A Study on the Effect of Packet Collisions on Battery Lifetime of 802.15.4 Motes

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Abstract— **An empirical study of the power consumption of commercial IEEE 802.15.4/ZigBee motes is presented. The analysis investigates the current that is drained by an 802.15.4 based module when the radio channel is occupied or packet losses take place. For this purpose, we developed a simple testbed where problems in the radio medium are emulated in a controlled way. This is accomplished by artificially introducing in the protocol stack of the nodes a probability that a Clear Channel Assessment (CCA) failure or a packet collisions occurs. The results demonstrate the importance of CCA failures and especially packet collisions in determining the consumption of Wireless Sensor Networks with a moderate or high traffic load. Thus, problems related to the occupation of radio channel can easily more than halve the battery lifetime in networks with just some tens of nodes where data must be updated several times per second.**

Keywords-IEEE 802.15 .4/ZigBee; Wireless Sensor Networks; CSMA/CA; Clear Channel Assessmen; packet collision.

I. INTRODUCTION

IEEE 802.15.4 is a leading standard in the ambit of wireless sensor networks (WSNs). IEEE 802.15.4 [1] specifications define the physical and Medium Access Control (MAC) layers for networking architectures of low-cost, low-bandwidth, short-range wireless nodes. IEEE 802.15.4 protocols offer the basis for WSN and Personal Area Network (PAN) standards, mainly ZigBee [2] but also ISA100.11a, WirelessHART or MiWi. The 802.15.4 chipset market is growing dramatically. In 2010, ZigBee/802.15.4 chipset shipments nearly doubled while the annual revenues for ZigBee/802.15.4 modules are expected to reach $1.7 billion in 2015 [3]. Applications for smart homes are the main target of these modules, but other fields (such as smart cities, industrial plant-process, medical monitoring or wellness) are gaining attention from vendors and developers.

IEEE 802.15.4/ZigBee compliant nodes (or 'motes'), which may operate in the ISM 868 MHz, 915 MHz or 2.4 GHz frequency bands, are designed to minimize the power consumption. They are normally battery powered and used in applications where battery replacement is generally unfeasible or too costly.

Aiming at predicting the battery lifetime in a real application of 802.15.4/ZigBee technology, the current drain in the motes must be thoroughly evaluated. In most cases, wireless communications are the main source of battery usage. IEEE 802.15.4 MAC is conceived to switch off the transceiver when no packet has to be transmitted or received. As a result, the nodes may remain in a power-saving (sleep) mode most of the time, so that the batteries can be operative for years However, due to the contention method applied by 802.15.4 to access the medium (CSMA/CA), the consumption of the radio transceiver is strongly related to the status of the radio channel. Thus, if the medium is not found to be idle or a packet collision occurs (because two nodes transmit simultaneously), the protocol may induce a non-negligible increase of power consumption. In this article, we empirically analyze the impact of both the channel occupation and the packet collision on the battery drained by commercial 802.15.4/ZigBee nodes. The paper extends an initial study already published in [4] where the collisions were not taken into consideration.

The paper is organized as follows: Section 2 summarizes the behavior of 802.15.4 MAC as well as the dynamics of CSMA/CA algorithm. Section 3 briefly comments some related literature on 802.15.4/ZigBee consumption. Section 4 details the utilized experimental testbed, while Section 5 shows and discusses the performed measurements. Finally, Section 6 draws the main conclusions of the paper.

II. IEEE 802.15.4 MAC

According to IEEE 802.15.4 specification there are two types of network devices. Full-Function Devices (FFD) may perform as the 'coordinator' or central node of a star topology or otherwise interact on a peer-to-peer basis forming a multi-hop mesh network. On the other hand, Reduced-Function Devices (RFDs), which are normally battery powered devices with limited capabilities, can only communicate with its coordinator (residing in a specific FFD).

Additionally, IEEE 802.15.4 MAC layer defines two possible operational modes:

(1) Under the beacon enabled mode, the coordinator node periodically broadcasts a special frame (a beacon) informing about the existence of the network and allowing the synchronization of the 'children' nodes. Children nodes must wake-up just in time to receive the beacon from their Coordinator and keep synchronized to the network. After every beacon and during a special period called superframe, packet exchanges between the coordinator and the devices take place. When the superframe is finished, all the nodes (including the Coordinator) can enter into the sleep mode. Thus, battery consumption can be also reduced in the Coordinators (which can also act as intermediate router in a multi-hop 802.15.4/ZigBee cluster-tree). This can be an important issue if Coordinators are also powered by batteries. However, long Beacon Intervals and extended sleep periods (apart from increasing packet delay) may provoke serious problems to keep the nodes synchronized because of clock inaccuracies. In fact, most commercial 802.15.4/ZigBee motes do not support beacon mode presently, most probably due to the difficulty to enable an efficient beacon tracking in the end devices.

(2) Under the non beacon or point-to-point mode, coordinators do not send beacons. As no synchronization

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exists, end devices can wake up (from its sleep mode) in any moment to send a data packet to the coordinator. In the opposite sense, if the coordinator wishes to send a data packet to an end device, it has to wait to be polled by the end device with a specific poll frame requesting the data.

Non-beacon mode is more appropriate for networking applications which can be implemented by a simple star topology consisting in a set of wireless sensors/actuators and a Coordinator powered from the main source. In these scenarios (which correspond to many practical cases of WSN applications), the Coordinator can maintain its radio receiver active all the time so it can communicate with any device in any moment. The permanent activity of the Coordinator allows clients to be in a power saving mode for long intervals of time. Thus, the devices can wake up at their will (on a periodic or event-driven basis) just to transmit the sensed data or to poll the Coordinator to check if there is any pending message.

A. CSMA/CA Algorithm

In both the beacon or point-to-point mode, the access is regulated by CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance). This medium access protocol obliges nodes to sense the radio medium before sending a data packet. So, according to IEEE 802.15.4 MAC, nodes willing to transmit data have to contend for the radio channel following the CSMA/CA protocol. Thus a source node must initially delay its transmission a random number of slots or backoff periods of 20 symbols (0.32 ms when the standard works in the 2.4 GHz band with 62.5 Ksymbols/s). This number is selected in the range [0, 2^{BE}-1], where BE is the backoff exponent, a variable that regulates the CSMA waiting process. After this inactive time, the node performs a Clear Channel Assessment (CCA) to test the availability of the radio channel. If the channel is not detected to be free, the BE exponent is increased in one unit (up to a maximum) and the procedure is reiterated. If the CCA operation consecutively fails a predetermined number of times, a channel access failure is assumed and the packet is discarded. On the contrary, if any CCA is successful, the radio transceiver of the node switches from the reception mode to the transmission mode (as 802.15.4 communications are half-duplex) and the data frame is emitted.

Normally, the packet is only considered to be adequately transmitted if a specific acknowledgment packet (ACK) is received from the target node within a certain time interval. This ACK response is emitted by the destination upon the reception of the data packet as long as CSMA/CA algorithm does not apply for ACK packets. However, both the data packet or the ACK itself may not arrive properly because of a transmission error or a packet collision. Collisions can be produced by the activity of other 802.15.4 nodes or by interfering devices performing in the same 2.4 GHz band. When the acknowledgment is not received, the source node iterates the whole CSMA/CA process (resetting BE to its initial value). The number of times that the transmission can be repeated is also bounded by the specification. Thus, when the transmitter reaches this maximum, without any acknowledging, the MAC layer presumes a sending failure and the packet transmission is cancelled.

III. RELATED WORK

Initial empirical works on the consumption of sensors in WSNs were devoted to devices which utilize proprietary stacks or just the physical layer of 802.15.4 (see, for example, the study in [5] about the CC1000 radio module of Mica2 motes by Crossbow [6]). However, many recent theoretical, simulation-based and, in less proportion, laboratory studies have focused on modeling and characterizing the performance of 802.15.4/ZigBee WSNs.

The experimental testbeds presented in [9] [10] analyzed the coexistence of 802.15.4 with other wireless technologies (802.11 and/or Bluetooth) operating in the same 2.4 GHz ISM band. Results suggested that 802.15.4 throughput may be seriously affected by such interferences. In [11] authors compared non-beacon and beacon transmission modes in a realistic scenario with two IEEE 802.15.4 development boards through different performance metrics. The study in [12] briefly summarizes the current consumption of commercial chipsets of diverse standards for wireless communications, including Bluetooth, Ultrawideband (UWB), 802.11 (Wi-Fi) and 802.15.4/ZigBee technologies, during packet transmission and reception.

The performance of CSMA/CA algorithm in 802.15.4 networks, has been analytically modeled in many articles such as [13][14][15][16][17] for both beacon-enabled and/or beaconless topologies. The correctness of these models is assessed by simulations. On the other hand, the datasheets of 802.15.4 radio modules normally describe the current consumption of the motes for the different basic states of the transceiver (idle, sleep, transmitting or receiving modes). Thus most battery models in the literature are merely based on the data offered by the vendors, without providing any validation with actual motes.

In [18], the proposed model for slotted (beaconed) 802.15.4 MAC is employed to predict the energy consumption per received data bit. However, the utilized consumption model for the different states of the nodes is not justified. A similar study, also focused on beacon enabled cluster-trees, is presented in [19]. The study offers a mathematical formulation to compute the consumption of the ZigBee Coordinator and the end devices of the cluster-tree depending on the emitted traffic and the beacon timing. For the calculus of the power consumption the model (which assumes that the radio state is idle during the CSMA/CA backoff time) utilizes the values offered by the datasheets of Chipcon (now acquired by Texas Instruments) CC2420 radio transceiver and the Microchip PIC18LF8720 low-power microcontroller.

The consumption in beaconed networks is also characterized in [20]. In that interesting paper authors present their own measurements of the power consumption of a CC2420 transceiver (although the experimental testbed for the measurements is not described). The paper also empirically characterizes the relationship between the received power and the bit error probability. As a result, the proposed model, which takes into account the dynamics of CSMA/CA mechanism, permits to calculate the mean required energy per data bit as a function of the path losses.

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The consumption of IRIS sensors, which employ an ATMEL AT86RF230 transceiver, is studied in [21]. The performed tests allow characterizing the current drained during the basic operations of the motes (association, binding and data transmission). The deployed testbed does not isolate the motes and does not either consider the effect of the activity in the radio medium on the consumption. The study in [22] develops a simple linear model to estimate the upper lifetime bound of a WSN. The model is based on measurements of the energy consumption and execution time of different operations on a Tmote Sky sensor mote (which is provided with a CC2420 radio module). As the study is intended to predict the longest possible sensor lifetime, neither the measurements nor the model contemplate the extra energy due to failed attempts to access the channel or lost messages provoked by collisions.

The work in [23] assesses the applicability of beaconed 802.15.4/ZigBee to industrial plant control applications. The evaluation is carried out through OMNeT++ simulations. The mean energy consumption per transmitted byte is estimated by assuming the battery model of a CC1000 radio module, which is not compliant with 802.15.4 standard.

The feasibility of using 802.15.4 specifications for medical Personal Area Networks is analyzed in works such as [24][25][26]. In particular [24] presents an analytical model to compute the lifetime of a hypothetic network of implanted 802.15.4 sensors. The study, which utilizes the typical consumption of a CC2420 chip, is carried out for both beacon and beaconless modes concluding that beaconed networks present more restrictions in term of available data rate and crystal tolerance. The applicability of 802.15.4 communications in medical WSNs is investigated in [25] and [26] through systematic simulations with OPNET and OMNeT++ tools. Aiming at calculating the energy consumed per message, authors in [26] utilize the model documented in the datasheets of Jennic JN5139 ZigBee modules.

The study in [27] analyses the reliability of 802.15.4 cluster-trees when three different sets of values are employed to define the parameterization of CSMA/CA algorithm. The same authors propose in [28] a cross-layer technique to tune the 802.15.4 MAC parameters. According to this technique, which is evaluated through ns-2 simulations of both single-hop and multihop WSN, the MAC parameters are adaptively defined to minimize battery usage. By means of simulations with Castalia 3.0 simulator, the article in [29] evaluates the energy consumption of sensor nodes in a multi-hop beacon-enabled WSN when using physical and logical channel quality estimators. All these three studies also employ the battery consumption model of a Texas Instruments CC2420 radio transceiver. In [30], CSMA/CA parameterization is studied in a real testbed with Jennic JN5139 modules. Authors measure a message loss rate in the range [0-5%] although the conditions in which these losses are induced are not under control. Furthermore the goal of the measurements is to evaluate the delivery ratio of the 802.15.4 motes, so power consumption is not considered.

IV. EMPLOYED TESTBED

The employed testbed network consisted of a simple 802.15.4 star topology. The star comprises a Coordinator node (acting as the network sink) and a (leaf) end-device, which performs as the sensor mote. The network was put into operation with two MSP4302618 Experimenter Boards [31] by Texas Instrument (TI), one of the most widespread vendors of 802.15.4/ZigBee technology. These boards incorporate a last generation MSP430 microcontroller and can be extended with different TI low-power RF wireless modules. For our experiments, the boards were connected to an 802.15.4-compatible CC2520EMK [32] transceiver working in the 2.4 GHz ISM band. The nodes were powered by two AAA 1.5V batteries.

In contrast with previous and other existing 802.15.4 transceivers, CC2520EMK enters into a sleep mode during most part of the random CSMA wait periods. Consequently, the consumption of these idle CSMA waiting times (which we measured in our previous work [4]) has been practically removed. This fact is coherent with the analytical models of battery consumption existing in the literature related to 802.15.4 technology, which almost unanimously assume that transceiver is turned off during the CSMA waits. Anyhow, CCA failures increase the number of CCA operations, so it may still impact on the current consumption.

In our experiments, we measured the current drained from the batteries by the whole board. To isolate the effects of radio communications on battery utilization, all the peripherals included in the board (e.g. LED diodes) were carefully turned off for the measurements. Similarly, non utilized GPIO (General Purpose Input Output) pins were set as outputs to minimize the consumption of not-connected inputs.

As the majority of commercial 802.15.4 radio transceivers, the CC2520EMK module works in the 2.4 GHz band. This chip implements the physical layer of IEEE 802.15.4 as well as some functionalities (such as CCA operation, frame filtering or automatic ACK generation) corresponding to the IEEE 802.15.4 MAC layer. The CC24XX & CC25XX families of IEEE 802.15.4 compliant transceivers are conceived to be utilized together with Z-Stack, the version of the 802.15.4/ZigBee stack designed by TI. In the boards of our testbed, Z-stack is loaded and run by the MSP430 microcontroller.

To emulate CCA failures and packet losses, the C source code of Z-stack was intentionally modified and recompiled before being installed in the microcontroller of the sensor mote. In particular we altered the procedure that executes the CCA for unslotted CSMA transmissions in the transceiver as well as the function that informs the sending node about the reception of ACK messages. So, the CSMA wait is performed (or not) depending on a constant probability and not on the actual state of the medium (which will be always free because wired transmissions are employed). Thus, this parameter, which is defined by the user for every experiment, decides the probability of assuming that the channel is busy and, consequently, the existence of a CCA failure. Similarly, packet retransmission is uniquely based on another user-defined probability, which determines the possibility of not detecting the reception of the ACK packets (which is basically equivalent to a packet collision). In the code, for every CCA operation and every packet transmission, a pseudo-random integer between 0 and (2^{16}-1) is generated. This number is normalized to 1 and compared with the existing CCA failure (or packet collision) probability to decide if a failure (or a collision) must take place.

The utilized testbed for the consumption characterization is depicted in Figure 1. The goal is to measure the current required by a generic sensing node (performing as an 802.15.4 end device) when it regularly sends data to a sink node (with the role of the Coordinator). This upstream traffic closely approximates the typical application of a Wireless Sensor Network.

As radio modules incorporate an SMA antenna connector, the communication between the motes is achieved through a 0.5 m long SMA-to-SMA cable. Thus, the interferences of any other device operating in the same unlicensed band (e.g. through Bluetooth or Wi-Fi connections) are avoided. The transmission power of the transceiver is chosen to be 0 dBm (1 mW) while the attenuation provoked by the cable and each SMA connector is under 0.1 dB/m and 1 dB respectively. Consequently, the power at the receptor is about -2 dBm, which is far from the limits imposed by the saturation of the radio receptor (6 dBm) and by the transceiver sensitivity (-98 dBm). This guarantees that any detected CCA failure or packet collision is caused by the failure and collision probabilities introduced in the ZigBee stack of the end device.

To estimate the mean current required by the sensor mote for the different considered scenarios, we utilized a true-rms Fluke 289 digital multimeter. For the range of 50 mA, this piece of equipment measures the DC current with an accuracy of 0.05% and a resolution of 1 µA. The multimeter is connected between the voltage source (of 3 V) and the supply pin of the experimental board (as it is reflected in Fig.1). In this board, the consumption of the transceiver or the microcontroller cannot be easily segregated from that of the rest of the board. Therefore the measurements compute the current drained by the whole board. After minimizing the effects of the peripherals, this consumption is essentially caused by the aggregated activity of the microcontroller and the radio transceivers.

The applications loaded in the motes were part of a control application provided with the demonstration kit. In the application, the end device, acting as a switch (e.g. a lamp switch), may send a simple command to the coordinator (which could be located in a bulb). In our experiments this command are programmed to be transmitted at regular intervals with a programmable periodicity. Each command is conveyed in a single 802.15.4/ZigBee packet with a MAC data payload of 25 bytes (9 bytes of application data plus the 16 byte overhead introduced by the ZigBee Network Layer and the ZigBee Application Support Sub-Layer). This scenario can represent the typical case of a ZigBee WSN where sensors periodically transmit a simple parameter which can be codified in some bytes, within the payload of a small packet.

V. OBTAINED RESULTS

We executed a series of systematic experiments using the previous testbed and modifying the probabilities of a CCA failure and packet collision. In all the experiments, the algorithms involved in the CSMA/CA access method were parameterized with default values defined by the 802.15.4 specification. (e.g. the minimum and maximum value for the Backoff exponent).

Packet rate was fixed to 5 data packets per second. In addition, the end device (in a typical ZigBee application) is programmed to poll the Coordinator in a periodic basis to request possible data. In our experiments, this poll process was programmed to be executed just one time every 5 seconds. Similarly, after sending any packet, end devices normally transmit a poll packet to the Coordinator to enable a response to the sent data. In our case, the time between the data packet and its corresponding poll packet was also set to a maximum of 5 seconds (thus, only one poll frame of this type is transmitted for every 25 packets). As a consequence, poll packets have a minor impact on battery consumption, which is mainly due to the data packets.

Different transmission scenarios were considered by varying the probabilities of experiencing a CCA failure or a packet collision.

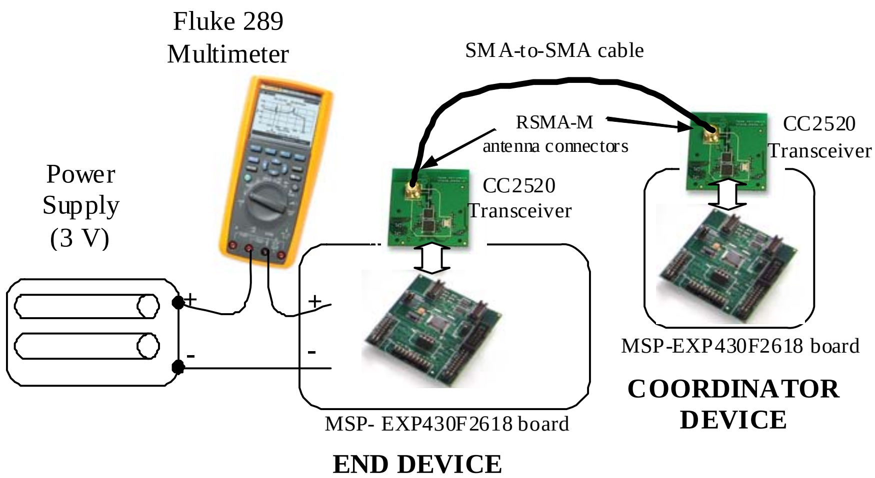

Figure 1. Experimental testbed

Authors in [16] analytically compute both the CCA failure probability and the packet collision in a beaconless 802.15.4 network. Their analysis assume that motes only employ carrier sensing techniques so that only the activity of other 802.15.4 nodes in the network can cause CCA failures. This implies that external interferences (by devices of other technologies working in the same band) and other channel errors are not considered to compute the CCA failure or packet collision probabilities. Even neglecting the effects of the interferences, author show that for data rates of 5 packets per second and per node, networks of 10 to 100 nodes may suffer probabilities of CCA failure and packet collisions in the range [0.1-0.9]. These probabilities clearly drop only if the nodes present a lower activity. Therefore, even in networks with a not very high number of nodes, a high rate of CCA failures and packet collisions must be expected if the motes update and transmit their sensed data frequently. Interferences just can deteriorate this behavior.

Taking into account this realistic data, we performed different experiments by modifying the probabilities of CCA failure and packet collisions from 0.0 (ideal case where the channel is always available and no loss occurs) to 1.0 (worst case where channel is always busy and all packets are lost), with constant increments of 0.1.

The measured mean current drained by the end device is depicted in Figure 2. We repeated the experiments for three limit cases: a) CCA operations may fail but no collision takes place; b) only packet collisions can occur (CCA always successes); c) CCA operation and collisions happen with the same probability. The two first cases allow isolating the effect of each process whereas the third case corresponds to the most realistic situation where collisions and CCA fails are strongly correlated.

Each displayed point in the figure represents the measurement of the mean drain current after the transmission of 9000 packets (about 30 minutes) under a constant probability of CCA failure and/or packet collision.

With collision probabilities higher than 0.8, the losses cause the sensor to disassociate from the coordinator very often. This resulted in an extremely high consumption (25.662 mA) as the end device is trying to re-associate to the Coordinator almost permanently.

The graphs show that CCA failures increase the power consumption. In particular, the extra consumption due to the repetition of the CCA operation ranges from 10% to 50%. The rise rate in the battery usage is accelerated for higher values of the probability of a CCA failure. This can be explained by the fact that the utilized version of ZigBee stack tries to retransmit the data packet once again whenever a channel access failure occurs (after 5 consecutive CCA failures). Thus, the increase does not follow a linear function.

On the other hand, packet collision is shown to have a higher impact on the battery usage. As long as the packet has to be retransmitted for every loss, the consumption rapidly grows with the collision probability. Figure also illustrates that the combination of both effects (collisions and CCA failures) strongly degrades the lifetime of the battery. So, for this more realistic situation, the drain current rockets for collision (and CCA failure) probabilities higher than 0.4. This fact should be carefully taken into account when designing a WSN where sensors are expected to have a short duty-cycle. In that scenario, collisions and channel access failures could easily reduce the battery lifetime (in a network with some tens of nodes) by a factor of 3 or 4 with respect to the ideal case with a free radio medium. Moreover, the employed uncorrelated model which decides the timing of CCA failures or packet losses can also be considered too optimistic. In fact, the periods of channel occupation or the activity of interferences normally follow correlated patterns which are better characterized by Markov processes. The existence of long periods of channel occupancy or other radio channel problems should even decrease the node lifetime in a real WSN application.

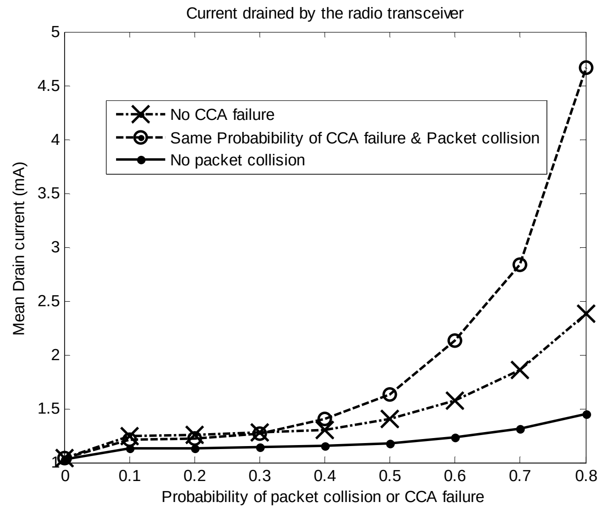

Figure 2. Average measured drain current as a function of the probability of CCA failure and/or packet collision.

VI. CONCLUSIONS

This paper has empirically studied the impact of CCA failures and packet collisions on the current consumption of an actual 802.15.4/ZigBee mote.

While other practical studies in the literature introduce CCA failures or packet losses in the 802.15.4 communications by adding wireless interfering sources, our study has implemented a simple testbed of two actual nodes where channel occupation and packet collisions are emulated via software by altering the protocol stack of the motes. Thus, the utilized testbed has permitted to carry out a set of systematic and repeatable measurements of the battery consumption for diverse preset values of the channel occupation and packet collision probabilities (which is not possible in a scenario where radio communication problems are induced by a background wireless traffic.)

Achieved results indicate that the combination of CCA failures and packet collisions may produce a severe drop in the battery lifetime of the nodes.

The paper has presented the preliminary results of an ongoing investigation. Future work should investigate the effects of other factors, considering a more complex stochastic process to simulate and correlate radio channel access failures and packet collisions. The accuracy of theoretical consumption models in the literature should be equally contrasted against the obtained measurements.

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