Power Control Algorithm for Wireless Sensor Networks using N-Policy M/M/1 Queueing Model

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***Abstract*— A critical issue in wireless sensor networks is the limited availability of power and hence optimizing power is very important. In any sensor node, transitions from idle to busy state and vice versa consume most of the power. We propose a new scheme to reduce the power consumption of nodes by reducing the number of transitions of the sensor node based on the number of packets in the queue i.e., queue threshold. We develop an analytical model of a wireless sensor network with finite buffer capacity and analyze the performance of the proposed scheme in terms of performance parameters such as power consumption and mean delay. We also derive the expression for the optimal value of threshold. Results show that the power consumption reduces by 42% for the optimal threshold value when compared to no threshold condition. We perform simulations and the results obtained show that the analytical results match with the simulation results thus validating the analytical model.**

Keywords- Wireless sensor network; mean delay; power consumption; queue threshold

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have broad applications like environment monitoring, target tracking and surveillance. A critical issue in wireless sensor networks is represented by the limited availability of power within the network and hence optimizing power is very important. There are two major techniques for maximizing the sensor network lifetime: the use of energy efficient routing and the introduction of sleep/active modes for sensors [1]. J. Carle et al. presented a good survey in [2] on energy efficient area monitoring for sensor networks. The authors have observed that the best method for conserving energy is to turn off as many sensors as possible, while still keeping the system functioning.

An analytical model was presented in [3] to analyze the system performance in terms of network capacity, power consumption and data delivery delay, against the sensor dynamics in on/off modes. Most existing work on sensor networks consider homogeneous sensor networks where all sensor nodes are assumed to have the same capabilities in communications, computation, memory storage, energy supply, reliability and other aspects. However, a homogeneous ad-hoc network has poor fundamental limits and performance. P. Gupta and P. R. Kumar have demonstrated the performance bottleneck of homogeneous ad-hoc network via theoretical analysis in [4], simulation experiments and test bed measurements [5]. Several recent papers have studied Heterogeneous Sensor Networks (HSNs) and these literatures showed that HSNs can significantly improve sensor network performance [6]. Since the power consumed by the individual nodes in the sensor network that affects the network lifetime is very crucial in all WSN applications, different algorithms for minimizing the power consumption have been already proposed and the proposed algorithms also show that there exists trade-offs between the power consumption and the data delivery delay [7].

In this paper, we propose a power minimization scheme by which the power consumption of individual nodes in the sensor network is reduced by reducing the number of transitions of the sensor node during its scheduled period of active time. We develop an analytical model for analyzing the system performance in terms of power consumption and data delivery delay. We consider a WSN model that consists large number of sensor nodes that are uniformly distributed in the field. A sink node at the centre collects data from the sensor nodes. All the sensors will be in active mode for a shorter duration of time period. During this scheduled period of active time, all the sensors will be in idle state or transmit state (also called as busy state). The sensors deliver the packets to the sink node during busy state.

Here, a sensor node, during its scheduled period of active time, remains in idle state switches to busy state when the node's buffer is filled at least with threshold number of packets (N) and the node switches back from busy state to idle state when there are no packets in the buffer. We also determine optimal threshold value (N^*) of N for which the sensor nodes consume very less power.

The rest of this paper is organized as follows. In section II, we present the system model. In section III, we present the performance analysis and provide numerical solutions for determining the mean delay, average power consumption of a sensor node and the optimum threshold value of N. Section IV describe the simulation model and the results and discussion are presented in section V. In section VI, we provide the conclusion and the aspects to be considered for future work.

II. SYSTEM MODEL

We consider a WSN that consists large number of sensors that are uniformly distributed and a sink node at the centre of the field collects data from nodes. In our WSN model, the following assumptions are made.

- All sensors in an HSN are identical
- The arrival of data packets to sensors is assumed to follow a Poisson process with mean arrival rate (λ) per node
- Packets are delivered from sensor to sink node with mean service time ($1/\mu$)
- Buffer capacity is finite
- No channel contention

Here, a sensor node, during its scheduled period of active time, remains in idle state, switches to busy state when the node's buffer is filled at least with threshold number of packets (N) and the node switches back from busy state to idle state when there are no packets in the buffer. Such switching actions between idle state to busy state and busy state to idle state are referred to as transitions. Since the focus of this work is to minimize the power consumption of individual sensor nodes in WSN by reducing the number of transitions during its scheduled period of active time, we analyze the behavior of a single sensor node.

III. PERFORMANCE ANALYSIS

As mentioned in section II, the arrival of data packets to sensors follows a Poisson process with mean arrival rate (λ) per node and a sensor node during its scheduled period of active time, remains in idle state and switches to busy state when the sensor node's buffer is filled at least with threshold number of packets (N) and switches back from busy state to idle state when there are no packets in the node's buffer. We analyze the performance of the system in terms of the following parameters.

A. A. Mean Delay

Mean delay experienced by the packets in a sensor node is defined as the average waiting time of the packets in the queue. To determine the mean delay experienced by the packets in a sensor node, the two-state transition diagram of a sensor node that switches from idle state to busy state and vice-versa shown in Fig. 1 is considered. For our analytical model, the following notations are used.

n	Number of packets in the sensor node's buffer
N	Threshold number of packets
k	Buffer capacity
M	Number of sensor nodes in a network
λ	Mean arrival rate per node
$\frac{1}{\mu}$	Mean service time
$P_I(n)$	Probability that the sensor is in idle state when there are 'n' packets
$P_B(n)$	Probability that the sensor is in busy state when there are 'n' packets
P_I	Steady state probability that the sensor is in idle state
P_B	Steady state probability that the sensor is in busy state
L	Mean number of packets in the sensor node's buffer
W_q	Mean waiting time of the packets in the queue

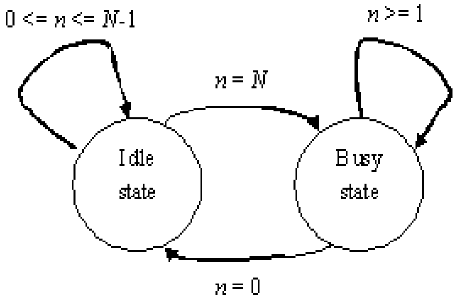

Figure 1. Two-state transition diagram of a sensor in idle state and busy state.

A WSN comprising of 'M' identical sensors has a mean arrival rate per node as λ. The steady state balance equations obtained for the analytical model as mentioned in Fig. 1 are given by equations from (1) to (6).

$$\lambda P_I(0) = \mu P_B(1) \tag{1}$$

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

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

$$(\lambda + \mu)P_B(n) = \mu P_B(n+1) + \lambda P_B(n-1)\,;2 \le n \le k-1 \,\&\, n \ne N \tag{4}$$

$$(\lambda + \mu)P_B(N) = \mu P_B(N+1) + \lambda P_B(N-1) + \lambda P_I(N-1) \tag{5}$$

$$\mu P_B(n) = \lambda P_B(n-1)\,;n = k \tag{6}$$

Solving the equations from (1) to (6), we get

$$P_I(n) = \rho^{-1} P_B(1) \quad 0 \le n \le N\text{-}1 \tag{7}$$

$$P_B(n) = \frac{1-\rho^n}{1-\rho}\; P_B(1) \quad ;1 \le n \le N \tag{8}$$

$$P_B(n) = \frac{\rho^{n-N}(1-\rho^N)}{1-\rho}\; P_B(1) \;;N+1 \le n \le k \tag{9}$$

where
$$\rho = \frac{\lambda}{\mu} \tag{10}$$

The steady state probability that the sensor in idle state (P_I) is determined as,

$$P_I = \frac{N(1-\rho)^2}{N(1-\rho) + \rho^{k+2}(1-\rho^{-N})} \tag{11}$$

The steady state probability that the sensor in busy state (P_B) is determined as,

$$P_B = 1 - P_I \tag{12}$$

The mean number of packets in the sensor (L) is given by

$$L = \sum_{n=1}^{N-1} nP_I(n) + \sum_{n=1}^{k} nP_B(n) \tag{13}$$

and hence L is reduced as

$$L = \frac{C_1 + C_2 + C_3}{2(N(1-\rho) + \rho^{k+2}(1-\rho^{-N}))} \tag{14}$$

where,

$$C_1 = N(N-1)(1-\rho) + 2N\rho$$

$$C_2 = 2(1-\rho^{-N})(k+1)\rho^k$$

$$C_3 = 2(1-\rho)^{-1}(1-\rho^N)\rho^{k-N+3}$$

The mean waiting time of the packets in the queue (W_q) is given by,

$$W_q = \frac{L}{\lambda} - \frac{1}{\mu} \tag{15}$$

B. *Average power consumption of a sensor node*

Based on the threshold value, the sensor node switches from idle to busy state and from busy state to idle state in a cycle and hence a cycle constitutes two transitions. The sensor node, during its scheduled period of active time undergoes many such cycles. To determine the average power consumption of a sensor node during its scheduled period of active time, consider the following parameters that are associated with the power consumption of a sensor node:

C_H	Power consumption during busy period/cycle in watts
C_T	Power consumption during transitions/cycle in watts
N_{cy}	Number of cycles per unit time
$P(N)$	Average power consumption/unit time in watts/sec

The number of cycles per unit time (N_{cy}) is given by

$$N_{cy} = \frac{\lambda(1-\rho)^2}{N(1-\rho) + \rho^{k+2}(1-\rho^{-N})} \tag{16}$$

$P(N)$ can be expressed as,

$$P(N) = C_H L + C_T N_{cy} \tag{17}$$

By substituting (14) and (16) in (17) and for large value of k, the average power consumption of a sensor node per unit time $P(N)$ is obtained and it is given by

$$P(N) = C_H\left(\frac{N-1}{2} + \frac{\rho}{1-\rho}\right) + C_T\left(\frac{\lambda(1-\rho)}{N}\right) \tag{18}$$

C. *Optimal threshold value (N^*) of N*

The optimal threshold value (N^*) of N based on equation (18) is determined to find the value of N for which the sensor node consumes minimum power and it is given by

$$N^* = \sqrt{\frac{2C_T\lambda(1-\rho)}{C_H}} \tag{19}$$

IV. SIMULATION MODEL

We consider Mica2 mote sensors for a wireless sensor network. We perform the simulation for a WSN using the parameters as in [8]. The various network parameters and the power consumption parameters of Mica2 mote sensors used for the simulation model are shown in Table I.

TABLE I.
NETWORK AND POWER CONSUMPTION SPECIFICATIONS

Mean arrival rate per node	100 packets/sec
Mean service time	5 msec
Number of sensor nodes	5 to 50
Threshold number of packets	1 to 20
Buffer capacity	50
Battery	3 V
Transmit current	20 mA
Current drawn during Radio off	20 µA
Current drawn during Radio on/off switching	22 mA

Simulations results are obtained for various scenarios by varying the number of nodes and threshold number of packets to determine the number of cycles per second, average power consumption and the mean delay experienced by the packets per node in a network. Simulation results clearly show that there exists trade-offs between the power consumption and data delivery delay and also the results show that the average power consumption is reduced by increasing the threshold value *N* and the minimum power is consumed for optimal threshold value N^*.

V. RESULTS AND DISCUSSION

In this section, the simulation and analytical results obtained are presented. By assuming the network and power consumption parameters as mentioned in Table I, simulation and analytical results are taken to find the number of cycles per second and the average power consumption per second of a sensor node and it is shown in Fig. 2 and Fig. 3.

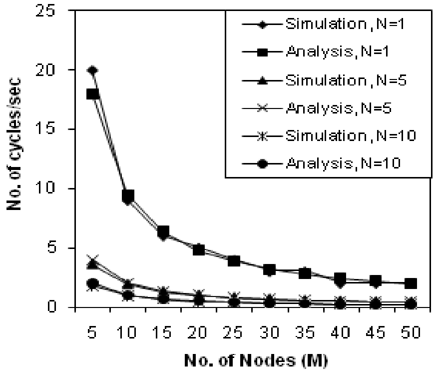

Figure 2. No. of nodes (*M*) vs no. of cycles/sec.

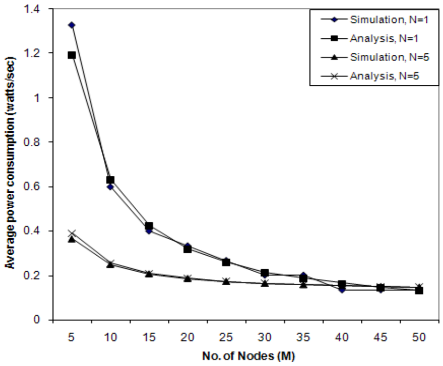

Figure 3. No. of nodes (*M*) vs average power consumption (watts/sec).

Fig. 2 shows that the number of cycles per second reduces as the number of sensor nodes increases in a network and also the number of cycles per second reduces as the value of *N* increases. Since the transitions from idle state to busy state and vice versa in a sensor node is based on the queue threshold (*N*), the number of cycles per second is reduced when *N* increases. Fig. 3 shows that the average power consumption per second is reduced since the number of cycles per second is reduced as the value of *N* increases.

Fig. 4 shows the power consumption saving (%) and by assuming mean arrival rate per node as 5, it is found that 40% and 42% of power is saved when the value of *N* is increased from 1 to 2 and from 1 to 5 respectively.

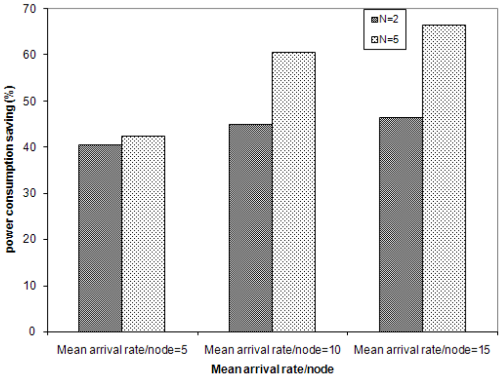

Figure 4. Mean arrival rate / node vs power consumption saving (%).

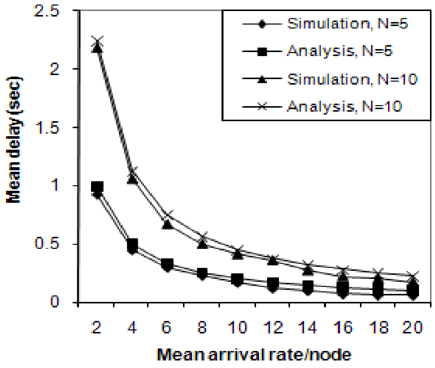

Figure 5. Mean arrival rate / node vs Mean delay (sec).

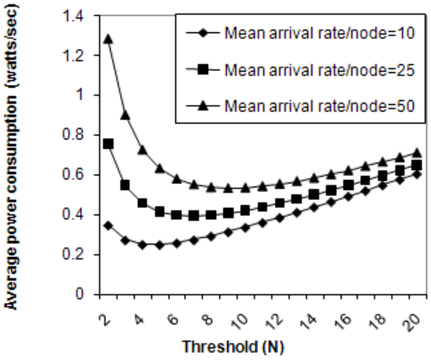

Figure 6. Threshold (*N*) vs Average power consumption (watts/sec).

Fig. 4 also shows that the power consumption saving is increased as the mean arrival rate per node increases. This is due to the reason that, as the arrival rate increases, the buffer is filled with *N* packets quickly and thus results with more transitions which lead to more power consumption in a sensor node. Since the mean delay of the system is directly proportional to *N*, the delay increases as *N* increases and it is shown in Fig. 5. From Fig. 4 and Fig. 5, it is also observed that there exist trade-off between the data delay and the average power consumption with respect to the value of *N*.

By assuming $\lambda = 10$, C_T and C_H values as mentioned in Table I, the optimal threshold value (N^*) using (19) is determined as $N^* = 5$. The average power consumption of a sensor node is determined for various values of *N* and it is found that the minimum power is consumed for optimal threshold value $N^* = 5$ and it is shown in Fig. 6. Thus from the various results obtained, it is concluded that the introduction of threshold (*N*) for making the sensor node to switch from idle state to busy state has significant effect with respect to the data delivery delay and the average power consumption of the sensor nodes.

VI. CONCLUSION AND FUTURE WORK

In this work, we have proposed a new power minimization scheme by which the power consumption of individual nodes in the sensor network is reduced by reducing the number of transitions of the sensor node during its scheduled period of active time. We have developed an analytical model of a wireless sensor network with finite buffer capacity and the system performance in terms of power consumption and data delivery delay has been determined. The results clearly indicate that the average power consumption can be reduced to a larger extent by having an optimum threshold value (N^*) which also increases data delivery delay. Clearly, the trade-offs that exists between the power consumption and data delivery delay are explored through the obtained results. We compare the analytical results with those of simulation results and the results also show that our analytical results present an excellent matching with simulation results under various scenarios showing the accuracy of our approach. The design of energy efficient routing algorithm for an HSN will be an interesting area of future research.

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