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Coexistence of IEEE802.15.4 with other Systems in the 2.4 GHz-ISM-Band

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Abstract – *Wireless systems continue to rapidly gain popularity. This is extremely true for data networks in the local and personal area, which are called WLAN and WPAN, respectively. However, most of those systems are working in the license-free industrial scientific medical (ISM) frequency bands, where neither resource planning nor bandwidth allocation can be guaranteed. To date, the* most widespread systems in the 2.4 GHz ISM band are IEEE802.11 *[7] and Bluetooth [6], with ZigBee [9] and IEEE802.15.4 [5] as upcoming standards for short range wireless networks.*
In this paper we examine the mutual effects of these different communication standards. Measurements are performed with real-life equipment, in order to quantify coexistence issues.

Keywords *– WPAN, Wireless PAN, IEEE802.15.4, IEEE802.11, Bluetooth, ZigBee, ISM-Band, coexistence, interference*

I. INTRODUCTION

Wireless systems continue to rapidly gain popularity. This is extremely true for data networks in the local and personal area, which are called WLAN and WPAN, respectively. However, most of those systems are working in the license-free industrial scientific medical (ISM) frequency bands, where neither resource planning nor bandwidth allocation can be guaranteed. To date, the most widespread systems in the 2.4 GHz ISM band are IEEE802.11 [7] and Bluetooth [6].

ZigBee and IEEE802.15.4 are two upcoming standards for short range wireless networks described in [9] and [5]. Their major application fields are home and building automation, as well as industrial sensor and actuator networks. Applications in medical monitoring systems are also envisaged. These applications require highest reliability in transmission. However, the IEEE802.15.4 is specified within open ISM-bands, as well. These are 868 MHz for Europe, 915 MHz for the Americas, and 2.4 GHz for worldwide use. As the 2.4 GHz-band provides the highest bandwidth per channel (250 kbps gross data rate) and the largest number of channels (16 non-overlapping channels), it is the prevalent band for IEEE802.15.4 RF-chips.

Thus, in a few months or years, we shall see three wireless systems in one frequency band with different modulation and channel access schemes. Additionally, other non-networking systems may emit electromagnetic waves, e.g. microwave ovens in the 2.4 GHz-band.

There are extensive studies about the utilization of the 2.4 GHz band, e.g. [11], and the mutual impact of WLAN and Bluetooth systems, e.g. [12] [13] [16]. Also the IEEE802.15.2 task group extensively examined this issue [4]. A coexistence simulator for Bluetooth and IEEE 802.11b is available at [1]. Additionally, studies describe the impact of other systems on IEEE802.11, e.g. of microwave ovens [14].

The coexistence issues of the new IEEE802.15.4 and ZigBee devices were examined in first simulations [15], but no quantitative measurements have yet been documented. This is the target of this contribution. The impact of the three most important interfering systems on IEEE802.15.4 are reviewed, i.e. of IEEE802.11, of Bluetooth, and of microwave ovens.

II. PROPOSED APPROACH

A. Definitions

Multiple wireless devices are said to "coexist" if they can be collocated without significantly impacting the performance of any of these devices [8]. Coexistence may also be defined as the ability of one system to perform a task in a given shared environment where other systems may or may not be using the same set of rules.

The given task of a wireless network is to transmit data with a certain quality of service (QoS) [18]. Primary QoS parameters are packet loss and transmission delay. Secondary, however important, parameters are jitter, availability and security.

Packet loss is defined as the probability that a packet, which is sent on the air at one station, cannot not be received at a second station. Packet loss may occur when the signal is interfered or attenuated.

B. Algorithms for Coexistence

The major problem with the parallel activity of different systems in one frequency band is the use of different modulation and channel access schemes.

- IEEE802.11 uses a DSSS-modulation in the b-substandard and a OFDM-modulation in the g-version. Starting from the distributed coordinated function (DCF) - a pure CSMA/CA-algorithm - several enhancements are in practice. They include the e-substandard (enhanced DCF), but also various proprietary extensions.

- Bluetooth applies a slow frequency hopping scheme. The channel access follows a master-slave-scheme.
- IEEE802.15.4 in the 2.4 GHz-band uses a orthogonal QPSK-modulation. The channel access is accessed via a CSMA/CA-algorithm, which may be supplemented by a master-(i.e. coordinator)-based time-slot scheme.

In the first step, all approaches for channel access and collision avoidance are designed to work only within one system, but not between different systems. In the meanwhile, various extensions have been developed to enhance coexistence:

- Many IEEE802.11-access points make use of a dynamic channel selection (DCS), after having analyzed the utilization of the different channels. For the 2.4 GHz-band, these mechanisms are mostly implemented in the management, but not specified in the standard. For the 5 GHz-version of IEEE802.11, the European version IEEE802.11h prescribes DCS and transmission power control (TPC).
- The Bluetooth specification v1.2 includes an adaptive frequency hopping (AFH) scheme, which reduces the number of available channels from 79. This was only possible after FCC allowed a minimum number of 15 channels for FH-systems in the 2.4 GHz-band. However, the identification of bad channels is not specified in the standard.
- Further extensions exist for the co-located use of Bluetooth and IEEE802.11-systems in one node. However, those approaches are proprietary, e.g. [10].
- The IEEE802.15.4 standard includes an Energy Detection (ED) functionality to determine the activity of the other systems, but no DCS is envisaged by the standard.

C. Basic Ideas

This contribution deals with real-life tests of the coexistence of IEEE802.15.4 systems with other devices working in the 2.4 GHz band to determine the mutual influence. The test conditions can be described as follows:

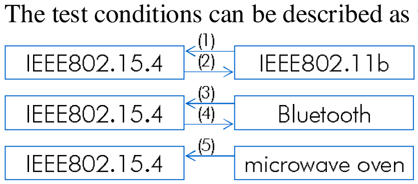

Fig. 1. Test scenarions of 2.4 GHz systems with IEEE802.15.4.

- The devices were performed with standard (commercial) equipment. No special antennas or dedicated access mechanisms were used.
- The other systems, against which the coexistence is tested, are IEEE802.11b, Bluetooth and microwave ovens leading to the test scenarios shown in fig. 1. For each scenario the impact is observed only unidirectional, i.e. when the impact of IEEE802.11b on IEEE802.15.4 is measured, no impact on IEEE802.11b is taken into account.
  As the impact of IEEE802.15.4-systems on microwave ovens is expected to be negligible, these measurements were not performed. Even more, no test equipment to measure such an influence was available.
- Whereas the devices are chosen to be typical, the tests include worst-case scenarios. For example, in test scenario (1) the IEEE802.11b system was run with the highest possible utilization rate for a prolonged time. In practical life, this utilization rate is achieved only at peak times, but not as a sustained data rate. As a consequence, the test-results can serve as a baseline, how to implement higher-level protocols for reliability and real-time behaviour. Those are of major importance for many industrial or medical applications.
- Although commercial hardware equipment was used, no statistical analysis tools are available on the market for IEEE802.15.4. The required software tools were developed within this work. They include test routines for the IEEE802.15.4-nodes and PC-based analysis tools.

It should be emphasized that the tests were run along various parameters to determine the relevant influence. For example, the interference of IEEE802.11b on IEEE802.15.4-systems (test scenario (1)) is verified along the following aspects:

- Test case 1.1: The channel selection is varied. The bandwidth of IEEE802.11b signals is 22MHz and of 802.15.4 signals is 5 MHz.
- Test case 1.2: The length of IEEE802.15.4 frames is varied.
- Test case 1.3: The distance of the IEEE802.15.4 is varied.
- Test case 1.4: The distance between the interfering IEEE802.11-station and the interfered IEEE802.15.4-stations is varied.
- Test case 1.5: CCA-Mode 1 (Energy Detection) is used for 802.15.4.

D. Test Equipment

For IEEE802.15.4 equipment, CC2420-chips from ChipCon [1] are used.

- two ChipCon Development Boards CC2420 DB 1.1 Rev 1.3: These boards come with a Atmel ATmega128 microcontroller with on-chip flash, which allows easy reprogramming of the systems. Additionally, PHY - and MAC-software is provided by ChipCon. The development boards come with an integrated PCB antenna.
- one ChipCon Evaluation Board CC2420 EB Rev.2.1: This boards provides a USB-connection, which allows easy connection to a PC. For monitoring, ChipCon's SmartRF-Studio and ChipCon Packet Sniffer can be used. The evaluation board is equipped with a Titanis antenna.

It shall be mentioned that the measurements were performed with boards from Freescale, as well. For these measurements Sensor Applications Reference Boards (SARD) were used with an HCS08 microcontroller, a MC13192 RF-chip with two PCB-antennas. However, as the results showed only slight deviations from the numbers given here, they are not examined in detail here.

Data is sent form one DB to another DB. The data frames contain a counter to enable the detection of lost packets. In those cases, in which the influence on IEEE802.15.4 systems is examined, the data is received by the Packet Sniffer and logged to a file on the host PC. In the next step, it is imported into an Excel file and then analyzed with the help of a VB script. The visualization is also done with MS Excel based tools.

The two test setups shown in Fig. 2 and 3 were use to run the measurements.

E. IEEE802.11 traffic characteristics

The test gives the maximum available load onto the interfering WLAN channel to characterize the worst case conditions. This worst case scenario has only limited real world relevance.

An FTP-Client is running on the WLAN client and transmits a large file to the FTP server, which is connected to the wired Ethernet of the Access Point. The 100 Mbits/s hub allows easy monitoring of the traffic characteristics. The medium net data rate achieved by this transmission is approximately 21 Mio Bytes / 50 s. At a net packet size of 1446 Bytes per Packet, this translates into ~290 packets / s. Consequently, a utilization rate of 55,6 % can be calculated.

The remaining time is reasonably be taken as

- interframce spaces: Short Interframe spaces between MAC data frames and MAC ACK frames are 10 μs, and Distributed Interframe Spaces at IEEE802.11 with DSSS is 50 μs.
- processing time at the client and the server computer.

III. TEST RESULTS

The worst case scenario is to run IEEE802.11b and IEEE802.15.4 systems with overlapping channels, e.g. the WLAN system transmits on channel 6 (2437 MHz) and the WPAN system on channel 16 (2440 MHz). The test results show (cf. fig.4), that approx. 90 % of all WPAN-frame are destroyed by the interfering WLAN-frames. A closer look to this diagram reveals the bursty character of the interference. One may conclude, that those IEEE802.15.4 frames, which are overlapped by a IEEE802.11 frame are destroyed. This can be expected, especially as the transmission power of IEEE802.11 is about 30 times larger than the one of IEEE802.15.4. The intensity is still about 4 times larger. It is of key importance that there remains enough idle time between the transmissions of IEEE802.11-frames, so that IEEE802.15.4 frames can be successfully transmitted. The CSMA/CA algorithm of IEEE802.11 and the required interframe spaces (IFS) account for those idle times.

A. Test Scenario 1.1

In this test case, the channel selection of the WPAN system is kept constant at channel 16 (2440 MHz), whereas the WLAN channel is varied. The utilization rate of the IEEE802.11b systems is calculated to be at 53 %, which is the maximum value. It can be seen from fig. 2, that the interference level is reduced with an increasing distance of the channels. If the WLAN system transmits on channel 4 with a centre frequency of 2427 MHz and covering a frequency band between 2416 MHz and 2438 MHz, no more influence on IEEE802.15.4 can be observed. Test setup (1) is used in this test case.

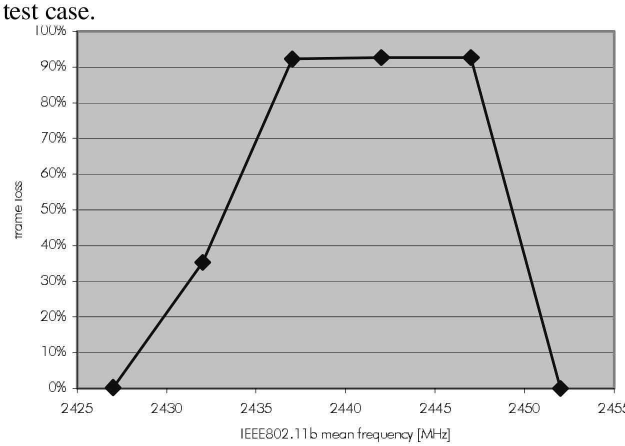

Fig 2: Loss of IEEE802.15.4 frames with a high activity IEEE802.11 DSSS; varying 802.11 channel, 802.15.4 channel kept constant at 2440 MHz.

B. Test Scenario 1.2

The probability of collisions with the interfering IEEE802.11b frames increases with the increase in in frame length of IEEE802.15.4 frames. However, this dependency is relatively low. It already starts at a high level (86.6 %) and varies within the range of some percent from test run to test run.

C. Test Scenario 1.3

The next set of results examines the packet loss at a constant distance between the IEEE802.15.4 stations. The IEEE802.15.4 channel selection is varied for the different graphs. The distance X, Y, Z to the IEEE802.11 station is varied from 0.5 m to 6 m and shown at the x-axis.

The results shown in Fig. 3 examine the packet loss at a distance A of 10m between the IEEE802.15.4 stations. From the results of this section, the following statements can be derived:

- The packet loss rate is not monotonous. In many cases, the loss rate at a distance of 0.5 m is higher than at 2 m. A distance of 0.5 m is still very near to the source antenna, so that the non-linearities of a near-field might still have an influence

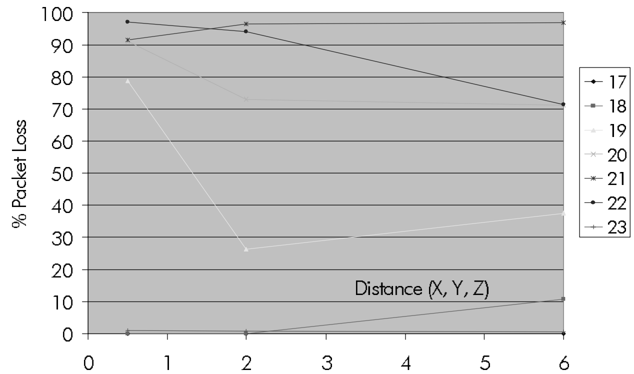

Fig. 3: Packet loss at a distance A of 10m

- Commonly, the edge between near-field and far-field is seen at a distance $d = 2 \cdot \lambda$, where $\lambda = 10$ cm at f = 2.4 GHz.
- After 2 m, the loss rate increases with larger distances, as the signal amplitude of IEEE802.11 at the IEEE802.15.4 receiver is further reduced.

D. Test Scenario 1.5: CCA-ED

In this scenario, an additional feature was applied. The Clear-Channel-Assignment-(CCA)-mode for the listen-before-talk-algorithm was set to CCA-ED, which means that CCA shall report a busy medium upon detecting any energy above the ED threshold. This mode is named "mode 1" in the IEEE802.15.4-standard.

The other measurements were run with CCA mode 2, which corresponds to "Carrier sense only". In this case, CCA shall report a busy medium only upon the detection of a signal with the modulation and spreading characteristics of IEEE 802.15.4. This signal may be above or below the ED threshold.

For ease of measurement, these tests were performed with two ChipCon-boards. These results examine the packet loss at a distance A of 10m between the IEEE802.15.4 stations.

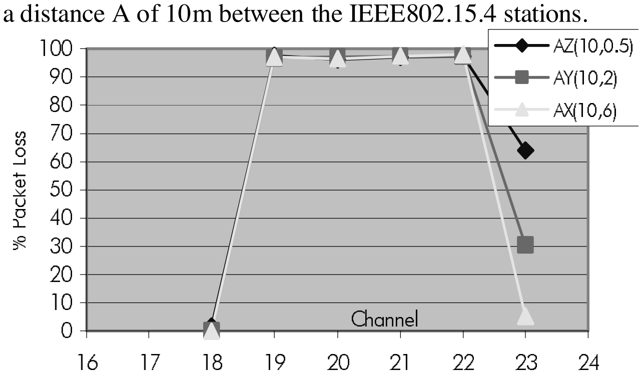

Fig. 4: Packet loss with CCA-mode 1at a distance A of 10m

E. Test Scenario 3: Bluetooth → 802.15.4

Two pairs of Bluetooth stations perform a FTP operation, i.e. copy a large file with the maximum upload bandwidth.

- One notebook makes an FTP transfer to the PDA, achieving a medium data rate of approx. 15 kbps.
- The other notebook makes an FTP transfer to the desktop PC. In this case, a medium data rate of approx. 50 kbps is achieved.

In this test case, 110 out of 1110 frames were lost. IEEE802.15.4 frames may be destroyed by a Bluetooth transmission at the same time slot with the same frequency. This explains the bursty character of the packet loss.

F. Test Scenario 4: 802.15.4 → Bluetooth

No impact of the IEEE802.15.4 stations onto the Bluetooth communications was observed. Admittedly, no analysis tool was available, so the mere data rate was observed.

G. Test Scenario 5: Microwave Oven → 802.15.4

The tests were performed with a standard household microwave oven (Sharp R-93ST with 900 W microwave power). Again, the worst case scenario was chosen, and the systems were put directly onto the top of the oven.

- The tests were performed for three channels (0x0B, 0x12 and 0x1B). The results were independent from the channel.
- The RSSI was reduced by 5.
- There was a distribution of between 4 and 10 CRC-errors for 1000 data frames.
- Between 5 and 20 data frames out of 1000 were completely destroyed.

Running the microwave oven at a distance of ~1 m, no influence on the IEEE802.15.4-performance was left

IV. COMPARISON WITH SIMULATION DATA

The 802.15.4 group did some early simulations based on simple radio models of the problem in appendix E section E.3.3 [9]. Figure 6 shows simulations of co-existence. The assumptions of these simulations are outlined there and are based on the very rarely read IEEE802.15.2 [4], which describes coexistence issues between Bluetooth

The following statements can be derived from the comparison of the measured with the simulated data:

- In case of small frequency offset, the simulated data shows two deviations from real life measurements.
  - The packet error rate never reaches 100 %, even under worst case, i.e. small separation, conditions. Closer investigation reveals that there is still a chance to transmit some IEEE802.15.4 packets, as the IEEE802.11 interframe spaces still may give room. However PER is above 95 %.
  - At larger separation, no significant decrease in PER was revealed in the measured data.
- In case of larger frequency offset, the simulated data shows a significant deviation from real life measurements, as PER is below 10 E-3 for all distances. As the measurements

were all run with 1000 frames, a higher precision could not be achieved – and would not be relevant for practical life.

V. CONCLUSION

The following statements can be derived from our measurements:

- There clearly is a coexistence issue in the 2.4 GHz band.
- Especially the impact of IEEE802.11 stations with high duty cycle against IEEE802.15.4 stations may be extremely critical, if the same carrier frequencies are selected. This scenario will lead to a timeout of the physical layer.
- The impact of other systems (Bluetooth or microwave ovens) on IEEE802.15.4 results in a enlarged packet error rate, however, the level of below 10 % is not critical.

It should be noted, that it still seems practical to prepare a change of frequency within a reasonable time even under the worst circumstances. Unfortunately, a dynamic adaptation of a frequency channel is neither part of the IEEE802.15.4 nor of the ZigBee standard.

This would be of major importance, because it allows a coexistence in fixed installation with a frequency plan, as proposed in fig. 5. IEEE802.15.4 may use the free space between two neigboring IEEE802.11-channels. Additionally the channels 25 and 26 are available, which leads to a total of 4 non-disturbed IEEE802.15.4 channels in a crowded IEEE802.11 environment.

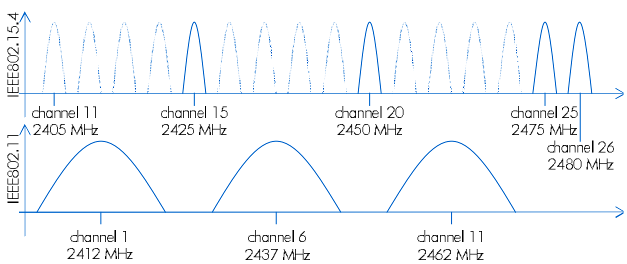

Fig 5: Frequency plan, which allows the parallel non-disturbed operation of three IEEE802.11 and four IEEE802.15.4 channels.

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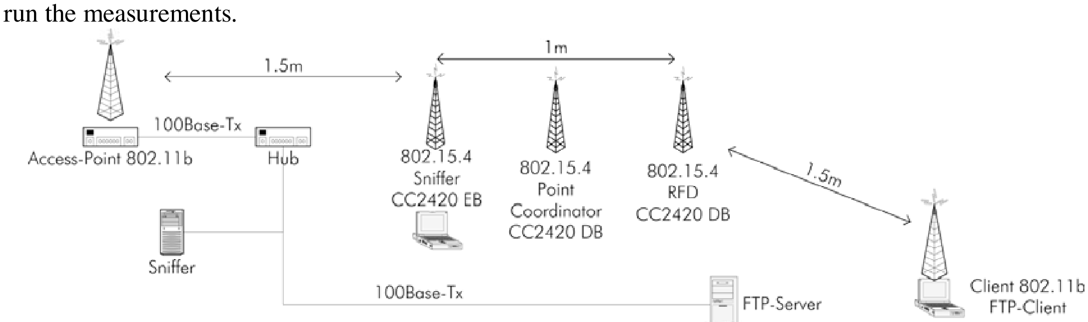

Fig. 2: Test setup 1 for IEEE802.11b DSSS and IEEE802.15.4 coexistence tests

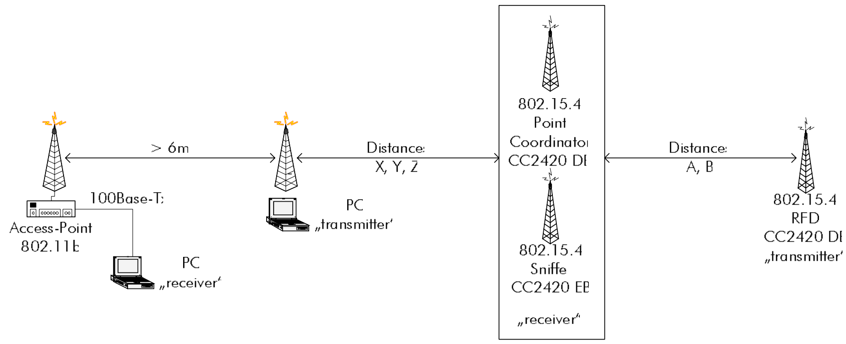

Fig. 3: Test setup 2 for IEEE802.11b DSSS and IEEE802.15.4 coexistence tests

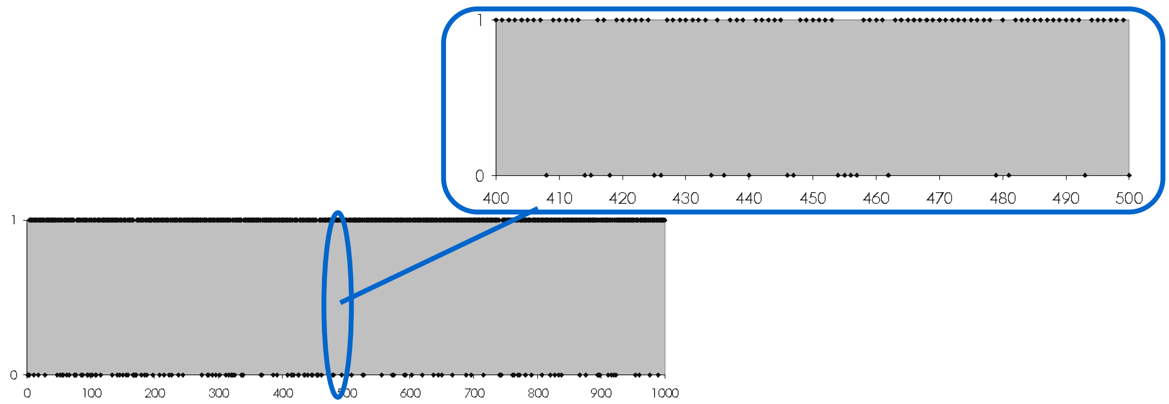

Fig. 4: Loss of IEEE802.15.4 frames with a high activity IEEE802.11 DSSS overlapping channel: The x-axis shows the number of the frame; a "0" on the y-axis indicates a successful transmission, a "1" stands for a frame loss

Channel		Distances b/w 805.11 & 802.51.4 node.	Distances between Senders and Receiver nodes of 802.15.4	
802.11	802.51.4		(A) 10 M	(B) 20 M
9 (2452MHz)	17, 18, 19, 20, 21, 22, 23, 24 (2435, …, 2470 MHz)	(X) 6M	17, 18, 19, 20, 21, 22, 23, 24	17, 18, 19, 20, 21, 22, 23, 24
		(Y) 2M	17, 18, 19, 20, 21, 22, 23, 24	17, 18, 19, 20, 21, 22, 23, 24
		(Z) 0.5M	17, 18, 19, 20, 21, 22, 23, 24	17, 18, 19, 20, 21, 22, 23, 24

Table 1: Test scenarios

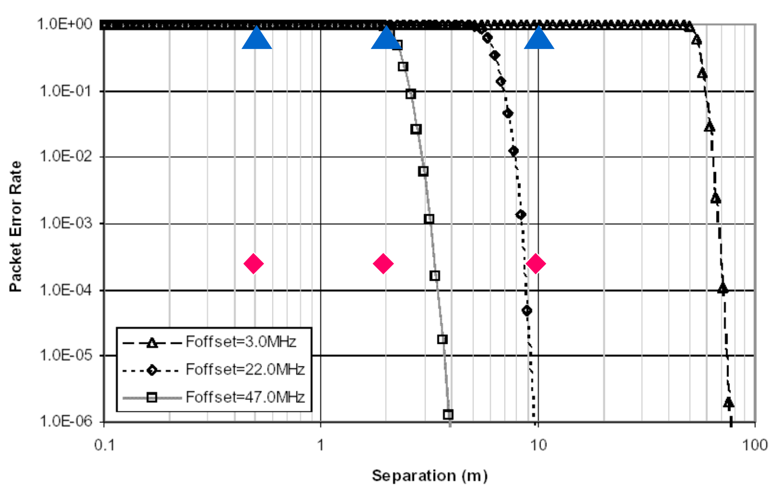

Fig. 6: Simulation vs. Real-life data: The simulated data is from IEEE802.15.4 work group [9], the single points are from own measurements