Finite Queuing Model Analysis for Energy and QoS Tradeoff in Contention-Based Wireless Sensor Networks

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Abstract- In contention-based sensor networks, nodes compete to access a shared channel for data transmission and collision is a common challenge. For power conservation, periodical active/sleep dynamics is adopted in the design of medium access protocol (MAC). At the same time, the quality of service (QoS) requirements (e.g., packet delay, packet loss rate and throughput) need to be satisfied. We develop a finite queuing model for the sensor node and derive the network performance in contention-based sensor networks. Furthermore, the impact of active/sleep dynamics and node buffer size on the tradeoff between power efficiency and QoS requirements is studied based on the model. Simulation results match well with our analysis results and validate the accuracy of our model and approach.

Keywords- Contention-based sensor networks, Finite queuing model, Power efficiency, QoS requirements

I. INTRODUCTION

Wireless sensor networks are composed of a large number of sensor nodes equipped with limited power resources, limited storage capacities and transmission range [1]. They can be deployed in various kinds of fields to perform the data gathering tasks, such as environmental monitoring and measurement. Since the transmission range is limited, sensor nodes often organize themselves into a multi-hop, wireless communication network.

In terms of medium access protocols, sensor networks can be classified into two groups. One class schedules nodes onto different sub-channels that are divided either by time (TDMA), frequency (FDMA) or orthogonal codes (CDMA). We refer to them as scheduled sensor networks which are largely contention-free. Another class is based on contention. Nodes compete for a share channel and collision happens during the contention procedure. We call them contention-based sensor networks. Compared with the scheduled sensor networks, they allocate resources on-demand and can be more flexible as topologies change, which gain much interest of researchers.

Due to the limited power resources of sensor nodes, power consumption is one of the most critical challenges in designing contention-based sensor networks. Much research work has been done to address the power consumption problem and a number of solutions have been proposed [2]. Among these power reduction techniques, the major approach is to put the sensor nodes into a low-power sleep state periodically. For instance, energy-efficient MAC layer protocols can be found in [3, 4, 5].

At the same time, the quality of service (QoS) requirements, such as packet delay, packet loss rate (due to buffer overflow) and throughput, need be satisfied in sensor networks [6].

Clearly, a tradeoff exists between power efficiency and QoS requirements. Revealing the dependency of network performance on proper active/sleep dynamics and node buffer size is necessary in the design of contention-based sensor networks.

So far, these network performances are almost always evaluated through simulations. Few works focus on the performance modeling of contention-based sensor networks. To the best of our knowledge, Liu, et al [7] propose an infinite queuing model of sensor nodes and analyze the performance in contention-free sensor networks. Chiasserini, et al [8] use an infinite queuing model to obtain the network performance in contention-based sensor networks. For simplicity, these models are not taking into account the buffer space of sensor nodes. However, buffer space is often scarce in sensor nodes (e.g. Mote [9] has only 512 bytes of data memory). It is necessary to minimize the buffer space without causing excessive packet loss. For this purpose, properly choosing the buffer space is also important in designing sensor networks.

In this paper, considering the limitation of buffer space, we model the sensor node as a finite FIFO queue model using a continuous time Markov chain (CTMC), which enables us to investigate the network performance as the active/sleep dynamics and node buffer size vary, and explore the tradeoff between power efficiency and QoS requirements in contention-based sensor networks. Through our elaborate analytical model, we aim at capturing the essential features of contention-based sensor networks, and giving strong insight into the design parameters that affect the network performance.

The remainder of the paper is organized as follows. In section II, we develop a finite node queuing model and obtain some useful performances of sensor node. Based on the queuing model, network performance metrics are computed and analyzed in section III. In section IV, we compare the analysis results of network performance to the simulation results. The whole paper is finally concluded in section V.

II. SYSTEM MODEL AND ASSUMPTION

We consider a contention-based sensor network composed of $N$ stationary sensor nodes. Nodes are randomly deployed in a $1000 \times 1000$ $m^2$ sensor field. We assume that for each node there exists at least one path connecting the sensor to the sink.

For energy conservation, the timeline of every node is divided into alternating active and sleep cycles. During the active period, nodes will turn on their radio transceivers to communicate with one another. After all the packet transmission has been completed or a certain operation point is
reached, the active period ends and the nodes will turn off their radio transceivers to enter a sleep period. In the sleep period, no packet transmission can be started, but the sensing units are still working. So pending packets are stored in a local node buffer and are to be sent in the forthcoming active period.

A. Data Flow Model

The sensor data of sensor nodes are organized into data packets of a fixed size. All the packets enter the finite buffer of sensor node and wait for the immediate transmission.

Observing that each sensor node alternates between active (A) and sleep (S) state. For the convenience of analysis, we assume that in active state, sensor nodes generate packets according to a Poisson process. In contention-based sensor networks, the relay packets will be delayed for channel contention. But the length of contention window is much smaller than the interval of packets, which has slight effect on the data flow. So the relay packets for other nodes can be also assumed as a Poisson process.

In our paper, we assume that in active period, the sensor node itself will generate packets according to a Poisson process with rate $\lambda_g$, and also relay packets coming from other nodes according a Poisson process with rate $\lambda_r$. In sleep period, the sensor node itself will generate packets according to a Poisson process with rate $\lambda_g$ and can not relay packets for other nodes.

B. Node Queuing Model

Assume the duration of the active period is exponentially distributed with mean $T_a$ and the duration of the sleep period is exponentially distributed with mean $T_s$. We can use a CTMC to model the node state. The transition diagram of the node state is shown in Fig. 1.

![Fig. 1. CTMC model of the node state](image1)

where $a = \frac{1}{T_a}$ is the transition rate from active to sleep state, and $s = \frac{1}{T_s}$ is the transition rate from sleep to active state.

We observe that the state of all next-hop nodes of the reference node is a collection of active/sleep processes. When all the next-hop nodes are in sleep state, we say the environment state of the reference node is Off, and the reference node can not relay any packets to its next-hop nodes. If at least one of its next-hop nodes is in active state, we say the environment state of the reference node is On, and the reference node can relay its packets. Thus we can also model the state of environment of the reference node as a CTMC model, shown in Fig. 2.

![Fig. 2. CTMC model of the environment](image2)

where $\alpha$ is the transition rate of the environment state from On state to Off state; $\beta$ is the transition rate of the environment state from Off state to On state.

Now we can model the reference node as a finite single server queue with server shutdown in a varying environment, as depicted in Fig. 3.

![Fig. 3. Sensor node queuing model](image3)

where $\lambda_a = \lambda_g + \lambda_r$ is the rate of the superposition of Poisson processes in active state; $\lambda_b = \lambda_g$ is the rate of Poisson process in sleep state, $M$ is the node buffer size, $\mu$ is the transmission rate of the reference node.

Note that in contention-based sensor networks, sensor nodes compete on the common channel for data transmission through random back-off scheme [3,10]. The back-off time is a random number with a discrete uniform distribution between 0 and $CW-1$, where $CW$ is the contention window size. So the probability of the reference node wins the channel is:

$$P_{\text{win}} = \sum_{i=0}^{CW-2} \frac{1}{CW} \left( \sum_{j=0}^{CW-1} \frac{1}{CW} \right)^{i+1} = \sum_{i=0}^{CW-2} \frac{1}{CW} \left( \frac{CW-i-1}{CW} \right)^{i+1}$$

where $n$ is the number of neighboring node of the reference node competing for the channel. As a result, the equivalent transmission rate of the reference node can be approximated as $\mu' = P_{\text{win}} \mu$.

The state of the reference node and its environment can be represented by the process $X(t) = (s(t), m(t), e(t))$, where $s(t) = A$ and $s(t) = S$ denote the sensor node in active and sleep state, respectively. $m(t)$ is the number of packets in the node buffer and $0 \leq m(t) \leq M$. $e(t) = 0$ and $e(t) = 1$ represent the environment of reference node in On and Off state, respectively.

Considering the contention between nodes and the limitation of buffer size, the transition diagram of the node queuing model can be shown in Fig. 4, which is different from the transition diagram depicted in [7].
Now let $P^a_{m,e}$ denotes the probability at which the reference node is active with $m$ packets in its buffer and the environment in state $e$. Correspondingly, $P^s_{m,e}$ denote the probability at which the reference node is sleep with $m$ packets in its buffer and the environment in state $e$. We can derive the steady-state balance equations from the transition diagram as follows:

\[
\begin{align*}
(a + \alpha + \lambda^+) P^a_{0,0} &= \beta P^a_{1,0} + s P^s_{0,0} + \mu P^s_{0,1} \\
(a + \beta + \lambda^+) P^a_{1,0} &= \alpha P^a_{0,0} + s P^s_{1,0} \\
(s + \alpha + \lambda^+) P^s_{0,0} &= \alpha P^a_{0,0} + \beta P^a_{0,1} \\
(s + \beta + \lambda^+) P^s_{1,0} &= \alpha P^s_{0,0} + \beta P^s_{0,1} \\
(a + \alpha + \mu^+ + \lambda^+) P^a_{m+1,0} &= \lambda^+ P^a_{m,1} + \beta P^a_{m+1,0} + s P^s_{m,0} + \mu P^s_{m+1,0} \\
(a + \beta + \lambda^+) P^s_{m+1,0} &= \lambda^+ P^s_{m,1} + \beta P^s_{m+1,0} + s P^s_{m,0} \\
(s + \alpha + \lambda^+) P^a_{m,0} &= \lambda^+ P^a_{m+1,0} + \beta P^a_{m,1} + s P^s_{m,0} \\
(s + \beta + \lambda^+) P^s_{m,0} &= \lambda^+ P^s_{m+1,0} + \beta P^s_{m,1} + s P^s_{m,0} \\
(a + \alpha)^+ P^a_{M,0} &= \lambda^+ P^a_{M-1,0} + \beta P^a_{M,0} + s P^s_{M,0} \\
(a + \beta)^+ P^s_{M,0} &= \lambda^+ P^s_{M-1,0} + \beta P^s_{M,0} + s P^s_{M,0} \\
(s + \alpha)^+ P^a_{M,0} &= \lambda^+ P^a_{M-1,0} + \beta P^a_{M,0} + s P^s_{M,0} \\
(s + \beta)^+ P^s_{M,0} &= \lambda^+ P^s_{M-1,0} + \beta P^s_{M,0} + s P^s_{M,0}
\end{align*}
\]

C. Node Performance Metrics

Using the C-K equation above, we can obtain the following performance metrics of the reference node:

i. The probability of the node in active and sleep state, $P_a$ and $P_s$, respectively:

\[
P_a = \frac{s}{a + s}, \quad P_s = \frac{a}{a + s}
\]

ii. The probability of the node in active state, its environment in On and Off state, $P_{a0}$ and $P_{a1}$; the probability of the node in sleep state, its environment in On and Off state, $P_{s0}$ and $P_{s1}$:

\[
\begin{bmatrix}
P_a & P_s & P_{a0} & P_{a1} & P_{s0} & P_{s1}
\end{bmatrix}
\]

iii. The probability of the node in active state, its environment in On state and the node buffer is empty, $P^a_{0,0}$; the probability of $M$ packets are in the node buffer, the node in active and sleep state, the environment in On and Off state,

\[
P^a_{M,0} = \frac{1}{[1,1,1]}(K_MK^{M-1} + I + K + \cdots + K^{M-1})D
\]

where

\[
K = \begin{bmatrix}
\begin{pmatrix}
(\mu + a + \alpha) - \beta & -s & 0 \\
\alpha & -(a + \beta) & 0 \\
0 & 0 & -a
\end{pmatrix}^{-1}
\begin{pmatrix}
\lambda^+ & 0 & 0 \\
0 & -\lambda^+ & 0 \\
0 & 0 & -\lambda^+
\end{pmatrix}
\end{bmatrix}
\]

\[
D = \begin{bmatrix}
\begin{pmatrix}
\alpha & \sigma & \sigma \\
\alpha & \sigma & \sigma \\
\alpha & \sigma & \sigma
\end{pmatrix}^{-1}
\begin{pmatrix}
\begin{pmatrix}
\alpha & \sigma & \sigma \\
\alpha & \sigma & \sigma \\
\alpha & \sigma & \sigma
\end{pmatrix}^{-1}
\begin{pmatrix}
1
\end{pmatrix}
\end{pmatrix}
\]

III. NETWORK PERFORMANCE MODEL

In this section, we first derive the parameters $\alpha$, $\beta$ and the relay packet rate $\lambda^+_r$ of each node. Second, using these parameters and the node performance metrics, we obtain some useful network performance.

A. Network Parameters Estimation

The parameters $\alpha$, $\beta$ characterize the behavior of the next-hop nodes of the reference node. In this paper, we assume that the active/sleep dynamics of the next-hop nodes are independent. We can compute the stationary probability $P_{off}$, with which the environment of the reference node is in Off state as follows:

\[
P_{off} = P_1 \prod_{k=0}^{H} P^k_{s}
\]

where $H$ is the set of all the next-hop nodes of the reference node, $k$ is the index of nodes. Since the sleep duration of each node is exponentially distributed with transition rate $s$, we can get:

\[
\beta = hs
\]

where $h$ is the number of all the next-hop nodes. $H$ and $h$ can be determined when the network topology and protocol are known. Then the parameter $\alpha$ can be estimated as:

\[
\alpha = \frac{P_{off}}{1 - P_{off}}\beta
\]

Remind that the average generated packet rate of the reference node is $P_a \lambda^+_g + P_s \lambda^+_g = \lambda^+_g$, and the relayed packet
rate is $P_{a,0}$. Define $\Lambda_1$ and $\Lambda_2$ as row vectors containing the $\lambda_g$ and $P_{a,0}$ of all sensor nodes, respectively. $\lambda$ can be obtained using the balance equation of network flow:
\[
\Lambda_2 = (\Lambda_1 + \Lambda_2)T
\]
where $T$ is the matrix of transition probabilities between the nodes. Element $t_{ij}$ represents the fraction of outgoing traffic of node $i$ that is forwarded to its next-hop $j$. When the routing policy is determined, the matrix $T$ can be obtained in our analysis. The reference node always forwards its packets along the highest priority route. Since we have assumed that the active/sleep dynamics of the next-hop nodes are independent, we can build $T$ with the following formula:
\[
t_{ij} = \theta_i \prod_{m \in R_j} P_{a,0}^{P_{a,0}} P_{a,0}
\]
where $R_j$ is the set of next-hop nodes that have higher priority than node $j$ in the routing table of node $i$, and $\theta_i$ is a normalization factor such that the sum of $t_{ij}$ over all $j$’s is equal to one.

### B. Network Performance

From our finite node queuing model, we can derive some network performance metrics such as average packet loss rate, network throughput, average packet delay, and average power consumption.

i. Average packet loss rate

In our model, packet loss is caused by the overflow of node buffer. The average packet loss rate of the whole network can be derived as:
\[
\bar{P}_{loss} = \frac{\sum_{k=1}^{N} \left[ \left( P_{a,0} + P_{a,0} P_{a,0} + P_{a,0} P_{a,0} + P_{a,0} P_{a,0} \right) \right] }{N \lambda_g}
\]
where $P_{a,0}$, $P_{a,0}$, $P_{a,0}$, and $P_{a,0}$ can be obtained from (8).

ii. Network throughput

Network throughput is the average packet arrival rate at the sink node, which is simply the overall effective packet generation rate of all the sensor nodes:
\[
C = N \lambda_g - \sum_{k=1}^{N} \left[ \left( P_{a,0} + P_{a,0} P_{a,0} + P_{a,0} P_{a,0} + P_{a,0} P_{a,0} \right) \right]
\]

iii. Average packet delay

Assume that the mean packets number in the buffer of the reference node is $m$, which can be calculated as:
\[
m = \sum_{m=0}^{M} m P_{m} + \sum_{m=0}^{M} m P_{m} + \sum_{m=0}^{M} m P_{m} + \sum_{m=0}^{M} m P_{m} = [1,1,1] \bar{P}_{loss} Q
\]
where
\[
Q = \begin{bmatrix}
\lambda(P_{a,0} - P_{a,0}) \\
\lambda(P_{a,0} - P_{a,0}) \\
2\mu(P_{a,0} - P_{a,0}) - 2M(P_{a,0} + P_{a,0}) + P_{a,0} + P_{a,0} + P_{a,0}
\end{bmatrix}
\]
From Little’s law [11] of the whole network, the average packet delay can be calculated as:
\[
\bar{D}_{net} = \frac{\sum_{i=1}^{N} \bar{m}_{i}}{C}
\]

iv. Average power consumption

The power consumption of sensor nodes can be divided into three parts. The first part is the power consumption due to sensing and processing in active state and sleep state, $PW_{a}$ and $PW_{s}$. The second part is the power consumption of the transceiver in transmission, reception and idle period: $PW_{trans}$, $PW_{recv}$, and $PW_{idle}$, respectively. The third part is the power consumption during transition from sleep state to active state: $PW_{tr}$. Obviously the first part is $P_{a,0}PW_{a} + P_{s,0}PW_{s}$.

The power consumption of reference node in transmission state can be calculated as:
\[
P_{win} = P_{a,0}PW_{trans}
\]
Due to the half-duplex transceiver, nodes cannot transmit and receive at the same time. So the probability of the reference node in reception and idle state is $P_{a} = P_{win}(P_{a,0} + P_{a,0})$.

Further, the probability of reference node in reception state and idle state can be calculated as $\frac{P_{a,0}}{\mu}((\lambda_g - \lambda_{a})$ and $\frac{P_{a,0}}{\mu}$, respectively. The second part can be calculated as:
\[
P_{win}(P_{a,0} - P_{a,0} + P_{a,0})(1 - \frac{\lambda_{a}}{\mu}) + P_{win}(P_{a,0} - P_{a,0})((1 - \frac{\lambda_{a}}{\mu})PW_{idle}
\]

The third part is the transition power consumption when nodes switch from sleep state to active state. In each period, the transition occurs once. So the third part can be obtained as:
\[
P_{tr} = \frac{E_{tr}}{T_{cycle}}
\]
where $E_{tr}$ is the transition energy consumption from sleep to active state, $T_{cycle}$ is the mean duration of one period.

So the power consumption of the reference node is:
\[
PW = P_{a,0}PW_{a} + P_{s,0}PW_{s} + P_{win}(P_{a,0} - P_{a,0})PW_{trans} + P_{win}(P_{a,0} - P_{a,0})(1 - \frac{\lambda_{a}}{\mu})PW_{idle} + \frac{E_{tr}}{T_{cycle}}
\]

The average power consumption of the whole network can be derived as follows:
IV. SIMULATION RESULTS

The goal of our research is to study the dependency of network performance metrics in terms of average power consumption, average packet delay, average packet loss rate and network throughput on the active/sleep dynamics and the buffer size $M$. In this section, we present the simulation results on NS-2, and compare them against our analytical results derived from the network model. The maximum transmission range of each node is set to be $250m$. We set the system parameters as follows: $N=30$, $CW=64$, $PW_{\text{tran}} = 500mW$, $PW_{\text{recv}} = 300mW$, $PW_{\text{idle}} = 300mW$, $E_{\text{tr}} = 0.025mJ$. In our simulation, the packet generation rates of all the sensor nodes are assumed to be same, $\lambda = 1 \text{ packet / s}$, $\mu = 48 \text{ packet / s}$, packet size $= 50 \text{ Bytes}$.

Fig. 5 presents the tradeoff between average packet delay and average power consumption with different values of duty cycle, which is equal to $P_d$. Fig. 6 presents the tradeoff between average packet loss rate and average power consumption with different values of duty cycle. In the simulation, the mean active duration is fixed to 0.16s. From the simulation and the analytical results, we can see that with the increase of duty cycle, the average packet delay and the average packet loss rate decrease at the expense of large average power consumption. Furthermore, the intersection point of simulation and analysis curves is closely matched in axes of duty cycle, which shows the accuracy of the queuing model in choosing proper duty cycles. The differences between the simulation and the analytical results can be attributed to the approximations made in our model.

Fig. 7 shows the dependency of average packet delay and average network power consumption on the mean duration of active period. Fig. 8 shows the dependency of average packet
loss rate and average network power consumption on the mean duration of active period. In this simulation, the duty cycle is set to be 30%. From Fig. 7, 8, we can obtain that the average packet delay and average packet loss rate increase with increase of the mean active duration. The reason is that when the active duration is larger, nodes also sleep longer simultaneously, which increases the packet delay in the node buffer and the overflow probability of node buffer. At the same time, we can also see that the average power consumption increases with the decrease of the mean active duration. This is because when the mean active duration decreases, the transition frequency increases and more transition energy are consumed. The change of average power consumption is not obvious in Fig. 7, 8 since the transition power is only a small fraction of the node power consumption in our simulation. From our analysis, we find that properly choosing the time scale of sleep/active dynamics is also important to the design of an energy-efficient network with QoS requirements.

wireless sensor networks. By using our analytical model, we can investigate the impact of active/sleep dynamics and buffer size on the network performance metrics in terms of average power consumption, packet delay, packet loss rate and network throughput. The simulation results match well with the analytical results which validate the accuracy of our model, and provide strong insight into the design of contention-based sensor networks.

Fig. 9 shows the impact of node buffer size $M$ on the average packet loss rate and the average power consumption. We can see that when the buffer size $M$ increases, the average packet loss rate decreases and the average power consumption almost remains unchanged. We also observe that when the buffer size $M$ is larger than 12, the curve of the average packet loss rate levels out to a fixed value. So the node buffer size can be properly chosen as 12 without any penalty of power consumption. Due to the limitation of the paper, the curve of network throughput is not shown here because it can be determined by the average packet loss rate.

V. Conclusion

In this paper, we consider a contention-based wireless sensor network where nodes alternate between two operation states: active and sleep, for energy conservation. Considering the limited buffer space of node, we present an analytical finite queuing model at each node to evaluate the tradeoff between power efficiency and the QoS requirements in contention-based sensor networks.

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