Performance Analysis of Slotted Carrier Sense IEEE 802.15.4 Acknowledged Uplink Transmissions

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***Abstract*—Advances in low-power and low-cost sensor networks have led to solutions mature enough for use in a broad range of applications, requiring various degrees of reliability. To facilitate this, a broad range of options are possible to tune reliability, throughput or energy cost in the IEEE 802.15.4 standard defining the medium access control (MAC) and physical layer for sensor networks. Knowing how to tune those knobs however requires detailed models of the protocol behavior under different conditions. In our earlier work, we have proposed a very accurate model for the slotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) access scheme of the IEEE 802.15.4 standard for the unacknowledged transmission mode. Because of the design of the 802.15.4 carrier sensing mechanism, modeling the performance of the network in case of acknowledged transmissions is not a trivial extension. In this paper, we hence derive such model and illustrate through simulations that it is extremely accurate. Next, using the model, guidelines are derived to optimize the energy or throughput performance of sensor networks using the IEEE 802.15.4 standard.**

I. Introduction

Wireless sensor networks are autonomous networks for monitoring purpose. Monitoring tasks vary however significantly in terms of delay and reliability requirements, e.g. monitoring the temperature in a building for data collection is less critical then monitoring the temperature for fire warning. To address these requirements, the IEEE 802.15.4 standard specifying a medium access control (MAC) and physical (PHY) layer, has been developed [1], [2]. Despite the huge variety of wireless sensor applications, all sensor networks are severely constrained in terms of power consumption. As a result, many of the design choices for 802.15.4 networks focus on reducing the energy consumption, while allowing larger delays or less reliability when that is acceptable. E.g., as illustrated in Fig. 1, the use of the acknowledgement for uplink transmissions is optional, which means that nodes can switch to the low-power sleep mode immediately after transmitting the packet. 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 as illustrated in Fig. 1.

In this paper, we propose a model that accurately captures the behavior of the network with and without acknowledged traffic and hence allows to reliably predict the performance and energy consumption of an 802.15.4 network. We focus on

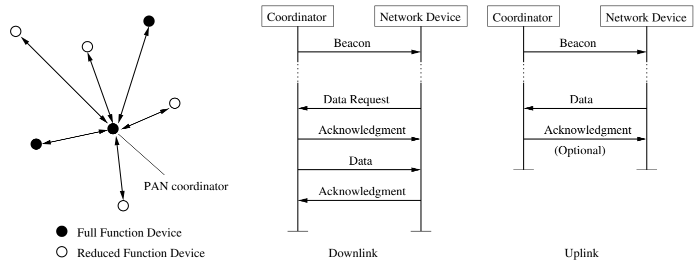

Fig. 1. Transmission schemes in a one-hop star 802.15.4 network. In the case of uplink transmission (monitoring scenario), the use of the acknowledgement is optional. In this paper, we model the network with and without acknowledgement to be able to address the performance of both possibilities.

the uplink scenario, since that is most relevant for monitoring in sensor networks. Also, we assume the network operates in the Beacon-enable slotted carrier sense multiple access mechanism with collision avoidance (CSMA/CA), which means that the slot boundaries of each device are aligned with the slot boundaries of the coordinator. This mode is indeed the most energy-efficient since it allows for nodes to sleep in between beacons. 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. However, due to this sleeping, nodes can potentialy wake up and sense the channel idle in between the data transmission and its acknowledgement. It is exactly the interplay between the idle slot in between data and acknowledgement and the two-slot sensing scheme that will make the performance modeling non-trivial.

The performance of the IEEE 802.15.4 protocol has been evaluated by simulation for small and low load networks in [3] and for dense networks in [4]. In contrast, in [5], we propose an analytical Markov model that predicts the performance and detailed behavior of the 802.15.4 slotted CSMA/CA mechanism with unacknowledged uplink traffic very accurately. The form of the analysis is similar to that of Bianchi for IEEE 802.11 DCF [6] 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 aware of the

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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 [6] 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 is particularly important in modeling the probability that the node sensed idle in between data and acknowledgement. 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 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. As proposed in [5], such conditions can be modeled by waiting a fixed number of slots before each new transmission attempt.

In the remainder, section II briefly describes the slotted CSMA/CA mechanism in IEEE 802.15.4, which is analyzed in Section III for acknowledged uplink 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). 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. 2 and its variables are explained below. Each device in the network has three 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, and if it exceeds $macMaxCSMABackoffs$, the packet will be discarded. CW is the contention window length, which defines the number of slots that need to be clear before the transmission can start. It is initialized to 2 each time a device starts sensing. BE is the backoff exponent, which is related to how many slot periods a device must wait before attempting to assess the channel. By specifying $aMacBE$, this maximum delay can be controlled. 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. Parameters used in the remainder of this paper are listed in Table I.

TABLE I
THE DIFFERENT PARAMETERS USED FOR THE MODEL.

Packets:	$L_{\text{Header}} = 2slots$	$A = \frac{80bit}{0.32\mu s} = \frac{80bit}{slot}$
	$L_{\text{Data}} = 120Bytes$	$L = L_{\text{Header}} + \frac{L_{\text{Data}}}{A}$
	L_{ACK} = 2 slots	$\lfloor t_{ACK} \rfloor = 1slot$
Parameters:	$aMAxBE = 5$	$CW = 2$
	$aMinBE = 3$	$NB = 5$
Power:	Rx = $40mW$	CCA=$40mW$
	Tx= $30mW$	$Idle$ =$0.8mW$

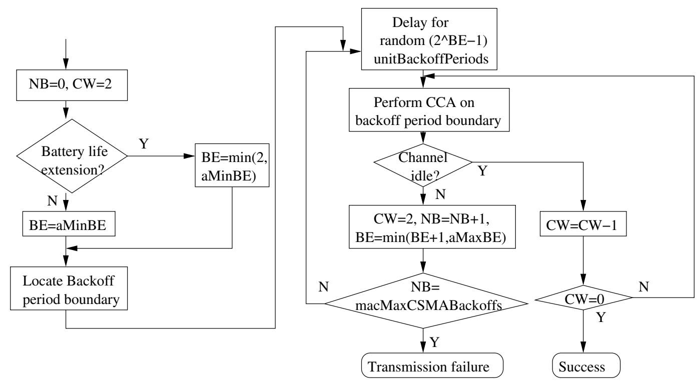


Fig. 2. Backoff mechanism for 802.15.4 CSMA

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 with uplink acknowledged traffic. We start from the notations and model introduced in [5] and extend the reasoning for the acknowledged case. We assume a network of a fixed number N of devices, and each device always has a packet available for transmission. Relaxing the saturation conditions for low throughput sensor networks is easily achieved based on the model for saturated traffic, as shown in [5]. 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.3). From this model, we obtain the stationary probability ϕ that the device attempts its Clear 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 [6].) Secondly, we couple the per

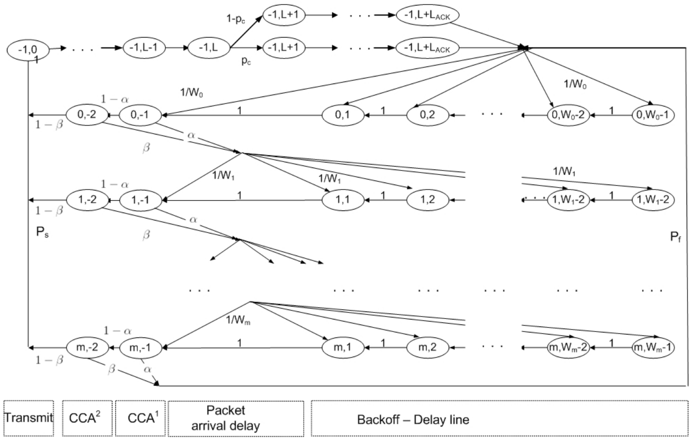


Fig. 3. Markov Model for IEEE 802.15.4

user Markov chains, to obtain an additional set of equations to be able to solve the system.

We first develop the Markov model to determine ϕ, see Fig. 3. 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 [6], 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]. Each packet of size L is followed by an idle period equal to t_{ACK} slot times, and an acknowledgement of size L_{ACK}. According to the 802.15.4 standard, the t_{ACK} should be less than or equal to $aTurnaroundTime + aUnitBackoffPeriod = 12 + 20 symbols$. As a result, this t_{ACK} can be larger than a backoff slot, and a station sensing the channel in between the data and its ACK can sense the channel to be idle. In fact, this is the main motivation for the two slot CCA. To take into account the effect of this idle time, we have to take the integer number of slots that fit into this time and can hence be sensed idle: $\lfloor t_{ACK} \rfloor = 1slot$. The acknowledgement for 802.15.4 is $11Bytes$ long, which is slightly more than a slot. We model the time as $\lceil L_{ACK} \rceil = 2slots$. Moreover, when the packet is lost with probability p_c (see Fig. 3), we assume we wait for the acknowledgement for the entire time.

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. 3 with the following transition probabilities:

$$P\{i,k|i,k+1\} = 1, \ k \geq 0 \tag{1}$$

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

$$P\{0,k|i,0\} = (1-\alpha)(1-\beta)/W_0, \ i < NB \tag{2}$$

$$P\{i,k|i-1,0\} = (\alpha + (1-\alpha)\beta)/W_i, \quad i \leq NB, k \leq W_i - 1 \tag{3}$$

$$P\{0,k|NB,0\} = (1-\alpha)(1-\beta)/W_0 + P_f/W_0 \tag{4}$$

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 $k \in \{-2, \max(L'-1, W_i - 1)\}$ where $L' = L + L_{ACK} + \lfloor t_{ACK} \rfloor$. Using Equation 3 we get

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

which leads to

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

From Equations 1- 4 we obtain

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

Since the probabilities must sum to 1,

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

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

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

The transmission failure probability P_f is

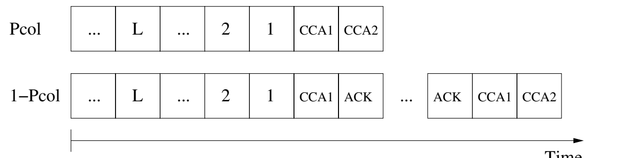


Fig. 4. Slot timing for the derivation of β, in case of an acknowleged transmission.

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

and the probability that a node starts to transmit is (this corresponds to the transmission probability τ in Bianchi's model):

$$\tau = P_s = \phi(1-\alpha)(1-\beta), \tag{11}$$

in which

$$\phi = \sum_{i=0}^{m} b_{i,0}. \tag{12}$$

We have now derived one relation between ϕ, α and β for the case of acknowledged traffic, 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. As shown in [5], the probability α to sense busy is the probability that there is a least one transmission in the medium by a node. This is the probability that a node starts sending in the network P_{send} times the average duration L^* of the channel occupation of a transmission, where

$$\begin{aligned} P_{\text{send}} &= (1-(1-\phi)^{N-1})(1-\alpha)(1-\beta), & (13)\\ L^* &= L + L_{ACK} \times (1 - P_{\text{netcol}}), & (14)\\ P_{\text{netcol}} &= 1 - \frac{P_{\text{success}}}{P_{\text{send}}} = 1 - \frac{N\phi(1-\phi)^{N-1}}{1-(1-\phi)^N}. & (15)\end{aligned}$$

Since the probability to have a successful transmission P_{success} is the probability that a node senses two times successfully, and the others not:

$$P_{\text{success}} = N\phi(1-\phi)^{N-1}(1-\alpha)(1-\beta). \tag{16}$$

Thus

$$\alpha = L^*[1-(1-\phi)^{N-1}](1-\alpha)(1-\beta), \tag{17}$$

which establishes a second non-linear relation between ϕ, α and β.

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 which denotes the probability to sense busy the second time. 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:

$$\beta = Pr(M_{CCA^2}(s) = -1 | M_{CCA^1}(s) \geq 0) \tag{18}$$

where $M(s) \geq 0$ denotes the probability that no station in the medium is transmitting. The superscript denotes the local time of the node doing its second sense as shown in Fig. 4.

The device doing its second CCA will sense busy 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 ($M_1(s) \geq 0$). Alternatively, the device will sense busy if the first idle slot was the slot between data transmission and acknowledgement. We will denote the latter probability as P_{betaACK}. As a result,

$$\begin{aligned} \beta &= P(M_1(s) \geq 0 \mid M_1(c) = -1, M_{CCA^1}(s) \geq 0)\\ &\quad \times P(M_1(c) = -1 \mid M_{CCA^1}(s) \geq 0) + P_{\text{betaACK}}\\ &= P(M_1(s) \geq 0 \mid M_{CCA^1}(s) \geq 0) \times P(M_1(c) = -1)\\ &\quad + P_{\text{betaACK}} \end{aligned} \tag{19}$$

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

$$\begin{aligned} &P(M_1(s) \geq 0 \mid M_{CCA^1}(s) \geq 0)\\ &= 1 - \frac{P(M_1(s) = -1 \cap M_{CCA^1}(s) \geq 0)}{Pr(M_{CCA^1}(s) \geq 0)}. \end{aligned} \tag{20}$$

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:

$$\begin{aligned} &P(M_{CCA^1}(s) \geq 0)\\ &= P(M_1(s) = -1 \cap M_{CCA^1}(s) \geq 0)\\ &+ P(M_1(s) \geq 0 \cap M_{CCA^1}(s) \geq 0), \end{aligned} \tag{21}$$

We can see in Fig. 4 that following cases result in an idle slot CCA^1 ($M_{CCA^1}(s) \geq 0$):

Case 1: A busy slot before the idle slot is counted in $P(M_1(s) = -1 \cap M_{CCA^1}(s) \geq 0)$. Three subcases can be considered:

- **Case 1.1:** In the first subcase, no acknowledgement follows the data transmission. This situation occurs when the packet transmission fails due to collision or transmission errors. In this paper, no transmission errors are considered. As a result, this probability to have no acknowledgement is the probability to have a lost packet transmission: $P_{\text{loss}} = 1 - (1-\phi)^N - N\phi(1-\phi)^{N-1} = P_{\text{send}} \times P_{\text{netcol}}$, where P_{send} is the probability to have a packet transmission in the network, and P_{netcol} the conditional network collision probability.
- **Case 1.2:** In the second subcase, the busy slot before the idle slot was due to the acknowledgement following a successful data transmission. The probability to have a successfule data transmission is $P_{\text{success}} = N\phi(1-\phi)^{N-1} = P_{\text{send}} \times (1 - P_{\text{netcol}})$.

- **Case 1.3:** The third subcase is the case the idle slot is the interframe space in between data and acknowledgement (t_{ACK}). This happens with probability P_{success}.

Case 2: An idle slot 1 before slot CCA^1 is counted in $P(M_1(s) \geq 0 \cap M_{CCA^1}(s) \geq 0)$. This can happen after an acknowledged successful transmission or an unacknowledged unsuccessful transmission, and the probability is the same as in the unacknowledged Case 2: $P(M_1(s) \geq 0 \cap M_{CCA^1}(s) \geq 0) = \sum_{i=1}^{\infty} P_{\text{send}}((1-\phi)^N)^{(i-1)}$.

The expression for β in the acknowledged case is hence (summing up all the cases):

$$\begin{aligned}\beta &= \left[1 - \frac{P_{\text{send}}[(2-P_{\text{netcol}})+P_{\text{netcol}}]}{P_{\text{send}}(2-P_{\text{netcol}}+\frac{1}{1-(1-\phi)^N})}\right] \\ &\times \;(1-(1-\phi)^{N-1}) \\ &+ \;\frac{P_{\text{send}}(1-P_{\text{netcol}})}{P_{\text{send}}(2-P_{\text{netcol}}+\frac{1}{1-(1-\phi)^N})} \qquad (22)\end{aligned}$$

which, for N large, can be simplified to;

$$\beta = \frac{2-P_{\text{netcol}}}{(2-P_{\text{netcol}}+\frac{1}{1-(1-\phi)^N})}. \qquad (23)$$

This establishes a third non-linear relation between ϕ, α and β.

The network operating point as determined by ϕ, α and β is determined by solving the three non-linear Equations 12, 17, 23. These three values are sufficient to determine the network throughput and energy consumption achieved during operation, as we will show in Section V.

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. The number of transmissions, collisions, access failures and CCA are tracked for a simulation run of 10^8 slots. Based on that, the actual statistics can be 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. 5 it can be seen that the value for β 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. It is clear in Fig. 5 that the model proposed here matches the simulation results much more accurately, both voor de case with and without acknowledgements. Next, in Fig. 6, ϕ gives us the probability to start sensing the first time. It is clear that the probability to start sensing does not vary a lot as function of network size. However, the probability to start sending P_{send} does, and this will be important for throughput validation. Since a transmission is started if the

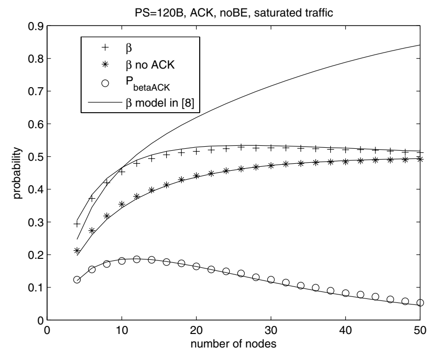


Fig. 5. The probabilities β and P_{betaACK} as predicted by the analytical model and simulation.

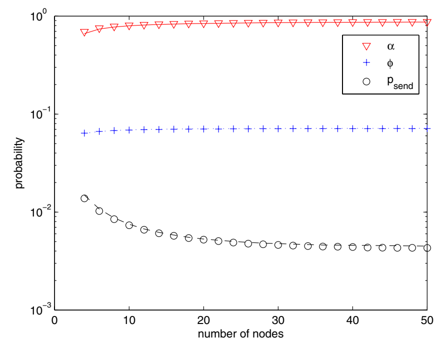


Fig. 6. The probabilities α, ϕ and p_{send} as predicted by the analytical model and simulation.

channel is sensed idle two times, it is α and β that will impact the throughput significantly. As α is modeled and simulated to vary little as function of network size N (Fig. 6), it is exactly β that is important. As argued before, no models for 802.15.4 have modeled β as accurate as we do in this paper. We now instantiate the model to assess the throughput and energy of the 802.15.4 access mechanism.

V. Throughput and Energy Analysis

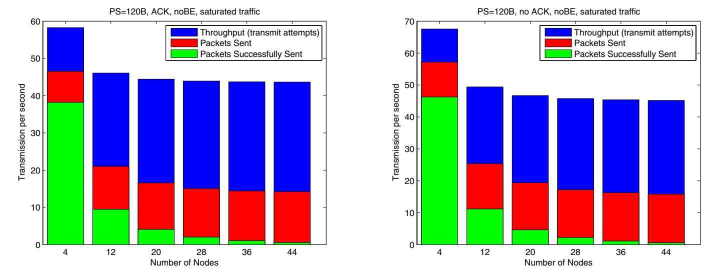
In this section we use the analytical model to study the energy and throughput behavior of 802.15.4 networks and derive some design guidelines. The network throughput for both saturated and unsaturated traffic conditions is given by the simple expression

$$S = ALN\phi(1-\phi)^{N-1}(1-\alpha)(1-\beta) = ALNP_{\text{success}}. \quad (24)$$

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.

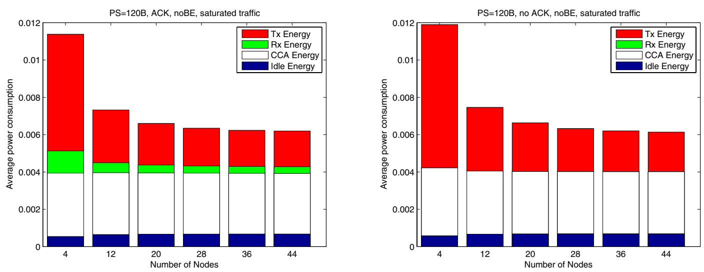
We now look how this net throughput is achieved. We compare the probability to start sending (P_{send}) , and the probability that a packet was sent successfully (P_{success}). It can be seen in Fig. 7 to what extent the throughput decreases as a function of network size for acknowledged and unacknowledged traffic. Clearly, when no acknowledgements are used, the probability to send a packet successfully is larger.

Next, we look at the energy consumption of 802.15.4 networks. We compute the percentage of time the transceiver is



(a) acknowledged traffic (b) no acknowledgements

Fig. 7. Transmit rate breakdown: number of packets generated - number of packets sent - number of packets successfully sent



(a) acknowledged traffic (b) no acknowledgements

Fig. 8. Energy cost breakdown: Tx energy - Rx energy - CCA energy - Idle energy

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. The resulting energy breakdown for a saturated network with and without acknowledgements is seen in Fig. 8. When no acknowledgements are required, the nodes can save a significant amount of receive energy (in Table I is it shown that the receive mode is most power hungry for 802.15.4 devices).

The total energy cost in the unacknowledged case is however larger, since more energy is spent in the transmission mode. A more fair comparison is however to see what is the average power needed to deliver packets successfully at a given rate. We plot the energy per bit versus net throughput per node for a range of packet sizes and acknowledged or unacknowledged traffic. Various network loads are generated by having nodes wait a varying fixed amount of time in between each packet transmission attempt (see [5]). 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. 9 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. 9). For higher loads, the net throughput decreases because of increased collision. Further, we note that the average power consumption increase with rate is mainly because of the increased Tx

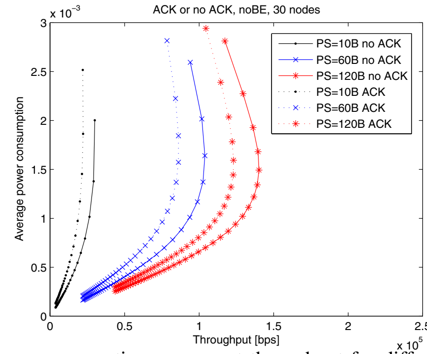


Fig. 9. Power consumption versus net throughput for different packet sizes in case of acknowledged and unacknowledged traffic.

power but also because of increased CCA power consumption. Clearly, to achieve a given packet delivery rate with minimal energy cost, the use of unacknowledged tranmissions seems to be optimal. We can hence conclude that the effort of the IEEE 802.15.4 standardization committee to design a standard that allows to trade energy cost with throughput or reliability was successful.

VI. Conclusion

In this paper, we have presented an analytical model for the medium access control layer in IEEE 802.15.4 standard in case of acknowledged uplink transmissions. 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 related to the use of acknowledgements can be derived.

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