

# Performance Analysis of Slotted IEEE 802.15.4 Medium Access Layer

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## Abstract

IEEE 802.15.4 is a standard for the medium access control (MAC) and physical layer protocols of wireless networks. This paper provides one of the first analytical evaluations of its MAC protocol for the slotted channel access mechanism in a star topology network. The form of the analysis is similar to that of Bianchi for IEEE 802.11 DCF. The key difference is in the main approximation assumption: Each device's carrier sensing probability, rather than its packet sending probability, is assumed independent. Also, unlike in 802.11, the slot duration is fixed since the channel is not constantly monitored by the stations. The performance predicted by the analytical model is very close to that obtained by simulation.

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## I. INTRODUCTION

Interest in low power wireless sensor networks led to work on the IEEE 802.15.4 standard which specifies the network’s medium access control (MAC) and physical (PHY) layer [1], [2], [3].

In IEEE 802.15.4 networks a central controller, called the PAN (personal area network) coordinator, builds the network in its personal operating space. The standard supports three topologies: star, peer-to-peer and cluster-tree. In the star topology communication is established between devices and the PAN coordinator; in the peer-to-peer topology any device can communicate with any other device within its range; and in the cluster-tree topology, most devices can communicate with each other within the cluster, but only some of them may connect to the infrastructure.

The standard identifies two channel access mechanisms. 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 PAN coordinator. However, if beacons are not available, a simpler unslotted CSMA-CA is used. This paper considers the slotted CSMA-CA mechanism.

Performance of IEEE 802.15.4 protocol was evaluated by simulation for small and low load networks in [4] and for dense networks in [5]. The analytical model for IEEE 802.15.4 developed in [6] seems to fail to match the simulation results.

This paper provides an analytical Markov model that predicts the performance of the 802.15.4 slotted CSMA-CA mechanism. The model incorporates details of the exponential delay lines and double channel assessment. The model and analysis are similar in form to the well-known formulation of Bianchi and its variants [7]-[15] for IEEE 802.11 standard [16]. However, the main approximation underlying that analysis, namely that each station’s probability to send a packet is independent, does not lead to performance predictions close to the simulation results of the IEEE 802.15.4 standard. The key approximation in our model is the independence of the carrier sensing probability which determines when the nodes

become active to listen to the channel. The resulting model is very different from the models for 802.11.

Section II briefly describes the slotted CSMA-CA mechanism in IEEE 802.15.4, which is analyzed in Section III. Section IV validates the accuracy of the model under saturation loads by comparing the analytical predictions and simulation results. Section V gives energy and throughput results for both saturated and unsaturated cases. Section VI concludes the paper.

## II. SLOTTED CSMA-CA MECHANISM

The beacons are used to synchronize the attached devices, to identify the PAN, and to describe the structure of superframes. The superframes are bounded by network beacons and divided into 16 equally sized slots. The beacon frame is sent in the first slot of each superframe.

The superframe can have an active and an inactive portion. During the inactive portion the coordinator does not interact with its PAN and may enter a low-power mode. The active portion 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. On the other hand, the CFP contains guaranteed time slots (GTSs). The GTSs appear at the end of the active portion starting at a slot boundary immediately following the CAP.

In the slotted CSMA-CA channel access mechanism, the backoff slot boundaries of every device in the PAN are aligned with the superframe slot boundaries of the PAN coordinator. Each time a device wishes to transmit data frames during the CAP, it must locate the boundary of the next slot period.

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. 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. Although the receiver of the device is enabled during the channel assessment portion of this algorithm, the device must discard any frames received during this time.

The slotted CSMA-CA mechanism works as follows. NB, CW and BE are initialized and the boundary of the next slot period is located (step 1). 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 provided that the remaining CSMA-CA algorithm steps—frame transmission, and any acknowledgement—can be completed before the end of the CAP. If the MAC sublayer cannot proceed, 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.

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 equal to 0, it must go to step 3, else start transmission on the boundary of the next slot period.

### III. FORMULATION

The core contribution of this paper is the analytical evaluation of the slotted CSMA-CA mechanism of IEEE 802.15.4 standard. We assume that there is a fixed number  $N$  of devices, and each device always has a packet available for transmission. This saturation assumption is relaxed in the performance evaluation section to model unsaturated traffic conditions. This can be done by adding a fixed number of delay slots to the model.

The analysis is in two steps. We first study the behavior of a single device using a Markov model. We then obtain the stationary probability  $\tau$  that the device attempts carrier channel assessment (CCA) for the first time within a slot. ( $\tau$  is the counterpart of the probability that the device transmits a packet in a ‘virtual’ slot in the analysis of 802.11 in [7].)

We now develop the Markov model, see Fig. 1. Let  $c(t)$  be the stochastic process representing the delay line and transmission counters of the device. The integer time  $t$  corresponds to the beginning of the slot times. In contrast with the model in [7],  $t$  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  $\alpha$  be the probability of assessing channel busy during  $CCA^1$ , and let  $\beta$  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.

Let  $s(t)$  be the stochastic process representing the delay line stages ( $s(t) \in \{1, \dots, m\}$ ), or the transmission stage ( $s(t) = 0$ ) 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. 1 with the following transition probabilities:

$$P\{i, k|i, k+1\} = 1, k \geq 0 \quad (1)$$

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

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

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

Equation 1 is the condition to decrement the delay line counter per slot. Equation 2 gives the probability of selecting a state in the first delay level after sensing the channel idle two times, provided that the current state is not in the last delay line. Equation 3 gives that probability that there is a failure both 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. Note that the number of transmission attempts is limited and either ends with success or failure.

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

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

which leads to

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

From Equations 1- 4 we obtain

$$b_{i,k} = \frac{W_i - k}{W_i} \left\{ (1-\alpha)(1-\beta) \sum_{j=0}^m b_{j,0} + P_f \right\}, \quad (7)$$

for  $i = 0$  and

$$b_{i,k} = \frac{W_i - k}{W_i} b_{i,0}, \quad (8)$$

for  $i > 0$ .

Since the probabilities must sum to 1,

$$1 = \sum_{i=0}^m \sum_{k=0}^{W_i-1} b_{i,k} + \sum_{i=0}^m b_{i,-1} + \sum_{i=0}^m b_{i,-2} \\ + \sum_{i=0}^{L-1} b_{-1,i} \\ = \sum_{i=0}^m b_{i,0} \left[ \frac{W_i + 1}{2} + 1 + (1-\alpha) \right. \\ \left. + (1-\alpha)(1-\beta)L \right]. \quad (9)$$

Substituting  $W_i = 2^i W$  leads to

$$1 = \frac{b_{0,0}}{2} [3 + 2(1-\alpha) + 2(1-\alpha)(1-\beta)L] \\ \times \left( \frac{1 - (\alpha + \beta - \alpha\beta)^{m+1}}{1 - (\alpha + \beta - \alpha\beta)} \right) \\ + W \left( \frac{1 - 2^{m+1}(\alpha + \beta - \alpha\beta)^{m+1}}{1 - 2(\alpha + \beta - \alpha\beta)} \right). \quad (10)$$

The transmission failure probability  $P_f$  is

$$P_f = b_{m,0}(\alpha - \beta\alpha + \beta), \quad (11)$$

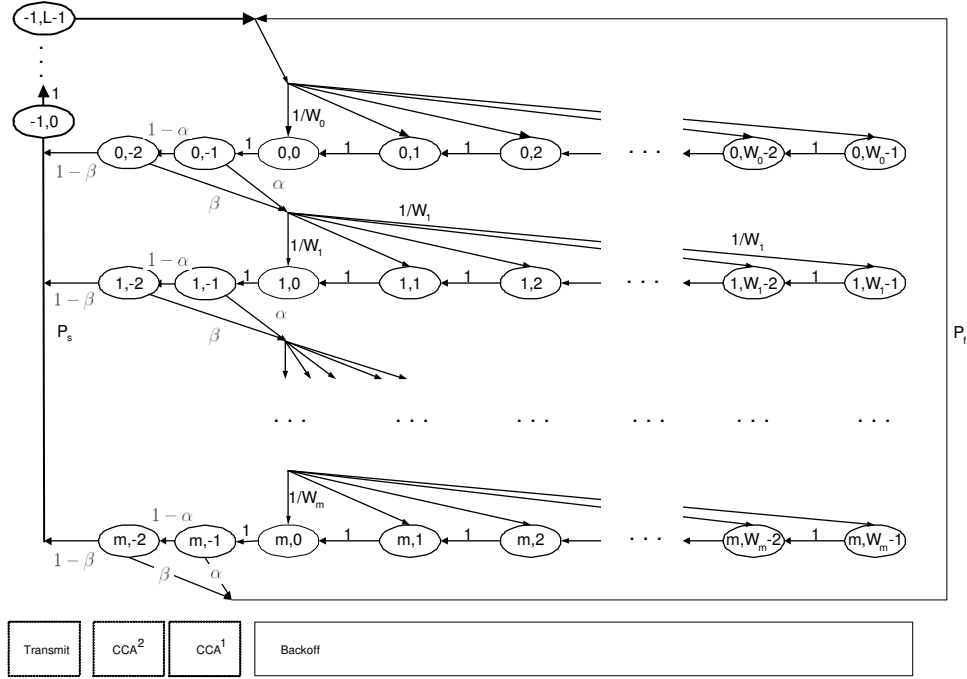


Fig. 1. Markov Model for IEEE 802.15.4

and the probability that a node starts to transmit is

$$P_s = \tau(1 - \alpha)(1 - \beta), \quad (12)$$

in which

$$\tau = \sum_{i=0}^m b_{i,0}. \quad (13)$$

Denote by  $M(s) = -1$  the event that there is at least one transmission in the medium by another node and by  $S^{i_1}(s) = -1$  the event that node  $i_1$  is transmitting. Then

$$\begin{aligned} \alpha &= P(M(s) = -1) \\ &= \sum_{n=0}^{N-2} \binom{N-1}{n+1} P(\bigcup_{k=1}^{n+1} S^{i_k}(s) = -1) \\ &= \sum_{n=0}^{N-2} \binom{N-1}{n+1} \\ &\quad P(S^{i_1}(s) = -1) P(\bigcup_{k=2}^{n+1} S^{i_k}(s) = -1 | S^{i_1}(s) = -1). \end{aligned} \quad (14)$$

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

$$\begin{aligned} P(S^{i_1}(s) = -1) &= \sum_{c=0}^{L-1} P(E_c) = LP(E_0) \\ &= L\tau(1 - \alpha)(1 - \beta), \end{aligned} \quad (15)$$

which requires the node to sense (with probability  $\tau$ ) 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  $\tau$ , 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.

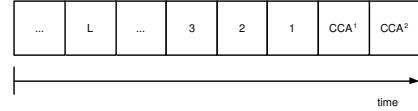


Fig. 2. Slot timing for the derivation of  $\beta$ .

Starting transmission at the same time slot moreover requires being in the sense state at the same time. Thus the conditional probability is

$$P(\bigcup_{k=2}^{n+1} S^{i_k}(s) = -1 | S^{i_1}(s) = -1) = \tau^n(1 - \tau)^{N-2-n}, \quad (16)$$

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

Thus

$$\alpha = L[1 - (1 - \tau)^{N-1}](1 - \alpha)(1 - \beta). \quad (17)$$

Lastly we need an expression for  $\beta$ . See Fig. 2. First define  $P_{\text{send}}$  as the probability that there is at least one station that starts to transmit:

$$\begin{aligned} P_{\text{send}} &= P(M(s, c) = (-1, 1)) = \frac{\alpha}{L} \\ &= (1 - (1 - \tau)^N)(1 - \alpha)(1 - \beta). \end{aligned} \quad (18)$$

To determine  $\beta$  we observe that the preceding slot must be idle. So  $\beta$  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,

$$\beta = Pr(M_{CCA^2}(s) = -1 | M_{CCA^1}(s) \geq 0) \quad (19)$$

where  $M(s) \geq 0$  denotes the probability that no station in the medium is transmitting. The subscript denotes the local time of the node doing its second sense as shown in Fig. 2. 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

$$\beta = P(M_1(s) \geq 0 \mid M_1(c) = -1, M_{CCA^1}(s) \geq 0) \times P(M_1(c) = -1 \mid M_{CCA^1}(s) \geq 0) \quad (20)$$

Here  $P(M_1(s) \geq 0 \mid M_1(c) = -1, M_{CCA^1}(s) \geq 0)$  is the probability that an idle slot is preceded by another idle slot.

We can see that

$$P(M_1(s) \geq 0 \mid M_1(c) = -1, M_{CCA^1}(s) \geq 0) = 1 - \frac{P(M_1(s) = -1 \cap M_{CCA^1}(s) \geq 0 \mid M_1(c) = -1)}{Pr(M_{CCA^1}(s) \geq 0 \mid M_1(c) = -1)}. \quad (21)$$

This means that to compute  $\beta$  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. All cases that result in an idle slot  $CCA^1$  are:

$$\begin{aligned} & P(M_{CCA^1}(s) \geq 0 \mid M_1(c) = -1) \\ &= P(M_1(s) = -1 \cap M_{CCA^1}(s) \geq 0 \mid M_1(c) = -1) \\ &+ P(M_1(s) \geq 0 \cap M_{CCA^1}(s) \geq 0 \mid M_1(c) = -1), \end{aligned} \quad (22)$$

From Fig. 2, the following cases result in an idle slot  $CCA^1$ :

- A busy slot 1 before the idle slot is counted in  $P(M_1(s) = -1 \cap M_{CCA^1}(s) \geq 0 \mid M_1(c) = -1)$ . 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  $P(M_1(s) = -1 \cap M_{CCA^1}(s) \geq 0 \mid M_1(c) = -1) = P_{\text{send}}$ .
- An idle slot 1 before slot  $CCA^1$  is counted in  $P(M_1(s) \geq 0 \cap M_{CCA^1}(s) \geq 0 \mid M_1(c) = -1)$ . 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  $2, \dots, i$ :  $P(M_1(s) \geq 0 \cap M_{CCA^1}(s) \geq 0 \mid M_1(c) = -1) = \sum_{i=1}^{\infty} P_{\text{send}}((1-\tau)^N)^{(i-1)}$ .

Finally, the probability that some node starts sensing during slot 1 is

$$P(M_1(c) = -1 \mid M_{CCA^1}(s) \geq 0) = (1 - (1-\tau)^{N-1}). \quad (23)$$

Then  $\beta$  is given by

$$\beta = \left[ 1 - \frac{P_{\text{send}}}{P_{\text{send}}(1 + \frac{1}{1-(1-\tau)^N})} \right] (1 - (1-\tau)^{N-1}) \quad (24)$$

which for large  $N$  can be simplified to;

$$\beta = \left[ 1 - \frac{P_{\text{send}}}{P_{\text{send}}(1 + \frac{1}{1-(1-\tau)^N})} \right] (1 - (1-\tau)^N) \quad (25)$$

from which one obtains

$$\tau = 1 - \left( 1 - \frac{\beta}{1-\beta} \right)^{1/N} \quad (26)$$

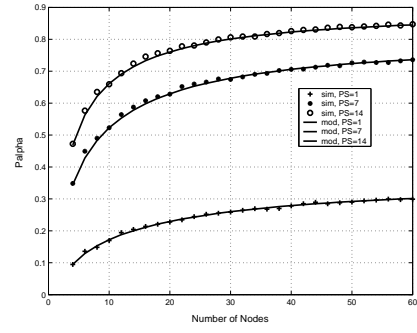


Fig. 3. Conditional probability to sense busy when sensing the first slot, increases with packet size ( $BE_{min} = 5$ ).

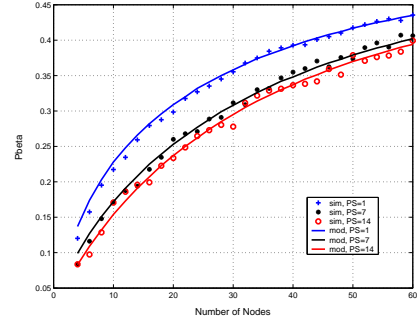


Fig. 4. Conditional probability to sense busy when sensing the second slot ( $BE_{min} = 5$ ).

One can show that  $\beta$  can never exceed  $1/2$ , which will be verified later.  $\tau$  is determined by solving the three simultaneous non-linear equations 13, 17, 26.

#### IV. MODEL BEHAVIOR AND VALIDATION

We first analyze the model behavior under saturation conditions, and compare the results with event-based simulation. The simulation models a network of  $N$  nodes that always have data to send. A range of packet sizes  $L$ , initial delay windows  $W_0 = 2^{BE_{min}}$  and network sizes  $N$  are considered. We assume that the delay window is doubled in each delay stage.

According to Eq. 17,  $\alpha$  increases with  $N$  and  $L$ , which is also illustrated in Fig. 3 both using Eq. 17 and by simulations. The ‘noise’ in the simulations results from the fact that performance is evaluated from a finite duration simulation, whereas the analytical model approximates the asymptotic behavior.  $\beta$  is less sensitive to  $L$ , but increases with  $N$  until it saturates around  $1/2$  (Fig. 4).

To determine the performance of the protocol, we have to know how much time is wasted in collisions. We compute the probability to collide when sending. Since the probability to sense,  $\tau$ , is independent, we have

$$p_{\text{col}} = 1 - (1-\tau)^{N-1}, \quad (27)$$

i.e.  $p_{\text{col}}$  is the probability that another user started CCA at the same moment. This formula matches event-based simulation for a range of  $N$  and  $L$  (Fig. 5).

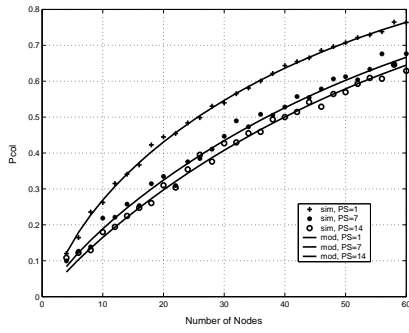


Fig. 5. Conditional collision probability.

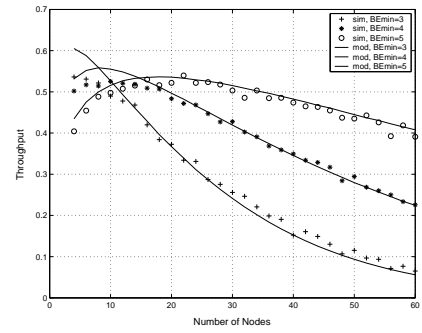


Fig. 7. Validated throughput ( $L = 7$ ).

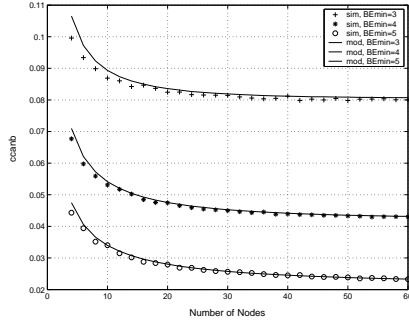


Fig. 6. Probability  $p_{\text{sensing}}$  to do CCA (first or second),  $BE_{\text{min}} = 5$ .

Next, we are interested in the time spent scanning the channel. A delay line has been introduced in the 802.15.4 protocol to minimize the number of channel idle senses, as these are typically energy expensive. The percentage of slots spent scanning the channel (per node) is:

$$p_{\text{sensing}} = \tau + \tau(1 - \alpha). \quad (28)$$

It can be seen in Fig. 6 that this percentage can be considerable in saturation, even for an enlarged  $BE_{\text{min}}$ .

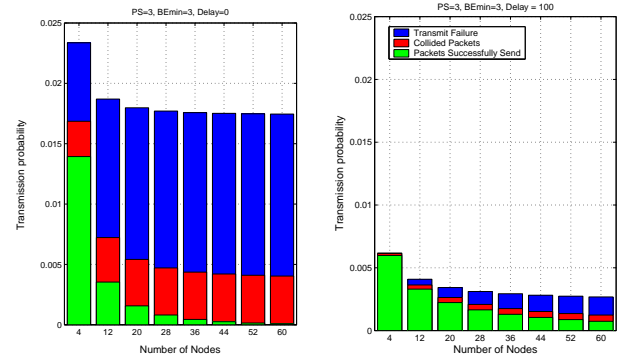
Finally, we consider the saturation throughput  $S$ , (Fig. 7), which we express as the number of slots occupied for a successful packet transmission of size  $L$  (ignoring the protocol overhead):

$$S = LN\tau(1 - \tau)^{N-1}(1 - \alpha)(1 - \beta). \quad (29)$$

It is the probability that a node in the network starts sensing alone, and has success during its channel assessments.

## V. ENERGY AND THROUGHPUT PERFORMANCE ANALYSIS

In this section we use the analytical model to study the energy and throughput behavior of both saturated and unsaturated 802.15.4 MAC. The saturated case reflects a sensor network scenario in which an event is detected by many sensors that want to transmit the gathered information at the same time. The unsaturated case reflects a scenario with periodic monitoring intervals. In the saturated case, packets keep being generated so the system is always in one of the states of the Markov model depicted in Fig. 1. To model the unsaturated case, we introduce a fixed delay of 100 or 10000 slots before going into the first delay stage, representing a



(a) No delay between transmit attempts (b)  $34ms$  delay between transmit attempts

Fig. 8. Transmit rate breakdown: number of packets generated - number of packets sent - number of packets successfully sent

delay of  $34ms$  or  $3.4s$  respectively after sending the previous packet (or failure to send it with probability  $P_f$ ).

We assume that collided packets, or packets that failed to be sent (with probability  $P_f$ ), are not retransmitted. We compare the probability to start a transmission attempt (entering delay line), the probability to start sending, and the probability that a packet was sent successfully (Fig. 8). It can be seen that, when a delay of 100 slots or  $34ms$  is introduced, the probability to start a transmission attempt is reduced significantly. However, the percentage of successful transmissions increases, and for large  $N$  a higher successful packet send rate is achieved.

Next, we study the energy consumption as a function of the load, network size  $N$ , packet size  $L$ , and initial window size exponent  $BE_{\text{min}}$ . We compute the average time the transceiver is in each of its four states listed in Table I, and multiply this time by the power consumption. Typically in sensor networks, the output power is limited. As a result, the power consumed during  $Rx$  and  $CCA$  is larger than the  $Tx$  power consumption [5]. We assume the power consumption during the sleep state is a factor 200 lower than  $Rx$  state, which is significant [5].

We assume the transceiver is in  $Tx$  mode when transmitting, in  $Rx$  mode when idle waiting (interframe spaces) or receiving, in  $CCA$  mode when performing CCA and in  $sleep$  mode when not in the aforementioned cases. Normalized energy per useful delivered bit is given in Fig 9. According to the standard, a total overhead of 5.2 slots is required for

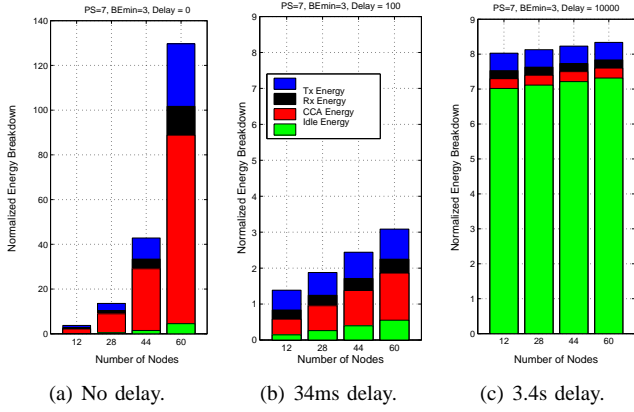


Fig. 9. Energybreakdown as function of load

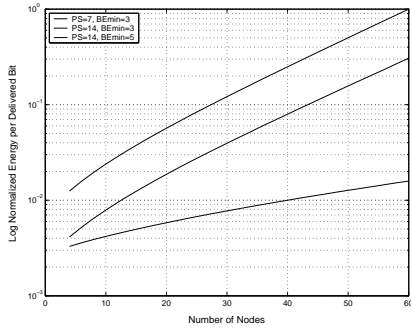


Fig. 10. Energy per bit for different parameter settings, saturation.

each packet, which consists of the preamble, MAC header, interframe spaces and acknowledgement. First, we study the energy needed as function of the load per node. It can be seen in Fig. 9(a) that the energy needed to send a bit is very high in saturation, because of increased sensing and (collided) transmission probabilities. For a lower load the energy per useful bit steadily decreases (Fig. 9(b)). However, for even lower loads, the energy per bit is increasing: Although the sleep power consumption is a factor 150 lower than the  $Tx$  power drain, sleep power dominates at very low loads.

Fig. 10 is a plot of the energy per useful bit as a function of packet size  $L$  and  $BE_{min}$ . As expected, the energy consumption decreases rapidly with increasing  $L$ , due to lower overhear per bit. Also, a higher  $BE_{min}$  decreases  $p_{col}$ , which improves the overall energy per bit.

## VI. CONCLUSION

In this paper, we have presented an analytical model for the medium access control layer in IEEE 802.15.4 standard. The model assumes a finite number of terminals and ideal channel conditions. The key approximation in the model is

that a device's carrier sensing probability is constant and independent. The validity of the analytical model is demonstrated by the fact that its predictions very closely match the simulation results. We then use the analytical model to predict energy consumption and throughput of unsaturated 802.15.4 networks.

## REFERENCES

- [1] 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
- [2] S. C. Ergen, *ZigBee/IEEE 802.15.4 Summary*, <http://www.eecs.berkeley.edu/csinem/academic/publications/zigbee.pdf>
- [3] 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.
- [4] 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.
- [5] 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.
- [6] 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.
- [7] G. Bianchi, *Performance Analysis of the IEEE 802.11 Distributed Coordination Function*. IEEE Journal on Selected Areas in Communications, vol.18, March 2000.
- [8] A. Kumar, E. Altman, D. Miorandi, M. Goyal, *New Insights from a Fixed Point Analysis of Single Cell IEEE 802.11 WLANs*. IEEE INFOCOM 2005.
- [9] M. Ergen. *I-WLAN: Intelligent Wireless Local Area Networking*. PhD Dissertation, UC Berkeley, December 2004.
- [10] M. Heusse, F. Rousseau, G. Berger-Sabbatel, A. Duda. *Performance Anomaly of 802.11b*. Proceedings of IEEE INFOCOM 2003.
- [11] G. R. Cantieni, Q. Ni, C. Barakat, T. Turletti. *Performance Analysis under Finite Load and Improvements for Multirate 802.11*. preprint submitted to Elsevier Science.
- [12] F. Cali, M. Conti, E. Gregori. *Dynamic Tuning of the IEEE 802.11 Protocol to Achieve a Theoretical Throughput Limit*. *IEEE/ACM Trans. Networking*, vol. 1., no.1. pp. 10-31, March 2002.
- [13] N. Vaidya, P. Bahl, S. Gupta. *Distributed Fair Scheduling in a Wireless LAN*. MOBICOM 2000, Aug. 2000.
- [14] Y. Xiao, *A Simple and Effective Priority Scheme for IEEE 802.11*. *IEEE/ACM Trans. Networking*, vol. 7, no. 4, pp. 473-489, Aug. 1999.
- [15] M. Ergen, P. Varaiya. *Admission Control and Throughput Analysis in IEEE 802.11*. *Springer Mobile Networks and Applications*, vol.10, no.5., pp. 705-706, October 2005.
- [16] LAN-MAN Standards Committee of the IEEE Computer Society, *Wireless LAN medium access control(MAC) and physical layer(PHY) specification*, IEEE, New York, NY, USA, IEEE Std 802.11-1997 edition, 1997

TABLE I  
802.15.4 TRANSCIVER POWER CONSUMPTION.

$Rx$	$CCA$	$Tx$	$Sleep$
$20mW$	$20mW$	$15mW$	$0.1mW$