

Usage of IEEE 802.15.4 MAC –PHY Model  
Mohamed-Haykel Zayani & Vincent Gauthier  
Laboratory CNRS S.A.M.O.V.A.R. - Dept RS2M  
Télécom SudParis - 9 rue C. Fourier  
91011 EVRY CEDEX FRANCE

E-Mails: {vincent.gauthier, mohamed-haykel.zayani}@it-sudparis.eu

## 1 Introduction

The m-file model an Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 Machine Access Control (MAC) layer channel in which multiple non-saturated stations compete to get access to the channel and to communicate with a sink. It is inspired from the IEEE 802.11 Model [1] developed by David Griffith and Michael Souryal (Emerging and Mobile Network Technologies Group, Information Technology Laboratory, National Institute of Standards and Technology). The objective behind this “adaptation” is to model a physical layer (PHY), including path loss and shadowing effects which interacts with the MAC model. The particularity of the proposed model lies in overstepping the node range disk shaped and taking into consideration the called “transitional area” [2, 3]. The model relies on the approach of Zuniga and Krishnamachari [2, 3]. The function `ZunPhyModel` performs the calculations at the PHY level and determines the probability of good frame reception towards channel (signal-to-noise ratio) and radio (modulation and coding) parameters.

## 2 M-file Inputs and Outputs

The IEEE 802.15.4 model requires several inputs. These inputs concern characteristics of a node and parameters provided by IEEE 802.15.4 standard (the values taken by the standard parameters are inspired from [4, 5, 6]). They are referred in the following subsection.

### 2.1 Inputs

Like in IEEE 802.11 model, the m-file tests different values for the per-station offered load,  $\lambda$ , measured in units of frame/s. The offered load values are stored in the vector `lvec`. The other parameters are as follows:

- Number of stations: `N_stations`
- Station system size in frames: `K`
- Minimum retry backoff window maximum counter value: `W0`
- Data rate in bits/s: `data_rate`
- Maximum number of frame transmission retries: `macMaxFrameRetries` (represents the maximum number of retries allowed after a transmission failure)
- Maximum number of backoff stages: `macMaxCSMABackoffs` (represents the maximum number of backoffs the CSMA-CA algorithm will attempt before declaring a channel access failure)
- Minimum value of the backoff exponent in the CSMA-CA algorithm: `macMinBE`
- Maximum value of the backoff exponent in the CSMA-CA algorithm: `macMaxBE`

- Size of MAC frame payload data in bits: `L_application`
- Size of overhead added in PHY layer in bits: `L_overhead`
- Acknowledgement (ACK) frame size at PHY layer in bits: `L_ACK`
- Mean propagation delay in seconds: `T_prop`
- Basic backoff time period used by the CSMA-CA algorithm in seconds: `aUnitBackoffPeriod`
- Idle state length without generating packets in seconds: `L0`
- Coefficient to translate the frame time length to the frame slot length in bits/slot: `A`
- Inter-Frame Space in seconds: `t_IFS`
- Maximum time to wait for an acknowledgement frame to arrive following a transmitted data frame in seconds: `macACKWaitDuration`
- RX-to-TX or TX-to-RX maximum turnaround time in seconds: `aTurnaroundTime`
- Time used to detect if the channel is busy or not in seconds: `sensing_time`
- Shadowing standard deviation in dB: `sigma_s`
- Tolerance for convergence of  $p_0$ : `p0_tolerance`

For the `ZunPhyModel` function (PHY layer), there are also specific inputs relative to Chipcom CC1000 [7] radio and physical layer parameters:

- Noise figure in dB: `NOISE_FIGURE`
- Bandwidth in Hz: `BW`
- Path Loss Exponent: `PATH_LOSS_EXPONENT`
- Shadowing standard deviation in dB: `SHADOWING_STANDARD_DEVIATION`
- Standard distance to measure the effect of path loss in meters: `D0`
- Transmission power in dBm: `Prdbm`
- Average white noise in dB: `NOISE`
- Wavelength in meters: `lambda`
- Data rate in bits: `DATA_RATE`
- Preamble length in bits: `PREAMBLE_LENGTH`
- Frame length in bits: `FRAME_LENGTH`
- Minimum node's range in meters: `distmin`
- Maximum node's range in meters: `distmax`

## 2.2 Outputs

The outputs of the m-file are almost the same as in the IEEE 802.11 Model [1]. They relate to the following vectors:

- Mean frame service time at the MAC layer: `ET`
- Standard deviation of the MAC layer service time: `Std_dev`
- Blocking probability: `P_blocking`
- Probability to find a node idle: `P_idle`
- Probability of transmission attempt fail: `P_failure`
- Average number of frames in a station's system: `L_value`
- Channel access failure probability (equation (19) in [6]): `P_cpf`

- Packet discarded due to retry limits probability (equation (20) in [6]):  $P_{cr}$
- Alpha probability (probability of finding the channel busy during the first carrier sensing):  $\text{Alpha}$
- Beta probability (probability of finding the channel busy during the second carrier sensing):  $\text{Beta}$
- Probability for successful frame sending:  $\text{Reliability}$
- Average frame delay, including waiting time on queue:  $D\_value$
- Average per-station throughput in bits/s:  $S\_avg$
- Instantaneous per-station throughput in bits/s:  $S\_inst$

### 3 Operation Details

The model of IEEE 802.15.4 is based on a Markov chain model [6] that captures the state of a station's backoff stage, backoff counter and the state of retransmission counter. It also uses an M/M/1/K queuing model that captures the effect of a finite buffer in the station. In the one hand, the Markov model determines the steady-state probability that a station senses the channel to transmit a frame and the probability that a frame experiences a failure (due to a collision or an insufficient signal-to-noise ratio). In the other hand, the queuing model provides the probability that the station is idle and performance metrics like throughput, taking, of course, into consideration Markov chain outputs.

#### 3.1 The Markov Chain Model

The model takes the scenario of  $N$  stations trying to communicate with a sink. The Markov Chain is detailed in Section III in [6]. The probability that a node attempts a first carrier sensing to transmit a frame, the probability that a node find the channel busy during CCA1 and the probability that a node find the channel busy during CCA2 are denoted by the variables  $\tau$ ,  $\alpha$  and  $\beta$ . These three probabilities are related by a system of three nonlinear equations that arises from finding the steady state probabilities of a variant of the IEEE 802.15.4 Markov Chain proposed in [6] and inspired by [8] to formulate the equations system. The m-file uses `fsolve` command to solve the system inspired from the equations (16), (17) and (18) in [6], with making some changes. When a node tries to send a frame, its backoff counter has already reached 0 and it is necessarily not idle (it has a frame to send), that is why we consider the product  $(1 - p_0)\tau$ , instead of  $\tau$ , as the probability that a node attempts the first carrier sensing to transmit a frame, where  $p_0$  represents the probability that a station is idle. The system considered is given as following:

$$\tau = \left( \frac{1 - x^{m+1}}{1 - x} \right) \left( \frac{1 - y^{n+1}}{1 - y} \right) b_{0,0,0} \quad (1)$$

$$\alpha = \left( L + \frac{N(1 - p_0)\tau(1 - (1 - p_0)\tau)^{N-1}}{1 - (1 - (1 - p_0)\tau)^N} L_{ACK} \right) \left( 1 - (1 - (1 - p_0)\tau)^{N-1} \right) (1 - \alpha)(1 - \beta) \quad (2)$$

$$\beta = \frac{1 - (1 - (1 - p_0)\tau)^{N-1} + N(1 - p_0)\tau(1 - (1 - p_0)\tau)^{N-1}}{2 - (1 - (1 - p_0)\tau)^N + N(1 - p_0)\tau(1 - (1 - p_0)\tau)^{N-1}} \quad (3)$$

Where:

- $x = \alpha + (1 - \alpha)\beta$
- $y = P_{fail}(-x^{m+1})$
- $m = \text{macMaxCSMABackoffs}$
- $n = \text{macMaxFrameRetries}$

And:

- $L$  is the length of the data frame in slots.
- $L_{ACK}$  is the length of an acknowledgement in slots.
- $N$  is the number of neighbouring stations.
- $b_{0,0,0}$  is the state where the state variables of backoff stage counter, backoff counter and retransmission counter are equal to 0 (an approximation is proposed in [6]).

The mechanism that computes these probabilities permits to determine the probability of collision  $P_{col}$ , the probability of loss due to channel and radio setups  $P_e$  and so to determine the probability of a failed transmission  $P_{fail}$ . In [6], only the collisions were considered as the only cause of loss. We think that the losses can also be provoked by a low SNR and/or by errors due to modulation and/or coding. The asymmetry can be also taken as a factor behind the expansion of transitional area [3]. The probability relative to this event is computed with `ZunPhyModel` function. The function is able to determine, for a given distance between two nodes, the probability of good frame reception.

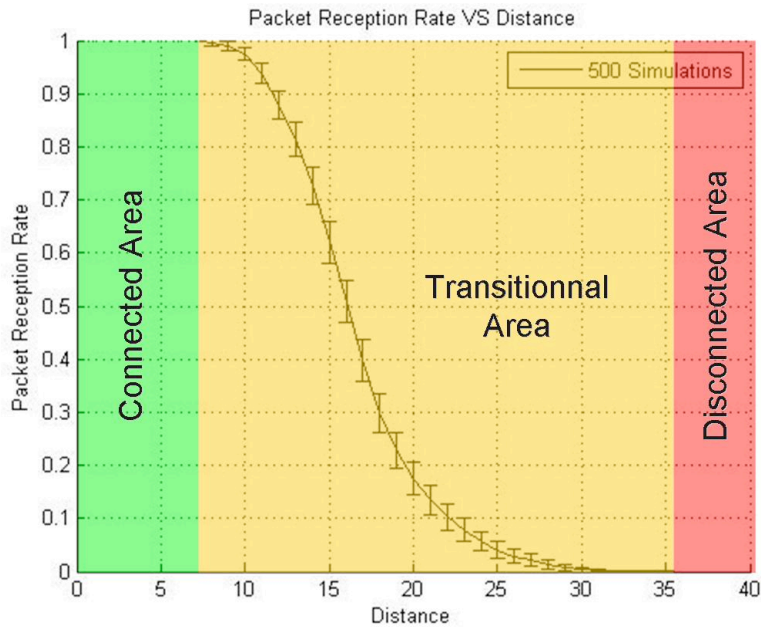


Figure 1: Evolution of probability of packet reception versus distance

The figure 1 gives an overview on the evolution of the packet reception rate versus the distance (in meters). It shows three different areas:

- The connected area where the packet reception probability is equal to 1 (green part).
- The disconnected area where the packet reception probability is equal to 0 (red part).
- The transitional area where the packet reception probability takes values between 0 and 1 (orange part) and where the measures are unstable, as supported in figure 2.

The model of Zuniga and Krishnamachari oversteps the node range disc-shaped one and permits to have more appropriate vision of the link behaviour.

We apply integration on the computation method, in order to calculate an average probability of good reception over the area situated between a node's minimum and maximum ranges.

Then, we consider  $P_{fail}$  and not only  $P_{col}$ .  $P_{fail}$  is given by:

$$P_{fail} = (1 - P_{col})(1 - P_e) \quad (4)$$

Where  $P_{col} = 1 - (1 - (1 - p_0)\tau)^{N-1}$ .

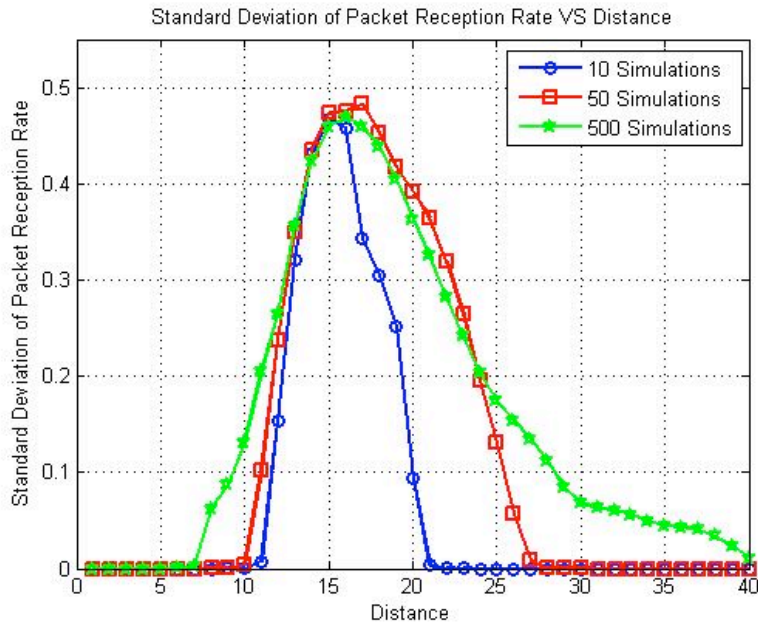


Figure 2: Evolution of standard deviation of packet reception rate versus distance

This mechanism is included in a larger loop that updates  $p_0$  since that it depends on  $P_{fail}$  ( $p_0$  is determined from  $ET$ , the mean MAC service time, and  $ET$  is computed with  $P_{fail}$ ).

The m-file solves the system of non-linear equations to determine  $\tau$  and therefore  $P_{fail}$ . Then  $P_{fail}$  is used to estimate the mean MAC service time (provided by the equation (34) in [6]), and to generate new value for  $p_0$  which will be used in the next iteration. The process continues until the value of  $p_0$  converges to a stable value. Once  $p_0$  converges, all outputs concerning queuing analysis can be computed for each value of  $\lambda$ .

### 3.2 The Queuing Model

The IEEE 802.15.4 model follows the same reasoning with the model of 802.11. More details are given in Readme file for using the 802.11 model Matlab code in [1].

## 4 Example Calculations

We propose to run a simulation to view most relevant outputs provided by the m-file. We fix input parameters as shown in Table 1 and Table 2 and we choose to start from a per-node offered load equal to 0.5 frames/s and increment this parameter by 0.5 until reaching a load of 50 frames/s. The evolution of the average wait time, the reliability, the average throughput and the instantaneous throughput versus the offered load are represented, respectively, in figure 1, 2, 3 and 4. The major observation is that IEEE 802.15.4 networks do not support “heavy” traffics. When the traffics are tied to a per-node offered load lower than 1 frame/s (800 bits/s), the performances remain acceptable (reliability, which represents also the average throughput over offered load, near to 0.7). More important per-node offered load, between 1 and 12.5 frames/s (800 bits/s and 10000 bits/s) causes performances degradation, causing a rapid weakening of the ratio average throughput versus offered load. The network saturation is observed at different performances levels starting from 12.5 frames/s (10000 bits/s). These observations can be explained by different causes:

- The low number of maximum backoff stages ( $\text{macMaxCSMABackoffs}=4$ ).
- The low size of largest contention windows (32).
- The low data rate that induces longer channel occupation (higher  $\alpha$  and  $\beta$  probabilities).

Table 1: Parameter values used in MAC layer

Parameter	Value
N_stations	10
K	51 frames
data_rate	19.2 kbits/s
W0	8
macMaxFrameRetries	3
macMaxCSMABackoffs	4
macMinBE	5
macMaxBE	3
L_application	800 bits
L_overhead	48 bits
L_ACK	88 bits
T_prop	222e-9 seconds
aUnitBackoffPeriod	320e-6 seconds
L0	0
A	80 bits/slots
t_IFS	640e-6 seconds
macACKWaitDuration	1920e-6 seconds
aTurnaroundTime	192e-6 seconds
sensing_time	128e-6 seconds
sigma_s	4
p0_tolerance	e-10

Table 2: Parameter values used in PHY layer

Parameter	Value
NOISE_FIGURE	23 dB
BW	30 kHz
PATH_LOSS_EXPONENT	4
SHADOWING_STANDARD_DEVIATION	4
D0	1 meter
Prdbm	5 dB
NOISE	15 dB
lambda	12.5 e-2 meters
DATA_RATE	19.2 kbits/s
PREAMBLE_LENGTH	40 bits
FRAME_LENGTH	808 bits
distmin	1 meter
distmax	20 meter

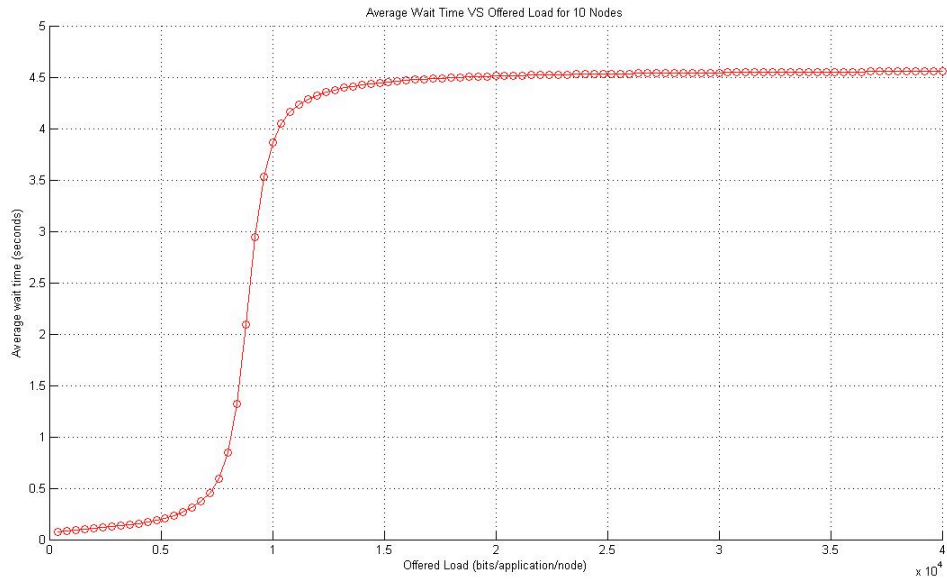


Figure 1: Average per-node wait time versus per-node offered load

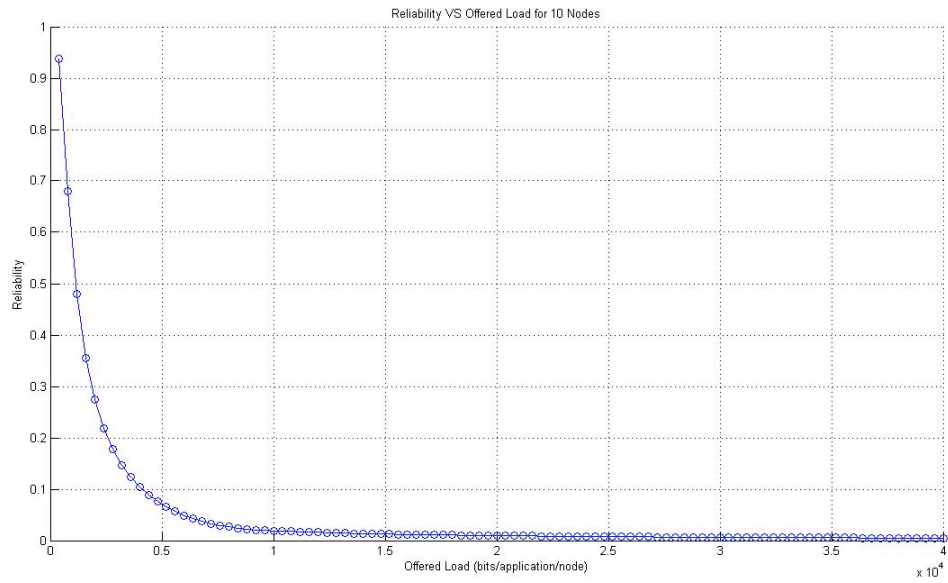


Figure 2: Per-node reliability versus per-node offered load

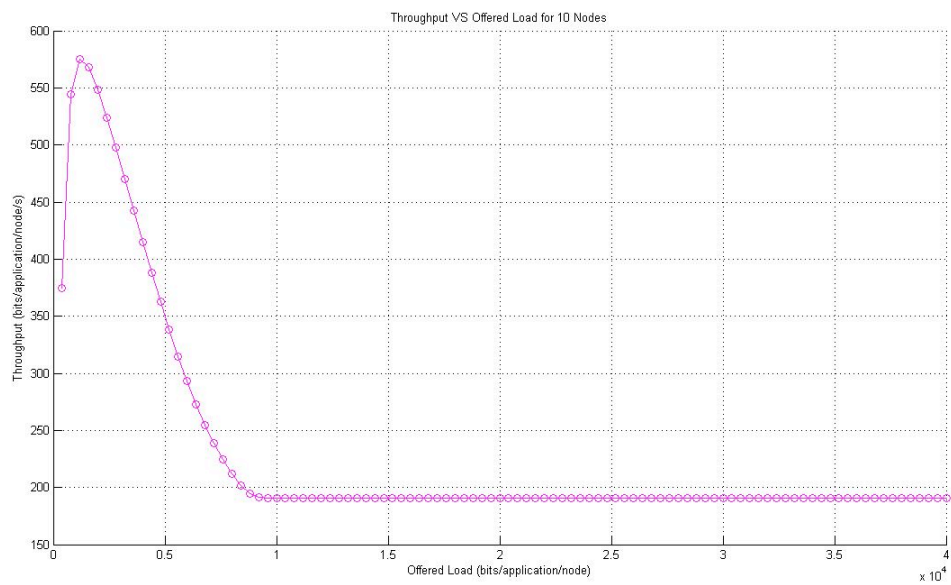


Figure 3: Average per-node throughput versus per-node offered load



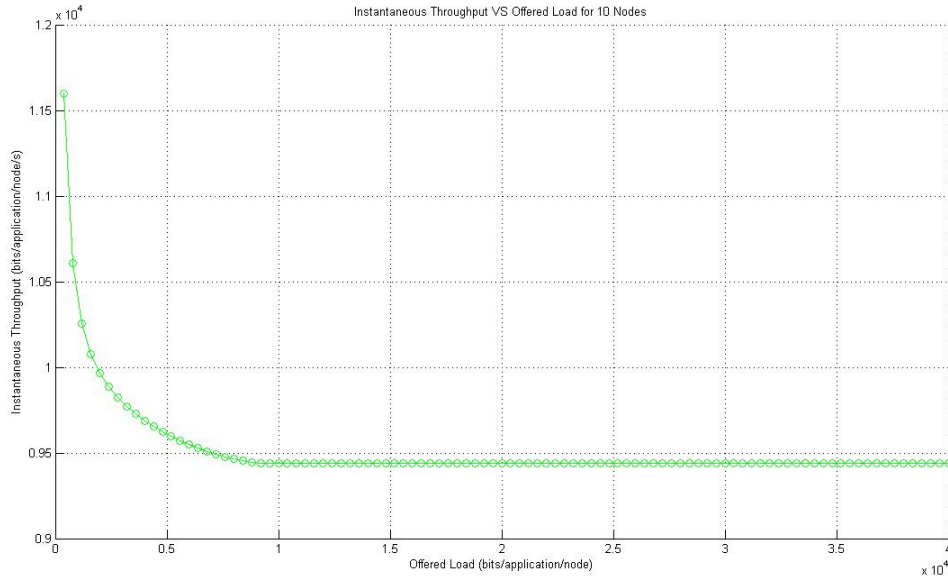


Figure 4: Instantaneous per-node throughput versus per-node offered load

## References

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