Performance Analysis of Slotted Carrier Sense IEEE 802.15.4 Medium Access Layer

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***Abstract*— The IEEE 802.15.4 standard defines the medium access control (MAC) and physical layer for sensor networks. One of the MAC schemes proposed is slotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), and this paper analyzes whether this scheme meets the design constraints of low-power and low-cost sensor networks. The paper provides a detailed analytical evaluation of its performance in a star topology network for both saturated and unsaturated periodic traffic.The form of the analysis is similar to that of Bianchi for IEEE 802.11 DCF only in the use of a per user Markov model to capture the state of each user at each moment in time. The key assumptions to enable this important simplification and the coupling of the per user Markov models are however different, as a result of the very different designs of the 802.15.4 and 802.11 carrier sensing mechanisms. The performance predicted by the analytical model is very close to that obtained by simulation. Throughput and energy consumption analysis is then performed and design guidelines are derived.**

I. Introduction

Despite the huge variety of wireless sensor applications, all sensor networks are severely constrained in terms of power consumption. The task of a sensor network consists of measuring a variable through the sensors, eventually (pre-)processing this information, and if opportune, transmitting the data to a data sink. It has been shown in various design cases [1] that some of the most power hungry tasks of sensors are related to communication: not only transmission and receive power, but the power needed while waiting (idle) and scanning the channel can be significant.

To address these requirements, the IEEE 802.15.4 standard which specifies the network's medium access control (MAC) and physical (PHY) layer, has been developed [2], [3], [4]. In IEEE 802.15.4 sensor networks a central coordinator builds the network in its operating space. The standard supports three networking topologies relevant to sensor networking applications: star, peer-to-peer and cluster-tree. Since most sensor network appliations involve monitoring tasks and reporting towards a central sink, and since the focus of this paper is on the 802.15.4. medium access control analysis, we focus on a one-hop star network.

The channel access schemes are designed to save energy and allow nodes to switch to low-power states to avoid expensive modes such as *transmission*, *reception* and *channel listening*. 802.15.4 compliant hardware has been designed with very lower power *idle* and *sleep* modes (Table I) to take advantage of those mechanisms optimally. Beacon-enabled networks use a slotted carrier sense multiple access mechanism with collision avoidance (CSMA/CA), and the slot boundaries of each device are aligned with the slot boundaries of the coordinator. To save energy, nodes do not have to listen to the channel continuously. While contending for the channel, nodes delay their carrier sensing by a random backoff delay. Only after that random delay, the contending node wakes-up to listen to the channel during maximally two backoff slots. As a result, the power consumption during channel listening is minimized. To receive data, pending data reception is announced through the beacon, and the data is sent by the central coordinator only after receiving the data request message that informs the coordinator that the device will be listening for the data. Finally, in the beacon-enabled mode, periods can be announced in the beacon during which the network will be asleep to save even more energy. In this paper, we will analytically verify the impact of this new slotted CSMA/CA mechanism on both throughput and energy consumption. We will mainly focus on the uplink scenario which is most relevant for sensor networks.

TABLE I

The different parameters used for the model.

Packets:	$L_{\text{Header}} = 2slots$	$A = \frac{80bit}{0.32\mu s} = \frac{80bit}{slot}$
	$L_{\text{Data}} = 120Bytes$	$L = L_{\text{Header}} + \frac{L_{\text{Data}}}{A}$
Variable	$NB = 5$	**range:** $[0..5]$
Parameters:	$aMinBE = 3$	**range:** $[0..3]$
Parameters:	$aMAxBE = 5$	$CW = 2$
Power:	*Rx* = $40mW$	*CCA*=$40mW$
	Tx= $30mW$	*Idle* =$0.8mW$
	Sleep = $0.16\mu W$	

The performance of the IEEE 802.15.4 protocol has been evaluated by simulation for small and low load networks in [5] and for dense networks in [6]. In contrast, this paper provides an analytical Markov model that predicts the performance and detailed behavior of the 802.15.4 slotted CSMA/CA mechanism. This is then verified for accuracy by detailed comparison to simulation. The model incorporates details of the exponential delay lines and double Clear Channel Assessment (CCA). The form of the analysis is similar to that of Bianchi for IEEE 802.11 DCF [10] only in the use of a per user Markov model to capture the state of each user at each moment in time. The assumptions to enable this important simplification and the coupling of the per user models are however different, as a result of the very different design of the 802.11 carrier sensing mechanism where nodes monitor the channel continously and are hence continously

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aware of the channel state. This small difference results in a key difference in the main approximation assumptions: Each device's carrier sensing probability, rather than its packet sending probability, is independent. Also, unlike in 802.11, the slot duration is fixed since the channel is not constantly monitored by the stations and only a fixed slot duration model keeps the system synchronized. Finally, the two-slot clear channel assessment leads to memory in the coupling of the per user individual Markov chains. The analytical model for IEEE 802.15.4 developed in [7], [8] fails to match the simulation results, since they used the same Markov formulation and assumptions as Bianchi in [10] for 802.11.

This problem has been reported in [9] as well, and a better model has been proposed there. However, after detailed analysis this model does not mimic the 802.15.4 behavior sufficiently either, since they do not correctly couple the per user Markov chains through the two-slot channel sensing. This will be explained in more detail in this paper in Section III.

We consider two traffic scenarios which are particularly relevant for sensor networks. First, we assume a large sensor network that has been deployed to monitor events. Upon the detection of an event, all sensors have data to send to a central data gathering device. This traffic condition is well modeled by a large number of nodes where each node has a packet to send. This is the saturation condition. Secondly, sensor networks are typically deployed for periodic monitoring purposes. Measurements should be transmitted at regular time intervals, but the measurement update period varies depending on the application instance.

In the remainder, section II briefly describes the slotted CSMA/CA mechanism in IEEE 802.15.4, which is analyzed in Section III for uplink traffic under saturation and unsaturated periodic traffic. Section IV validates the accuracy of the model by comparing the analytical predictions and simulation results. Section V gives energy and throughput results and gives some design guidelines that can be derived easily with the proposed model. Section VI concludes the paper.

II. IEEE 802.15.4 SLOTTED CSMA/CA MECHANISM

We briefly explain the 802.15.4. medium access control mechanism. The network operation consists of a contention access period (CAP) and a contention free period (CFP). A device that wishes to communicate during the CAP competes with other devices using a slotted CSMA/CA mechanism while the CFP contains guaranteed time slots (GTSs). In the slotted CSMA/CA channel access mechanism, the backoff slot boundaries of every device are aligned with the slots of the coordinator. Each time a device wishes to transmit data frames during the CAP, before accessing the channel, a random number of backoff slots should be waited. During this time, the device is idle but not scanning the channel to save energy. After the random delay, a two slot clear channel assessment is carried out.

The exact mechanism that has to be followed before accessing the channel is depicted in Fig. 1 and it's variables are explained below. Each device in the network has three

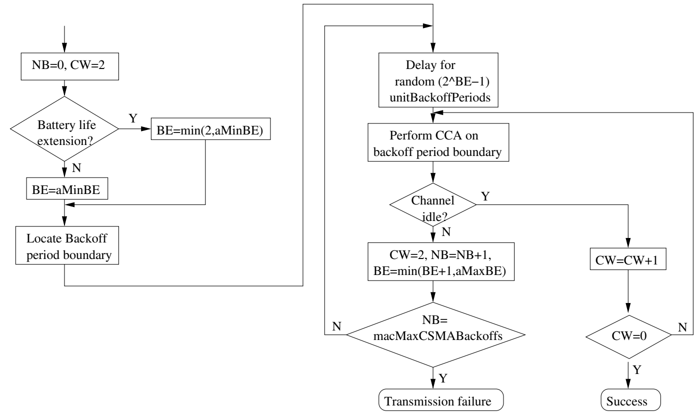

Fig. 1. Backoff mechanism for 802.15.4 CSMA

variables: NB, CW and BE. NB is the number of times the CSMA/CA algorithm was required to delay while attempting the current transmission. It is initialized to 0 before every new transmission. CW is the contention window length, which defines the number of slot periods that need to be clear of activity before the transmission can start. It is initialized to 2 before each transmission attempt and reset to 2 each time the channel is assessed to be busy. BE is the backoff exponent, which is related to how many slot periods a device must wait before attempting to assess the channel. The initial value differs when `Battery Extension` is enabled, since in that case the number of slots to wait before sensing the channel is decreased to minimize energy spent while waiting.

The slotted CSMA/CA mechanism works as follows. NB, CW and BE are initialized and the boundary of the next slot period is located (step1). The MAC layer delays for a random number of complete slot periods in the range 0 to $2^{BE}-1$ (step 2) and then requests PHY to perform a CCA (clear channel assessment) (step 3). The MAC sublayer then proceeds if the remaining CSMA/CA algorithm steps—frame transmission—can be completed before the end of the CAP. Otherwise, it must wait until the start of the CAP in the next superframe and then repeat the evaluation.

If the channel is assessed to be busy (step 4), the MAC sublayer increments both NB and BE by one, ensuring that BE is not more than *aMaxBE*, and CW is reset to 2. If the value of NB is less than or equal to *macMaxCSMABackoffs*, the CSMA/CA must return to step 2, else the CSMA/CA must terminate with a Channel-Access-Failure status. The parameters used are listed in Table I.

If the channel is assessed to be idle (step 5), the MAC sublayer must ensure that the contention window is expired before starting transmission. For this, the MAC sublayer first decrements CW by one. If CW is not 0, it must go to step 3, else start transmission in the next slot period.

III. FORMULATION

The core contribution of this paper is the analytical modeling of the slotted CSMA/CA mechanism of the IEEE 802.15.4 standard. We limit the analysis to unacknowledged uplink data transmission for brevity. Next, we will extend the formulation for unsaturated traffic conditions.

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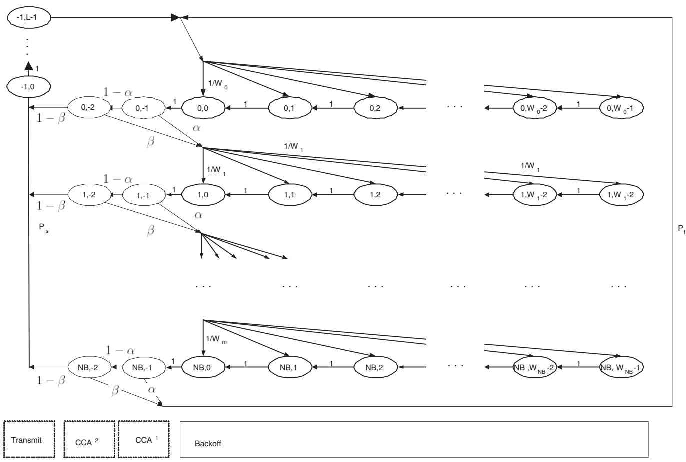

Fig. 2. Markov Model for IEEE 802.15.4

A. Uplink saturation

We assume a network of a fixed number N of devices, and each device always has a packet available for transmission. The analysis is in two steps, and the goal is to find a set of equations that uniquely define the network operating point. We first study the behavior of a single device using a Markov model (Fig.2). From this model, we obtain the stationary probability ϕ that the device attempts it's carrier channel assessment (CCA) for the first time within a slot. (ϕ is the counterpart of the probability τ that the device transmits a packet in a virtual slot in the analysis of 802.11 in [10].) For 802.11 in saturated traffic conditions, a device is always listening to the channel when not transmitting: $\phi = 1 - \tau$. In 802.15.4, this ϕ is a function of the exponential delay line as explained in Section II. Secondly, we couple the per user Markov chains, to obtain an additional set of equations to be able to solve the system. This coupling is very different than for 802.11. Indeed, in 802.11 networks, users constantly monitor the channel and are hence aware of the medium state. For 802.15.4, this is not the case. It will be shown later that two additional equations are required to determine the system.

We first develop the Markov model to determine ϕ, see Fig. 2. Let $c(t)$ be the stochastic process representing the delay line and transmission duration counters of the device. The integer time t corresponds to the beginning of the slot times. In contrast to the model in [10], t corresponds directly to system time. After the delay counter is decremented to zero, $c = 0$, the values $c = -1$ and $c = -2$ correspond to the first CCA (CCA^1) and second CCA (CCA^2), respectively.

Let α be the probability of assessing channel busy during CCA^1, and let β be the probability of assessing it busy during CCA^2, given that it was idle in CCA^1. Next, when entering the transmission state, L slots should be counted, where L denotes the packet transmission duration measured in slots[1].

Let $s(t)$ be the stochastic process representing the delay line stages ($s(t) \in \{0, \cdots, NB\}$), or the transmission stage ($s(t) = -1$) at time t. We assume that the probability to start sensing is constant and independent of all other devices and of the number of retransmissions suffered. With this assumption, $\{s(t), c(t)\}$ is the two-dimensional Markov chain of Fig. 2 with the following transition probabilities:

$$\begin{aligned} P\{i,k|i,k+1\} &= 1,\ k \geq 0 & (1)\\ P\{0,k|i,0\} &= (1-\alpha)(1-\beta)/W_0,\ i < NB & (2)\\ P\{i,k|i-1,0\} &= (\alpha + (1-\alpha)\beta)/W_i, & \\ & \qquad i \leq NB, k \leq W_i - 1 & (3)\\ P\{0,k|NB,0\} &= (1-\alpha)(1-\beta)/W_0 + P_f/W_0 & (4) \end{aligned}$$

The delay window W_i is initially $W_0 = 2^{aMinBE}$ and doubled any stage until $W_i = W_{max} = 2^{aMaxBE}, (aMaxBE - aMinBE) \leq i \leq NB$.

Equation 1 is the condition to decrement the delay line counter per slot. Equation 2 states that it is only possible to enter the first delay line from a stage that is not the last one ($i < NB$) after sensing the channel idle two consecutive times and hence transmitting a packet. Equation 3 gives the probability that there is a failure on both channel assessments or sensing slots (CCA) and the station selects a state in the next delay level. Equation 4 gives the probability of starting a new transmission attempt when leaving the last delay line, following a successful or failed packet transmission attempt. Note that the number of transmission attempts is limited and either ends with a packet transmission or failure P_f.

Denote the Markov chain's steady-state probabilities by $b_{i,k} = P\{(s(t), c(t)) = (i,k)\}$, for $i \in \{-1, NB\}$ and $k \in \{-2, \max(L-1, W_i - 1)\}$. Using Equation 3 we get

$$b_{i-1,0}(\alpha + (1-\alpha)\beta) = b_{i,0}\,, 0 < i \leq NB, \qquad (5)$$

which leads to

$$b_{i,0} = [(\alpha + (1-\alpha)\beta)]^i b_{0,0}\,, 0 < i \leq NB. \qquad (6)$$

From Equations 1- 4 we obtain

$$\begin{aligned} b_{i,k} &= \frac{W_i - k}{W_i}\{(1-\alpha)(1-\beta)\sum_{j=0}^{NB} b_{j,0} + P_f\}, i = 0; \\ b_{i,k} &= \frac{W_i - k}{W_i} b_{i,0}, i > 0. & (7) \end{aligned}$$

Since the probabilities must sum to 1,

$$\begin{aligned} 1 &= \sum_{i=0}^{NB}\sum_{k=0}^{W_i-1} b_{i,k} + \sum_{i=0}^{NB} b_{i,-1} + \sum_{i=0}^{NB} b_{i,-2} + \sum_{i=0}^{L-1} b_{-1,i} \\ &= \sum_{i=0}^{NB} b_{i,0}\left[\frac{W_i + 3}{2} + (1-\alpha)(1 + (1-\beta)L)\right]. & (8) \end{aligned}$$

Substituting the expression for W_i this leads to the expression for $b_{0,0}$ in Eq. 9, where $d = aMaxBE - aMinBE$. The transmission failure probability P_f is

$$P_f = b_{NB,0}(\alpha - \beta\alpha + \beta), \qquad (10)$$

and the probability that a node starts to transmit is (this corresponds to the transmission probability τ in Bianchi's model) $\tau = P_s = \phi(1-\alpha)(1-\beta)$, in which

[1]We assume that this duration is an integer number of slots in the remainder.

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$$1 = \frac{b_{0,0}}{2}\{[3+2(1-\alpha)(1+L-\beta L)] \times [\frac{1-(\alpha+\beta-\alpha\beta)^{NB+1}}{1-(\alpha+\beta-\alpha\beta)}] + 2^d W_0[\frac{(\alpha+\beta-\alpha\beta)^{d+1}-(\alpha+\beta-\alpha\beta)^{NB}}{1-(\alpha+\beta-\alpha\beta)}] + W_0[\frac{1-[2(\alpha+\beta-\alpha\beta)]^{d+1}}{1-2(\alpha+\beta-\alpha\beta)}]\}. \quad (9)$$

$$\phi = \phi_1 = \sum_{i=0}^{m} b_{i,0}. \quad (11)$$

We have now derived one expression for ϕ from the per user Markov models. By determining the interactions between users on the medium, we will now derive expressions for the remaining unknowns α and β.

Let $M(s) = -1$ be the event that there is at least one transmission in the medium by a node $S^i(s) = -1$ the event that node i is transmitting. Then the probability α that another node sensing the channel finds it to be occupied is

$$\begin{aligned} \alpha &= P(M(s)=-1) \\ &= \textstyle\sum_{n=0}^{N-2} \binom{N-1}{n+1} P(\bigcup_{k=1}^{n+1} S^{i_k}(s)=-1) \\ &= \textstyle\sum_{n=0}^{N-2} \binom{N-1}{n+1} P(S^{i_1}(s)=-1) \times \\ &\quad P(\bigcup_{k=2}^{n+1} S^{i_k}(s)=-1 | S^{i_1}(s)=-1). \end{aligned} \quad (12)$$

Let E_c denote the event that node i_1 is in state $(-1, c)$. The probability that node i_1 is transmitting is

$$\begin{aligned} P(S^{i_1}(s)=-1) &= \sum_{c=0}^{L-1} P(E_c) = LP(E_0) = LP_s \\ &= L\phi(1-\alpha)(1-\beta), \end{aligned} \quad (13)$$

which requires the node to sense (with probability ϕ) two slots before transmission and the following two slots to be empty (with probability $(1-\alpha)(1-\beta)$).

To express the conditional probability in terms of ϕ, the transmission pattern needs to be understood: If there are two or more transmissions in a particular slot, the transmissions must start at the same slot, because devices that transmit later would detect earlier transmissions and would not start transmitting. Starting transmission simultaneously moreover requires sensing at the same time. Thus the conditional probability is

$$P(\bigcup_{k=2}^{n+1} S^{i_k}(s)=-1 \mid S^{i_1}(s)=-1) = \phi^n(1-\phi)^{N-2-n},$$

which requires nodes $i_2, ..., i_{n+1}$ to sense and the remaining $N-2-n$ nodes not to sense in the sense slot of i_1. Thus

$$\alpha = L[1-(1-\phi)^{N-1}](1-\alpha)(1-\beta). \quad (14)$$

From this, we can derive a second expression for ϕ:

$$\phi_2 = [1-(1-\frac{\alpha}{L(1-\alpha)(1-\beta)})]^{\frac{1}{N-1}} \quad (15)$$

A third relation is needed to be able to solve the system and determine the operating point. For this purpose, we derive an expression for β. A packet transmission starts when the channel has been sensed idle two consecutive times. Although the probability to sense (busy) the first time is independent across users, the probability to sense busy the second attempt is not. Indeed, shared knowledge about the first slot being empty for all users strongly impacts the probabilities in the second slot. The same reasoning leads to the packet send probabilities to be correlated across users, i.e. after the shared knowledge of two empty slots. Although the authors in [9] correctly assess the correlated sending probability, they do not correctly address the effect for the second sensing probability. As a result, a detailed analysis of the sensing probabilities in their model does not match simulation results. To determine β it is hence required to take into account that the preceding slot must be idle for the medium. Since β is the probability that there is a transmission in the medium when the considered device does its second sense, given that the medium was idle during its first sense:

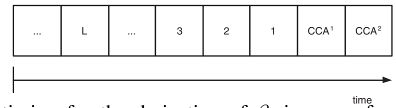

Fig. 3. Slot timing for the derivation of β, in case of an unacknowleged transmission.

$$\beta = Pr(M_{CCA^2}(s) = -1 | M_{CCA^1}(s) \geq 0) \quad (16)$$

where $M(s) \geq 0$ denotes the probability that no station is transmitting. The superscript denotes the local time of the node doing its second sense as shown in Fig. 3. The device will sense busy only if some other node in the medium was sensing its second time during our device's first sense and started a new transmission in slot CCA^2. This can only happen if this node started sensing in slot 1 ($M_1(c) = -1$) and the channel was then idle ($M_1(s) \geq 0$). That is

$$\begin{aligned} \beta &= P(M_1(s) \geq 0 \mid M_1(c) = -1, M_{CCA^1}(s) \geq 0) \\ &\quad \times P(M_1(c) = -1 \mid M_{CCA^1}(s) \geq 0) \\ &= P(M_1(s) \geq 0 \mid M_{CCA^1}(s) \geq 0) \times P(M_1(c) = -1) \end{aligned} \quad (17)$$

Here $P(M_1(s) \geq 0 \mid M_{CCA^1}(s) \geq 0)$ is the probability that a given idle slot is preceded by another idle slot. Also, the last simplification to $P(M_1(c) = -1)$ is possible since the probability to start sensing is independent of the medium status during that slot or the following slot. We can see that

$$\begin{aligned} &P(M_1(s) \geq 0 \mid M_{CCA^1}(s) \geq 0) \\ &= 1 - \tfrac{P(M_1(s)=-1 \cap M_{CCA^1}(s) \geq 0)}{Pr(M_{CCA^1}(s) \geq 0)}. \end{aligned} \quad (18)$$

This means that to compute the nominator of this probability we have to list all cases that result in an idle slot CCA^1 ($M_{CCA^1}(s) \geq 0$), and see which of those have a busy slot 1 before ($M_1(s) = -1$). Indeed, all cases that result in an idle slot CCA^1 are, obviously, the sum of the ones with a busy slot 1 and an idle slot 1:

$$\begin{aligned} &P(M_{CCA^1}(s) \geq 0) \\ &= P(M_1(s) = -1 \cap M_{CCA^1}(s) \geq 0) \\ &+ P(M_1(s) \geq 0 \cap M_{CCA^1}(s) \geq 0), \end{aligned} \quad (19)$$

From Fig. 3, these cases result in an idle CCA^1:

- **Case 1:** A busy slot 1 before the idle slot is counted in $P(M_1(s) = -1 \cap M_{CCA^1}(s) \geq 0)$. This is the case when there is a start of a transmission L slots before the slot CCA^1. In that case both CCA^1 and CCA^2 are guaranteed to be idle, which happens with probability $P(M_1(s) = -1 \cap M_{CCA^1}(s) \geq 0) = P_{\text{send}}$.
- **Case 2:** An idle slot 1 before slot CCA^1 is counted in $P(M_1(s) \geq 0 \cap M_{CCA^1}(s) \geq 0)$. If a node starts sensing during idle slot 1, given that the following slot CCA^1 is idle, we know for sure this node will start transmitting during slot CCA^2 and cause a *busy* event. This occurs in a slot $i, 1 \leq i < \infty$ when there is a start of a transmission L slots before slot i and no node senses in slots $2, \ldots, i$: $P(M_1(s) \geq 0 \cap M_{CCA^1}(s) \geq 0) = \sum_{i=1}^{\infty} P_{\text{send}}((1-\phi)^N)^{(i-1)}$.

The probability that a station starts transmitting P_{send} is:

$$\begin{aligned} P_{\text{send}} &= P(M(s,c) = (-1,1)) = \tfrac{\alpha}{L} \\ &= (1-(1-\phi)^N)(1-\alpha)(1-\beta). \end{aligned} \tag{20}$$

The probability that a node starts sensing during slot 1 is

$$P(M_1(c) = -1) = (1-(1-\phi)^{N-1}). \tag{21}$$

Then β is given by

$$\beta = \left[1 - \frac{P_{\text{send}}}{P_{\text{send}}(1 + \frac{1}{1-(1-\phi)^N})}\right](1-(1-\phi)^{N-1}) \tag{22}$$

which for large N can be simplified to obtain:

$$\phi_3 = 1 - (1 - \frac{\beta}{1-\beta})^{1/N} \tag{23}$$

The network operating point as determined by ϕ, α and β is determined by solving the three non-linear Equations 11, 14, 23. These three values are sufficient to determine the network throughput and energy consumption achieved during operation, as we will show in Section V. First, it is shown how unsaturated traffic scenarios that are relevant in the context of sensor networks can be modeled.

B. Extension to unsaturated traffic conditions

So far we have modeled saturated traffic conditions, in which case all nodes constantly have packets to send. This case can be used to model the performance in sensor networks in which sensors want to send data at the same moment, e.g. when an event is detected. In reality, however, this is not always the case since often sensor networks are designed to continuously monitor a variable and send the measurement to a central sink. We will focus on modeling the particular scneario in which packet transmission attempts are carried out periodically, irrespective of the success of that attempt. Indeed, since the traffic is unacknowledged, it is not possible to know the outcome of a transmission. Moreover, we will assume that when a packet transmission failure is reported due to consecutive busy sensing of the channel, the transmission will be delayed. This can be obtained by tuning the parameter X_1 in the following term that should be added to Eq. 9:

$$b_{0,0} \times X_1 \times [\frac{1-(\alpha+\beta-\alpha\beta)^{m+1}}{1-(\alpha+\beta-\alpha\beta)}] \tag{24}$$

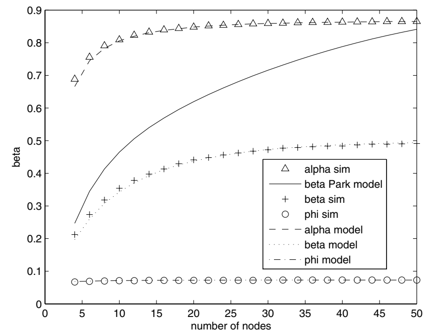

Fig. 4. The probabilities α, β and ϕ as predicted by the analytical model and simulation.

IV. Model Validation

To validate the proposed analytical model, a Monte-Carlo simulation of the 802.15.4 contention procedure is developed in Matlab. Since the 802.15.4 CSMA/CA scheme can be captured with a fixed duration backoff slot, it is possible to consider a new slot each simulation step. The system state during each slot is tracked using state vectors of dimension N. Three vectors represent the values of *NB*, *CW* and *BE*. A fourth vector *delay* reprensents both the state of the node (-1 if idle, 0 if transmitting and contention, > 0 in the delay link). When a node its in transmit state, the remaining transmission time in slots in maintained in the corresponding element of the fifth vector (*busyFor*). The number of transmissions, collisions, access failures and CCA are tracked for a simulation run of 10^8 slots. Based on that, the collision probability, failure probability and average number of CCA per channel access can be computed and compared to the prediction of the analytical model.

We evaluate the above derived expressions for ϕ, α and β. In Fig. 4 it can be seen that the value for ϕ as predicted by the model is very accurate. The difference between the proposed model and the model in [9] is illustrated by comparing the results for β. As explained above, the model in [9] fails to correctly model this β since it does not correctly capture the fact that only a successful CCA^1 can result in a second CCA^2. As a result, their expression for β and also the network equilibrium that depends on that expression is not exact. It is clear in Fig. 4 that the model proposed here matches the simulation results much more accurately and saturates for higher N. Finally, the third system parameter α is shown to be predicted very accurately by the proposed analytical model. We now instantiate the model to assess the throughput and energy of the 802.15.4 access mechanism.

V. Throughput and Energy Analysis

In this section we use the analytical model to study the energy and throughput behavior of both saturated and unsaturated 802.15.4 networks and derive some design guidelines. The network throughput for both saturated and unsaturated traffic conditions is given by the simple expression

$$S = ALN\phi(1-\phi)^{N-1}(1-\alpha)(1-\beta) = ALNP_{\text{success}}. \tag{25}$$

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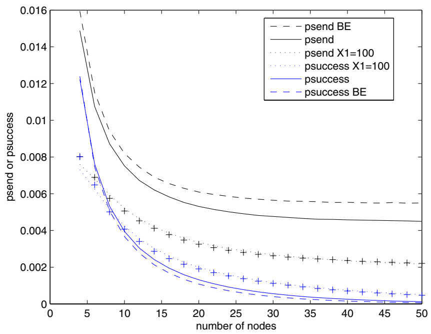

Fig. 5. Achieved throughput versus number of packets sent for saturation, saturation with `Battery Extension` and unsaturated traffic. For the periodic traffic, the model is shown to approximate the simulation results very closely.

where $A = \frac{80bit}{3.2\mu s}$ is a normalization constant to convert to bps. The probability that a single node sends a packet successfully is P_{success}. The throughput corresponds to the probability that a node in the network starts sensing alone, and has success during its channel assessments.

We now look how this net throughput is achieved. We compare the probability to start sending (P_{send}) , and the probability that a packet was sent successfully (P_{success}). It can be seen in Figure 5 that with `Battery Extension` more packets are sent, but less net throughput is achieved and a lot of energy and channel resources are wasted in collided transmissions. For sensor networks that are expected to generate a lot of traffic across the nodes simultaneously, BE should be as large as possible. When a delay of 100 slots or $32ms$ is introduced, the probability to start a transmission attempt is reduced significantly. However, a higher net throughput is achieved for high N in the unsaturated traffic case compared to the saturated case (Fig. 5).

Next, we look at the energy consumption of 802.15.4 networks. We compute the percentage of time the transceiver is in each of its five states Tx, Rx, CCA, $Idle$ or $sleep$ (Table I), and multiply this time percentage by the power consumption of that state. We assume the transceiver is in Tx mode when transmitting, in Rx mode when waiting (interframe spaces) or receiving, in CCA mode when performing CCA, in $idle$ mode in the exponential delay line, and in $sleep$ mode when not in the aforementioned cases.

In sensor networks, we are interested in the average power needed to deliver packets at a given rate. We plot the energy per bit versus net throughput per node for a range of MAC parameter settings such as BE and L (for BE see Table I). According to the 802.15.4 physical layer in the $2.4GHz$ band, a maximum bitrate of $250kbps$ is possible. It can be seen in Fig. 6 that the actual achieved bitrate is much lower in reality because of protocol overhead and collisions. As expected, larger packet sizes ($120B$ in this case) perform the best, both in terms of power consumption and achieved throughput. For a lower load the energy per useful bit steadily decreases (Fig. 6). For higher loads, the net throughput decreases because of increased collision. Lowering the initial BE results in a very small power consumption improvement for a given packet size.

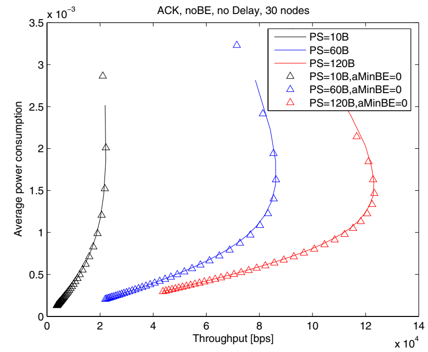

Fig. 6. Power consumption versus net throughput for different BE parameter settings.

Since the power consumption in the idle state is typically very low for 802.15.4 transceivers, the gains are very small. Further, we note that the average power consumption increase with rate is mainly because of the increased *Tx* power but also because of increased *CCA* power consumption. Efforts to decrease that *CCA* power consumption are hence very useful.

VI. Conclusion

In this paper, we have presented an analytical model for the medium access control layer in IEEE 802.15.4 standard. The validity of the analytical model is demonstrated by the fact that its predictions closely match the simulation results. We then use the analytical model to predict energy consumption and achieved throughput of saturated and unsaturated 802.15.4 networks, based on which some design guidelines can be derived. It is shown that for saturated networks, it is best to choose a larger exponential delay backoff. For unsaturated networks, smaller backoff values improve the energy consumption but these energy savings are very small.

References

[1] J.M. Rabaey et al, *PicoRadio supports ad hoc ultra low power wireless networking,* IEEE Computer, vol.33, pp. 42-48, 2000.

[2] LAN-MAN Standards Committee of the IEEE Computer Society, *Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)*, IEEE, 2003

[3] S. C. Ergen, *ZigBee/IEEE 802.15.4 Summary*, http://www.eecs.berkeley.edu/ csinem/academic/publications/zigbee.pdf

[4] J. Zheng and M. J. Lee, *Will IEEE 802.15.4 Make Ubiquitous Networking a Reality?: A Discussion on a Potential Low Power, Low Bit Rate Standard*, IEEE Communications Magazine, June 2004.

[5] G. Lu, B. Krishnamachari and C. S. Raghavendra, *Performance Evaluation of the IEEE 802.15.4 MAC for Low-Rate Low-Power Wireless Networks*, Workshop on Energy-Efficient Wireless Communications and Networks (EWCN '04), April 2004.

[6] B. Bougard, F. Catthoor, D. C. Daly, A. Chandrakasan and W. Dehaene, *Energy Efficiency of the IEEE 802.15.4 Standard in Dense Wireless Microsensor Networks: Modeling and Improvement Perspectives*, Proc. Design Automation and Test in Europe Conference and Exhibition, pp.196-201, March 2005.

[7] J. Misic, V. B. Misic and S. Shafi, *Performance of IEEE 802.15.4 Beacon-enabled PAN with Uplink Transmissions in Non-saturation Mode - Access Delay for Finite Buffers*, Proc. First International Conference on Broadband Networks, pp. 416-425, October 2004.

[8] J. Misic, S. Shafi and V. B. Misic, *The Impact of MAC Parameters on the Performance of 802.15.4 PAN,* Ad hoc Networks, vol. 3(5), pp. 509-528, September 2005.

[9] T.R. Park, T.H. Kim, J.Y. Choi, S. Choi, and W.H. Kwon, *Throughput and energy consumption analysis ofIEEE 802.15.4 slotted CSMA/CA,* Electronics Letters, September, 2005.

[10] G. Bianchi. *Performance Analysis of the IEEE 802.11 Distributed Coordination Function.* IEEE Journal on Selected Areas in Communications, vol.18, March 2000.

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