mathematical analysis of average traffic load per node

It is assumed that all the nodes are deployed in a sensor field which is formed in an $L \times L$ area. The unique sink is located at the center of the sensor filed as shown in Fig. 5. All the sensors are homogeneous. In data transmission, each of them is set to the same maximum transmission range, which is set to r meters. Each node has a unique ID numbers to configure optimal system parameters on it. The width of each shell is also r meters. We can divide the whole area into M concentric shells with a step size of r meters ($L = M \times 2r$) as exemplified in Fig. 5 ($M = 4$). The ith shell is denoted as S_i, which is composed of nodes whose distances to the sink are between ir and $(i + 1)$ r meters. Nodes are uniformly and randomly distributed, so that the node density is uniform throughout the network: $p = Q_N / A_{\text{net}}$, where Q_N is the numbers of nodes and A_{net} is the network area. Every node in the whole sensor filed is assumed to have an identical sensing data rate w to retrieve the environmental or target information. It is also assumed that a packet can traverse each shell using only one hop transmission, although in reality a packet can be transmitted more than one time within the territory of a single shell.

As illustrated in Fig. 5, a sensor field with sink node in the center is divided into M concentric bands. Note that all traffic has to go through a node in shell S_1. Because the inherent requirement of packets-relay must be conducted in sensor network, the inner-shell nodes would have higher mean arrival rate on traffic load than those of outer-shell nodes. It is reasonably assumed that the nodes of the shell S_i have their own mean arrival rate (λ_i). We derive the mathematical expressions of per-node traffic load in each shell starting from the outermost shell to the innermost shell. The per-node traffic loads (mean arrival rates for nodes) in S_M (λ_M) and S_{M-1} (λ_{M-1}) are derived as follows:

$$\begin{aligned}\lambda_M &= \frac{\text{total traffic loads outside } S_{M-1}}{\text{numbers of nodes in } S_M}\\ &= \frac{p\{(2Mr)^2 - \pi[(M-1)r]^2\}\cdot w}{p\{\pi(Mr^2) - \pi[(M-1)r]^2\}} = \frac{w}{(2M-1)}\left[\frac{4M^2}{\pi} - (M-1)^2\right]\\ \lambda_{M-1} &= \frac{\text{total traffic loads outside } S_{M-2}}{\text{numbers of nodes in } S_{M-1}}\\ &= \frac{p\{(2Mr)^2 - \pi[(M-2)r]^2\}\cdot w}{p\{\pi[(M-1)r]^2 - \pi[(M-2)r]^2\}} = \frac{w}{(2M-3)}\left[\frac{4M^2}{\pi} - (M-2)^2\right]\end{aligned}$$

More generally, all the data sensed by whole nodes outside S_{i-1} have to be delivered to S_i (ith shell) eventually. Hence the mean arrival rate (λ_i) for nodes in S_i is given by

$$\begin{aligned}\lambda_i &= \frac{\text{total traffic loads outside } S_{i-1}}{\text{numbers of nodes in } S_i}\\ &= \frac{p\{(2Mr)^2 - \pi[(i-1)r]^2\}w}{p\{\pi(ir)^2 - \pi[(i-1)r]^2\}} = \frac{w}{(2i-1)}\left[\frac{4M^2}{\pi} - (i-1)^2\right]\end{aligned} \tag{21}$$

where $i = 1, 2, \ldots, M$. The nodes in the innermost shell (S_1) would have to undertake the largest traffic loads because all relay-data workload from outer-shell nodes must be forwarded, and its mean arrival rate $\lambda_1 = \frac{4M^2 w}{\pi}$. The nodes in the outermost shell (S_M) would have the smallest traffic loads because of no relay data, and their mean arrival rate $\lambda_M = \frac{w}{(2M-1)}[\frac{4M^2}{\pi} - (M-1)^2]$.

From (21), taking $M = 4$, a considerable gradient among the per-node mean arrival rates (average traffic loads) in different shells can be calculated and listed as a vector as follows:

$$[\lambda_4, \lambda_3, \lambda_2, \lambda_1] = [1.625w, 3.274w, 6.457w, 20.37w]$$

Just only having four shells in a sensor network, the ratio of mean arrival rate in the innermost shell (λ_1) to that in the outermost shell (λ_4) can be over 12 times, which illustrates a rather impressing deterioration on mean arrival rates symbolized by the energy hole problem. Hence, the lifetime of innermost shell S_1 dominates the lifetime of the whole sensor network. Any improvement of power consumption on the nodes in this dominant shell (S_1) implies both the alleviation of EHP and the lifetime elongation of the sensor network.

5.2 Lifetime elongation by the proposed queue-based approach

Being stuck by EHP, the nodes in dominant shell (S_1) will be destined for a much shorter lifetime compared to the nodes in outer shells, given that all nodes are equipped with the same battery energy budget. What is even worse, once the nodes in shell S_1 are depleted of energy, the sink is disconnected from the rest of the sensor network. Moreover, the valuable and residual battery energy resources stored in the outer nodes will be useless and wasted eventually.

With little management cost on tuning sensor node's sensing rate, a fixed data sensing rate (w) is firstly considered. Having a fixed w, we can obtain the corresponding mean arrival rate (mean traffic loads) for nodes in each shell from (21). Applying (17), the average power consumption patterns that correspond to nodes in each shell can be found and analyzed for further optimization. Because of no relay-data need, the nodes in the outermost shell has the smallest mean arrival rate, and we use it as the base for the normalized mean arrival rates for the nodes in inner shells. That is, setting $\lambda_M = \lambda_b$, the mean arrival rate for nodes in other shells can be expressed in terms of λ_b.

Data Simulation 2:

Taking $M = 4$ in (21), the normalized mean arrival rates (mar) for the nodes in each shell are given by the following vector,

$$[\lambda_4, \lambda_3, \lambda_2, \lambda_1] = [\lambda_b, 2.02\lambda_b, 3.98\lambda_b, 12.5\lambda_b]$$

The system parameters are the same as those of Data Simulation 1 in Sect. 4. Based on (17), the λ_b is assumed to be 0.1 and 0.2, and the average power consumption patterns, $F(\lambda_i, N)$, for nodes in four shells are depicted in Figs. 6 and 7, respectively. The highest contour in Fig. 6 is the one having mean arrival rate $\lambda_1 = 12.5\ \lambda_b = 1.25$ with choosing $\lambda_b = 0.1$ as the base sensing rate. As expected, this curve representing the power consumption patterns in dominating shell S_1 is higher above than other curves that have much lower power consumptions for outer shells. Of course, the ideal case is that these four curves can have almost identical altitude in power consumption patterns, which indicating most of nodes in each shell have similar lifetime by balancing node energy expenditures.

The power consumption patterns of the nodes in the innermost shell dominate the whole lifetime of the network. However, the proposed N-policy queue-based scheme may provide an effective and feasible way to alleviate the power consumption of nodes in the innermost shell. From Fig. 6, the optimal N value is $N^* = 5$ and the average power consumptions of nodes in shell S_1 for $N = 1$ and $N = 5$ are 50.66 and 37.16, respectively. Hence the PCIF can reach 26.6% if we apply the proposed scheme to the nodes in the dominant shell S_1. This promising result brings a cost-effective response. Similarly in Fig. 7 with choosing $\lambda_b = 0.3$ as the base sensing rate, the PCIF can reach 27.2% while the power consumptions of nodes in shell S_1 for $N = 1$ and $N^* = 7$ are 125.58 and 91.40, respectively.

Generally the system lifetime of a sensor network has various definitions based on functionality. It may be defined as the time instant till the first node runs out of its battery energy [19]. It may also be defined as the time instant till the proportion of dead nodes exceeds a certain threshold. It is assumed that the per-node energy budget is E

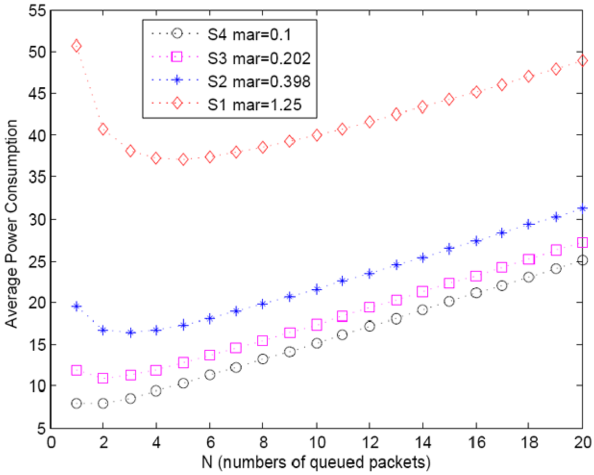


Fig. 6 Power consumption patterns for four shells with $\lambda_b = 0.1$

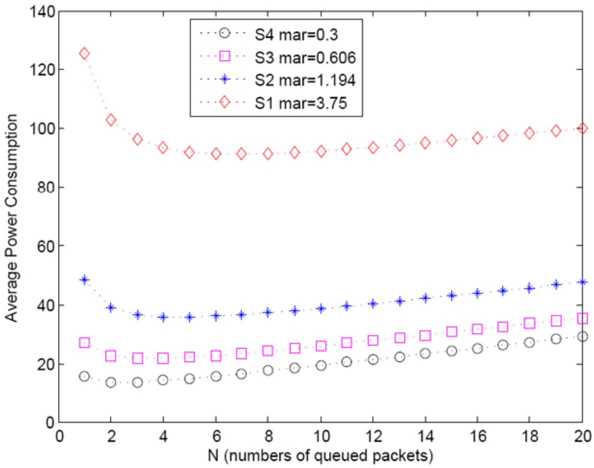


Fig. 7 Power consumption patterns for four shells with $\lambda_b = 0.3$

installed for the homogeneous sensor network. In this article, we take the notion of functional lifetime that the network lifetime is defined as the mean lifetime of nodes in dominant shell S_1. Then focusing on the average power consumption of nodes in the dominant shell S_1 in Fig. 7, we calculate the network lifetime improvement level defined by the following expression:

$$\text{Lifetime Elongation Index (LEI)} = \frac{(\text{Lifetime with N-policy}) - (\text{Lifetiem without N-policy})}{\text{Lifetime without N-policy}} \times 100\%$$

Taking numerical data in the highest curve S_1 from Fig. 7, the lifetime with N-policy $= (E/91.40)$ and the lifetime without N-policy $= (E/125.58)$. Thus the LEI $= [(E/91.40) - (E/125.58)]/(E/125.58) = 27.2\% =$ PCIF as defined in expression (20). Hence the quantified improvement on PCIF for nodes in dominating shell S_1 implies the quantified elongation on the whole network lifetime. From the view

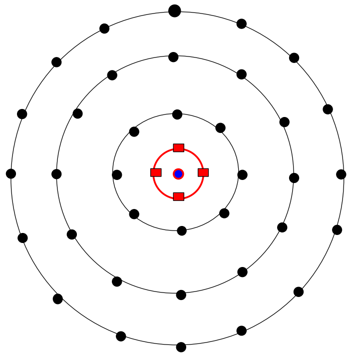


Fig. 8 Regular planar network

point of network lifetime, we use the metric NELI instead of the metric PCIF for the following network simulation experiments.

5.3 Network simulation experiments

In order to evaluate and verify the proposed queued-based approach, simulation experiments are conducted using the NS-2 network simulator [18] in this subsection. Because the nodes in innermost shell will have a quite larger amount of power consumptions compared to nodes in outer shells, the lifetime of sensor network are primarily dominated by lifetimes of nodes in innermost shell. To alleviate EHP effectively, we focus on how to improve power consumption patterns in the nodes of innermost shell. Without loss of generality, the planar network shown in Fig. 8 is considered [19].

We use the topology in which the center node is in the data sink, and there are M concentric circles, each containing nodes along its circumference. The kth ring, or radius $k \cdot r$, contains $B \cdot k$ nodes, evenly deployed on the perimeter of a circle. For example, taking $B = 4$, the number of nodes in the 1st and the 2nd rings are evenly deployed with four nodes and eight nodes, respectively. Thus there are a total of $\frac{M(M+1)}{2} \cdot B$ nodes deployed for the sensor network with M rings. In our simulation environment, we take $M = 4$, and the total number of sensor nodes is 41 nodes, including the data sink. The sensor nodes have no mobility. Every sensor node simply delivers data packets to the sink node without considering any routing energy waste.

All wireless sensor nodes transmit packets using wireless radios with a bandwidth 250 Kbps, and the sources use UDP as the transport protocol. In terms of energy consumption, we adopt power consumption elements listed in Data Simulation 2 of the previous subsection. Each simulation is run for 3600 time units may provide us hour long traces. The simulation results are conducted by varying both mean arrival rate (λ) of data packets and control parameter N value. Each data point in Figs. 9 and 10 is the average of 50 runs for each condition with the same topology. The network simulation results are shown in Figs. 9 and 10 with base sensing rate (λ_b) set at 0.1 and 0.3, respectively.

Basically, these two graphs are all concave downward, which is in agreement with the geometrical implication of (18) in term of LEI metric. The downward-cavity characteristics shown on each curve bring important and convincible information that the

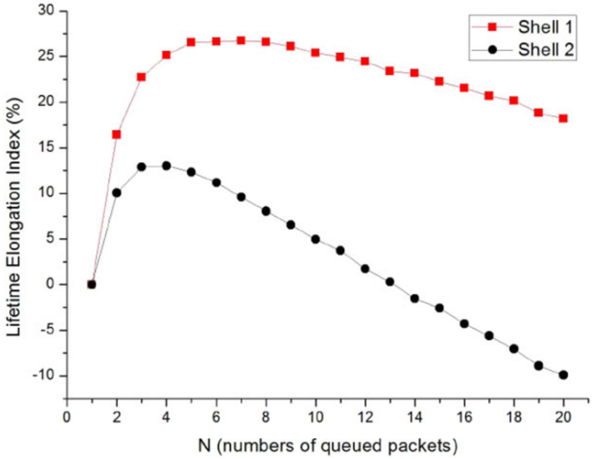


Fig. 9 LEI curves with $\lambda_b = 0.1$

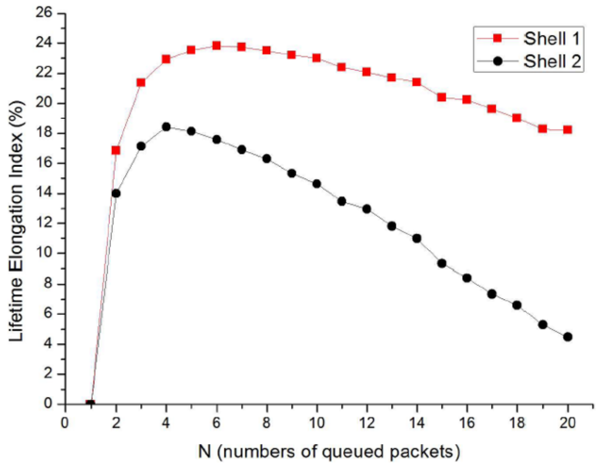


Fig. 10 LEI curves with $\lambda_b = 0.3$

optimality approach by the proposed queue-based scheme is effective and feasible. The effectiveness and feasibility of the proposed N-policy power-saving scheme have been verified by the downward concavity on each LEI curves in Figs. 9 and 10. Moreover, the improvement degree on lifetime can be verified by using the NS-2 simulation results. Let us take the curve of shell 1 (red square boxes) in Fig. 10 as an example, the average lifetime of sensor nodes in the innermost shell may be prolonged by an amount 23.84% where the optimal LEI metric occurred on $N^* = 6$. Hence the lifetime prolongation for wireless sensor network may be achieved and the threat to lifetime security may also be alleviated significantly.

5.4 Sensitivity analysis on system power elements

Observing $F(N)$ in (17), the set of system power elements (C_s, C_h, C_b, C_{id}) expresses some rudimental influences on power consumption. To provide some reference data on how they affect N and LEI values, numerical illustrations have been

Table 3 Optimal N and LEI values for variables C_s

(C_s, C_h, C_b, C_{id})	N^*	LEI (%)
(5, 2, 200, 4)	3	6.43
(10, 2, 200, 4)	5	14.44
(15, 2, 200, 4)	6	21.34
(20, 2, 200, 4)	7	*27.22*
(25, 2, 200, 4)	8	32.24
(30, 2, 200, 4)	8	35.59
(35, 2, 200, 4)	9	40.39

Table 4 Optimal N and LEI values for variables C_h

(C_s, C_h, C_b, C_{id})	N^*	LEI (%)
(20, 1/4, 200, 4)	19	33.85
(20, 1/2, 200, 4)	14	32.31
(20, 1, 200, 4)	10	30.16
(20, 2, 200, 4)	7	*27.22*
(20, 4, 200, 4)	6	22.92
(20, 6, 200, 4)	4	20.44
(20, 8, 200, 4)	3	18.00

conducted on sensitivity analysis based on changes in multifarious sets of system power elements. To show the varying tendency on LEI for each power element clearly, only one power element is varied each time while keeping other three constant. The distributions of service time and mean arrival rates are assumed to be the same as those in Data Simulation 2 except choosing $\lambda_b = 0.3$. The set (C_s, C_h, C_b, C_{id}) = (20, 2, 200, 4) is set to be the baseline set for our numerical investigations.

Firstly, Table 3 shows that optimal N^* increases gradually as C_s increases. It also reveals that LEI has some significant improvement as C_s increases. Logically, the proposed queue-based power-saving technique can be used to alleviate the total average times of triggering the radio server, and the power element C_s implies fixed energy consumption incurred per busy cycle by switching from idle mode to busy mode and vice versa. Hence the transitional energy waste between idle mode and busy mode can therefore be reduced significantly as C_s becomes larger (bottom rows in Table 3). On the other hand, the first four rows in Table 3 display that LEI becomes deteriorated in a hasty manner (from 27.22% down to 6.43%) as C_s is decreased from 20 to 5 in step of 5. As C_s gets smaller promptly, it seems reasonable that the effect on transitional energy saving would become less influential in the total average power consumption accordingly, and then the corresponding LEI value would be lowered.

Secondly, how about the impact profile is for the power element C_h on LEI? Table 4 displays that LEI and optimal N^* can be increased slightly as C_h decreases. Basically, the total average holding power is proportional to the numbers of queued packets (N). When C_h increases, the total average holding power for the queued packets would get larger and the corresponding LEI would become worse associated with smaller N values.

Table 5 Optimal N and LEI values for variables C_b

(C_s, C_h, C_b, C_{id})	N^*	LEI (%)
(20, 2, 140, 4)	7	33.16
(20, 2, 160, 4)	7	30.91
(20, 2, 180, 4)	7	28.95
(20, 2, 200, 4)	7	*27.22*
(20, 2, 300, 4)	7	20.96
(20, 2, 400, 4)	7	17.04
(20, 2, 600, 4)	7	12.40

Table 6 Optimal N and LEI values for variables C_{id}

(C_s, C_h, C_b, C_{id})	N^*	LEI (%)
(20, 2, 200, 1)	7	27.73
(20, 2, 200, 2)	7	27.49
(20, 2, 200, 3)	7	27.35
(20, 2, 200, 4)	7	*27.22*
(20, 2, 200, 5)	7	27.08
(20, 2, 200, 6)	7	26.95
(20, 2, 200, 7)	7	26.82

For power consumption of radio server in busy state (C_b), Table 5 demonstrates that LEI can be increased as C_b decreases, while optimal N^* is same as that of the baseline set as implied by (18). With a similar situation in Table 4, the last row in Table 5 shows that LEI becomes deteriorated as well (from 27.22% down to 12.40%) as C_b is increased by three times of the baseline value. The point to such a steep gradient arises from prompt increase of C_b values (from 200 to 600), which increases the total average power consumption significantly. Hence, the effect from transitional energy saving become less influential in the total average power consumption and then the corresponding LEI values become lowered inevitably.

Theoretically, the proposed queuing model can mitigate the total average times of transition switching from one mode to another. Observing data in Tables 3 and 5, it indicates that our queue-based approach is more effective in power/energy patterns when the transitional energy can occupy higher proportion of total average power/energy consumption. Shih et al. [10] have shown that the transitional energy when switching from one mode to another significantly impacts the total power consumption. Their work has also demonstrated that as packet size is reduced, the energy consumption is dominated by the startup transient and not by the active transit time. In additional to increasing the data size transmitted in a burst, our queue-based approach can also be used to alleviate such a problem by way of reducing total average times of switching modes. Finally for power element C_{id}, LEI obtains a little improvement as C_{id} increases, while optimal N^* is same as that of the baseline set as shown in Table 6.

The impact patterns on LEI by four variables $\{C_s, C_h, C_b, C_{id}\}$ in sensitivity analysis are illustrated in Fig. 11 as well. There are four sub-figures in Fig. 11. The sub-

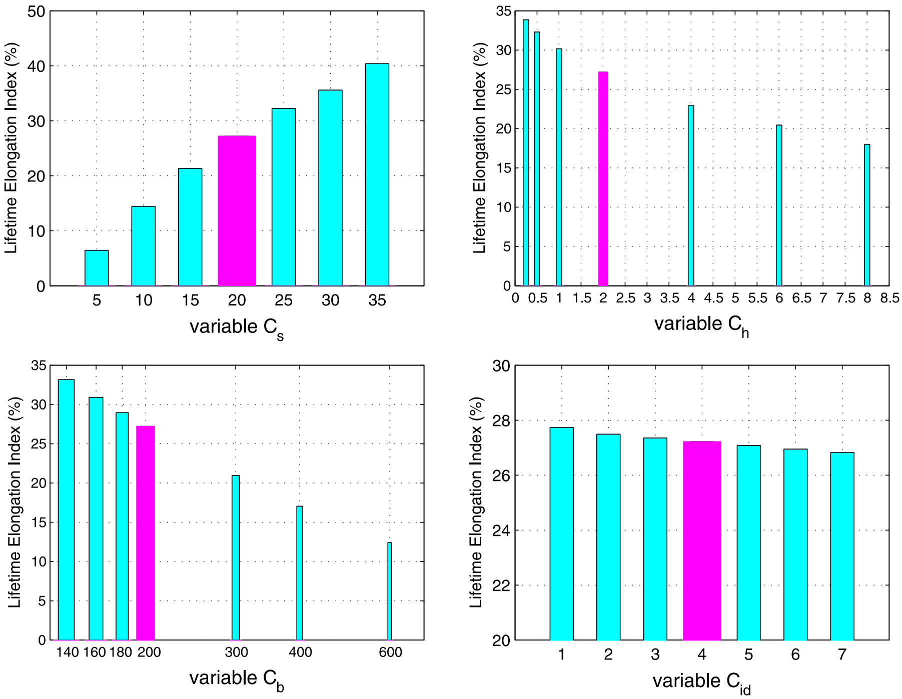


Fig. 11 The impact patterns on LEI by four variables $\{C_s, C_h, C_b, C_{id}\}$

figures for four variables C_s, C_h, C_b and C_{id} are depicted in the top left-handed, top right-handed, bottom left-handed and bottom right-handed, respectively. One dark pink bar in each sub-figure implies the LEI value (27.22%) for our baseline set $(C_s, C_h, C_b, C_{id}) = (20, 2, 200, 4)$. Is any alternative to moderate such a decline from larger C_b? One approach might be observed from (17). The $F(N)$ is affected by this power factor (C_b) in terms of the product term ($C_b\rho$). Hence, in case of missions with larger C_b (e.g., longer transmission range), the sensor network administrator could probably consider the compensation approach by reducing the server's utilization value to mitigate the LEI impact from larger C_b under mission specification.

6 Conclusions

The energy hole problem (EHP) exists in most of many-to-one sensor networks, and appears to be a security threat to the lifetime of WSN. We focus on prolonging the lifetime of nodes in the innermost shell by alleviating power consumption. Based on the mathematical power model of a generic sensor node platform, there exists an optimal queue number (N) that minimizes power consumption in sensor node. In this article, we have provided and analyzed the theoretical aspects of the queue-based power-saving technique which reveals the feasibility of reducing power consumption foe sensor nodes. The MATLAB-based data simulations demonstrate that a significant improvement level on estimated power consumption can be achieved. Then the proposed queue-based approaches on a generic sensor node platform are applied to prolong sensor network lifetime by way of mitigating the EHP.

In a wireless sensor network, the EHP around the sink is an unavoidable risk which deteriorates the network lifetime due to the unbalanced energy depletion. We would like to point out that the EHP is inherent in many-to-one sensor networks, and the optimal solution we can do is to reduce the innermost shell's power consumption. With little or no extra management cost, the proposed approach can be expanded and applied to increase the average lifetime on the nodes in the dominant shell of the sensor network. To validate and evaluate the proposed design scheme, we have also conducted network simulations using the NS-2 simulator. The simulation results are used to show that the network lifetime may be prolonged by about 23% due to the saving on the innermost shell's average power consumption. Hence the proposed approach indeed provides a feasibly cost-efficient solution to improve the lifetime security for the sensor network.

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