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Modeling and Prolonging Techniques on Operational Lifetime of Wireless Sensor Networks

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***Abstract*—Power consumption is an essentially important issue and an interesting challenge to prolong the lifetime of wireless sensor network (WSN). 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 operational 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) around the sink node. In this article, we propose a novel power-saving scheme to alleviate the EHP based on the Min(N, T) policy M/G/1 queuing model. With little management cost, the proposed queue-based power-saving technique can be applied to prolong the lifetime of sensor network economically and effectively. For the proposed queue-based model, mathematical framework on performance measures have been formulated. And also we analyze the average traffic load per node for concentric sensor network. Focusing on the nodes located in the innermost shell of WSN, numerical and NS2 network simulation results validate that the proposed approach indeed provides a feasibly cost-effective approach for lifetime elongation of sensor networks.**

Keywords-Wireless sensor networks; energy hole problem; sink node; energy efficiency; queuing theory;

I. INTRODUCTION

Wireless sensor network (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 [1~2]. 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 longer as possible [3].

To prolong the lifetime of WSN, power-saving technique is an attractive research domain and also a critical issue obviously. 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 node [4]. 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 [5] show that up to 90% of total initial energy can be left unused when the network lifetime is over. And also with analytical results, [6] 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.

In this article, we focus on power-saving technique for prolonging the operational lifetime in WSN. A queue threshold, N, is specified for the concept of "queued wakeup". 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 wakeup" scheme, when the total numbers of queued packets approaches N, the sensor node triggers its transmitting function of radio server, and starts the transmission process for the queued packets in a burst. The queue-based scheme provides two key advantages. One is that it can mitigate the total average times of contending the medium among sensor nodes. The other is that it can alleviate the total times of switching between busy mode and idle mode of radio transmitter. Shih et al. [7] has shown that the transitional energy when switching from one mode to another significantly impacts the total power consumption. Because queued packets would incur latency delay inevitably, another decision parameter T is considered to avoid long-term waiting in case of sparse arrival scenario. Combining these two parameters, we propose an effective and feasible power-saving technique to prolong lifetime of WSN using Min(N,T) policy M/G/1 queuing theory.

The key contributions of this paper are threefold: (i) with little management cost, we provide the sensor network administrator with a feasible and economical power-saving

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technique to prolong operational lifetime of WSN (ii) we adopt queue-based modeling, and formulate 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 NS2-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.

II. Related Works

IEEE 802.11 standard [8] specifies a CSMA/CA (Carrier Sense and Multiple Access/Collision Avoidance) protocol for reducing the collision probability in multiple accesses. The adopted exponential backoff mechanism can effectively provide the basic function for collision avoidance. This backoff can only reduce the collision probability among nodes competing for the access right of air channel. However it does not address the issue how to alleviate the total average times of medium contention for each sensor node. In other words, it starts packet transmission as long as there is any one arriving packet in its buffer. In S-MAC [9] protocol, it switches periodically among the modes of sleep, wake-up, listen and then returns to sleep. Each active period is fixed size of 115 ms, with a variable sleep period. And the length of sleep period dictates the duty cycle of S-MAC.

B-MAC [10] 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 assessment and packet backoffs for channel arbitration, link layer acknowledgement for reliability, and low power listening for low power communication. STEM [11] protocol uses two-radio architecture, and it saves power by keeping the data radio sleep until communication is needed. The wakeup radio listens periodically using a low duty cycle, which reduces the energy of idle listening. STEM uses an asynchronous beacon packet in special wakeup channel to wake up the intended receiver. By and large, the issues about mitigating total average times of triggering radio transmission throughout node's lifetime are not a concern for these open literatures [8-11].

A queue threshold, N, is specified in the concept of "queued wakeup." 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 wakeup" 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 wakeup, the abovementioned MAC protocols, like IEEE 802.11, S-MAC, STEM, or B-MAC can be regarded as taking N=1. Using the similar concept, Miller et al. [12] adopts a queue threshold with N=2 to reduce the energy consumption comparing with the STEM protocol. Inspired by their research, we would ask questions: Is it possible to provide a strategy for choosing the queue threshold N? 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.

The N-policy queued approach would inevitably incur latency delay for those packets staying in queue buffer. To prevent queued packets from waiting too long to be sent to the data sink, a T-policy [13] is required whenever the total number of queued packets seem never reaching N in case of excessively long latency delay. For T-policy, the radio server is triggered on as soon as the time units after the end of the last busy period has reached predetermined T units. Having a timer T would avoid endless waiting which may happen in some applications with sparse arrival scenario. For example, in habitat monitoring, there are long periods of inactivity, followed by a short period of network traffic, referred to as a burst. If total number of arriving packets in a certain burst cannot reach N, then T-policy would save those stale queued packets, and trigger on the radio server to transmit them in due course.

III. Mathematical Preliminaries

A. *Proposed Model for Generic Sensor Nodes*

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 at the same depth only communicate to their parent sensor in a one-hop environment. The final destination node could be a data sink, a base station or a data cluster.

Without loss of generality, we consider two major operational states for the radio server of the sensor node: idle and busy, which are equivalent to the monitoring and active states respectively. In general, the idle state is mapped to the lowest value of the radio server power consumption, which can be viewed as the state of turning off the transmitting function of 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. The busy state can be viewed as the state of turning on the radio server. We study the behavior of a single sensor by developing the Min(N, T) policy M/G/1 queuing model, in which the operational flow for a generic sensor node can be modeled as shown in Figure 1. In Figure 1, before accumulating N data packets in queue buffer and before reaching T time units, the function of transmitter in radio server is turned off (Server in Idle Mode). At the instant of the N^{th} packet arrival or the queuing time reaching T time units, the radio server (Server in Busy Mode) transmits packets in the buffer exhaustively.

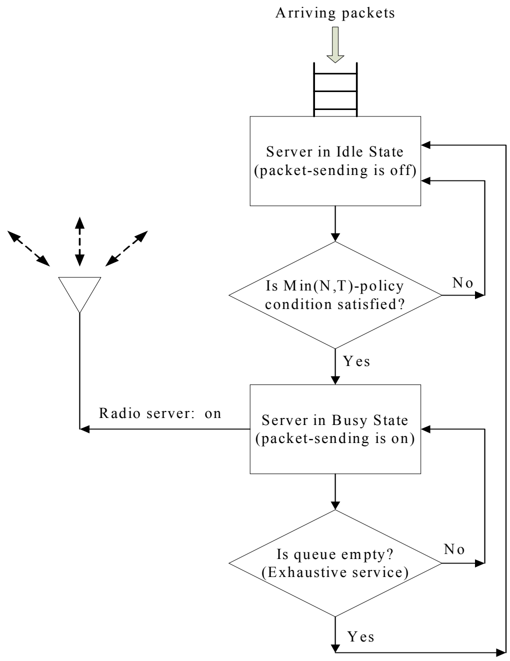

Figure 1 Proposed operational model for a generic sensor node

Based on the Min(N, T) policy mentioned above, the radio server starts transmitting service when no packets arrives during the first m (m = 0, 1, 2,…) vacations (total length of mT) after the system is empty and either one of the following two scenarios happens:

(a) In Figure 2, during the $(m+1)^{th}$ T period, at least N packets has arrived. In this scenario, at the instant of the N^{th} packet arrival, the radio server is turned on, and begins service for transmitting packets. This is the case of service started by N-policy condition.

(b) In Figure 3, during the $(m+1)^{th}$ T period, at least one packet and at most (N–1) packets arrive. In this scenario, the radio server keeps idle until the end of its $(m+1)^{th}$ time slot and then returns to the system to begin service for transmitting packets. This is the case of service started by T policy.

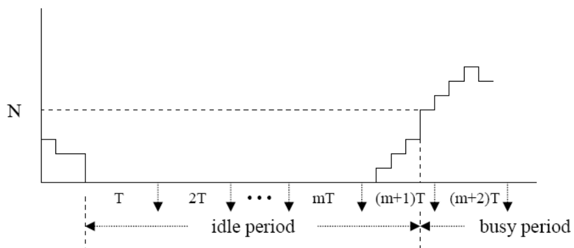

Figure 2 Scenario of transmitting service started by N-policy condition

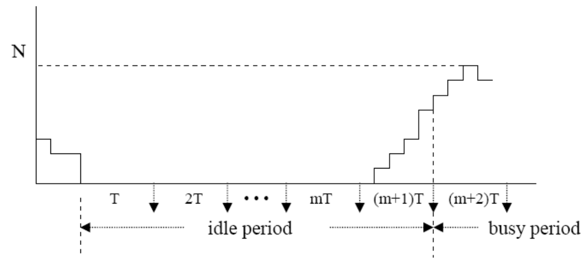

Figure 3 Scenario of transmitting service started by T-policy condition

Let the random variable Ki (i = 1, 2, …) be the inter-arrival times for packets. They are independently, identically and exponentially distributed with a mean arrival rate λ. Let the random variable A_n (n = 1, 2, …) denote the arrival times. In other words, A_n is the epoch when the n-th arriving packet appears. Hence, the A_n can be expressed in terms of Ki as follows:

$$A_n = \sum_{i=1}^{n} K_i$$

We assume that the service time, S, for each packet is generally distributed with mean service time E[S] = 1/μ. Since the sum of n independent random variables have a common exponential distribution, which is an Erlang-n distribution, thus random variable A_n has the following distribution function $F_n(t)$. Let N(t) be the number of packets arriving at the system during [0, t].

$$F_n(t) = \Pr\{A_n \le t\} = \int_{x=0}^{t} \frac{\lambda\,(\lambda x)^{n-1}}{(n-1)!} e^{-\lambda x} dx$$

$$= 1 - \sum_{k=0}^{n-1} \frac{(\lambda t)^k}{k!} e^{-\lambda t} = \Pr\{N(t) \ge n\}$$

Note that $F_n(t) - F_{n+1}(t) = \dfrac{(\lambda t)^n e^{-\lambda t}}{n!} = \Pr\{N(t)= n\}$.

Using the probability generating function (PGF) approach and well-known decomposition property [14], Hur et al. [15] in 2003 developed the probability distribution of the number of customers (packets) at a steady state for the Min(N, T) policy M/G/1 queuing system. Following their results in expression (6), the expected number of packets (L_{NT}) is given by

$$L_{NT} = L_0 + \frac{E[X(X-1)]}{2\,E[X]} = \rho + \frac{\lambda^2\, E[S^2]}{2\,(1-\rho)} + \frac{\sum_{n=1}^{N}(n-1)\,F_n(T)}{\sum_{n=1}^{N} F_n(T)} \qquad (1)$$

Where

L_0 = the expected number of packets present in the ordinary M/G/1 queuing system without N or T policy.

X = the random variable denoting the number of packets waiting in the queue buffer when the busy period begins, and $E(X) = \dfrac{\sum_{n=1}^{N} F_n(T)}{F_1(T)}$

B. *System Performance Measures*

With the proposed sensor model, several performance metrics of interest can be developed based on the theory of an M/G/1 queuing system with Min(N,T) policy. These performance metrics include various expected length of system parameters, which are useful for evaluating critical power consumption function.

B.1 Expected length of busy period

Following the result of Gakis [16], we obtain the expected length of the busy period, denoted by B_{NT}, as follows:

$$E[B_{NT}] = \frac{\sum_{n=1}^{N} F_n(T)}{1-e^{-\lambda T}} E[B_o] = \frac{E[X]\,E[S]}{1-\rho} \tag{2}$$

Where E(Bo) denoting the expected length of the busy period of the ordinary M/G/1 queue, and E[Bo] = E[S] / (1–ρ).

B.2 Expected length of idle period

Suppose that E[Io] is the expected idle period of the ordinary M/G/1 queue, and since the length of times between two successive arriving packets are identically, independently and exponentially distributed with a mean of 1/λ, E[Io] = 1/λ. Again following the result of [20], we have the expected length of the idle period, denoted by I_{NT}, as follows:

$$E[I_{NT}] = \frac{\sum_{n=1}^{N} F_n(T)}{1-e^{-\lambda T}} E[I_o] = \frac{E[X]}{\lambda} \tag{3}$$

Mapped to the corresponding performance metric on sensor node, the $E[I_{NT}]$ implies the average period that the transmitting function of radio server is turned off for saving sensor's energy. This parameter would have positive promotion on the degree of energy-saving, but on the other hand, it would inevitably have negative influences on the throughput of system.

B.3 Expected length of busy cycle

The busy cycle for Min(N,T) policy M/G/1 system, denoted by Ω_{NT}, is the length from the beginning of the last radio server turned-off period to the beginning of the next turned-off period. Since the busy cycle is the sum of the turned-off period (I_{NT}) and the busy period (B_{NT}), we get

$$E[\Omega_{NT}] = E[I_{NT}] + E[B_{NT}] = \frac{E[X]\,E[S]}{1-\rho} + \frac{E[X]}{\lambda} \tag{4}$$

IV. Power Consumption and Data Simulation

A. Power Consumption Function

The total expected power consumption function, $P_C(N,T)$ is developed for the proposed model. Our objective is to establish the closed form of power consumption function in terms of relevant parameters and power consumption elements for practical situations. Since there is only one 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 factor, is given by C_s. Let

C_s = setup energy for per busy cycle
C_h = holding power for each packet present in the system
C_b = power consumption while radio server is in busy state
C_{id} = power consumption while radio server is in idle state

By the definitions of each power consumption factors, the power consumption function is given by

$$P_C(N,T) = C_h\, L_{NT} + \frac{C_s}{E[\Omega_{NT}]} + C_b \frac{E[B_{NT}]}{E[\Omega_{NT}]} + C_{id} \frac{E[I_{NT}]}{E[\Omega_{NT}]} \tag{5}$$

Where L_{NT}, $E[\Omega_{NT}]$, $E[B_{NT}]$, and $E[I_{NT}]$ are given in (1), (4), (2), and (3), respectively. Putting them into (5) yields

$$P_C(N,T) = C_h[\rho + \frac{\lambda^2 E[S^2]}{2(1-\rho)} + \frac{\sum_{n=1}^{N}(n-1)F_n(T)}{\sum_{n=1}^{N} F_n(T)}] + C_s \frac{\lambda(1-\rho)}{E[X]} + C_b\, \rho + C_{id}(1-\rho) \tag{6}$$

B. Data Simulation and Performance Improvement

The analytic study of the behavior of $P_C(N,T)$ would have been an arduous task to undertake since the control parameters N and T appear in (6) which are highly non-linear and complicated. Instead, some numerical examples are presented and intensively studied by applying the proposed models. For illustrative purpose, it is assumed that packets for sensor node arrive according to a Poisson process with mean arrival rate λ. The service times are independent and identically distributed random variable obeying an arbitrary distribution function S(t) (t ≥ 0) with the first moment E[S] and second moment $E[S^2]$. All simulations are performed with MATLAB 7.6 on Intel Core 2 Quad CPU 2.4GHz clock, 2G RAM). Custom MATLAB scripts are written to simulate the proposed power-saving scheme. Simulations are compared with ordinary M/G/1 queuing case without Min(N, T) policy.

Data Simulation 1:

Let the system's parameters be as follows:

- Mean arrival rate of packets: λ=1.0
- Service time of radio server having mean E[S]=0.1 and the second moment $E[S^2]$=0.01
- Power consumption factors: $[C_{id}, C_b, C_s, C_h]$=[3, 150, 10, 0.5].

Based on (6), we first study the effect of varying N while keeping T constant, and then varying T while keeping N constant.

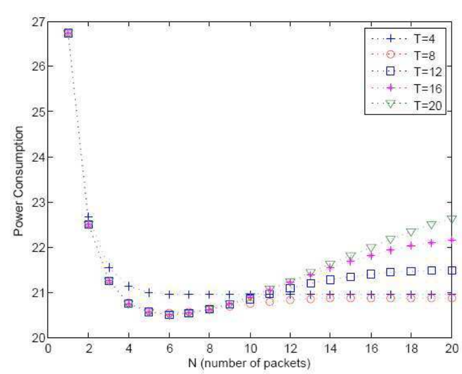

Figure 4. Power consumption, T constant

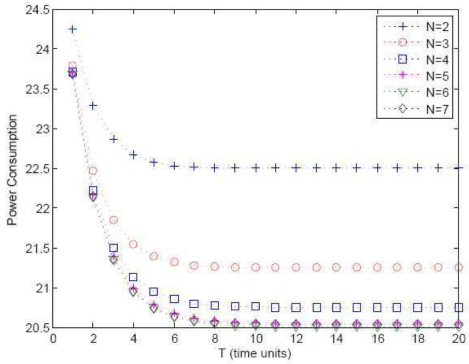

Figure 5. Power consumption, N constant

Since contour plots provide the best graphical representation of the optimization problem, and also possess a powerful visualization that permits the solutions of the optimization problem by inspection. We have the graphical results using MATLAB software package as shown in Figures 4 and 5. In Figure 4, a relative low point in power consumption can be achieved around N* = 6 or 7 for various T values. For each contour with fixed T value, a local minimal for power consumption emerges. This improvement phenomenon has strengthened the effectiveness and feasibility of applying the proposed Min(N, T) policy queued approach into the MAC-based medium-contention process. In Figure 5, each contour has a turning point to reach a lower plateau, which implies larger T values would have almost little influence upon the power consumption after crossing the turning point. For example, most of contours in Figure 5 appear to have a turning point to reach a lower plateau when approaching T = 10.

C. *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:

Power Consumption Improvement Factor (PCIF)

$$= \frac{P_C(N=1,\ T) - P_C(N,\ T)}{P_C(N=1,\ T)} \times 100\% \qquad (7)$$

Where $P_C(N=1, T)$ represents the power consumption of an ordinary M/G/1 system without the N-policy (i.e., N=1). The impact from T parameter appears to be lesser as T value reaches a lower plateau (T=10) as shown in Figure 5. We take T=10 as an example, the PCIF at (N,T)=(6,10) yields almost 19.54% of improvement level. As revealed in Figure 4, Since $P_C(N, T)$ is concave upward, the function PCIF is thus concave downward.

V. LIFETIME ELONGATION TECHNIQUES IN WSN

A. *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 × L area. The unique sink is located at the center of the sensor filed as shown in Figure 6. 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. 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×2r) as exemplified in Figure 6 (M=4). The *i*th shell is denoted as S_i, which is composed of nodes whose distances to the sink are between *i*r and (*i*+1)r meters. Nodes are uniformly and randomly distributed, so that the node density is uniform throughout the network: $p = Q_N/A_{net}$, 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.

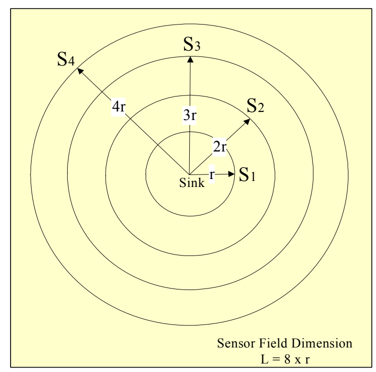

Figure 6 A sensor field consisting of four shells.

As illustrated in Figure 6, 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 load (mean arrival rate for nodes) in S_M (λ_M) and $S_{M\text{-}1}$ (λ_{M-1}) are derived as follows:

$$\lambda_M = \frac{\text{total traffic loads outside } S_{M\text{-}1}}{\text{numbers of nodes in } S_M}$$

$$= \frac{p\ \{(2\,M\,r)^2 - \pi[(M-1)\,r]^2\} \cdot w}{p\ \{\pi(M\,r^2) - \pi[(M-1)\,r]^2\}} = \frac{w}{(2M-1)}[\frac{4\,M^2}{\pi} - (M-1)^2]$$

$$\lambda_{M-1} = \frac{\text{total traffic loads outside } S_{M\text{-}2}}{\text{numbers of nodes in } S_{M\text{-}1}}$$

$$= \frac{p\ \{(2\,M\,r)^2 - \pi[(M-2)\,r]^2\}\cdot w}{p\ \{\pi[(M-1)\,r]^2 - \pi[(M-2)\,r]^2\}} = \frac{w}{(2M-3)}[\frac{4\,M^2}{\pi} - (M-2)^2]$$

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

$$\lambda_i = \frac{\text{total traffic loads outside } S_{i-1}}{\text{numbers of nodes in } S_i}$$

$$= \frac{p\ \{(2M\,r)^2\ -\ \pi\,[(i-1)\,r]^2\}\ w}{p\ \{\ \pi\ (i\,r)^2\ -\ \pi\,[(i-1)\,r]^2\}} = \frac{w}{(2i-1)}[\frac{4\,M^2}{\pi} - (i-1)^2] \qquad (8)$$

Where i = 1, 2, …, 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 $\lambda_1 = \frac{4\,M^2\,w}{\pi}$.The nodes in the outermost shell (S_M) would have the smallest traffic loads because of no relay-data, and its mean arrival rate $\lambda_M = \frac{w}{(2M\text{-}1)}[\frac{4M^2}{\pi} - (M-1)^2]$. From equation (8), 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:

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

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.

B. *Lifetime elongation by 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 equation (8). Applying equation (6), the average power consumption patterns that correspond to nodes in each shell can be found out, 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.

Recalling that most of contours in Figure 5 appear to have a turning point to reach a lower plateau when approaching T = 10, it implies that T values larger than 10 would have almost little influence upon the power consumption. Thus we set T=10 for follow-on simulation examples in calculating power consumption for the sake of simplicity.

Data Simulation 2:

The system parameters are assumed as follows:

- Mean arrival rate (mar) : λ_i , i = 1, 2, 3, and 4
- Other system's parameters as used in Data Simulation 1

Taking M=4 in equation (8), the normalized mar for the nodes in each shell are given by the following vector,

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

If λ_b is set to be 0.1 and 0.3, then we have corresponding mean arrival patterns as follows:

(i) $\lambda_b = 0.1$, $[\lambda_4 , \lambda_3 , \lambda_2 , \lambda_1] = [0.1 , 0.202 , 0.398 , 1.25]$

(ii) $\lambda_b = 0.3$, $[\lambda_4 , \lambda_3 , \lambda_2 , \lambda_1] = [0.3 , 0.606 , 1.194 , 3.75]$

Based on equation (6), the λ_b is assumed to be 0.1 and 0.3, and the average power consumption patterns, $P_C(\lambda_i, N)$, for nodes in four shells are depicted in Figures 7 and 8 respectively. The highest contour in Figure 7 is the one having mean arrival rate λ_1=12.5λ_b=1.25 with choosing λ_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.

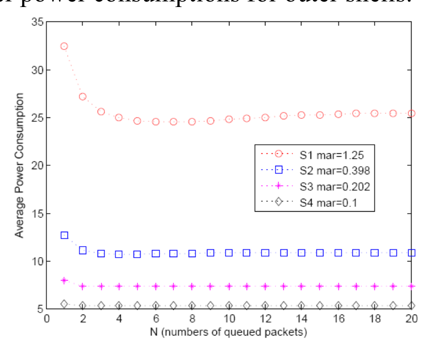

Figure 7 Power consumption patterns for four shells with λ_b=0.1

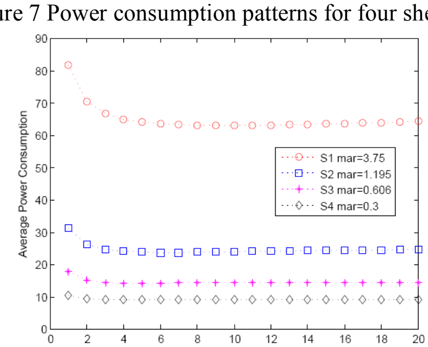

Figure 8 Power consumption patterns for four shells with λ_b=0.3

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 Figure 7, 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 Figure 8 with choosing λ_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 [18]. 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 Figure 8, we calculate the network lifetime improvement level in terms of metric LEI (Lifetime Elongation Index) defined as follows:

$$\text{LEI} = \frac{[\text{Lifetime with } P_C(\text{N, T})] - [\text{Lifetime with } P_C(\text{N=1, T})]}{\text{Lifetime with } P_C(\text{N=1, T})}$$

The terms "Lifetime with P_C(N, T)" and "Lifetime with P_C(N=1, T)" in the above expression imply equivalently "Lifetime with N-policy" and "Lifetime without N-policy" respectively. Taking numerical data in the highest curve S_1 from Figure 8, 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 (7). 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 point of network lifetime, we use the metric LEI instead of the metric PCIF for the following network simulation experiments.

C. Network simulation experiments

In order to evaluate and verify the proposed queued-based approach, simulation experiments are conducted using the NS2 network simulator [17] 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 Figure 9 is considered [18].

We use the topology which the center node is in the data sink, and there are M concentric circles, each containing nodes along its circumference. The k^{th} ring, or radius k·r, contains B·k nodes, evenly deployed on the perimeter of a circle. For example, taking B=4, the number of nodes in the 1^{st} and the 2^{nd} rings are evenly deployed with four nodes and eight nodes, respectively. Thus there are a total of [M(M+1)B]/2 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.

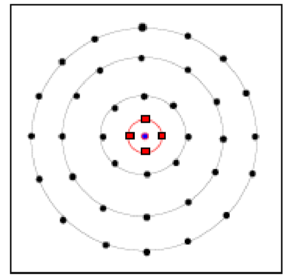

Figure 9 Regular Planar Network

All wireless sensor nodes transmit packets using wireless radios with a bandwidth 250Kbps, and the sources use UDP as the transport protocol. In terms of energy consumption, we adopt power consumption factors 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 Figures 10 and 11 is the average of 100 runs for each condition with the same topology. The network simulation results are shown in Figures 10 and 11 with base sensing rate (λ_b) set at 0.1 and 0.3 respectively.

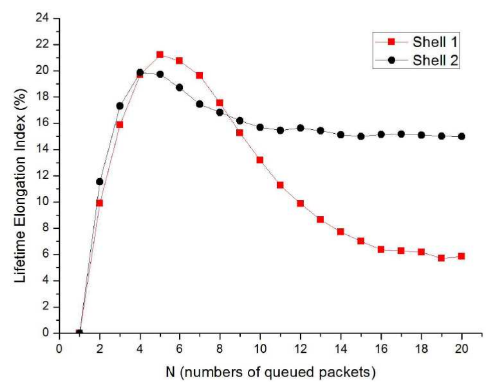

Figure 10 LEI curves with λ_b=0.1

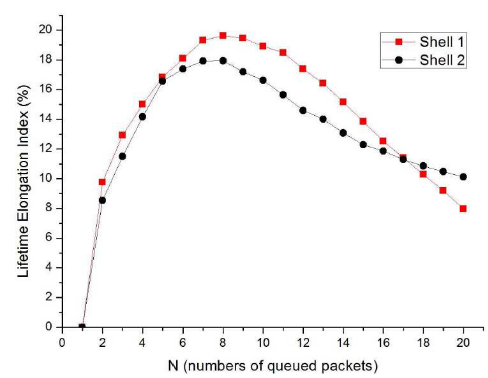

Figure 11 LEI curves with λ_b=0.3

Basically, these two graphs are all concave downward, which is in agreement with the geometrical implication of contours of Figure 4 in term of LEI metric. The downward-cavity characteristics shown on each curve bring important and convincible information that the optimality approach by the proposed queue-based scheme is effective and feasible. The effectiveness and feasibility of the proposed scheme has been verified by the downward concavity on each LEI curves in Figures 10 and 11. Moreover, the improvement degree on lifetime can be verified by the NS2 simulation results. Let us take the curve of shell 1 (red square boxes) in Figure 11 as an example, the average lifetime of sensor nodes in the innermost shell may be prolonged by an amount 19.63% where the optimal LEI metric occurred on N*=8. Hence the lifetime prolongation for wireless sensor network may be achieved and the threat to lifetime security may also be alleviated significantly.

VI. CONCLUSIONS

The energy hole problem (EHP) exists in most of many-to-one sensor networks, and appears to be a security threat to the operational lifetime of WSN. We focus on prolonging the lifetime of nodes in the innermost shell by alleviating power consumption. 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 simulation demonstrates 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 NS2 simulator. The simulation results are used to show that the network operational lifetime may be prolonged by about 23% due to the saving on innermost shell's power consumption. Hence the proposed approach indeed provides a feasibly cost-efficient solution to improve the operational lifetime for the sensor network.

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REFERENCES

[1] I. F. Akyilidiz, W. Su, Y. Sankarasubramaniam and E. Cayirci, "Wireless Sensor Networks: A Survey," *Computer Networks*, vol. 38, no. 4, pp. 393-422, 2002.

[2] D. Culler and W. Hong, "Wireless Sensor Networks," *Communications of the ACM*, 47(6), pp. 30-33, 2004.

[3] C. E. Jones, K. M. Sivalingam, P. Argawal and J. C. Chen, "A Survey Energy Efficient Network Protocols for Wireless Networks," *Wireless Networks*, vol. 7, pp.343-358, 2001.

[4] J. Li and P. Mohapatra, "An Analytical Model on the Energy Hole Problem in Many-to-one Sensor Networks," in Proc. of IEEE VTC Fall 2005, Dallas, TX.

[5] J. Lian, K. Naik and G. Agnew, "Data Capacity Improvement of Wireless Sensor Networks Using Non-uniform Sensor Distribution," *International Journal of Distributed Sensor Networks*, vol. 2, no. 2, pp. 121-145, Apr.-June 2006.

[6] W. Ye, J. Heidmann and D. Estrin, "Medium Access Control with Coordinated Adaptive Sleeping for Wireless Sensor Networks," *IEEE Transactions on Networking*, vol. 12, no. 3, pp.493-506, June 2004.

[7] E. Shih, S. Cho, F. S. Lee, B. and H. Calhoun, "Design Considerations for Energy-efficient Radios in Wireless Moicrosensor Networks, *Journal of VLSI Signal Processing*, vol. 37, pp'77-94, 2004.

[8] IEEE, "Wireless LAN Medium Control (MAC) and Physical Layer (PHY) Specification," IEEE Std. 802.11-1999 edition (R2003).

[9] Ye, W., Heidemann, J., and Estrin, D. "An Energy Efficient MAC protocol for Wireless Sensor Networks," in Proc. IEEE INFOCOM, June 2002, pp. 1567-1576.

[10] J. Polastre, J. Hill and D. Culler, "Versatile Low Power Media for Wireless Sensor Networks," in Proc. ACM SenSys, Nov. 3-5, 2004.

[11] C. Schurgers, V. Tsiatsis and M. Srivastava, "STEM: Topology Management for Energy Efficient Sensor Networks," *Aerospace Conference Proceedings*, 2002, IEEE, vol. 3, pp.3-1099 ~3-1108.

[12] M. J. Miller and N. H. Vaidya, "A MAC Protocol to Reduce Sensor Network Energy Consumption Using a Wakeup Radio," *IEEE Transactions on Mobile Computing*, vol. 4, no.3, pp. 228-242, May/June 2005.

[13] D. P. Heyman. The T-policy for the M/G/1 queue. *Management Science* 23, 775-778, 1977.

[14] D. Gross and C. M. Harries, Fundamentals of Queuing Theory, 3rd edition, Wiley, New York, 1998.

[15] Hur, S., Kim, J. and Kang, C. (2003) An analysis of the M/G/1 system with N and T policy. *Applied Mathematical Modeling* 27, 665-675.

[16] Gakis, K. G., Rhee, H. K. and Sivazlian, B. D. (1995) Distribution and the first moments of the busy and idle periods in controllable M/G/1 queuing models with simple and dyadic policies. *Stochastic Analysis and Applications* 13, 47-81.

[17] UCB/LBNL/VINT Network Simulator, http://www-mash.cs.berkeley.edu/ns/

[18] A. Giridhar and P. R. Kumar, "Maximizing the Functional Lifetime of Sensor Networks," in Proc. Fourth ACM/IEEE International Symposium Information Processing in Sensor Networks (IPSN'05), pp.5-12, April 2005.