Performance Study of IEEE 802.15.4 Using Measurements and Simulations

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***Abstract*— IEEE 802.15.4 was developed to meet the needs for simple, low-power and low-cost wireless communication. In the past couple of years it has become a popular technology for wireless sensor networks. It operates primarily in the 2.4 GHz ISM band, which makes the technology easily applicable and worldwide available. However, IEEE 802.15.4 is potentially vulnerable to interference by other wireless technologies working in this band such as IEEE 802.11 and Bluetooth. This paper gives a short overview of the IEEE 802.15.4 and carefully analyzes the properties and performance of IEEE 802.15.4 through measurement of the RSSI, PER and run lengths distribution using real off-the-shelf hardware. Furthermore we present simulation results from the evaluation of the IEEE 802.15.4 MAC protocol. Finally, we address the coexistence between IEEE 802.11 and IEEE 802.15.4 and measure the impact these two wireless technologies have on each other when operating concurrently and in range.**

I. INTRODUCTION

In the past decade several short range wireless technologies have been developed as an answer to the increasing demand for portable and flexible connectivity. In addition to the upsurge in the deployment of IEEE 802.11 based WLANs, few complementary low-power and low-cost technologies, among which IEEE 802.15.4, are establishing their place on the market as enablers of the emerging wireless sensor networks (WSNs). The IEEE 802.15.4 standard was specifically developed to address a demand for low-power, low-bit rate connectivity towards small and embedded devices. Furthermore the standard is trying to solve some problems that were inadequately taken into account by Bluetooth technology.

Since the release of the standard in 2003 and the emergence of the first products on the market there have been several analytical and simulation studies in the literature, trying to characterize the performance of the IEEE 802.15.4 [1], [2]. Furthermore, a lot of effort has been put on the energy efficiency characterization and optimization of the protocol stack for wireless sensor networks [3]–[6]. Unfortunately there is not enough reported results on the practical insights gained from measurement campaigns. The IEEE 802.15.4 and IEEE 802.11b/g are envisioned to support complimentary applications and therefore it is very likely that they will be collocated. Since both types of devices operate in the 2.4 GHz ISM frequency band, it is of great importance to understand and evaluate the coexistence issues and limitations of the two technologies. According to [7] the IEEE 802.15.4 network has little or no impact on IEEE 802.11's performance. However IEEE 802.11 can have a serious impact on the IEEE 802.15.4 performance if the channel allocation is not carefully taken into account [8]. Both of these studies are theoretical and simulation based.

In this paper we present our simulation studies and measurements with actual IEEE 802.15.4 products. We are particularly interested in finding out useful metrics to design reliably home or outdoor sensor networks. Due to that we focused to find out not only simple coverage and throughput values, but paid a special attention to measure error run lengths characteristics and verify interference assumptions between IEEE 802.15.4 and IEEE 802.11.

The reminder of the paper is organized as follows: section II gives an overview of the IEEE 802.15.4 standard. In section III we present results from measurements made to characterize the basic behavior of IEEE 802.15.4 both in indoor and outdoor environments. The performance evaluation of the IEEE 802.15.4 MAC is given in section IV. In section V we study the coexistence between IEEE 802.11b/g and IEEE 802.15.4. Finally, we conclude the paper in section VI.

II. OVERVIEW OF THE IEEE 802.15.4

We shall now give a brief overview of the IEEE 802.15.4 standard [9], focusing on the details relevant to our performance study. For a more comprehensive introduction to the IEEE 802.15.4 technology, as well as some foreseen application scenarios, we refer the reader to [1].

The 802.15.4 is a part of the IEEE family of standards for physical and link-layers for wireless personal area networks (WPANs). The WPAN working group focuses on short range wireless links, in contrast to local area and metropolitan area coverage explored in WLAN and WMAN working groups, respectively. The focal area of the IEEE 802.15.4 is that of low data rate WPANs, with low complexity and stringent power consumption requirements. Device classification is used for complexity reduction. The standard differentiates between full function device (FFD), and reduced function device (RFD), intended for use in the simplest of devices. An RFD can only communicate with an FFD, whereas an FFD can communicate with both other FFDs, and RFDs.

The IEEE 802.15.4 supports two PHY options. The 868/915 MHz PHY known as low-band uses binary phase shift keying (BPSK) modulation whereas the 2.4 GHz PHY (high-band) uses offset quadrature phase shift keying (O-QPSK) modulation. Both modulation modes offer extremely good bit error rate (BER) performance at low Signal-to-Noise Ratios (SNR). Figure 1 compares the performance of the 802.15.4 modulation technique to Wi-Fi and Bluetooth. The graph clearly illustrates that IEEE 802.15.4 modulation is anywhere from 7 to 18 dB better than the IEEE 802.11 and IEEE 802.15.1 modulations , which directly translates to a range increase from 2 to 8 times the distance for the same energy per bit, or an exponential increase in reliability at any given range.

The IEEE 802.15.4 physical layer offers a total of 27 channels, one in the 868 MHz band, ten in the 915 MHz band, and, finally, 16 in the 2.4 GHz band. The raw bit rates on these three frequency bands are 20 kbps, 40 kbps, and 250 kbps, respectively. Unlike, for example, Bluetooth, the IEEE 802.15.4 does not use frequency hopping but is based on direct sequence spread spectrum (DSSS). This is very relevant for our measurements on inter-technology interference reported in section V. For more details on the physical layer design, such as the modulation schemes used, we refer the reader to [9]. In this paper we are focusing solely on measurement in the 2.4 GHz frequency band as that is the area where inter-technology problems can be prominent and due to the fact that it is a tempting for larger scale sensor deployments.

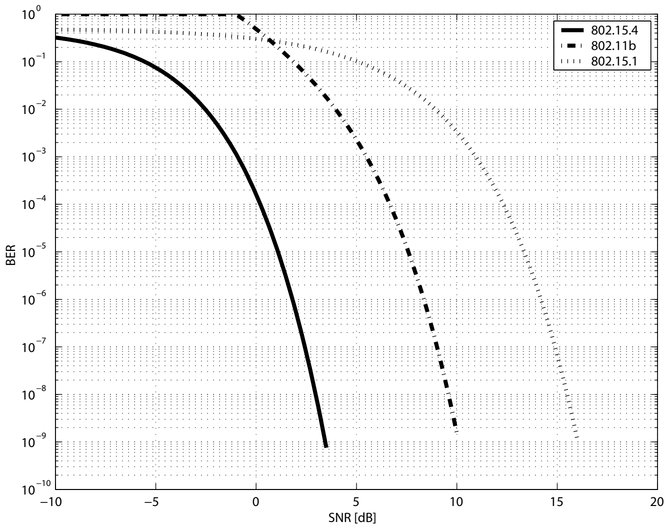

Fig. 1. Theoretical bit error rate in an AWGN channel for IEEE 802.15.4, IEEE 802.11b and IEEE 802.15.1

The IEEE 802.15.4 MAC layer is fundamentally that of CSMA/CA system together with optional time slot structure and security functionality. The network can assume either a star topology, or operate in peer-to-peer mode. In each case an FFD device acting as a coordinator manages the local network operations.

The standard defines four frame types, namely beacon frames, data frames, acknowledgment frames and MAC control frames. Beacon frames are used by the coordinator to describe the channel access mechanism to other nodes. Two fields found in beacon frames are relevant for further discussion. The beacon order (BO) subfield specifies the transmission interval of the beacon, called the beacon interval (BI) by the identity $BI = B \times 2^{BO}$, where B is a base superframe duration, and $0 \leq BO \leq 14$. If $BO = 15$ the coordinator transmits beacon frames only when requested to do so, such as on receipt of a beacon request command. The superframe order (SO) subfield specifies the length of time during which the superframe is active, superframe duration (SD), as $SD = B \times 2^{SO}$ symbols. If $SO = 0$, the superframe following the transmission of the frame is not active. Data frames are used to send varying amount of payload (2–127 bytes), while acknowledgment frames are used to increase reliability for data frame and control frame transmissions. Finally, the control frames are used to carry out network management functions, such as association to and disassociation from the network.

III. CHANNEL MEASUREMENTS

Depending on the RF environment and the power output consumption required for a given application, IEEE 802.15.4 compliant wireless devices are expected to transmit in a range of 10–75 meters. In this section we evaluate through measurements, using off-the-shelf IEEE 802.15.4 radio, the PER (Packet Error Rate) and the RSSI (Received Signal Strength Indicator) both in indoor and outdoor environments in order to examine the basic characteristics of the IEEE 802.15.4 communication channel. Additionally we measured the run lengths distribution both in indoor and outdoor environments. We used the results to calibrate the error model in ns-2 in order to more realistically map the measurement and the simulation environment used for performance analysis of the MAC in section IV.

The measurements for PER and RSSI in the indoor scenario were made up to 32 meter distance between the transmitter and the receiver with PSDU sizes of 20, 40, 80 and 127 bytes. For both the transmitter and the receiver we used the evaluation CC2420EB board from Chipcon [10]. The system operates at 2.4 GHz band and offers a bit rate of 250 kbps. In the outdoor scenario the measurements were done up to maximum of 70 meters between the sender and the receiver and fixed packet size of 20 bytes. As a transmitter in this case, we used a Telos MoteIV running TinyOS [11]. In every measurement event 5000 packets were sent at a rate of 20 packets/s. The results were averaged over several trials. The respective results are shown in Figure 2 and Figure 3 for the indoor environment and Figure 4 and Figure 5 for the outdoor environment. Packet error rate measurements indicate that the 802.15.4 radio has a rather good performance indoor since the PER is less than 3.5% at 32 m distance. It should be further mentioned that the indoor measurements were done in a softly partitioned office environment without any serious obstacles for the propagating signal. The outdoor measurements were performed only with the smallest possible packet length, because we wanted to test the behavior of the 802.15.4 for real outdoor applications where the aim is to send as little data as possible to be more energy efficient.

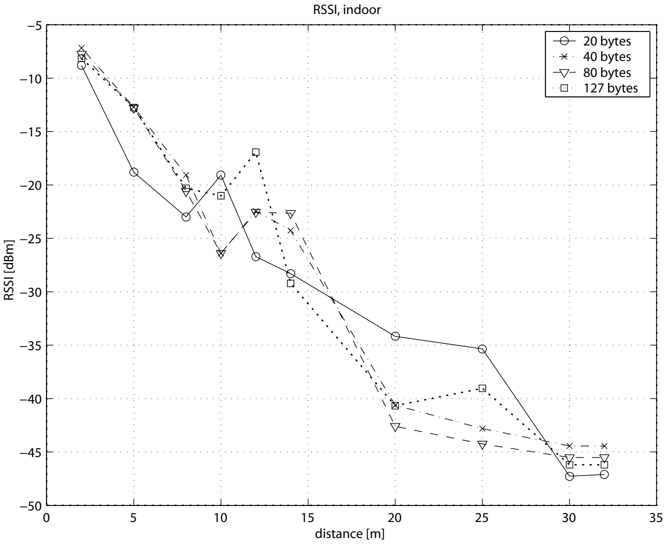

Fig. 2. RSSI in indoor environment.

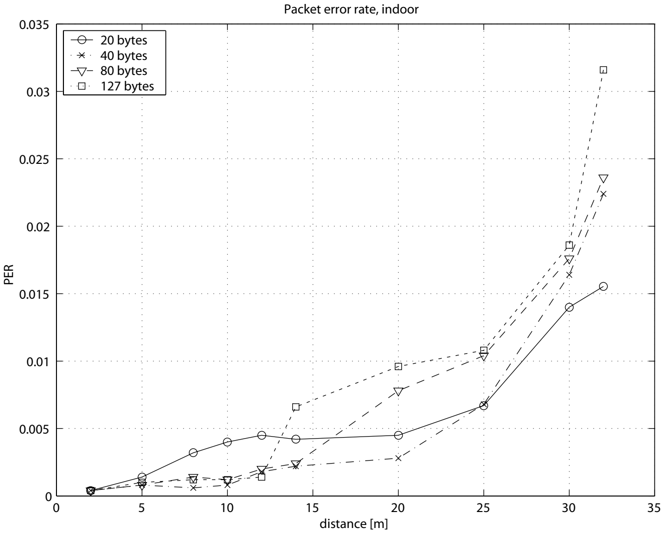

Fig. 3. Measured PER in indoor environment.

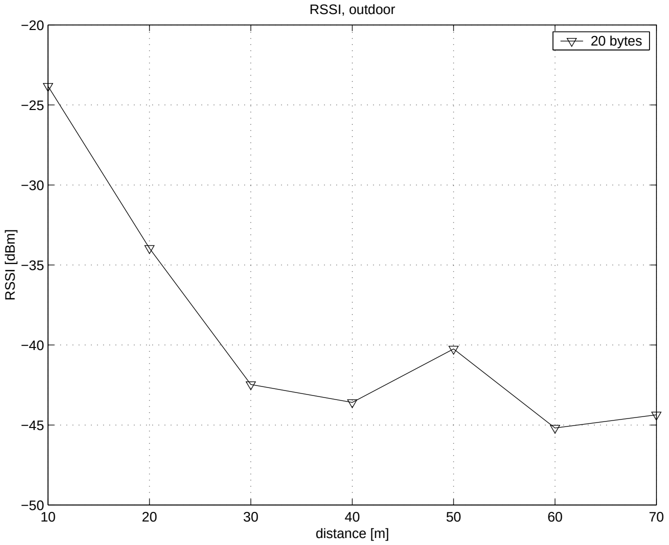

Fig. 4. RSSI in outdoor environment.

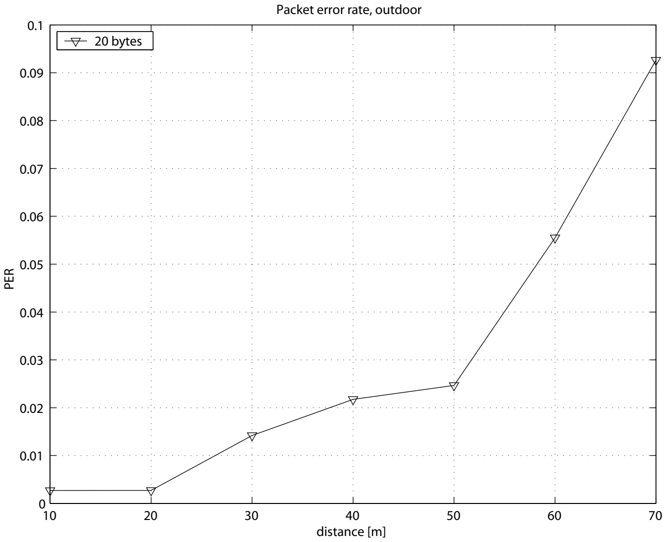

Fig. 5. Measured PER in outdoor environment.

Recent studies have revealed the existence of three different reception regions in a wireless link: connected, transitional and disconnected. The transitional region is often quite significantly characterized by high variances in the reception rates and the asymmetric connectivity [12]. It is particularly important concept, since we are ultimately interested in how to dimension reliably home and sensor networks. Being in the transitional region can have a significant impact on the performance of the upper-layer protocols and particularly on the routing protocols. The unpredictability in the transitional region (due to high variance of the link quality) itself makes many adaptive algorithms suboptimal or unfair. Figure 6 shows the packet reception rate ($PRR = 1 - PER$) vs. distance for an off-the-shelf receiver in a real indoor and outdoor environment. Our results show that the outdoor channel is not very stable since the transitional region is rather large. We assume that this is due to multi-path fading the wireless link experienced during the measurements.

As mentioned earlier in this section, in order to appropriately chose and error model for the simulation studies, we measured the run lengths distribution in a single IEEE 802.15.4 link in indoor and outdoor environment. We want to remind the reader that a run is defined as a sequence of error-free packets. We compared the results with the Complementary Cumulative Distribution Function (CCDF) of the run lengths

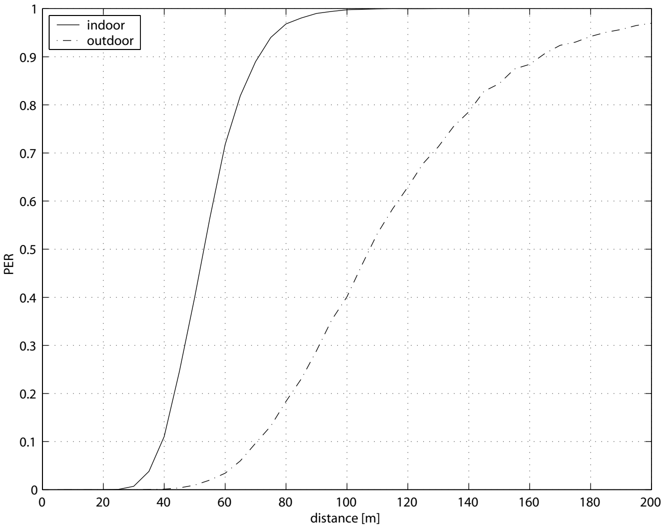

Fig. 6. Analytical prediction of the transitional region.

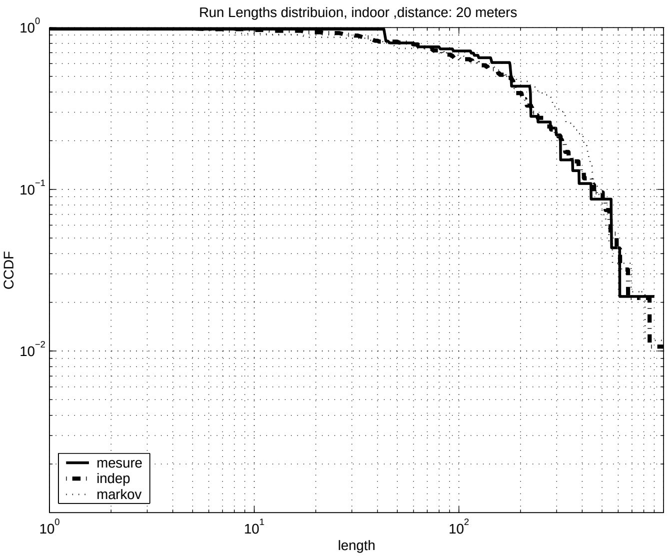

Fig. 7. Run lengths distribution, indoor, distance 20 m.

of the independent (Bernoulli)[1] and two-state Markov (Gilbert-Elliot) error model[2]. The results from the comparison in the indoor environment are shown on Figure 7. It can be noticed that both error models reproduce the measured run lengths distribution very well for communication distance of 20 m and packet size of 35 bytes (MAC load of 20 bytes). The reason for the good fit of the both error models, which are suitable for modelling of a wired channel, is the good reliability and stability of the 802.15.4 channel up to 30 m (see Figure 3). In the outdoor environment (we do not show the results due to space limitations) both error models fit very well up to 20 m, where the PER is less than 1%. For longer distances both the independent and the two-state Markov model do not closely follow the measured results. The model that fits better is the two-state Markov model with a transition probability from bad to bad state given by a parameter $\alpha = 0.5$. In the previously mentioned Markov model α was set to 0.001.

IV. PERFORMANCE EVALUATION OF THE MAC PROTOCOL

The previous section gives a rather comprehensive characterization of how single active IEEE 802.15.4 channel behaves in indoor and outdoor scenarios. In order to understand how these figures can be expected to change when several transmitters attempt to access the channel, several simulations were performed. The simulations were carried out with ns-2 simulator [13], using the IEEE 802.15.4 extension developed at City College of New York [14]. We did take care to check that the simulator was calibrated to reproduce measured statistical results in case of single point-to-point links. Parameters varied were number of nodes attempting to send data, the payload size, backoff and superframe orders, and the duty cycle of the MAC. Star topology was used throughout, with all nodes located close enough as to prevent hidden terminal problem.

First simulations were run in a slotted mode, with minimal backoff and superframe order parameters. Figure 8 shows the obtained throughput as a function of the offered load for various node counts. Clearly the obtained throughput is far from the theoretical transmission capacity. This shows that the low backoff and superframe orders should only be used if the resulting short channel access time is critical, and the offered load is very low. For all other cases the resulting large number of collisions is inefficient energy-wise and leads into very poor utilization of the channel.

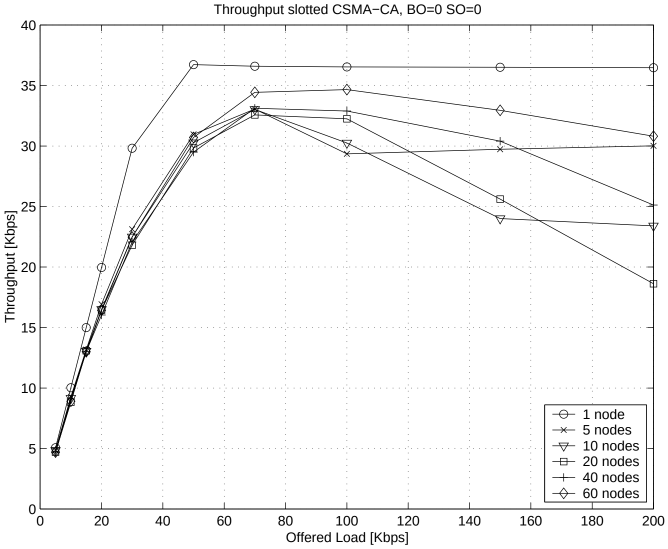

Fig. 8. Throughput of slotted CSMA-CA with BO $= 0$ and SO $= 0$.

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[1] The independent error model simply assumes that the failure of a frame transmission is given by a fixed probability p. This, of course, implies that there are no correlations between the success of successive frame transmissions.

[2] The Gilbert-Elliot error model uses two state Markov chain to model burst errors. It hast two states, good and bad, and the probabilities for changing the state are given in a transition matrix.

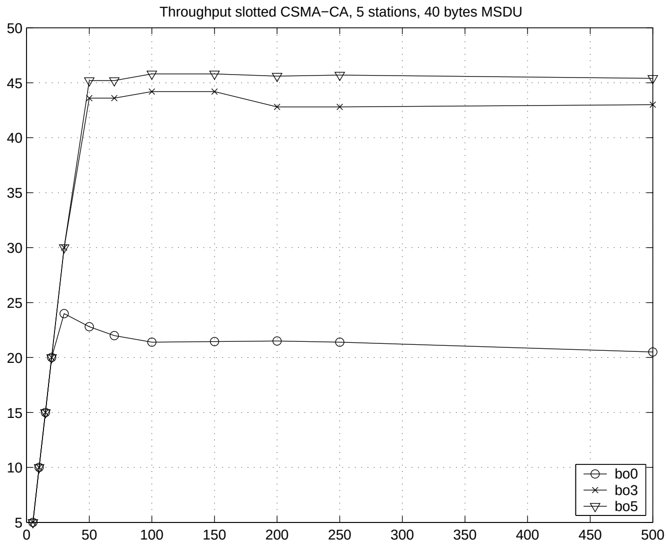

Fig. 9. Throughput of slotted CSMA-CA, 5 station, 40 bytes MSDU.

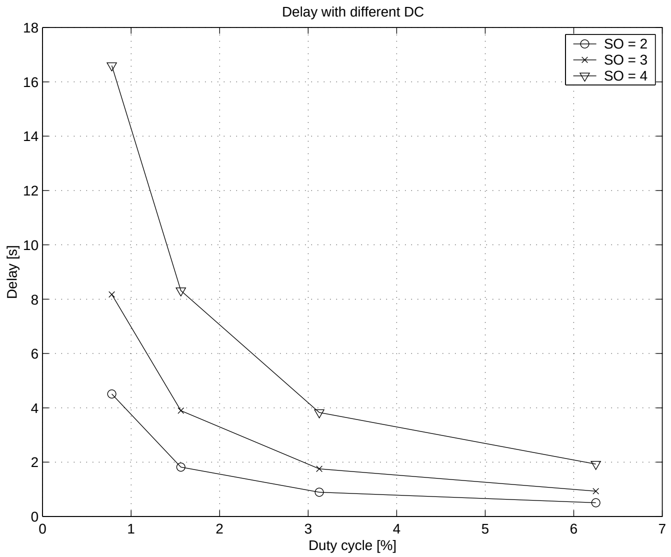

Fig. 10. End-to-end delay vs. duty cycle.

The channel clearly becomes saturated very fast, but until that a good utilization level is obtained. Additionally, in Figure 9 it is seen that relatively small increases in the backoff order are beneficial to the throughput achieved.

Although the IEEE 802.15.4 specification has been designed to minimize the active power consumption of compliant devices, the goal of many months operation from a single battery cannot be achieved by active power reduction alone. Low power consumption can be achieved by letting the device sleep for the majority of its operational time, only waking it into active mode for brief periods. Enabling such low duty cycle operation is at the heart of the IEEE 802.15.4 standard, and it is an important consideration during the design of the network device. We conclude this section by observing the effect of varying the duty cycle on end-to-end delay. The intuitive $1/DC$ behavior of the delay is clearly seen on Figure 10, further highlighting the basic tradeoff between latency and power consumption.

V. COEXISTENCE WITH IEEE 802.11 TECHNOLOGY

In the past decade number of wireless communication devices were developed to operate in the unlicensed 2.4 GHz ISM band. Since many of them are ubiquitous today, the issue of coexistence and/or interference between different technologies among which IEEE 802.11b/g, Bluetooth, IEEE 802.15.4 etc. is getting more importance.

In this regard we were interested in the interference effects that might appear when communication between two IEEE 802.15.4 and two IEEE 802.11b/g nodes is taking place simultaneously. Figure 12 depicts the channel placement of IEEE 802.15.4 in the 2.4 GHz band in respect to the three non-overlapping channels of IEEE 802.11. The interference measurement were done on a topology as shown in figure 11. We studied two cases: firstly IEEE 802.11b interfered an ongoing communication between two IEEE 802.15.4 devices and secondly IEEE 802.15.4 interfered both 802.11b and 802.11g transmissions. Measurements were done for various offsets between the central frequencies of IEEE 802.15.4 and IEEE 802.11b/g channels. In the first case we observed the PER of the 802.15.4 communication for different packets sizes. The results are shown in Figure 13. It can be clearly seen from the graph that the performance degradation is severe if the operational frequencies are not shifted by at least 7 MHz. As expected the PER will be larger for bigger packet sizes since the larger packets are more prone to errors than the smaller once.

In the second case the IEEE 802.15.4 interferer was transmitting packets of 127 bytes in length with a channel occupation of 5%. The results (which we do not present here due to space limitations) show that the interference impact on 802.11b can be seen only when the offset between the central frequencies is 2 MHz and the 802.11b packet length is longer than 600 bytes. Interference on the IEEE 802.11g transmission is not noticeable most likely due to the robustness of the OFDM modulation used.

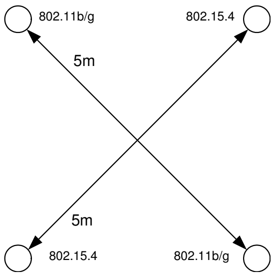

Fig. 11. Interference testbed.

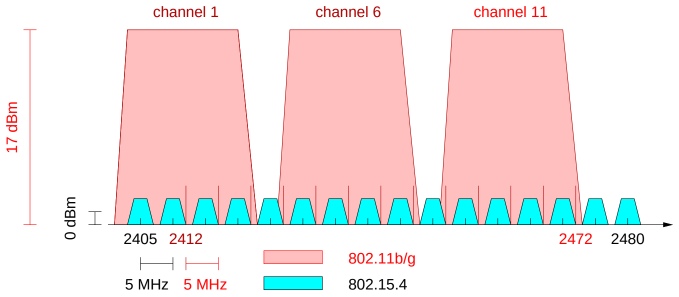

Fig. 12. IEEE 802.11b/g and IEEE 802.15.4 channels.

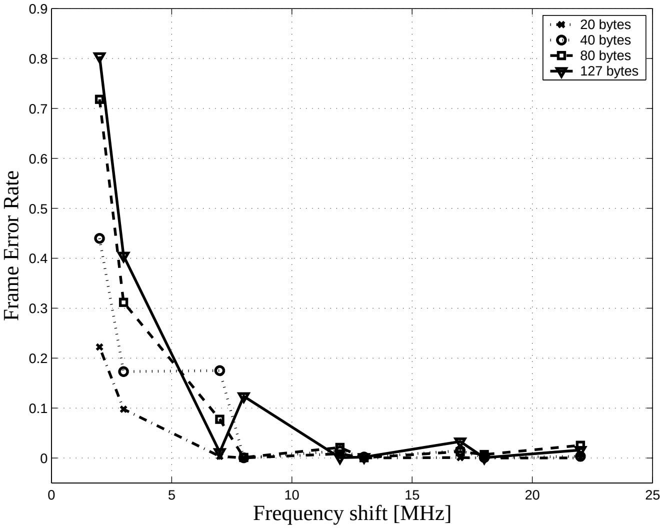

Fig. 13. IEEE 802.15.4 FER when interfered by a 802.11 transmission.

VI. CONCLUSION

The overall goal of this paper was to contribute and help through measurements and simulations towards dimensioning of the sensor networks for future applications using IEEE 802.15.4 technology. We examined the reliability of the point-to point communication with a real IEEE 802.15.4 hardware by measuring the RSSI, PER and the run lengths distribution both in indoor and outdoor environments. Using these measurements we calibrated the ns-2 simulator in order to be able to produce more real simulation environment and evaluate the IEEE 802.15.4 MAC in a reliable way. Our results clearly showed that the simulated throughput is far away from the maximum transmission capacity of the channel and higher throughput can be achieved by relatively small increase in the backoff order. We also confirmed that the end to end delay is very much correlated with the duty cycle: lower duty cycles enable lower power consumption but on the other hand increase the latency.

Since one of the PHY modes of the IEEE 802.15.4 operates in the 2.4 GHz ISM band the coexistence with the other devices working in the same band (e.g. IEEE 802.11 and Bluetooth) is of great importance for maintaining the desired performance. We analyzed through measurements the coexistence impact IEEE 802.11b/g has on 802.15.4 and vice versa. We can conclude, based on our results, that the IEEE 802.15.4 operation has practically no negative influence on the concurrent IEEE 802.11 communication. However if no care is taken about the operational channels of the two technologies, the IEEE 802.11 itself will have a negative effect on the performance of the IEEE 802.15.4 transmission. Our measurement showed that there should be at least 7 MHz offset between the operational frequencies for a satisfactory performance of the IEEE 802.15.4.

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