An Analytical Model for IEEE 802.15.4 with Sleep Mode Based on Time-varying Queue

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***Abstract*—A novel queuing model in this paper is proposed to provide a tool for performance evaluation to IEEE 802.15.4 Medium Access Control (MAC) protocol with sleep mode enabled. IEEE 802.15.4 node with sleep mode enabled behaves in a different way from other queuing models because the node goes to sleep periodically and thus packets arriving in sleep period accumulate in the beginning of the active portion, which makes a heavier load at the beginning than any other time. This model analyzes this behavior by using an embedded discrete-time Markov chain model that includes the slot number in the states to obtain the time-varying queue length. To obtain the service time, we introduce the virtual service time into this model which makes the proposed queuing model different from models in any previously published works. The accuracy of the proposed model is validated by Monte Carlo simulations. The proposed model can accurately evaluate the performance of IEEE 802.15.4.**

***Index Terms*—IEEE 802.15.4, queuing analysis, CSMA/CA, virtual service time, throughput.**

I. Introduction

IEEE 802.15.4 has been widely used in ultra low power, low complexity and low data rate applications with the rapid development of wireless personal area networks (WPAN) and wireless sensor networks (WSN) [1], Since the publication of IEEE 802.15.4 standard in 2006 [2], IEEE standards working group 15.4 has made three amendments to the standard on adding alternative physical layer extensions in the latest three consecutive years. These amendments significantly expand the application of IEEE 802.15.4 in every aspect of our lives around the world.

IEEE 802.15.4 is designed especially for ultra low power networks, which has strict restrictions on the energy consumption of these battery-powered nodes in the networks. To address the energy consumption requirements, making nodes work in sleep/wakeup cycle is a simple and effective solution. Sleep mechanism in IEEE 802.15.4 which enables nodes entering sleep mode periodically is optional but crucial. This mechanism is highly effective in energy saving. A detailed description of the benefits of sleep mechanism is provided in [3].

To the best of our knowledge, models proposed for performance evaluations so far, like [4], [5] and more recent work [6], have given accurate performance evaluations for CSMA/CA mechanism of IEEE 802.15.4. But they do not perform detailed queuing analysis taking sleep mode into consideration. J. Mišić et. al have proposed an M/G/1/K system with vacations to analyze the beacon enabled mode of an IEEE 802.15.4 cluster [7]. However, the assumption that every node enters sleep mode for a geometrically distributed time after its buffer becomes empty differs much from the actual mechanism and makes the analytical results diverge from the simulation results. C. Buratti has mentioned in [8] a similar modeling approach by dividing the superframe into slots and analyzing the behavior of the node in each slot. But no queuing analysis is considered because he assumed that each node transmits only one packet in a superframe. In our previous work [9], we have not analyzed the queuing behavior of nodes in the network because that work focused on the slot-based modeling of this protocol in real time applications which requires a new coming packet must be transmitted immediately.

In contrast with these works, we provides a novel analytical queuing model in this paper. The time-varying characteristics of queue length due to the sleep mechanism influence the number of nodes competing for channel and hence the service time of each packet. To accurately describe the queuing behavior, average queue length is not sufficient. In this study, we focus on the accurate description of the queuing behavior by dividing time into backoff slots and using embedded discrete-time Markov chain to model the queuing behavior.

The remaining parts of this paper are organized as follows: Section II provides three analytical models in detail. Section III presents some key performance metrics and numerical results, followed by a conclusion of the whole paper in Section V.

II. Analytical Model Formulation

IEEE 802.15.4 uses superframe structure which consists of an active period and an optional inactive period. The superframe is bounded by network beacons periodically transmitted by PAN coordinator. The beacon interval BI and superframe duration SD are determined by $macBeaconOrder$ $(BO, 0 \leq BO \leq 14)$ and $macSuperframeOrder$ $(SO, 0 \leq SO \leq BO \leq 14)$, respectively.

$$BI = aBaseSuperframeDuration \times 2^{BO}, \quad (1)$$

$$SD = aBaseSuperframeDuration \times 2^{SO}, \quad (2)$$

where $aBaseSuperframeDuration$ is the minimum duration of a superframe.

In our study, we consider the single-hop star topology with a PAN coordinator which serves as the center of the star

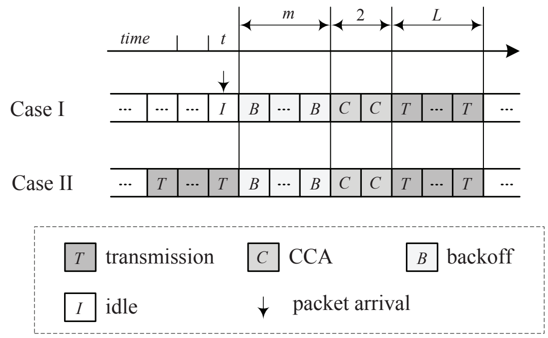

Fig. 1. Slot timing for virtual service time

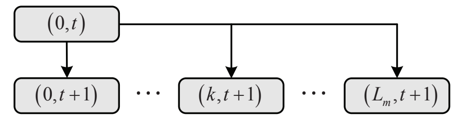

Fig. 2a. State transitions when the buffer is empty ($n = 0, t + d \le T_A$)

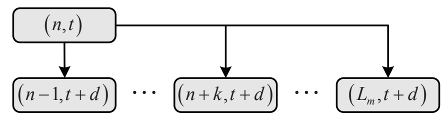

Fig. 2b. State transitions when the buffer is not empty ($0 < n \le L_m, t+d \le T_A$)

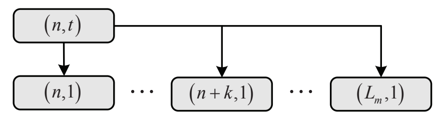

Fig. 2c. State transitions across the boundary of superframe ($0 < n \le L_m, t + d \ge T_A$)

network, and N nodes which can only communicate with the coordinator in the active period of the superframe using slotted CSMA/CA. All nodes in the star network can hear each other. No acknowledgement is implemented in this study for the sake of energy efficiency. Meanwhile, we suppose the packet arrival process has no aftereffect and denote the arriving probability of k packets and k packets at least during s slots by $q(k, s)$ and $q^+(k, s)$, respectively.

A. Embedded Discrete-time Markov Queuing Model

To fully describe the queuing behavior of IEEE 802.15.4 nodes, we implement the concept of virtual service in our analysis. If some node in the network is transmitting, other nodes with pending packets have to wait until current transmission ends. We define this waiting as virtual service, then each node is an virtual server for packets from all other nodes in the network. We call this waiting time as virtual service time. We tag a certain node in the network and study its behavior in the rest of the paper.

As illustrated in Fig. 1, the virtual service time d can be divided into three parts: m slots for backoff mechanism, 2 slots for clear channel assessment (CCA), and L slots for packet transmission. m is different in two cases. Case1: if the tagged node is idle in the tth slot when a packet arrives in that slot, m is the gap between the tth slot and the slot when a certain node first senses the channel. Case 2: if the channel is occupied by some node (including the tagged node) in the tth slot and the transmission ends in that slot, m is the number of slots between the end of last transmission and the start of the following CCA firstly performed by a certain node. Let $p_s(m, t)$ represent the probability that the tagged node first finishes backoff in the tth slot and $p_f(m, t)$ be the probability that some node finishes backoff process in the tth slot while the tagged node competes the backoff process some slots later.

Therefore, with the concept of virtual service, we model the queuing behavior of an IEEE 802.15.4 node on the basis of embedded discrete-time Markov chain analysis by dividing the active portion of the superframe into backoff slots (dented as slot hereafter). The number of packets in the buffer of each node in each slot of the superframe is defined as a state in the embedded discrete-time Markov chain analysis.

Let (n, t) stand for the state that the tagged node buffers n packets in the tth slot of the superframe where n takes value from 0 to L_m and t ranges from 1 to T_A. L_m is the maximum queue length and T_A is the number of slots in the active portion of superframe. Then the state transitions in this Markov chain model describing the queuing behavior of a IEEE 802.15.4 node is shown in Fig. 2.

When the buffer is empty, the node shall transit to the next slot, as described in Fig. 2a. The transition probability is

$$p((k, t + 1)|(0, t)) = \begin{cases} q(k, 1), & 0 \le k < L_m \\ q^+(k, 1), & k = L_m \end{cases} \tag{3}$$

The packet arrival duration is $T_A + 1$ when $t = T_A$.

When the buffer is not empty and $t + d < T_A$, as Fig. 2b depicts, the transition probabilities can be determined by

$$\begin{aligned} p((n + k, t + d)|(n, t)) = {} & p_s(m, t)q(k + 1, d) \\ & + p_f(m, t)q(k, d). \end{aligned} \tag{4}$$

When $n + k = L_m$, we replace $q(k, d)$ with $q^+(k, d)$.

In IEEE 802.15.4, nodes shall not start transmission in the last $L + 2$ slots of the superframe because there is no sufficient number of slots for transmission. In this case, the node should transit from (n, t) directly to the first slot of the next superframe without any packet transmission. The time duration between the two states is $\tau = T_A + T_I - t$. The transition probabilities should be

$$\begin{aligned} p((n + k, 1)|(n, t)) = {} & p_s(m, t)q(k + 1, \tau) \\ & + p_f(m, t)q(k, \tau). \end{aligned} \tag{5}$$

When $n + k = L_m$, $q(k, \tau)$ is also replaced by $q^+(k, \tau)$.

To determine $p_s(m, t)$ and $p_f(m, t)$ in the virtual service time model, we need the number of nodes competing for the channel in the tth slot of the superframe provided that the tagged node has packets waiting for transmission, denoted by

$N_c(t)$. Assume in this study that each node in the network is independent on each other, then the probability distribution of $N_c(t)$ is

$$P(N_c(t) = i) = \binom{N-1}{i-1}(1 - p_o(t))^{i-1}(p_o(t))^{N-i}, \quad i = 0, 1, \ldots, N-1, \tag{6}$$

where $p_o(t)$ is the probability that the node is idle in the tth slot of the superframe, which is determined by

$$p_o(t) = \pi_{(0,t)}/p_t, \tag{7}$$

in which p_t is the steady state probability that is transited through $(n, t)(n = 0, 1, \ldots, L_m)$. In this paper, we denote π_S as the steady state probability of state S.

B. Virtual Service Time Model

From $d = m + L + 2$ we can see that the probability distribution of virtual service time d is only determined by the probability distribution of m. According to different distribution of m, the determination of $p_s(m, t)$ and $p_f(m, t)$ will be discussed in three cases.

1) Case I: If some other node finishes transmission in the tth slot and the tagged node is already in bakcoff state before the that slot, we can suppose that the CSMA/CA process of the tagged node has reached the steady state until the tth slot. Then the steady state probability that the tagged node performs previous CCA in any slot ranging from the $(t - W_{M-1} + 1)$th (W_{M-1} is the maximum backoff window length) to the tth (and detects a busy channel), denoted by π_c, is given by

$$\pi_c = 1/\overline{w}, \tag{8}$$

where $\overline{w}$ is the equivalent backoff window length between consecutive CCA slots, given by

$$\overline{w} = \sum_{i=0}^{M-1} \sum_{j=0}^{W_i - 1} j p_b(i, t)/W_i, \tag{9}$$

where $p_b(i, t)$ is the probability distribution of backoff stages when the CSMA/CA process starts in the tth slot.

The probability that the tagged node performs CCA in the $(t+m+1)$th slot given that it does not sense the channel from the $(t + 1)$th slot to the $(t + m)$th slot, denoted by $p_d(m, t)$, can be determined as follows,

$$p_d(m, t) = \pi_c(W_{M-1} - m)/W_{M-1}, m = 0, 1, \ldots, W_{M-1} - 1. \tag{10}$$

Then $p_s(m, t)$ and $p_f(m, t)$ are given by

$$p_s(m, t) = p_d(m, t) \left[\sum_{i=m}^{Q} p_d(i, t) \right]^{N_c(t)-1}, \tag{11}$$

and

$$p_f(m, t) = \sum_{i=m+1}^{Q} p_d(m, t) \times \left\{ \left[\sum_{i=m}^{Q} p_d(i, t) \right]^{N_c(t)-1} - \left[\sum_{i=m+1}^{Q} p_d(i, t) \right]^{N_c(t)-1} \right\}, \tag{12}$$

respectively, in which $Q = W_{M-1} - 1$.

2) Case II: If a new packet comes in the tth slot when the tagged node is idle, the tagged node begins to backoff in the $(t+1)$th slot of the superframe, or the tagged node finishes last transmission in the tth slot and the node commences a new backoff process in the $(t + 1)$th slot, for the tagged node the distribution of the gap between two consecutive transmission or between idle state and transmission, m obeys the uniform distribution in the interval $[0, W_0 - 1]$.

$$p'_d(m, t) = 1/W_0. \tag{13}$$

It is reasonable in this case to suppose that the other nodes competing for the channel with it have reached steady state in backoff process. Then the probability that the tagged node first senses the channel in the $(t+m+1)$th slot is determined by

$$p_s(m, t) = p'_d(m, t) \left[\sum_{i=m}^{W_{M-1}-1} p_d(i, t) \right]^{N_c(t)-1}, \tag{14}$$

while $p_f(m, t)$ can be determined in the same way as (12).

3) Case III: At the beginning of the superframe, when all nodes with pending packets start CSMA/CA process in the first slot, the distribution of m is the same as (13) for each node.

The probability that the tagged node succeeds in accessing the channel after m slots in the first backoff stage is the probability that all other nodes backoff at least m slots which is determined as

$$p_s(m, t) = \frac{1}{W_0} \left(\frac{W_0 - m + 1}{W_0} \right)^{N_c(t)-1}. \tag{15}$$

$p_f(m, t)$ can also be determined in the same way as (12).

C. CSMA/CA Model

To determine the virtual service time distribution of a data packet, we need to obtain the success probability of the first and the second CCA, as well as the distribution of backoff stages in CSMA/CA mechanism of IEEE 802.15.4. The Markov-chain-based CSMA/CA model for a single node in the network under saturated condition is shown in Fig. 3, which is extended from that of Bianchi's for IEEE 802.11 DCF [10] and Pollin's in [6]. This model differs from the two by improving several significant aspects to match the IEEE 802.15.4 described below.

Let $s(t)$ be the backoff stage counter and transmission indicator and $w(t)$ be the backoff window length counter and transmission slots counter provided that the CSMA/CA process starts in the t + 1th slot of the superframe. Then $(s(t), w(t))$ $(s(t) = 0, \ldots, M-1; w(t) = 0, 1, \ldots, W_{M-1}-1)$ stands for the $w(t)$th backoff state in the $s(t)$th backoff stage while $(s(t), w(t))$ $(s(t) = 0, 1, \ldots, M-1; w(t) = -1, -2)$ represents the $w(t)$th CCA state in the $s(t)$th backoff stage. Meanwhile, denote the $w(t)$th transmission state with $(s(t), w(t))$ $(s(t) = -1; w(t) = 1, 2, \ldots, L)$.

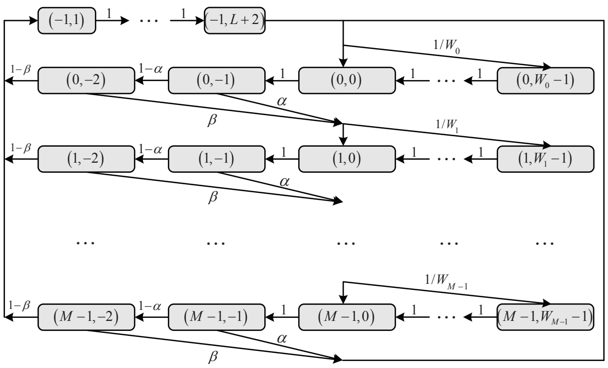

Fig. 3. Markov model for CSMA/CA mechanism of IEEE 802.15.4

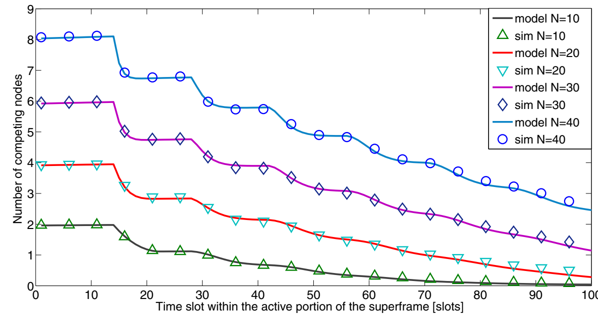

Fig. 4. Number of competing nodes versus number of nodes in the network for different number of nodes

Let α and β stand for the probabilities that the channel is assessed to be busy during the first CCA and during the second one provided that the first reported idle, respectively. Obviously, α is the probability that there are at least one node transmitting in the network when the tagged node performs its first CCA. If there is more than one node transmitting simultaneously, then all these nodes must detect the channel in the same slot. Denote the probability that a certain node finishes backoff process and starts CCA in a given slot with probability ϕ, then $\phi = \sum_{i=0}^{M-1} \pi_{(i,0)}$. Then α is given by

$$\alpha = L\left[1-(1-\phi)^{N_c(t)-1}\right](1-\alpha)(1-\beta). \quad (16)$$

Meanwhile, Derived in a similar way as [6], β has the following form.

$$\beta = \left[1-(1-\phi)^{N_c(t)-1}\right]\left[2-(1-\phi)^{N_c(t)}\right]^{-1}. \quad (17)$$

Since the node may accumulate a large amount of packets during the inactive portion, the number of competing nodes decreases from the start of the superframe to the end. This decline has significant impact on α and β. Therefore, α and β depend on the location of current slot from the start of the superframe. We take this crucial dependence which is not considered in [6] and [10] into account by recalculating these two probabilities in different CSMA/CA process.

However, since the duration of a data packet transmission is large compared to the average time spent in the backoff mechanism of a CSMA/CA process, the change in the number of competing nodes is a slow process. As a result, we can approximate α and β in each backoff stage of the same CSMA/CA procedure as the same.

Given that the channel is busy, the probability that a node with pending packets stays in its ith backoff stage if current CSMA/CA process starts in the $(t+1)$th slot of the superframe, denoted by $p_b(i,t)$, should be

$$p_b(i,t) = \frac{\sum_{j=-1}^{W_i-1} \pi_{(i,j)}}{\sum_{i=0}^{M-1}\sum_{j=-1}^{W_i-1} \pi_{(i,j)}}. \quad (18)$$

III. Numerical Results

In the following analysis, we first evaluate the accuracy of the probability for the tagged node to access the channel before examining whether the queue length matches the simulation results. In last step, we compare the throughput derived from the model and simulations.

We develop a Monte Carlo simulator in Matlab. Some simulation parameters are: The PHY, MAC header, and payload is 6, 7, and 107 bytes respectively. Transmission rate is 250 kb/s. Both BO and buffer size are 5. SO is 2 and the number of nodes is 20 unless specified. Other parameters are set to be the default defined in the standard.

A. Probability to Access the Channel

The probability to access the channel mainly rely on the number of competing nodes which is given in (7). Fig. 4 illustrates the number of competing nodes as a function of the time slot within the active period of the superframe for different number of nodes in the network. This figure shows a close match between the predicted results and the simulation results. The use of effective backoff window length as an alternative of the distribution of the backoff window length attributes to the difference between the model analysis and simulation results near the end of the superframe when the packet arrival rate is comparatively large.

From Fig. 4, the number of competing nodes experiences two apparent stages, the first one of which lasts from the beginning of the superframe to the 14th slot, while the second one lasts from the end of the first one to 28th slot. The reason is that the minimum number of slots for a packet transmission is 14 slots (0 backoff slot, 2 CCA slot and 12 transmission slot).

The success probabilities of the tagged node as a function of the number of nodes in the network for different packet arrival rate during the first stages in contrast with the predicted results are described in Fig. 5. As predicted, at the beginning of the superframe, the access probability decreases with the rise of either the number of nodes or the packet arrival rate.

B. Queue Length

As stated, our aim of the model is to find out the time-varying characteristics of the queue length; therefore, we work out the average queue length,

$$L(t) = n_q(t)/p_t, \quad (19)$$

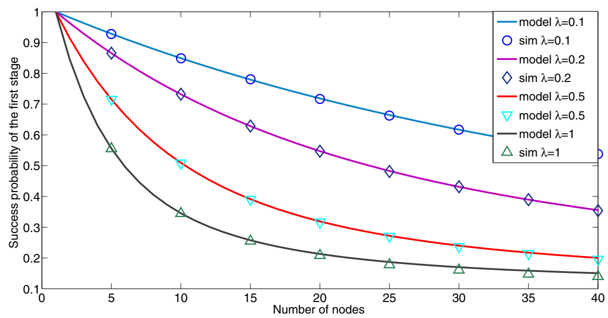

Fig. 5. Success probability of the first stage versus number of nodes in the network for different packet arrival rate

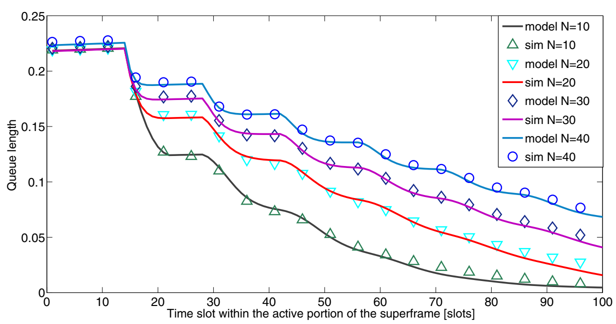

Fig. 6. Queue length of each node versus time within the active period for different number of nodes

in which $n_q(t)$ is the average number of packets in the buffer of the node in the tth slot of the superframe.

We compare the queue length in different slot of the superframe obtained by model analysis and simulations for different number of nodes in Fig. 6. It can be observed that the queue length from model analysis matches very well with the simulations. As expected, the queue length which is larger at the beginning of the superframe than any other time decreases as the superframe comes to an end.

C. Throughput

We can obtain the throughput, i.e., number of packets that a node transmits per second in the channel,

$$S = T_A S_p / T_p \tag{20}$$

where S_p is the average number of packets per state transition in the embedded discrete-time Markov chain queuing model and T_p denotes the average number of backoff slots consumed per state transition.

Fig. 7 compares the predicted and simulated throughput. Our model analysis matches the simulation results perfectly. From (20), the increase in either duty cycle or packet arrival rate leads to the rise in the throughput.

IV. Conclusions

In this paper we have proposed a novel queuing model to analyze the impact of time-varying load due to sleep mode in

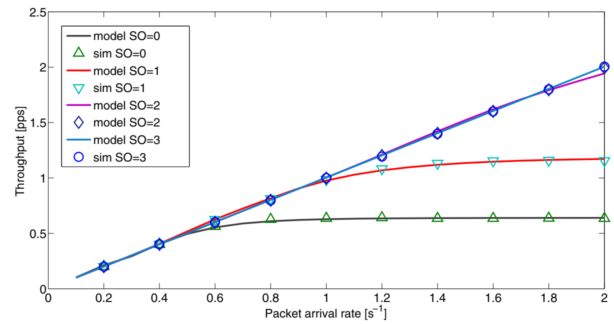

Fig. 7. Throughput of each node versus packet arrival rate for different duty cycle

IEEE 802.15.4 and to evaluate the performance in single-hop networks. We have presented three submodels including an embedded discrete-time Markov queuing model, a virtual service time model and a Markov-based CSMA/CA model. In this model we take into account the time-varying characteristics of the service time due to time-varying load in different slot of the superframe and derive virtual service time distribution instead of service time distribution which has never been used in other studies. The analytical results of dynamic queue length and throughput are observed to well match the simulation results, which show that the proposed model can accurately evaluate the performance of IEEE 802.15.4.

V. Acknowledgement

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