Impact of the Parameterization of IEEE 802.15.4 Medium Access Layer on the Consumption of ZigBee Sensor Motes

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***Abstract*—This paper presents an analysis of the impact that the parameterization of the CSMA/CA algorithm (employed by IEEE 802.15.4 Medium Access Layer) has on the consumption of ZigBee motes. For this purpose, the study introduces an analytical model that permits to compute the mean drain current of low duty cycle sensor motes. The results show that the energy required by the re-association process required after a packet loss cannot be neglected when setting the values of CSMA/CA parameters.**

Keywords-IEEE 802.15.4, ZigBee, CSMA/CA

I. INTRODUCTION

IEEE 802.15.4 (which describes the Physical Layer and Medium Access Control [1]) and ZigBee [2] specifications define a protocol stack for the development of short-range and low power communications for Wireless Personal Area Networks (WPANs) and Wireless Sensor Networks (WSNs). These protocols are basically intended to provide networking solutions for low-bandwidth sensor devices.

The low-cost and simplicity of IEEE 802.15.4/ZigBee compliant motes, together with their capability to configure self-organizing networks, has made this technology an attractive choice for a wide set of applications including domotic systems, health telemonitoring or industrial plant-process control.

IEEE 8021.15.4/ZigBee networks typically consist of a set of battery-powered sensor nodes ('motes'), which periodically (or sporadically) send their sensed data to one or several data sinks. To maximize the nodes' battery lifetime, the activity of the nodes' radio transceivers must be reduced so they remain most of the time in a low-power ('sleep') state. The idea is that the transceiver only has to 'wake up' (to be active) in order to sense and transmit (or receive) the data for a small fraction of time.

Many possible advantages of employing IEEE 802.15.4 are strongly affected by the configuration of the Medium Access Control (MAC) sublayer. IEEE 802.15.4 MAC employs CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) to regulate the participation of the nodes in the network. The 802.15.4 specification permits the setting of some parameters of the CSMA/CA contention algorithm (although default values are proposed). This paper investigates the effects of this parameterization on the power consumption of the motes. With this goal, an analytical model is proposed to characterize the mean drain current in an IEEE 802.15.4 node as a function of the CSMA/CA parameters, the node duty cycle and the radio transmission conditions. In contrast with other works in the literature, the model pays a special attention to the power required by the re-association procedures that packet losses provoke.

This paper is organized as follows: Section II reviews the CSMA/CA algorithm, which defines the behavior of the 802.15.4 MAC. Section III reviews the existing works that analyze the effects of the parameters of CSMA/CA on the performance of 802.15.4 networks. Section IV presents the model that computes the mean consumption of an 802.15.4 node. Section V discusses the results obtained with the proposed model. Finally, Section VI summarizes the main conclusions of the paper.

II. REVIEW OF CSMA/CA ALGORITHM

IEEE 802.15.4 standard discriminates two classes of nodes: Full-Function Devices (FFD) and Reduced-Function Devices (RFD). FFDs can assume the role of network 'Coordinators' and be in charge of the communications of a set of nodes (the 'children' or 'leaf' nodes) according to a star or a cluster-tree topology. Conversely the role of RFDs (devised for very simple 'motes' with limited resources) just allows the node to communicate (as an 'end' node) with a single FFD acting as its Coordinator. Simultaneously, the MAC layer of IEEE 802.15.4 offers two alternative operational modes: (1) Under the beacon mode, the Coordinator periodically broadcasts a special frame (a 'beacon'), which announce the existence of the Coordinator (and the corresponding WPAN) while enabling the synchronization of the children nodes. The beacon informs the children if they have any pending packet. If this is not the case and the children have not data to send (or after sending the data), both the children and the Coordinator can enter a sleep (low-consumption) mode. (2) Under the beaconless mode (which is massively implemented in commercial 802.15.4 motes as it avoids the need for synchronization with the Coordinator), the children can wake up from the sleep mode in any moment to send (or ask for) data. This obliges the Coordinator to be active at any time. Beacon mode is recommendable when the Coordinator (or the intermediate routers in a multi-hop cluster-tree) is powered by batteries. Conversely non-beacon mode typically suits applications which can be deployed by a simple star topology formed by a set of wireless sensors and a Coordinator powered from the main source

The Medium Access Control (MAC) in beaconless 802.15.4 networks is governed by non-slotted CSMA/CA. According to this protocol, nodes desiring to transmit a packet have to wait a random time chosen between 0 and (2^{BE}-1) backoff periods. A backoff period is 0.32 ms, which

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is the time corresponding to 20 symbols (the duration of a symbol is 16 µs when the nodes operate in the 2.4 GHz band, with a rate of 250 kbps or 64.5 Ksymbols/s). *BE* is the Backoff Exponent, an increasing variable that regulates the limit of the CSMA waiting times. Its initial value is set by the parameter *macMinBE*. Once this random time is elapsed, the node checks the availability of the radio medium through a Clear Channel Assessment (CCA). If the channel is detected to be busy, the exponent *BE* is incremented by 1 (up to a maximum value *macMaxBE*) and a new random waiting time is chosen and executed before performing the next CCA. This process can be repeated *macMaxCSMABackoffs* times. Thus, if the CCA fails *macMaxCSMABackoffs*+1 consecutive times, a channel access failure is assumed to have occurred, the packet is dropped and the transmissions concludes. Otherwise, if a CCA succeeds, the channel is considered to be free and the node switches its radio transceiver from the receiver state to the transmitter state. For this purpose a turnaround time of 0.192 ms (12 symbols) is reserved. Then, the device proceeds to transmit the packet and (optionally) waits for an acknowledgment (ACK) message from the receiving node (after switching again the radio transceiver from the transmission to the reception mode). CSMA/CA wait is not accomplished for the sending of an ACK, so that the receptor sends the acknowledgement as soon as it receives the packet. However, the transmitted packet or the ACK message can experience a collision due to interferences, reflections, shadowing effects or the activity of other nodes in the same 802.15.4 network. So, if the ACK is not received in a predetermined period, the node retransmits the packet after executing the aforementioned backoff algorithm of CSMA (resetting the initial value of BE to *macMinBE*). The number of times that a packet can be retransmitted is limited by the parameter *macMaxFrameRetries*. Thus, a sending failure is assumed after transmitting the packet *macMaxFrameRetries* +1 times without receiving the corresponding ACK.

Consequently the dynamics of the MAC layer of 802.15.4 standard heavily depend on these four parameters: *macMaxCSMABackoffs*, *macMaxFrameRetries*, *macMinBE* and *macMaxBE*, which are set to constant values in the nodes. The ranges and default values recommended by the standard for these parameters are tabulated in Table I.

TABLE I. ALLOWED RANGES FOR 802.15.4 MAC PARAMETERS

Parameter	***Range***	***Default Value***
macMinBE	[0-7]	3
macMaxBE	[3-8]	5
macMaxFrameRetries	[0-7]	3
macMaxCSMABackoffs	[0-5]	4

III. RELATED WORK

The effects of the MAC parameter setting on the performance of 802.15.4 networks have been recently studied by different research papers.

The study in [3] compares the reliability of 802.15.4 cluster-trees when three different sets of values are employed to define the parameters *aMacFrameRetries*, *macMaxCSMAbackoffs*, *macMaxBE* and *macMinBE*. By means of simulations with NS-2 Network Simulator tool, the study shows that 802.15.4 cluster-trees may severely underperform if the default set of parameters is utilized. The performance is computed in terms of packet delivery ratio, message latency and energy consumption per node. The same authors present similar conclusions in [4]. In this case the study, based on both simulations and some experimental results in a real testbed, are focused on single-hop topologies. Both studies employ the battery consumption model of a CC2420 radio transceiver but assuming that nodes remain in the sleep mode during the backoff periods (which is not true in actual 802.15.4 motes as recovering from this state requires a non-negligible time).

The influence of the parameter *macMaxFrameRetries* (called maximum number of retransmission times) on the throughput, packet delivery ratio and energy consumption in 802.15.4 beacon enabled networks is examined in [5]. The study proposes a Markovian chain model to characterize the performance of the network although most analysis are based on simulations with NS-2. The study concludes that a low value for *macMaxFrameRetries* reduces the power consumption. As the traffic load increases, if just one packet attempt is permitted, the throughput increases.

In [6] authors evaluate the impact of the parameterization of *macMaxCSMAbackoffs*, *macMaxBE* and *macMinBE* on the packet loss probability and packet latency in 802.15.4 beaconless 802.15.4 star topology (under unslotted CSMA/CA). The analysis (which considers different traffic loads) is also based on NS-2 simulations. The paper does not evaluate the performance in terms of battery consumption.

Most of these papers address the problem of the scalability of 802.15.4 networks. The employed simulation or analytical model normally assumes that channel occupation and packet collisions are uniquely due to the activity of other 802.15.4 sensor motes. The network scale is evaluated considering an elevated concentration of nodes in the same transmission area under relatively heavy traffic load, which are not always the actual application scenario for a ZigBee network.

In most implementations of the transceivers used for 802.15.4 networks, devices operate in 2.4 GHz ISM band. Thus 802.15.4 communications are exposed to the interferences of other popular standards such as Bluetooth and especially 802.11 (Wi-Fi). The effects of these interferences are becoming more unavoidable [7] with the expansion of the new versions of IEEE 802.11 (such as 802.11n), which employ a higher bandwidth (two channels of 20 MHz instead of the 20 MHz single channel of the previous versions). Thus, packet collisions and channel occupancy in many 802.15.4/ZigBee networks which just require a few sensors (e.g. some biosensors belonging to the WPAN of the same patient) may be basically determined by external interferences. In those scenarios network scalability is not the most relevant issue when analyzing the performance of 802.15.4 technology. The power required by the sensors will be mainly linked to the operations executed by a single node during the duty cycle and the transmission conditions imposed by the interferences.

In any case, the aforementioned studies do not take into consideration that packet losses may oblige the sensor nodes to re-associate with the Coordinator. This operation of re-association must be considered to compute the mean drain current in the nodes as they may introduce an important extra consumption in the case of frequent losses.

IV. ANALYTICAL MODEL FOR BATTERY CONSUMPTION

In this section we offer an analytical expression that permits to compute the main current drained in a sensor mote which periodically sends a data to the Coordinator.

In our analysis we consider that no polling takes places so that the only existing data traffic is upstream (i.e. from the mote to the Coordinator). The current required for the initial start-up phase is also ignored. Similarly, we assume that the power required by sensing (data acquisition and processing) can be neglected when compared with the current drained by wireless communications. However, studies such as [8] reveal that (depending of the employed sensor and the sampling frequency) the sensing process may suppose an important part of the battery consumption in the wireless mote. Under this assumption, the battery consumption basically depends on the state of the radio transceiver. In general terms, for most commercial 802.15.4-enabled motes, four states are possible: transmission, listening, idle (during CSMA/CA backoffs and turnaround time) and sleep states (for which the consumption is minimized).

Basing on the drain current and the time spent in these states, we can estimate the mean current that must be supplied to the mote to transmit a packet of n bytes flowing from the application layer:

$$I_{active}(n) = \frac{t_{onoff} I_{onoff} + t_{listening} I_{listening} + t_{tx}(n) I_{tx} + t_{idle} I_{idle}}{t_{act}(n)} \tag{1}$$

where $t_{listening}$ ($I_{listening}$), $t_{tx}(n)(I_{tx})$ and t_{idle} (I_{idle}) are the mean time (and mean current) that the mote requires in the listening, transmission and idle states, respectively, to transmit the n user data bytes. Besides t_{onoff} and I_{onoff} are the total time and current necessary to wake up and turn off the transceiver as well as to transmit the data from/to the processing unit (e.g: the microcontroller) connected to the transceiver. Finally, $t_{act}(n)$ indicates the time of the complete activity period:

$$t_{act}(n) = t_{onoff} + t_{listening} + t_{tx}(n) + t_{idle} \tag{2}$$

If T is the update period of the data (i.e. the time between two consecutive transmissions of the sensed magnitudes) we have that the mean current at which the battery is drained is:

$$I_{drain}(n) = \frac{t_{act}(n)}{T} I_{active}(n) + \left(1 - \frac{t_{act}(n)}{T}\right) \cdot I_{sleep} \tag{3}$$

where I_{sleep} is the current in the sleep mode while the term $\left(\frac{t_{act}(n)}{T}\right)$ actually represents the duty cycle of the mote.

The drain current in the different states, as well as the time t_{onoff}, are determined by the particular mote that is being utilized. Conversely, the times in the different states can be calculated as a function of the data size (n), the dynamics imposed by CSMA/CA algorithm (illustrated in Figure 1) and the frequency of the collisions and the channel access failures.

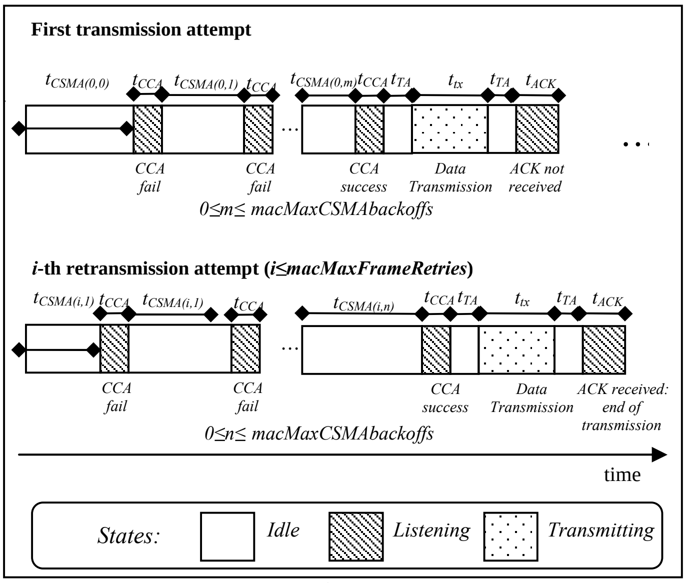

Figure 1. Timing and evolution of the transceiver state during the application of the CSMA/CA algorithm

In our analysis both processes (access failures and collisions) are assumed to follow independent and self-uncorrelated stochastic processes) [1]. In particular, if p_o denotes the probability that the channel is occupied when the CCA operation is performed and p_c is the probability of a packet collision (i.e. the probability that a packet is not acknowledged after being transmitted), we have that the average listening time (i.e. the periods in which the sensor performs a CCA or waits for an ACK) required to transmit a packet can be computed as:

$$t_{listening} = \sum_{i=0}^{mMaxF} (1-p_{CSMAfail})^i \cdot p_c^i \cdot \cdot \left\{ p_{CSMAfail} \cdot mMaxb \cdot t_{CCA} + (1-p_{CSMAfail}) \cdot \left(\overline{n}_{CCA} \cdot t_{CCA} + t_{ACK} \right) \right\} \tag{4}$$

where:

-*mMaxF* is *macMaxFrameRetries* (the maximum number of times that a transmission can be retried)

[1] Authors in [9] offer an analytical expression to compute the probabilities p_o and p_c as a function of the number of nodes contending in the 802.15.4/ZigBee network. The expression does not take into account the presence of other interfering sources. See [10] for an empirical characterization of the bit error probability as a function of the received power.

-*mMaxb* is *macMaxCSMABackoffs*, the maximum number of times that the CSMA algorithm is repeated before a CCA failure is considered.

-t_{ACK} is *macAckWaitDuration*, the maximum time (0.864 ms or 54 symbols) that the receiver waits for the ACK before proceeding with the next attempt.

-$p_{CSMAfail}$ defines the probability of suffering a channel access failure (after *mMaxb*+1 failed CCA operations):

$$p_{CSMAfail} = p_o^{mMaxb+1} \tag{5}$$

- $\overline{n}_{CCA}$ is the mean number of CCA operations which are executed in an attempt that does not finish in a channel access failure. It can be computed as:

$$\overline{n}_{CCA} = \left(\frac{1-p_o}{1-p_{CSMAfail}}\right)\sum_{i=0}^{mMaxb} p_o^i\left(i+1\right) \tag{6}$$

Similarly, the time in the idle state (t_{idle}) imposed by the CSMA waits and the turnaround time can be computed as:

$$t_{idle} = \sum_{i=0}^{mMaxF} (1-p_{CSMAfail})^i \cdot p_c^i \cdot \\ \cdot\left\{p_{CSMAfail} \cdot t_{CSMAfail} + (1-p_{CSMAfail}) \cdot (t_{CSMAnofail} + t_{TA})\right\} \tag{7}$$

where:

-t_{TA} is the turnaround time (0.192 ms or 12 symbols), reserved for the transceiver to switch from reception to transmission (in the opposite sense the turnaround time is included in *macAckWaitDuration*).

-$t_{CSMAfail}$ describes the mean time required by the (*mMaxb*+1) CSM/CA waits of a transmission attempt that concludes in a channel access failure (after (*mMaxb*+1) CCA failures):

$$t_{CSMAfail} = \sum_{i=0}^{mMaxb}\left(\frac{1}{2}(2^{\min(macMinBE+i,macMaxBE)}-1)\cdot t_{backoff}\right) \tag{8}$$

being $t_{backoff}$ the duration of a backoff period (0.32 ms or 20 symbols)

-$t_{CSMAnofail}$ stands for the mean expected delay introduced by the CSMA/CA waits of an attempt that does not finish in a channel access failure (that is to say, an attempt with a successful CCA). This time can be computed [9] as:

$$t_{CSMAnofail} = \left(\frac{1-p_o}{1-p_o^{mMaxb+1}}\right)\sum_{i=0}^{mMaxb} p_o^i \cdot \\ \cdot\left\{\sum_{j=0}^{i}\left(\frac{1}{2}(2^{\min(macMinBE+j,macMaxBE)}-1)\cdot t_{backoff}\right)\right\} \tag{9}$$

On the other hand, the mean time ($t_{tx}(n)$) that the radio transceiver is in the transmission state (for a packet payload of *n* data bytes) is:

$$t_{tx}(n) = \left(\frac{8\cdot(O_H+n)}{r}\right)\cdot\sum_{i=0}^{mMaxF}(1-p_{CSMAfail})^{i+1}\cdot p_c^i \tag{10}$$

where *r* is the binary rate of 802.15.4 (250 kbps when operating at ISM 2.4 GHz band[2]) while O_H is the total packet overhead (preamble, frame delimiter, headers of MAC, Network and Application Sublayer and CRC field) of the 802.15.4/ZigBee data packet. For our study we assume that O_H is 31 bytes. Note that in the expression (10) the summation $\sum_{i=0}^{mMaxF}(1-p_{CSMAfail})^{i+1}\cdot p_c^i$ is the mean number of times that a packet is transmitted.

A. Effect of the node re-association

In the previous model, the mean drain current of the 802.15.4 node has been computed Assuming that nodes just associate to the 802.15.4/ZigBee network during the initial start-up. Consequently the battery consumption is only caused by the cyclic transmission of user data bytes. Thus, the presented equations neglect the current required by the exchange of messages that take place during the different phases of the star-up. These phases basically consist of the active scanning phase (to detect the presence of the Coordinator), the association phase to join the Coordinator WPAN and the ZigBee binding phase (which is necessary to connect compatible ZigBee endpoints at the application layer). However, in most cases, after a packet loss (induced by collisions or by a channel access failure), the node will try to re-associate with a Coordinator[3] (if the orphan scanning is not implemented or if the realignment command is not received after the orphan scan). This re-association process may take several seconds with a mean current consumption of more than 20 mA. Aiming at incorporating the extra consumption caused by the re-associations, the mean activity time needed to transmit a packet has to be recomputed as:

$$t_{act}(n) = t_{onoff} + t_{listening} + t_{tx}(n) + p_f \cdot t_{reassoc} \tag{11}$$

where $t_{reassoc}$ is the time required for the whole re-association process (including the binding and active scan phases) and p_f defines the probability of packet loss. This probability can be directly derived [9] from the probabilities of packet collision (p_c) and channel access failure ($p_{CSMAfail}$):

$$p_f = (1-p_{CSMAfail})^{aMaxF+1}\cdot p_c^{aMaxF+1} + \\ + \sum_{i=0}^{aMaxF}\left(p_{CSMAfail}\cdot(1-p_{CSMAfail})^i\cdot p_c^i\right) \tag{12}$$

[2] The 2006 revision of the standard allows different modulations when the node works in the 868/915 MHz ISM bands. These new modulations permit to improve the bit rate up to 100 Kbps (for the 868 MHz band) and 250 Kbps (for the 915 MHz band). Conversely, in 802.15.4 devices operating in 2.4 GHz ISM band, the only permitted instantaneous bit rate is 250 kbps as long as just QPSK modulation (with 2 Megachip/s and 62.5 Ksymbol/s) is enabled

[3] It is up to the developer to define the number of losses that must take place before the device can be assumed to be orphan so that the MAC has to be reset and a new association procedure is triggered (or an orphaned device realignment procedure is performed). Our model assumes that any loss generates a re-association .

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Similarly the mean current ($I_{active}(n)$) required to transmit a packet can be redefined as:

$$I_{active}(n) = \frac{t_{onoff} I_{onoff} + t_{listening} I_{listening} + t_{tx}(n) I_{tx} + t_{idle} I_{idle} + p_f \cdot t_{reassoc} I_{reassoc.}}{t_{act}(n) + p_f \cdot t_{reassoc}} \quad (13)$$

where $I_{reassoc}$ is a new term that defines the mean current required during the whole re-association phase.

Again the values of $I_{reassoc}$ and $t_{reassoc}$ rely on the employed mote but also on the number of scanned channels to detect the presence of the coordinator, the values of the CSMA/CA parameters and the probability of suffering packet losses during the re-association.

V. Analysis of the Impact of the MAC Parametrisation

In this section, we show and comment some numerical results obtained with the previous model. To compute these results we employ the battery consumption model of the Texas Instrument CC2480 ZigBee processor which we have presented in [11]. The CC2480 processor utilizes the Z-Stack of Texas Instrument, which is one of the most widely employed implementations of 802.15.4/ZigBee stack for the deployment of wireless sensor networks. In contrast with other chips that only implement an 802.15.4 transceiver, the CC2480 processor provides full ZigBee functionality, as far as it integrates the whole Z-Stack in a single chip. The current absorbed in the different states is summarized in Table II. The analyzed device keeps the transceiver in the listening mode during the idle periods (which is not the case of other commercial ZigBee motes), so the values of I_{idle} and $I_{listening}$ coincide. The Table also includes the mean drain current and time required by the re-association process. These values were measured in the most favorable case (without losses) in which the re-association always successes. The measurement of $I_{reassoc}$ and $t_{reassoc}$ were obtained in a network configured with the default values of the CSMA/CA parameters) so that they can be regarded as a rough approximation of the typical consumption during the re-association of a 802.154/ZigBee mote. In the presented results, in order to analyze the limit case in which association has the lowest impact, we assume that just one channel is scanned.

In the presented analysis we consider the typical case of a WSN formed by sensors with a low duty cycle and a low user data payload (2 bytes). In particular we tested our model with data rates lower than 1 packet per second which implies that duty cycle is always below 4% for all results (with a percentage of time in the transmission mode always under 0.25%). Unless the network is composed by hundreds of nodes within the same transmission range, a node will create very low interference in other nodes. Consequently packet losses will be provoked by 'external' factors (e.g.: Wi-Fi or Bluetooth interferences) which can be characterized by the probabilities p_o and p_c.

We firstly analyze the impact of the initial and maximum values of the backoff exponent (BE) by changing the limits *macMaxBE* and *macMinBE* (and configuring the other parameters with the default values). Results for three different values of p_o and p_c are depicted in Figures 2 and 3. As we assume that the radio conditions (modeled by p_o and p_c) are not affected by the contention CSMA/CA algorithm, the larger the values of *macMaxBE* and *macMinBE*, the higher the consumption. Obviously this is due to the fact that CSMA/CA random waits increase for higher values of *macMaxBE* and *macMinBE.* In any case the graphs show that the increase in the consumption is especially remarkable for extremely noisy environments. On the other hand, as the noise is reduced the results rapidly converge. This is especially true in the case where the modified parameter is *macMaxBE* as long as most transmission will be executed after the first CSMA wait (which is decided by *macMinBE*) and the effect of the parameter *macMaxBE* is minimized. Figures 2 and 3 do not include the consumption due to the re-association. The previous conclusions about the effects of *macMinBE* and *macMaxBE* are completely different if that consumption is added. Fig. 4, estimated for the case in which *macMinBE* is changed (results are similar for *macMaxBE*) shows that the impact of the election of both parameters is almost negligible.

TABLE II. Summary of drain current for different 802.15.4/ZigBee operations in the mote

Operation	State	Mean Required Current (mA)	Duration (ms)
Inactivity	Sleep mode	I_{sleep}=0.00075	Variable
Transmission of a packet of *n* bytes with sensed data	Transmission of a packet	I_{tx}=30.5 mA	Variable
	Listening (& idle)	$I_{listening}$= I_{idle} =32.5 mA	Variable
	Activation/deactivation of the ZigBee processor (radio transceiver is off)	I_{onoff}=13 mA	t_{onoff}=13
Association to the coordinator (without packet losses and default CSMA parameters)	Scanning in 1 channel	$I_{reassoc}$ =26.6 mA	$t_{reassoc}$ = 2000 ms
	Scanning in 16 channels	33.8 mA	up to 27500 ms

If we consider that p_o and p_c as processes that do not depend on the CSMA/CA dynamics, the parameters *macMaxBE* and *macMinBE* do not affect the probability of having a packet loss. On the contrary, the parameters *macMaxFrameRetries* and *macMaxCSMAbackoffs* clearly determine the loss probability (see equation (12)) and consequently the consumption provoked by the re-association. Figures 5 and 6 shows the impact on the drain current of the selection of the maximum number of transmission attempts (*macMaxFrameRetries*) when the other parameters are set as recommended by the specification. Results indicate that a low selection of *macMaxFrameRetries* (under the default value of 3) may dramatically impact on the consumption, in particular as the noise decreases. This is because in less noisy environments, 3 or 4 transmission attempts are enough to avoid the packet loss and, consequently, the cost of the re-association. The importance of the packet losses can be detected if we repeat the analysis without taking into account the battery consumption provoked by the re-association. Results for this case are represented in Figure 7. Now, the value of *macMaxFrameRetries* seems to be irrelevant for environments with low noise. As the noise augments, the increase of *macMaxFrameRetries* increments the activity of the node and consequently the consumption.

The analysis of the impact of the parameter *macMaxCSMAbackoffs* (which can be observed from figures 8 and 9) offers a similar conclusion: if the number of maximum allowed CSMA waits is selected under the default value (4) the battery consumption is dramatically impacted due to the current needed by the frequent re-associations.

VI. CONCLUSIONS

This paper has investigated the effects of the parameterization of 802.15.4 MAC on the current required by IEEE 802.15.4/ZigBee sensor motes. The study is based on an analytical model that fully characterizes the dynamics of CSMA/CA algorithm. As a novelty the model also computes the power consumption provoked by the node re-association when packet loss occurs. Taking into account this extra component in the consumption, the obtained results seem to indicate that in typical WSNs (where sensors have a low duty cycle) the default values of the CSMA parameters *macMaxFrameRetries* and *macMaxCSMAbackoffs* proposed by the IEEE 802.15.4 specification exhibit a reasonable performance in terms of the expected battery lifetime.

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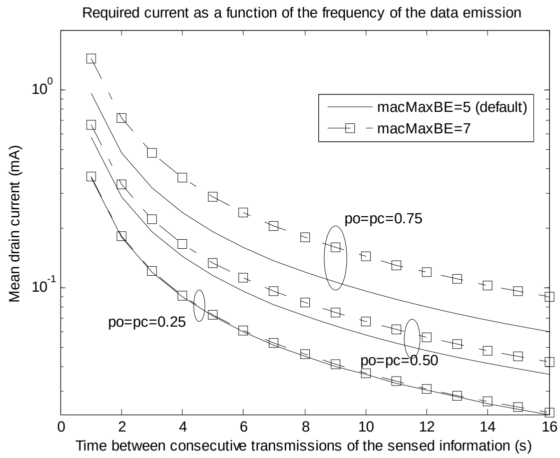

Figure 2. Mean drain current as a function of the frequency of data emission and two values of *macMaxBE.* Power consumption due to re-associations not considered

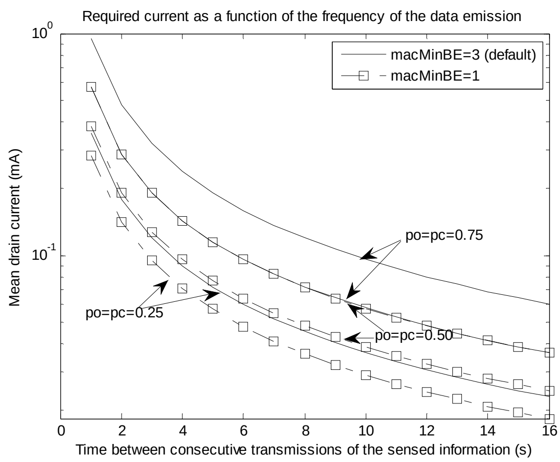

Figure 3. Mean drain current as a function of the frequency of data emission and two values of *macMinBE.* Power consumption due to re-associations not considered

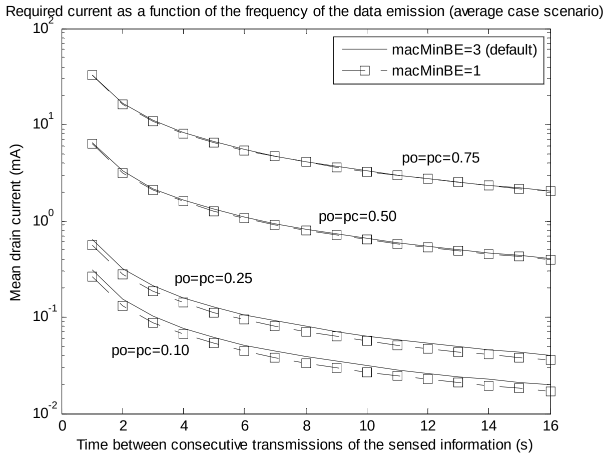

Figure 4. Mean drain current as a function of the frequency of data emission and two values of *macMinBE (*re-associations are considered)

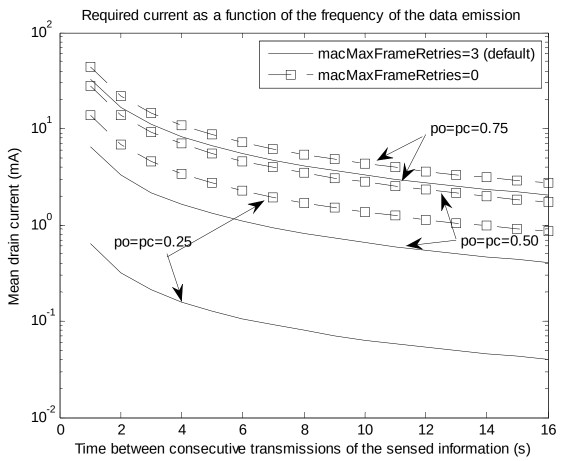

Figure 5. Mean drain current as a function of the frequency of data emission and two values of *macMaxFrameRetries (*re-associations are considered)

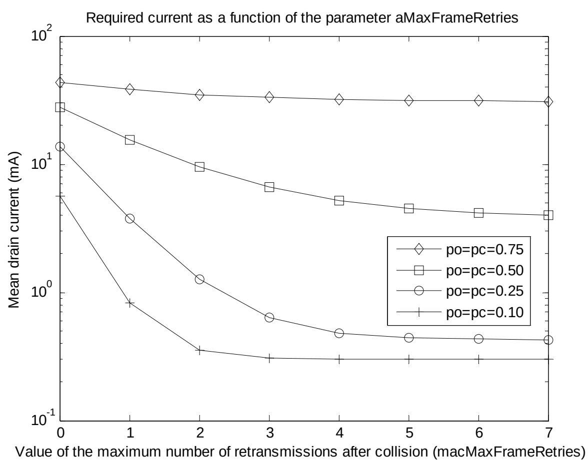

Figure 6. Mean drain current as a function of *macMaxFrameRetries* (rate=1 packet/s) *(*re-associations are considered)

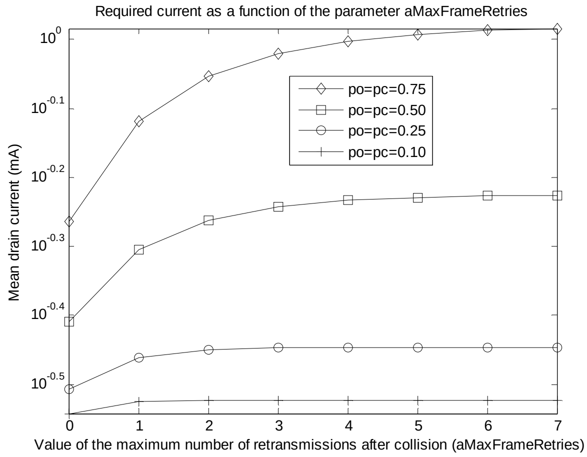

Figure 7. Mean drain current as a function of *macMaxFrameRetries* (rate=1 packet/s). Power consumption due to re-associations not considered

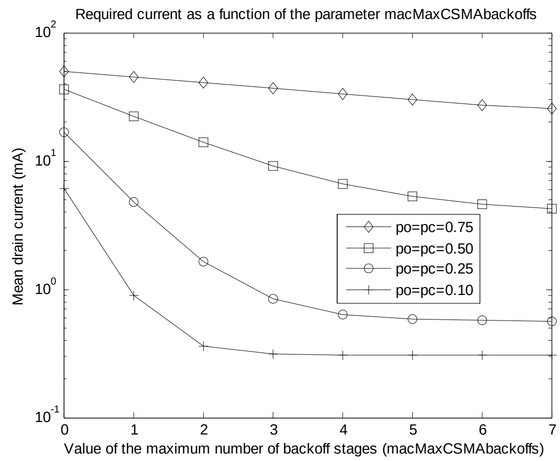

Figure 8. Mean drain current as a function of *macMaxCSMABackoffs* (rate=1 packet/s) *(*re-associations are considered)

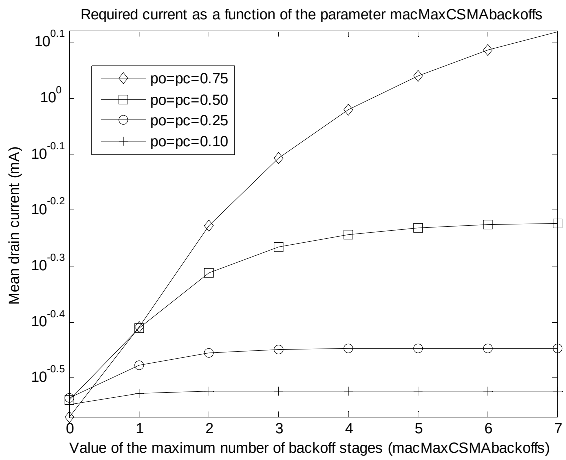

Figure 9. Mean drain current as a function of *macMaxCSMABackoffs* (rate=1 packet/s). Power consumption due to re-associations not considered