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Performance Analysis and a Proposed Improvement for the IEEE 802.15.4 Contention Access Period

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***Abstract*— IEEE 802.15.4-2003 [1] was introduced to address the market need for connecting low-rate devices in a wireless personal area network (WPAN). A slotted CSMA/CA medium access control (MAC) protocol is defined in the standard to coordinate the channel access of a large number of wireless devices. In this paper, we propose a novel Markov chain for IEEE 802.15.4 MAC, which faithfully captures all the essential features of the protocol, and thus can provide valuable insight into the strengths and weaknesses of this multiple access scheme. The evaluation reveals that the double carrier sensing mechanism specified in 802.15.4 MAC is not an optimal design, and a slight modification in the protocol can result in further performance improvement in terms of throughput, delay and energy efficiency.**

I. INTRODUCTION

As our daily life is surrounded by more and more electronic devices, there is a pressing need to network them together in an easy, and preferably wireless fashion. To address this need, the *ZigBee Alliance* [2] and the *IEEE 802 Working Group* joined forces in 2000 to investigate a low data rate solution with multi-month to multi-year battery life and very low complexity. This effort eventually led to the quick standardization of IEEE 802.15.4-2003 [1], a new protocol for low-power and low cost wireless networking for residential and industrial environments. Since its ratification, IEEE 802.15.4 has witnessed rollouts of numerous product solutions, and achieved rapid market acceptance. To further leverage the success that 802.15.4 enjoys, the ZigBee Alliance released its first specification in December 2004, based upon the physical (PHY) and medium access control (MAC) layer of IEEE 802.15.4 protocol.

Recently, the field of wireless personal area networking (WPAN) in general, and IEEE 802.15.4 in particular, has become the focus of extensive research. [3] and [4] provide an excellent introduction to the protocol stack, design requirements and evolution of the IEEE 802.15.4 draft standard. [5] and [6] carefully study the performance of IEEE 802.15.4 MAC protocol using the simulation modules developed in the $ns2$ environment. [7] extends the initial investigation in [5] and discusses a wider range of issues in the IEEE 802.15.4 MAC protocol. N. Golmie et al. consider the possible application of IEEE 802.15.4 to the medical environment and simulate the protocol in a health-care/hospital scenario using $OPNET$. Since IEEE 802.15.4 may operate at the 2.4GHz industrial, scientific and medical (ISM) band, its coexistence with IEEE 802.11b/g raises concerns from the existing 802.11 community. The impact of potential interference on the network performance is examined by I. Howitt et al. in [9]. A Markov chain was proposed in [10] to evaluate the saturation throughput of 802.15.4. [11] further extended the Markov chain and used it in conjunction with an $M/G/1/K$ queueing model to analyze the delay and throughput performance of IEEE 802.15.4 under non-saturation traffic. Nonetheless, various approximations have been made in [10] and [11] to simplify the analysis related to Markov process, and no simulation results have been provided to validate the proposed model. For instance, the probability that carrier sensing will find the channel busy is dependent on whether the carrier sensing is performed during the channel busy period or not. However, [10] ignores this critical nuance and only uses two average probabilities (i.e., α and β) for all possible scenarios in the analysis.

In this paper, we propose a new Markov chain model for IEEE 802.15.4 MAC protocol, which takes *all* the major aspects of medium access control mechanisms into consideration. An efficient iterative methodology is then employed to solve the chain numerically. Using this Markov model, the saturation throughput of an IEEE 802.15.4 network can be accurately calculated. An investigation on the effect of various MAC features, especially that of the double carrier sensing mechanism, was then performed. Based upon the insights thereby revealed, a slight modification of IEEE 802.15.4 MAC is proposed to improve the performance of the protocol.

The analysis presented in this paper may bear some resemblance to the Markov chains defined for the IEEE 802.11 DCF [12]. However, the direct application of the model introduced therein does not lend itself to a valid analysis for IEEE 802.15.4, as the random backoff performed in this new MAC always proceeds regardless of whether the channel is idle or busy, which represents one of several significant deviations from the IEEE 802.11 DCF protocol. In addition, it is worthwhile to note that other statistics of interest, such as service delay distribution, can also be readily computed using the model proposed herein, which is another desirable feature that distinguishes this Markov chain from previous analysis focused on the general CSMA/CA mechanism or the IEEE 802.11 DCF. Due to space constraints, however, the delay analysis will not be addressed in this paper.

The rest of the paper is organized as follows. In section II, a brief introduction to IEEE 802.15.4 protocol is offered. Section III defines the new Markov model, and elaborates the corresponding numerical solution. The saturation throughput of an IEEE 802.15.4 network is then computed in section IV, based upon the solution to the Markov model. Section V compares the analysis and simulation results, and provides an in-depth discussion on how the key MAC parameters may impact the network throughput. The protocol evaluation sheds further light on some possible minor protocol changes, which nevertheless can increase the system throughput, and lower the delay and energy consumption. The paper concludes with section VI, which also outlines future research work.

II. The IEEE 802.15.4 MAC Protocol

A. Overview of IEEE 802.15.4 MAC protocol

IEEE 802.15.4 can operate in both a beacon-enabled mode and an ad hoc non-beacon mode. As depicted in Figure 1, a *superframe* structure has been defined in the protocol for the beacon-enabled mode.

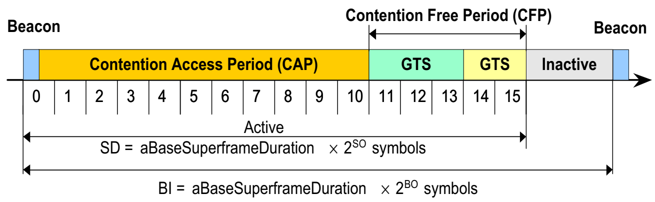

Fig. 1: IEEE 802.15.4 superframe structure.

Each superframe starts with a *beacon* frame sent by an elected *coordinator*, which is followed by a contention access period (CAP), and a contention free period (CFP). Before the arrival of the next beacon, which signals the beginning of a new superframe, nodes in the WPAN may enter an inactive period and stay in a low power mode so that the energy consumption can be further conserved. During the CAP period, if a beacon is successfully detected, the channel should be accessed in a slotted CSMA/CA fashion. In the CFP, however, exclusive channel access for each node is always granted by the coordinator.

As shown in the equation below, the detailed structure of a superframe can be specified by such MAC attributes as $macBeaconOrder$ (BO) and $macSuperframeOrder$ (SO). BI and SD represent the duration of beacon interval and the length of the *active* superframe duration, respectively. Figure 1 also demonstrates that the active portion of the superframe SD is further divided into $aNumSuperframeSlots$ equal slots.

$$\begin{cases} BI = 2^{BO} \times aBaseSuperframeDuration \\ \qquad\qquad\qquad\qquad 0 \le BO \le 14 \\ SD = 2^{SO} \times aBaseSuperframeDuration \\ \qquad\qquad\qquad\qquad 0 \le SO \le BO \le 14 \end{cases}$$

It is necessary to clarify the relation amongst various time slots defined in the standard, since the concept of a time slot plays a crucial role in the operation of 802.15.4. Specifically, if the default values are used, each active period contains 16 $aBaseSuperframeDuration$ (see Figure 1), which in turns consists of 48 backoff period units.

Since the Markov model in this paper is proposed for the CAP period within a superframe structure, we will concentrate on the slotted CSMA/CA mechanism in the rest of the paper. Interested readers should refer to [5]–[7] for further details on superframe structure and CFP operation.

B. Slotted CSMA/CA in CAP

In the slotted CSMA/CA, each node maintains three parameters, namely the number of random backoffs (NB), backoff exponent (BE), and contention window (CW), for every packet. Once a frame reaches the head-of-line (HOL) in the buffer, it should locate the backoff period boundary and perform a delay for a random number of units of backoff period. This random number is drawn from the interval $[0, 2^{BE} - 1]$, based upon the uniform distribution. Each unit of backoff period should equal to $aUnitBackoffPeriod$ number of physical symbols, and BE is first initialized to the value of $macMinBE$. Hereafter, the terms *time slot* and *backoff period unit* will be used interchangeably.

Upon the completion of the random delay, the node should sense the carrier on the backoff period boundary. If the wireless medium is found idle, CW is decremented and another channel sensing is immediately attempted at the succeeding backoff period slot boundary. The packet can only be transmitted when the CW reaches 0 and the node still senses the channel to be idle. Whenever the medium becomes busy before CW reaches 0, NB is incremented, and a new random backoff is started, as long as NB has not exceeded the maximum number of backoffs. The duration of this random backoff retry is drawn from the interval $[0, 2^{min(BE+1, aMaxBE)} - 1]$, again according to the uniform distribution. The MAC parameter $aMaxBE$ is the default maximum value of backoff exponent. Also, note that upon each random backoff retry, CW is reset to its initial value $\widetilde{CW}$ (i.e., 2). After the packet transmission, the existence or lack of an acknowledgment from the intended recipient indicates whether the transmitted packet is successfully delivered or not.

III. Markov Model

In the following analysis, we assume that the WPAN network under investigation is in the saturation mode, which implies that there is always at least one packet awaiting transmission at each node in the network. The Markov model then shall establish an upper bound for the throughput performance of the network. We further assume that all nodes are within the range of direct transmission of each other. Moreover, the physical channel conditions are ideal, and no transmission error occurs. For ease of analysis, all frames are assumed to have the same fixed length.

As illustrated in Figure 2, the operation of the WPAN network is essentially a renewal process, thanks to the saturation assumption. Every operation cycle starts with a busy period,

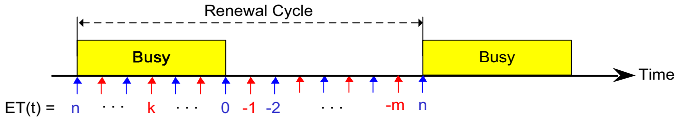

Fig. 2: Renewal process: IEEE 802.15.4 operation cycle.

which could be either a successful transmission or a collision, followed by an idle period, which corresponds to the random backoff and/or carrier sensing. The node that completes the channel sensing first will access the channel, and thus start the next busy period.

To faithfully model the behavior of each 802.15.4 node during the CAP period, the discrete time Markov chain requires three state variables $[NB(t), RC(t), ET(t)]$. The timeline is slotted at the granularity of a unit of backoff period, and the triplet $[NB(t), RC(t), ET(t)]$ changes values only at the boundary of each slot. $NB(t)$ stands for the number of random backoff retries, while $RC(t)$ is the duration of the remaining random backoff time (in terms of slots), plus the value of $CW(t)$. As a special case, $NB(t)$ corresponding to successful transmission and collision assumes value *-1* and *-2*, respectively. The third variable $ET(t)$ helps locate the time slot in an operation cycle, as portrayed in Figure 2. $ET(t) = \pm k$ means that the observation time instance is k slots away from the end of the ongoing channel busy period, and the sign (i.e., "+" or "-") associated with k is determined based upon whether the observation time instance is during or after the transmission, respectively. Note that the state variable $ET(t)$ only has local significance within each cycle, and its value renews whenever a new cycle starts.

A high level view of the resultant Markov chain is provided in Figure 3. The details within each stage of the chain are concealed, due to the limit on space. Nevertheless, for illustrative purposes, the internal structure for stage 0 and stage 4, which correspond to the case where $NB(t) = 0$ and $NB(t) = 4$, are depicted in Figures 4 and 5, respectively. For the sake of clarity, labels have been placed besides the probability of the transition entering the states to indicate the source of that particular transition. Also, transitions with similar meaning are colored identically for ease of understanding. In addition, a light grey box has been placed around the group of states which can be described by the same equation. Parameters a_m and b_m in these figures are the probabilities that the wireless channel is observed to be busy or idle, where $m = -k + 1 - \widetilde{CW}$ and $k \in [-\widetilde{CW} - 2^{min(BE(t), aMaxBE)} + 1, -\widetilde{CW}]$. More elaboration will be offered when the corresponding equations are introduced in the following derivation.

While the MAC protocol data unit (MPDU) size supported by IEEE 802.15.4 ranges from 0 bytes to 127 bytes, for Figures 3, 4 and 5 we select an arbitrary MPDU size of 79 bytes to demonstrate how the Markov model can be constructed. Including the acknowledgment and the proper interframe spacing (IFS) period, a successful transmission of one physical layer protocol data unit (PPDU) with the aforementioned MPDU size translates to a channel time of 12 slots. Similarly, the

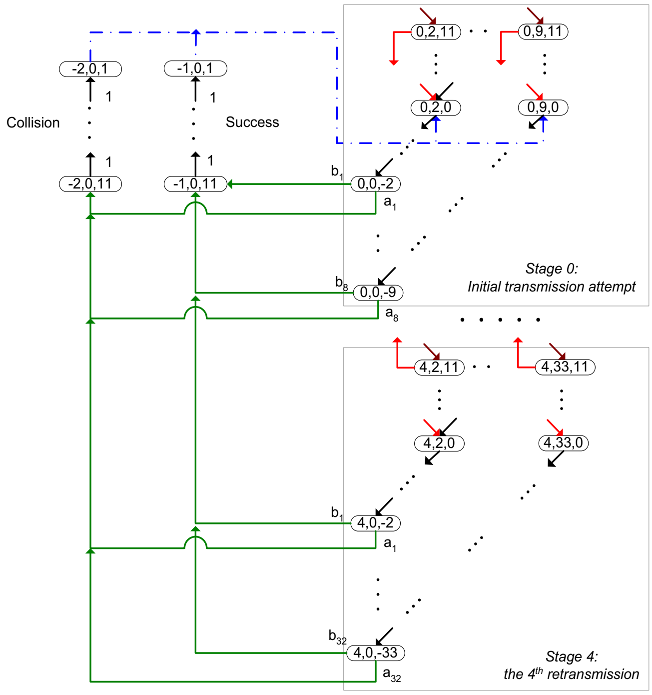

Fig. 3: Markov chain for IEEE 802.15.4.

frame transmission time plus the timeout for a collision also occupies approximately 12 slots. If ET^+_{max} and ET^-_{max} denote the maximum positive and negative value that $ET(t)$ can assume, respectively, ET^+_{max} equals 12 in the example Markov model. Due to the saturation condition, the wireless channel will not be idle for over $(\widetilde{CW} + 2^{min(BE(t), aMaxBE)} - 1)$ (i.e., $-ET^-_{max}$) slots, which bounds $ET(t)$ on the negative-value side. Nevertheless, it is important to note that an MPDU size of 79 bytes is chosen here for illustrative purposes only. The Markov chain can be defined, and the corresponding equation derived for any MPDU length that is permissible in IEEE 802.15.4.

Other key MAC parameters used in the example, which assume the default values suggested by the standard, are listed in Table I.

TABLE I: Backoff-related MAC parameters

$macMinBE$	$aMaxBE$	$\widetilde{CW}$	$macMaxCSMABackoffs$
3	5	2	4

To facilitate the following explanation, we use $s_{i,j,k}(t)$ to represent the state (i, j, k) at time t. Let $\pi_{i,j,k}$ be the steady state probability of that state.

$$\pi_{i,j,k} = \lim_{t \to \infty} Prob\{NB(t) = i, RC(t) = j, ET(t) = k\}$$

$P\{s_{i,j,k}|s_{i',j',k'}\}$ denotes the transition probability from state $s_{i',j',k'}(t)$ to state $s_{i,j,k}(t+1)$, whose values are expressed in Equation 1 below.

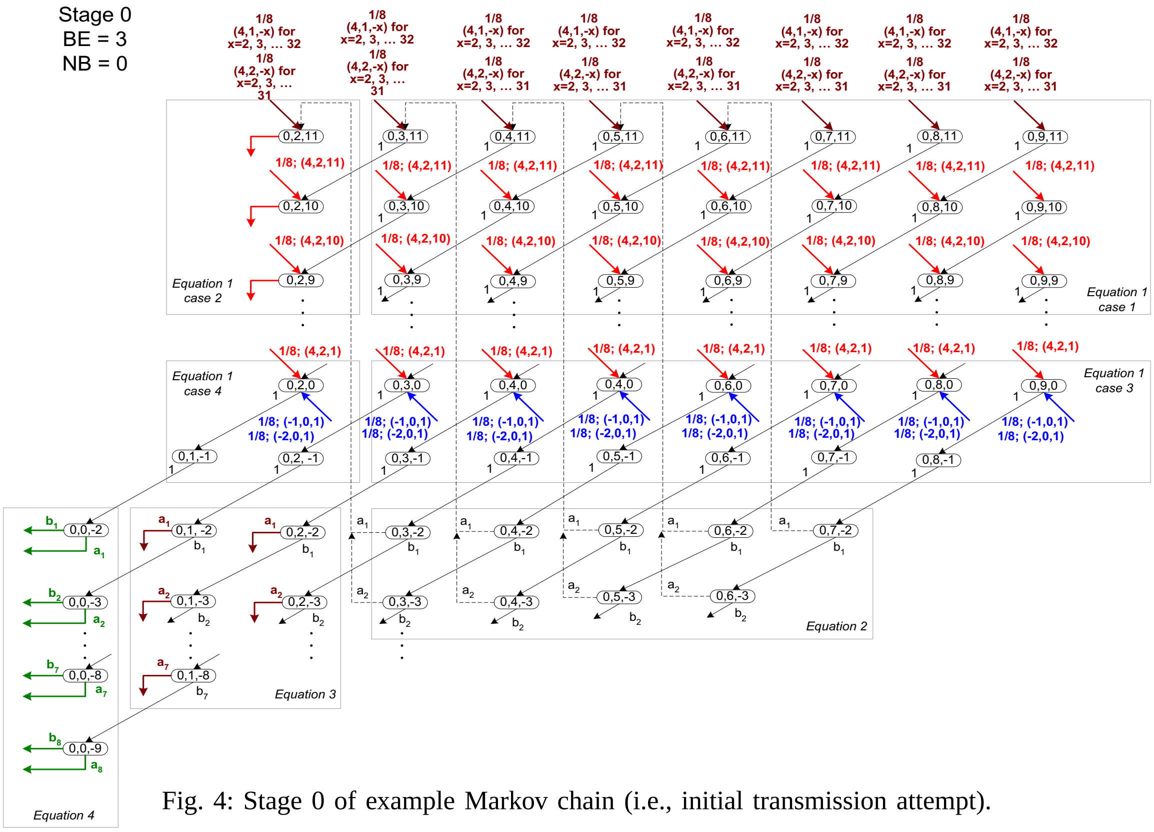

Fig. 4: Stage 0 of example Markov chain (i.e., initial transmission attempt).

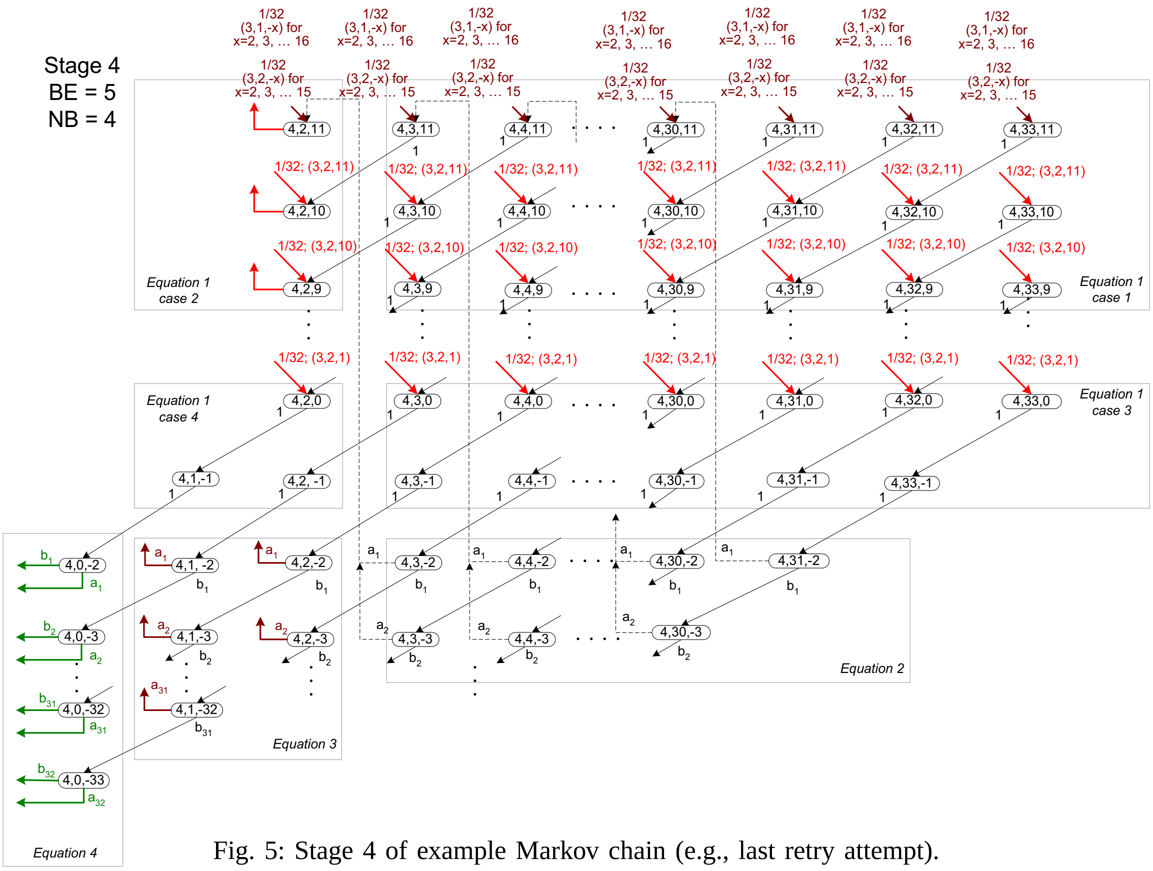

Fig. 5: Stage 4 of example Markov chain (e.g., last retry attempt).

$$\begin{cases} P\{s_{i,j-1,k-1}|s_{i,j,k}\} = 1 \\ \quad k \in [1, ET^+_{max}] \\ \quad j \in [\widetilde{CW}+1, \widetilde{CW}+2^{min(BE(t),aMaxBE)}-1] \\ P\{s_{\hat{i},m,k-1}|s_{i,\widetilde{CW},k}\} = 1/2^{\widetilde{BE(t)}} \\ \quad k \in [1, ET^+_{max}],\ m \in [\widetilde{CW}, \widetilde{CW}+2^{\widetilde{BE(t)}}-1] \\ P\{s_{i,j-1,k-1}|s_{i,j,k}\} = 1 \\ \quad k \in [-\widetilde{CW}+1, 0] \\ \quad j \in [\widetilde{CW}+1, \widetilde{CW}+k+2^{min(BE(t),aMaxBE)}-1] \\ P\{s_{i,j-1,k-1}|s_{i,j,k}\} = 1 \\ \quad k \in [-\widetilde{CW}+1, 0],\ j \in [\widetilde{CW}+k, \widetilde{CW}] \end{cases} \tag{1}$$

The first and third cases in Equation 1 correspond to the scenarios when the node is performing random backoff. For the second case, the node completes random backoff, and senses the channel busy. If the $NB(t)$ is less than $macMaxCSMABackoffs$, the node for sure has to backoff. Otherwise, the packet will be dropped and a new HOL packet begins its own random backoff. Accordingly, the auxiliary variables $\hat{i}$ and $\widetilde{BE(t)}$ used in the second case should be equal to *0* and $macMinBE$ respectively, when $i = macMaxCSMABackoffs$, and $i+1$ and $min(BE(t)+1, aMaxBE)$, otherwise. An example of this scenario is the transition from state $[4,2,1]$ to one of the states $[0,j,0]$ with probability $1/2^{macMinBE}$. In this scenario, the node starts carrier sensing after the channel is released by the previous transmission, and senses the medium idle with probability 1, since all other nodes in this slotted system at this moment are either sensing the carrier or yet to complete their ongoing random backoff.

When $k \in [-2^{min(BE(t),aMaxBE)}+2, -\widetilde{CW}]$ and $j \in [\widetilde{CW}+1, \widetilde{CW}+k+2^{min(BE(t),aMaxBE)}-1]$, the node always continues its random backoff, as shown in Equation 2.

$$\begin{cases} P\{s_{i,j-1,k-1}|s_{i,j,k}\} = b_{-k+1-\widetilde{CW}} \\ P\{s_{i,j-1,ET^+_{max}}|s_{i,j,k}\} = a_{-k+1-\widetilde{CW}} \end{cases} \tag{2}$$

Equation 3 describes the case when k and j fall into the intervals $[-\widetilde{CW}-2^{min(BE(t),aMaxBE)}+2, -\widetilde{CW}]$ and $[1, min(\widetilde{CW}, \widetilde{CW}+k+2^{min(BE(t),aMaxBE)}-1]$, during which carrier sensing is attempted. The variable i and auxiliary variables $\hat{i}$ and $\widetilde{BE(t)}$ in the second part of Equation 3 have identical meaning to those used in Equation 1.

$$\begin{cases} P\{s_{i,j-1,k-1}|s_{i,j,k}\} = b_{-k+1-\widetilde{CW}} \\ P\{s_{\hat{i},m,k-1}|s_{i,j,k}\} = a_{-k+1-\widetilde{CW}}/2^{\widetilde{BE(t)}} \\ \qquad m \in [\widetilde{CW}, \widetilde{CW}+2^{\widetilde{BE(t)}}-1] \end{cases} \tag{3}$$

In both Equations 2 and 3, based upon whether the channel is considered busy or not, the third state variable $ET(t+1)$ for the destination of the transition differs, and so does the associated transition probability.

If $j = 0$ and $k \in [-\widetilde{CW}-2^{min(BE(t),aMaxBE)}+1, -\widetilde{CW}]$, the node can transmit the queued HOL packet, and either a successful delivery or a collision will result, which correspond to the first and second cases of Equation 4, respectively.

$$\begin{cases} P\{s_{-1,0,ET^+_{max}}|s_{i,0,k}\} = b_{-k+1-\widetilde{CW}} \\ P\{s_{-2,0,ET^+_{max}}|s_{i,0,k}\} = a_{-k+1-\widetilde{CW}} \end{cases} \tag{4}$$

The transition probability within each transmission is always 1, which is shown in the first two cases of Equation 5. Upon the completion of a transmission, irrespective of whether it is successful or not, a transition always leads back to stage 0, which is reflected in the last case of Equation 5.

$$\begin{cases} P\{s_{-1,0,k-1}|s_{-1,0,k}\} = 1 & k \in [2, ET^+_{max}] \\ P\{s_{-2,0,k-1}|s_{-2,0,k}\} = 1 & k \in [2, ET^+_{max}] \\ P\{s_{0,j,0}|s_{i,0,1}\} = 1/2^{macMinBE} & i \in [-2,-1] \\ & j \in [\widetilde{CW}, \widetilde{CW}+2^{macMinBE}-1] \end{cases} \tag{5}$$

To relate a_m and b_m with steady state probabilities $\pi_{i,j,k}$, we introduce another set of auxiliary variables τ_m as

$$\tau_m = P\{\text{The node starts to transmit}|ET(t) = -m-\widetilde{CW}+1\}$$

For the sake of simplicity, we further assume that τ_m only relies on state variable $RC(t)$ and ignore its dependency on the exact backoff stage $NB(t)$. Note that this assumption has been widely employed in previous Markovian analysis [12]. τ_m then can be written as:

$$\tau_m = \frac{\sum_{i=v}^{maxNB} \pi_{i,0,-m-\widetilde{CW}+1}}{\sum_{i=v}^{maxNB}[\sum_{j=0}^{W_i-m} \pi_{i,j,-m-\widetilde{CW}+1}]} \tag{6}$$

To shorten the expression, W_i and $maxNB$ are used in Equation 6 to denote $2^{min(macMinBE+i,aMaxBE)}$ and $macMaxCSMABackoff$, respectively. Furthermore, the range of m is bounded by $[1, 2^{aMaxBE}]$, and the relation between v and m meets the following condition

$$\begin{cases} v = 0, & when\ m \in [1,8] \\ v = 1, & when\ m \in [9,16] \\ v = 2, & when\ m \in [17,32] \end{cases} \tag{7}$$

For a WPAN with N nodes, a_m and b_m can be further written as:

$$\begin{cases} b_m = (1-\tau_m)^{N-1} & m \in [1,\ 2^{aMaxBE}] \\ a_m = (1-b_m) & m \in [1,\ 2^{aMaxBE}] \end{cases} \tag{8}$$

Since all the transition probabilities have been expressed as functions of $\pi_{i,j,k}$, the Markov chain can be numerically solved, using an iterative approach outlined as follows.

Assume the Markov chain contains a total of M states. Number all the states in an increasing order, namely from 1 to M. Let $\vec{\pi} = [\pi_1, \pi_2, ...\pi_M]$ be the steady state distribution, and $\vec{\pi}_0$ represent an arbitrary initial state vector. ***P*** denotes the transition probability matrix of the Markov chain.

For an ergodic irreducible Markov chain, the following limit exists, independent of the value of initial vector $\vec{\pi}_0$.

$$\lim_{L\to\infty} \vec{\pi}_0 \times \underbrace{\boldsymbol{P} \times \boldsymbol{P} \times \ldots \boldsymbol{P}}_{L} = \vec{\pi} \tag{9}$$

To solve the Markov chain, therefore, we first create $\vec{\pi}_0$ by assigning the entry state of the Markov chain $[0, j, 0]$ with an equal probability of $\frac{1}{2^{macMinBE}}$ and setting all other initial state probabilities to 0. Then, $\vec{\pi}_0$ can be plugged into Equation 6 to calculate τ, which in turn is used to compute the state transition probability $\boldsymbol{P}$ by following Equation 8. Multiplying $\vec{\pi}_0$ with $\boldsymbol{P}$ yields a new state distribution vector $\vec{\pi}_1$, which is used to update the state transition matrix $\boldsymbol{P}$. The new $\boldsymbol{P}$ is again multiplied with $\vec{\pi}_1$ to obtain yet another new state distribution vector $\vec{\pi}_2$. Following this iterative approach, a convergence to the steady state distribution $\vec{\pi}$ can be finally achieved.

IV. THROUGHPUT ANALYSIS

Based upon the solution of the Markov model, the saturation throughput of an IEEE 802.15.4 network with N nodes can be obtained. Use P_s to denote the probability that the wireless channel sees the beginning of a successful delivery.

$$P_s = \sum_{m=1}^{2^{aMaxBE}} P\{ET = -m - \widetilde{CW} + 1\} \cdot N\tau_m(1-\tau_m)^{N-1}. \tag{10}$$

The $P\{ET = -m - \widetilde{CW} + 1\}$ in Equation 10 represents the probability that a node stays in the states whose third variable equals $-m - \widetilde{CW} + 1$. For $m \in [1, 2^{aMaxBE}]$, this probability can be further expanded as:

$$P\{ET = -m - \widetilde{CW} + 1\} = \sum_{i=v}^{maxNB} [\sum_{j=0}^{W_i - m} \pi_{i,j,-m-\widetilde{CW}+1}], \tag{11}$$

where $maxNB$ and W_i were initially introduced in Equation 6, while v and m satisfy the constraint specified in Equation 7.

Define *throughput* S as the fraction of time slots used by the network to successfully deliver the packet payload. If the transmission of payload bits consumes $T_{payload}$ slots, S then can be expressed as:

$$S = P_s \times T_{payload} \tag{12}$$

Finally, substituting Equation 10 and 11 into Equation 12, the saturation throughput of an IEEE 802.15.4 network can be easily computed.

V. PERFORMANCE EVALUATION AND IMPROVEMENT

To validate the analytical model, we have developed a custom event-driven discrete time simulator for IEEE 802.15.4, using the C programming language. The PHY and MAC layer parameters used in the simulation are listed in Tables I and II.

The network throughput obtained by analysis and simulation for different parameter combinations are reported in Figure 6. Since results from both analysis and simulation almost overlap each other in all the cases, the validity and accuracy of proposed analysis are verified.

TABLE II: Key parameters used in simulation.

Synchronization Header (SHR)	5 octets
PHY Header (PHR)	1 octet
MAC Header (MHR)	7 octets
FCS	2 octets
ACK + PHR + SHR	11 octets
aUnitBackoffPeriod	20 PHY symbols
aTurnaroundTime	12 PHY symbols
Data Rate	250kbps
macBattLifeExt	FALSE
Propagation delay	1μs

The impact of the key MAC parameters on the throughput performance are clearly revealed in Figure 6. In Figure 6(a), the two cases share the same *macMinBE/aMaxBE* tuple, but have different *macMaxCSMABackoffs* values. Meanwhile, Figure 6(b) illustrates the scenario where two systems have the same $macMaxCSMABackoffs$, yet maintain different *macMinBE/aMaxBE*. A comparison of the two figures clearly suggests that *macMinBE/aMaxBE* tuple has slightly more direct influence on system throughput than *macMaxCSMABackoffs* does. Moreover, both Figure 6(b) and 6(c) indicate that larger value of $macMinBE$ and/or $aMaxBE$ usually leads to higher throughput.

Another interesting phenomena that can be observed is that the system throughput first increases along with the number of nodes in the network, when $macMinBE$ and $aMaxBE$ are reasonably large. After the number of nodes passes a certain threshold point, the throughput then starts to drop, since the effect of collision begins to dominate. This explains why some of the curves in Figure 6 do not monotonically decrease, with the number of nodes in the network.

In addition, we have evaluated the performance of IEEE 802.15.4 for various MPDU sizes, as shown in Figure 6(d). As expected, a bigger payload results in a higher throughput in the network. It is worthwhile to note that the maximum size of MPDU that IEEE 802.15.4 can support is *127* bytes, which is equivalent to a MAC service data unit (MSDU) of *118* bytes, if a four-byte address field is used. Hence, a payload of *120* bytes in Figure 6(d) represents a frame size that cannot be accepted at the corresponding MAC service access point (SAP). Nevertheless, this result helps establish an upper bound for the saturation throughput that a network can never outperform with the given backoff parameters.

Designed for low-power devices, IEEE 802.15.4 attempts to lower power consumption by relying solely on a random backoff to avoid collision and thus reducing the number of carrier sensings, as presumably a random backoff drains much less power, if at all, as compared to carrier sensing. However, our study shows that a single carrier sensing, instead of sensing twice as prescribed in the standard, can achieve the same goal of collision avoidance, while consuming even less energy. More specifically, Figure 7(a) and 7(b) depict the throughput and channel access delay performance of a set of scenarios, where only the number of carrier sensings (i.e., the parameter $\widetilde{CW}$) that has to be performed before the transmission attempt is different. As can be readily noticed in Figure 7, the scenario in which only single carrier sensing is required can offer the highest throughput and lowest channel access delay. Hence, we suggest minimizing the number of carrier sensings down to one, which can further optimize the protocol performance, and reduce energy consumption without incurring any additional implementation complexity.

VI. CONCLUSIONS AND FUTURE WORK

The impact of modeling and analysis of wireless networks cannot be over-emphasized as it can establish bounds for the performance metrics of interest and provide valuable insight into protocol design and improvement.

In this paper, we propose an accurate analytical model for IEEE 802.15.4 MAC protocol, and offer an iterative solution to the Markov chain. In order to validate the model, both simulation and analysis results are presented and compared. In addition, key observations on throughput performance are made and a protocol improvement suggested.

We have so far focused on the case where $BatteryLifeExtension$ is turned off. But our Markov model can be easily adapted to deal with the scenario where $BatteryLifeExtension$ is switched on. The channel error probability can also be readily incorporated into the Markov chain.

As future work, we will use this model to compute the *service delay distribution* for 802.15.4. The Markov model presented here establishes an upper bound for the saturation throughput in an IEEE 802.15.4 system. Normally, the low rate WPAN is expected to operate in the light or medium loading regimes. To model these regimes, we also plan to extend the current analytical framework to model the IEEE 802.15.4 network under non-saturation traffic conditions. In addition, the insights obtained hereby can help us design variations of the IEEE 802.15.4 MAC protocol that can improve the energy efficiency, without compromising the throughput or delay performance.

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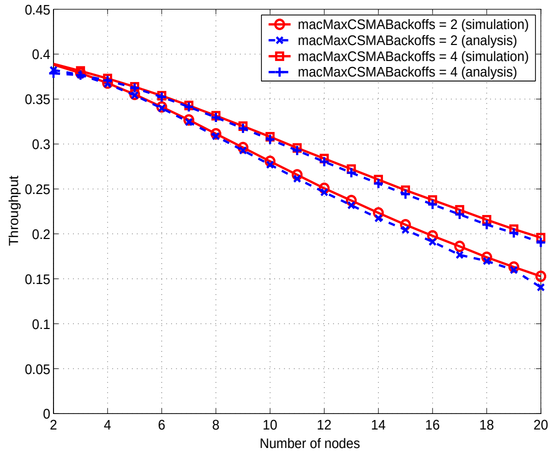
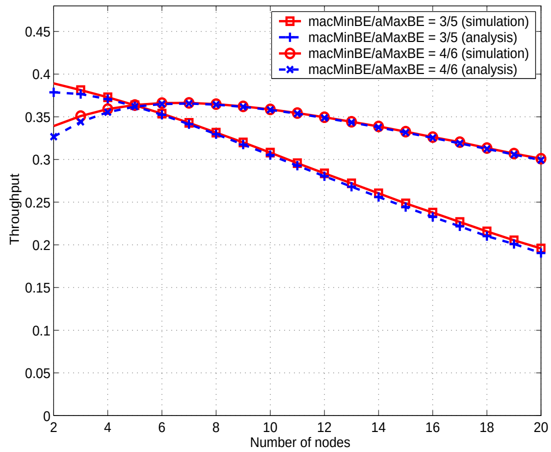
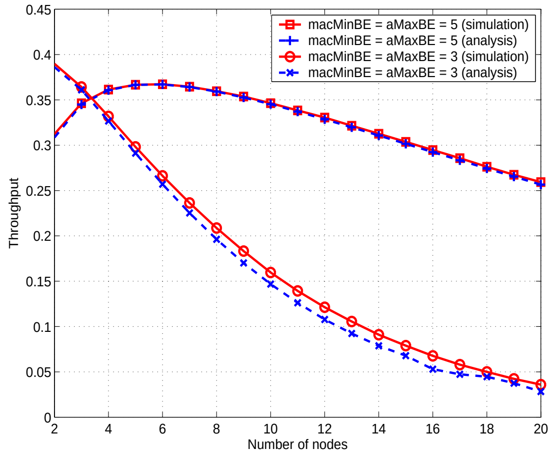


(a) macMin = 3, aMaxBE = 5



(b) macMaxCSMABackoffs = 4



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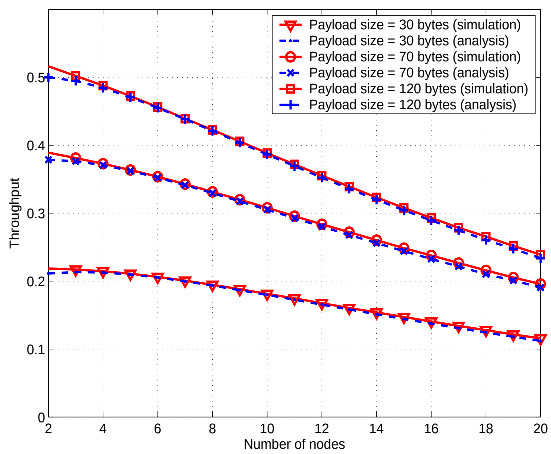
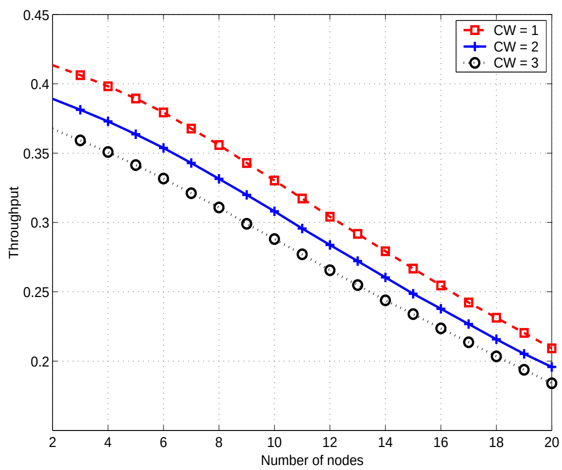
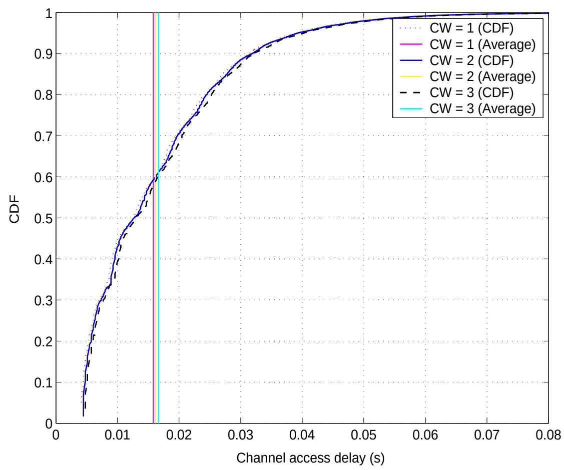


(d) macMaxCSMABackoffs = 4, macMinBE/aMaxBE=3/5

Fig. 6: Saturation throughput



(a) Throughput



(b) Channel access delay

Fig. 7: Impact of $\widetilde{CW}$ on system performance