Modeling the S-MAC protocol in Single-Hop Wireless Sensor Networks

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Abstract—In this paper, we present a new analytical model to accurately evaluate the throughput, service delay and the energy consumption of S-MAC protocol. Our model takes into account the impact of several factors together, including periodic listen and sleep cycle, various incoming traffic loads, the backoff mechanism in S-MAC, the queuing behavior at the MAC layer, and the dependency of service delay distributions among the nodes. Simulations show that our analytical results are highly accurate. Based on our model, we study how the listen and sleep cycle effects the trade-off between energy consumption and quality of service (QoS) requirement, and further derive the optimal value for duty cycle under different traffic conditions.

Keywords—Wireless sensor networks (WSN), performance analysis, S-MAC, duty cycle, energy efficiency.

I. INTRODUCTION

Wireless sensor networking is an emerging technology with a wide range of potential applications such as environment monitoring, homeland security and digital warfare. Such a network is composed of a great number of sensing devices equipped with limited power sources. Thus, a critical concern is the efficient use of limited energy while satisfying the QoS requirement.

From the energy efficiency standpoint, a simple and effective solution is to place the node in sleep mode. Many MAC protocols designed for wireless sensor network (WSN) have adopted this idea. The well-known S(Sensor)-MAC protocol [1] is one of them. It reduces energy consumption by introducing a periodic listen and sleep cycle into IEEE 802.11 DCF. Recently, several analytical models have been proposed to analyze the impact of sleep on the network performance in WSN [2]. However, only a few works focus on modeling the S-MAC protocol [3-4]. In [3], the authors study the trade-off between energy consumption and average delay, but they use the probability taken from the analytical result for the IEEE 802.11 DCF under saturated condition [5] to compute the contention delay under non-saturated condition. The model presented in [4] provides an analysis of energy consumption, but it fails to consider an important fact that the probabilities of different nodes having no packets in their transmission queues are not independent of each other.

In this paper, we provide an analytical model that can accurately evaluate the performance of S-MAC, which includes throughput, service delay and energy consumption, under different traffic conditions. Using our model, we study the impact of duty cycle on the tradeoff between service delay and energy consumption, and derive the optimal value of duty cycle to obtain maximum energy efficiency under different traffic conditions.

The remainder of the paper is organized as follows. In section II, we provide an overview of S-MAC protocol. In section III, we present our analytical model and provide an analytical characterization of throughput, service delay and energy consumption as a function of traffic load, number of nodes and other protocol-specific parameters. Based on the model, we use energy efficiency as a criterion to obtain the optimal duty cycle value in section IV. Simulation and numerical results are shown in Section V. Finally, we conclude this paper in section VI.

II. S-MAC PROTOCOL

S-MAC is an energy-efficient MAC protocol specially designed for wireless sensor networks. The main idea of S-MAC is to put nodes into sleep periodically to reduce energy waste caused by overhearing and idle listening.

To avoid overhearing, S-MAC lets a node go to sleep for a certain period of time after receiving RTS or CTS packets that are not destined to it. This mechanism efficiently prevents a node from overhearing the following DATA and ACK packets. For the idle listening problem, S-MAC adopts a periodic listen and sleep idea, so a node can reduce idle listening by going to sleep periodically if it is not engaged in any transmissions or receptions. A complete period of listen and sleep is called a cycle in S-MAC, and the portion of listen time in a cycle is called duty cycle ($dc$), which is designed as a protocol parameter. Since the duration of listen time is set to be a constant value, the length of a cycle is determined by the value of $dc$.

III. ANALYTICAL MODEL FOR S-MAC

In this section, we present an analytical model to evaluate the performance of S-MAC under different traffic conditions. The rest of this section is organized as follows. In section III-A, we first present a Markov chain model to study the node behavior. In section III-B, we derive the service delay distribution, which is used in analyzing the queuing behavior based on the M/G/1/$\infty$ model in section III-C. In section III-D, throughput performance is obtained through Little’s Law. In section III-E, the network behavior is studied by computing the cycle probabilities. And finally, we derive the energy consumption in section III-F.
we can calculate packets in node’s transmission queue. By solving (3) and (4), a Markov chain. We have:

\[
P_k = P_k \left[ \frac{1 - (1 - p)^W}{W - (1 - p)[1 - (1 - p)^W]} \right] \]

Where \( W \) is the constant contention window size and \( p \) is the probability that at least one of the \( n-1 \) remaining nodes transmits a packet, which is also the probability that the tagged node fails to win the channel.

Let \( b_i \) be the stationary distribution probability of this Markov chain. We have:

\[
b_i = \begin{cases} 
(1 - p)b_{i+1} + b_0 + p \sum_{i=0}^{W-1} b_i \frac{1}{W} & 0 < i < W - 2 \\
b_0 + p \sum_{i=0}^{i-1} b_i \frac{1}{W} & i = W - 1
\end{cases} \tag{2}
\]

Using the normalized condition, we can obtain the closed-form solutions for this Markov chain, so the transmission probability \( p_i \) can be represented as:

\[
p_i = b_0 = \frac{p[1 - (1 - p)^W]}{W - (1 - p)[1 - (1 - p)^W]} \tag{3}
\]

In addition to the relationship between \( p \) and \( p_i \) described in (3), \( p \) can also be calculated through [6]:

\[
p = 1 - \left[ (1 - p)[1 - (1 - p)^W] \right]^{1-1} \tag{4}
\]

where \( p_0 \) is the steady-state probability that there are no packets in node’s transmission queue. By solving (3) and (4), we can calculate \( p \) and \( p_i \) with a given \( p_0 \).

**B. Service Delay Distribution**

Before analyzing the service delay distribution, we first calculate the successful transmission probability of a node in a cycle, denoted as \( p_{STC} \), and the probability that a node being successfully transmitting in a cycle initially extracts a backoff counter equal to \( i \), denoted as \( P(BC = i | STC) \). In order to successfully transmit in a cycle, a node has to first decrement its backoff counter to zero, and then make sure that there are no other transmissions on the channel when it starts to transmit. So the probability that a node with a backoff counter initially equal to \( i \) will successfully transmit in a cycle is:

\[
P_{STC} = (1 - p)^{\sigma i} \tag{5}
\]

Thus we have:

\[
p_{STC} = \sum_{i=0}^{\sigma} P(BC = i | STC) \]

\[
= \frac{(1 - p)[1 - (1 - p)^W]}{Wp} \tag{6}
\]

where \( P(BC = i | STC) = \frac{p(1 - p)^i}{(1 - p)^W} \).

Service delay is defined as the time from the moment the packet is at the head of the queue ready to be transmitted, until an acknowledgement for this packet is received. We therefore the time spent for synchronization is omitted. Therefore the service delay can be calculated as the sum of the following delay components: (1) delay due to the lost transmission opportunity caused by sleep, denoted as \( t_s \); (2) delay due to the node’s failure to successfully transmit in a cycle, denoted as \( t_t \); (3) delay due to the backoff procedure in the successfully transmitting cycle, denoted as \( t_b \); (4) delay due to the transmission, denoted as \( t_x \). On account of the slotted operation of the protocol, the packet service delay can be viewed as an integer multiple of a time slot defined in S-MAC protocol. In the rest of this letter, we denote \( F(z) \) be the probability generating function (PGF) of delay \( f \) (e.g. \( T(z) \) is the PGF of delay \( t_s \)).

Under non-saturated condition, the distribution of \( t_s \) depends on whether the next packet to be served is (a) from the transmission queue or (b) a new arrival one. From the definition of \( p_0 \) we know that case (a) happens with probability \( 1 - p_0 \) and case (b) happens with probability \( p_0 \).

In case (a), \( t_s \) is the time from the previous packet being successfully transmitted until the beginning of the next cycle, so \( T(z) \) in case (a) can be expressed as:

\[
T_s(z) = \sum_{i=0}^{\sigma} P(BC = i | STC) \frac{1}{z^{(t_s - t_s - \sigma)}} \tag{8}
\]

Where \( T_s \) is the duration of a cycle, \( T_s \) is the average transmission time and \( \sigma \) is the duration of a slot. In case (b), \( t_s \) is the time from the arrival of the new packet to the beginning of the next cycle. Assuming a random packet arrival time, \( T(z) \) in case (b) is:

\[
T(z) = \sum_{i=0}^{\sigma} \frac{1}{z^{(t_s - t_s - \sigma)}} \frac{T_d}{\sigma} \tag{9}
\]

Thus:

\[
T(z) = (1 - p_0) T_s(z) + p_0 T(z) \tag{10}
\]

With the probability \( p_{STC} \) and \( P(BC = i | STC) \), we can further calculate \( T(z) \) and \( T(z) \) as follows:

\[
T(z) = \sum_{i=0}^{\sigma} (1 - p_0) P_{STC} \frac{1}{\sigma^{i-\sigma}} \tag{11}
\]

\[
T(z) = \sum_{i=0}^{\sigma} P(BC = i | STC) \frac{1}{\sigma^{i-\sigma}} \tag{12}
\]

\[
T(z) = \sum_{i=0}^{\sigma} P(BC = i | STC) \frac{1}{\sigma^{i-\sigma}} \tag{13}
\]

The PGF of total service delay can thus be represented as:

\[
T(z) = T(z) T(z) T(z) T(z) T(z) \tag{14}
\]
To numerically invert this generating function, we use the lattice-poisson algorithm in [7], and the inversion formula used in this algorithm is:

\[ g_t = \frac{1}{2hr} \sum_{i=0}^{\infty} T_d \left( r e^{-rT_d} \right) g_{r+s} \]

where \( r \) is a real number and \( l \) is an integer. By using \( r = 10^{-1/2} \) and \( l = 1 \), the inversion error can be less than \( 10^{-8} \).

The average service delay can be easily obtained by differentiating (14):

\[ E[t_d] = (p_{stc}^{-1} - p_{0}/2)T_{st} + p_{0}T_{sc} + p_{0}T_{s} \]

where

\[ T_{sc} = \frac{(1-p)(1-pW(1-p)\sigma^2 - (1-p)\sigma^2)}{p[1-(1-p)\sigma^2]} \]

C. M/G/1/∞ Queueing Model

We assume that packet arrivals to any node to be a Poisson process with the same rate \( \lambda \) (in packet per second). Based on the M/G/1/∞ model, we can calculate \( p_{st} \) through:

\[ p_{st} = 1 - \rho = 1 - \lambda E[t_d] \]

Since \( E[t_d] \) can be expressed as a function of \( p_{st} \), we can use (18) to calculate \( p_{st} \) with a given \( \lambda \) using numerical techniques.

In addition, by applying the Pollaczek-Khinchin formula [8], the average packet delay \( T \) including the queuing delay and the service delay can be calculated as:

\[ T = \frac{1}{\lambda} + \frac{\lambda(\sigma^2 + 1/E[t_d])}{2(1-\rho)} \]

where \( \sigma^2 \) is the variance of the service delay distribution.

D. Throughput

The throughput \( S \) can be computed via Little’s Law as [9]:

\[ S = \frac{E[N]E[P]}{E[t_d]} \]

where \( E[P] \) is the average amount of payload bits transmitted in a successful transmission, and \( E[N] \) represents the average number of competing nodes, which is:

\[ E[N] = n(1 - p_{st}) \]

E. Cycle Probabilities

According to the events occurring on the channel, we can divide the cycle into three kinds: an idle cycle, a successful transmission cycle and a collision cycle. In an idle cycle, all nodes in the network have no packets to be transmitted, so there will be no contention for the channel. In a successful transmission cycle, only one of the nodes which have packets in their transmission queues wins the channel and successfully delivers its packet. While in a collision cycle, nodes with packets to be transmitted select the same backoff counter and cause a RTS collision for them transmit their RTS packets simultaneously. Define \( P_{st}, P_{st}, P_{col-m} \) to be the occurrence probabilities of an idle cycle, a successful transmission cycle and a collision cycle caused by \( m \) nodes, respectively.

Since the collision between the nodes plays a significant part in determining the length of time nodes spend to deliver a packet, the service delay distributions of different nodes are not independent of each other and so are the probabilities \( p_{st} \), although they have the same value. Consequently, we cannot use a method similar to [4] for deriving the cycle probabilities \( P_{st}, P_{st}, P_{col-m} \). Here we present a new method to solve this problem.

According to the definition of unified throughput, \( S \) is:

\[ S = \frac{P_{st}E[P]}{T_{st}} \] (22)

Thus probability \( P_{st} \) can be computed by substitute (20) into (22). Moreover, \( P_{st} \) and \( P_{col-m} \) can be expressed as a function of \( P_{st} \) and \( p_{st} \), so we are able to obtain the probability \( P_{st} \) and \( P_{col-m} \) by solving the following equations.

\[ P_{st} = (1 - p_{st})(1 - p_{st})p_{st}[1 - (1 - p_{st})p_{st}]^{-1} \]

\[ P_{col-m} = (1 - p_{st})^{\eta}[1 - (1 - p_{st})p_{st}]^{-1} \]

where \( 1 - (1 - p_{st})p_{st} \) is the probability that at least one node in the network will transmit in a given time slot.

F. Energy Consumption

The average energy consumption of the network during a cycle can be calculated using the obtained cycle probabilities:

\[ E_{cycle} = E_{st}P_{st} + E_{st}P_{st} + \sum_{m=2}^{\infty} P_{col-m}E_{col-m} \]

where \( E_{st}, E_{st} \) and \( E_{col-m} \) are the average network energy consumption in an idle cycle, a successful transmission cycle and a collision cycle, respectively.

IV. OPTIMAL VALUE OF DUTY CYCLE

Duty cycle is a very important parameter in S-MAC protocol. It affects the performance of S-MAC not only by changing the length of time nodes spend in sleep, but also by changing node behavior and network behavior. For example, if we choose a small duty cycle value, nodes will spend more time in sleep, which means there will be more chance for new packets to arrive during this period. So at the beginning of the next cycle, the average number of competing nodes will increase. This will bring about a higher collision probability and thus have a great influence on the network performance.

In this section, we use the presented analytical model to obtain the optimal value of duty cycle. Generally, lower duty cycle gives more efficient energy consumption, but it increases the service delay. Because there is a tradeoff between energy consumption and service delay, we can not only consider one performance and neglect the other. Here, we choose the energy efficiency to be the criterion for choosing our optimal duty cycle value. The energy efficiency is defined [10] as:

\[ \eta = \frac{\text{total amount of data delivered}}{\text{total amount of energy consumed}} \]

To obtain the energy efficiency, we need to calculate the...
ratio of the successfully transmitted data in one packet to the average energy consumed by a node to successfully transmit it. Since we have already got the average service delay and the average energy consumption of the network during a cycle, the average energy spent by a node to transmit a packet can be calculated as:

\[ E = \frac{E_{\text{cycle}}}{n \cdot T_{sl}} \cdot E[I_d] \]  

(27)

So energy efficiency \( \eta \) is:

\[ \eta = \frac{E[P]}{E} \]  

(28)

We can see that energy efficiency \( \eta \) takes into account both energy consumption and average service delay, which makes it a better metric to evaluate the tradeoff. Since \( \eta \) is a function of duty cycle, we can find the optimal duty cycle value to achieve maximum energy efficiency through optimization techniques.

### TABLE I. PARAMETERS FOR S-MAC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet Payload</td>
<td>100 Bytes</td>
</tr>
<tr>
<td>Slot Time</td>
<td>1 ms</td>
</tr>
<tr>
<td>MAC Header</td>
<td>20 Bytes</td>
</tr>
<tr>
<td>SIFS</td>
<td>5 µs</td>
</tr>
<tr>
<td>PHY Header</td>
<td>10 Bytes</td>
</tr>
<tr>
<td>DIFS</td>
<td>10 µs</td>
</tr>
<tr>
<td>RTS Packet</td>
<td>10 Bytes</td>
</tr>
<tr>
<td>Ptx</td>
<td>36 mW</td>
</tr>
<tr>
<td>CTS Packet</td>
<td>10 Bytes</td>
</tr>
<tr>
<td>Ptx,Pidle</td>
<td>14.4 mW</td>
</tr>
<tr>
<td>ACK Packet</td>
<td>10 Bytes</td>
</tr>
<tr>
<td>Psleep</td>
<td>15 µW</td>
</tr>
<tr>
<td>W</td>
<td>64</td>
</tr>
<tr>
<td>ListenTime</td>
<td>0.1432 s</td>
</tr>
</tbody>
</table>

V. SIMULATION AND NUMERICAL RESULTS

Our analytical model is verified by ns-2 simulator (version 2.31). Table I lists the values of parameters used in the simulations and numerical analysis. In addition to the setting in Table I, we assume that all nodes are located in a small area so that the propagation delay can be ignored.

Fig. 2 compares the simulation and analytical results of the service delay distribution. We can observe that our analytical results have a good match with the simulation.

Fig. 3 shows the predicted and simulated cycle probabilities against traffic load. Fig. 4 shows predicted and simulated throughput, average service delay and energy consumption against traffic load. From Fig. 4, it can be observed that throughput increases linearly with the packet arrival rate before node becomes saturated. This characteristic is obvious if we substitute (21) and (18) into (20), and we can further calculate that the slope is \( n \cdot E[P] \). It can be also observed that lower traffic load induces larger energy consumption. This is because the nodes spend more energy in idle cycles. In idle cycles, every node has to sense the channel throughout the predetermined listen duration, so a lot of energy is wasted in idle listening. However, in a successful transmission cycle or a collision cycle, nodes can go to sleep upon hearing the RTS packet from other nodes.

Fig. 5 shows the predicted cycle probabilities against duty cycle. Fig. 6 shows the relative service delay, relative energy consumption and relative energy efficiency with duty cycle varying from 0.05 to 1. From Fig. 6, we can see that with the increase of duty cycle, the average service delay decreases at

![Fig. 2. Service delay distribution (n = 5, dc = 0.5 and \( \lambda = 1 \)](imageURL)

![Fig. 3. Impact of packet arrival rate on cycle probabilities (dc = 0.1 and n = 5)](imageURL)

![Fig. 4. Impact of packet arrival rate on throughput, average delay and energy consumption (dc = 0.1 and n = 5)](imageURL)

![Fig. 5. Service delay distribution (n = 5, dc = 0.5 and \( \lambda = 1 \)](imageURL)
the expense of larger energy consumption. We can also observe that when the duty cycle is 0.15, there is a faster decrease in service delay and a faster increase in energy consumption. As depicted in Fig. 5, when the duty cycle is small, the nodes are in saturated condition. As long as the nodes are in saturated condition, the network behavior will not change. Thus, the decrease in service delay and the increase in energy consumption in saturated condition are simply caused by reducing the time nodes spend in sleep. However, once the duty cycle is large enough to turn the nodes into non-saturated condition, the network behavior will not remain the same. As shown in Fig. 5, with the increase of duty cycle, the probability of collision cycle decreases, which will further reduce the average service delay. This explains why there is a faster decrease in average service delay when duty cycle is 0.15. Similarly, the increase of the probability of idle cycle leads to the fast increase in energy consumption. The maximum energy efficiency appears at the point where duty cycle is 0.35.

Fig. 7 shows the optimal value of duty cycle with different packet arrival rates. We can see that the optimal value of duty cycle increases with the packet arrival rate and the number of nodes in the network.

![Fig. 5. Impact of duty cycle on cycle probabilities (λ = 0.2 and n = 5)](image)

![Fig. 6. Impact of duty cycle on relative service delay, relative energy consumption and relative energy efficiency (λ = 0.2 and n = 5)](image)

VI. CONCLUSION

In this paper, we provide an analytical model to compute the throughput, service delay and energy consumption of S-MAC protocol in single-hop network under non-saturated condition. Using our model, we can investigate the impact of duty cycle on network performance. Furthermore, we demonstrate how to obtain the optimum value of duty cycle under service delay and energy saving requirements. Simulation and analytical results show that our model can accurately evaluate the performance of S-MAC protocol, and guide the designers to determine the dominating protocol parameter according to different traffic conditions.

REFERENCES


