Compatibility of IEEE802.15.4 (ZigBee) with IEEE802.11 (WLAN), Bluetooth, and Microwave Ovens in 2.4 GHz ISM-Band – Test Report –

Revised Version V0.3: 12th September 2004

1 Abstract

ZigBee and IEEE802.15.4 are two upcoming standards for short range wireless networks described in [7] and [8]. Their major application fields are home and building automation, as well as industrial sensor and actuator networks. Applications in medical monitoring systems is also envisaged.
These applications require highest reliability in transmission. However, the IEEE802.15.4 is specified within open ISM-bands. 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 most bandwidth per channel (250 kbit / s gross data rate) and the largest number of channels (16 non-overlapping channels), it is the most prevalent band for IEEE802.15.4 RF-chips.
However, there is an increasing number of other devices and systems which may interfere with the IEEE802.15.4 communication. The objective of this test is to evaluate this interference. The three most important interfering systems are reviewed:

- WLAN-systems of IEEE802.11,
- Bluetooth, and
- microwave ovens.

All tests are performed with commercially available equipment without any adaptation or tuning. It is not the idea to re-run laboratory based or systematic RF-analyses. The results shall give a rough indication on the mutual interference of the different systems and thus shall enhance the "feeling" of wireless system operators about the challenges or real-world wireless applications.
Additionally, this reports describes the most important frequency characteristics of the above mentioned systems.

Prof. Dr.-Ing. Axel Sikora
Steinbeis Transfer Centre for Embedded Design and Networking
University of Cooperative Education Loerrach
Hangstrasse 46-50
D79539 Lorrach
Germany
http://www.ba-loerrach.de/stzedn
sikora@ba-loerrach.de

tel: +49-7621-2071-441
fax: +49-7621-2071-495

Remark: For the tests, commercially available products were used. Their choice may not reflect the author's preferences. No recommendation is connected with their use. All product or service names are the property of their respective owner.

Table of Contents

1 Abstract 1
2 IEEE802.15.4 3
2.1 Test Environment 3
2.2 Frequency characteristics 3
2.3 WPAN traffic characteristics 4
2.4 WPAN characteristics without WLAN traffic 5
3 IEEE802.15.4 vs. 802.11 6
3.1 Test environment 6
3.2 Frequency characteristics 7
3.3 WLAN traffic characteristics 8
3.4 WPAN characteristics with WLAN interference 9
3.4.1 Worst case test results 9
3.4.2 Channel selection test results 10
3.5 WLAN characteristics with WPAN interference 10
3.5.1 Preliminary remarks 11
3.5.2 Test results 11
4 IEEE802.15.4 vs. Bluetooth 12
4.1 Test environment 12
4.2 Frequency characteristics 13
4.3 Traffic characteristics 14
4.4 Test results 14
5 IEEE802.15.4 vs Microwave Oven 14
5.1 Test environment 14
5.2 Frequency characteristics 15
5.3 Test results 15
6 Conclusions 16
7 Sources 16

2 IEEE802.15.4

2.1 IEEE802.15.4 test environment

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 re-programming of the systems. Additionally, PHY- and MAC-software is provided by ChipCon. However, their use is restricted by a MAC software license agreement.
  The development boards are used with the 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 used with a Titanis antenna.

The WPAN traffic is sent between the two development boards. The evaluation board is connected to a Notebook-PC, where the received data is stored to a file.
As each frame of the traffic flow contains an identifier, it is well possible to analyze the amount of lost packets. This analysis is performed with the help of Visual Basic for Applications (VBA) under MS Excel.

2.2 IEEE802.15.4 frequency characteristics

The selection of the 16 channels for IEEE802.15.4 systems is shown in table 1, the bandwidth characteristics is shown in fig.1.

channel	11	12	13	14	15	16	17	18
mid frequency [MHz]	2405	2410	2415	2420	2425	2430	2435	2440
channel	19	20	21	22	23	24	25	26
mid frequency [MHz]	2445	2450	2455	2460	2465	2470	2475	2480

Table 1: Channels of IEEE802.15.4 in the 2.4 GHz-ISM-band

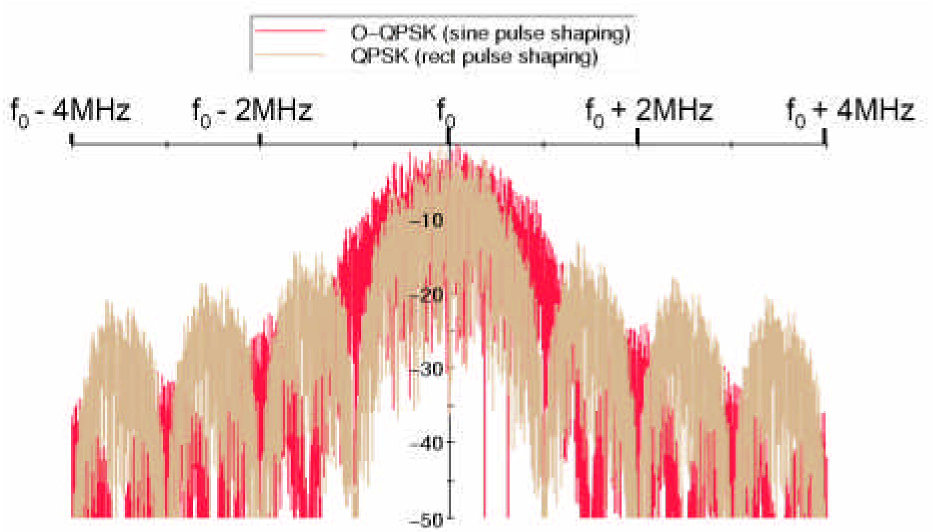

Fig 1: Frequency behaviour of IEEE802.15.4 in the 2.4 GHz-ISM-band (courtesy oi Freescale [5])

The output power is 0dBm, which corresponds to one 1mW.

2.3 IEEE802.15.4 traffic characteristics

The traffic generation of the IEEE802.15.4 WPAN is based on the MAC_DEMO_01 “Knight Rider” demo program, being delivered together with the ChipCon Development Boards. One device acts as the PAN coordinator. The other device associates as a RFD on the network after performing an active scan. It then sends frames to its point coordinator. The length of the data frames varies.

data length	frame size	
bytes	bytes	bits
5	9	72
8	12	96
28	32	256
48	52	416
68	72	576

Each data packet is acknowledged with an acknowledgement packet having a length of 5Bytes = 40 Bits. Both packet types have a PHY and a synchronisation header of 6 Bytes, each.

High Traffic Load

Figure 2 shows the timing characteristics, which is, that each data packet and its corresponding acknowledgement have a distance of 1051 µs and 869 µs, respectively. This means, that each 1.92 ms a total of (15 + 6 + 5 + 6) Bytes = 256 Bits is transmitted, in case of the 5 byte data length.

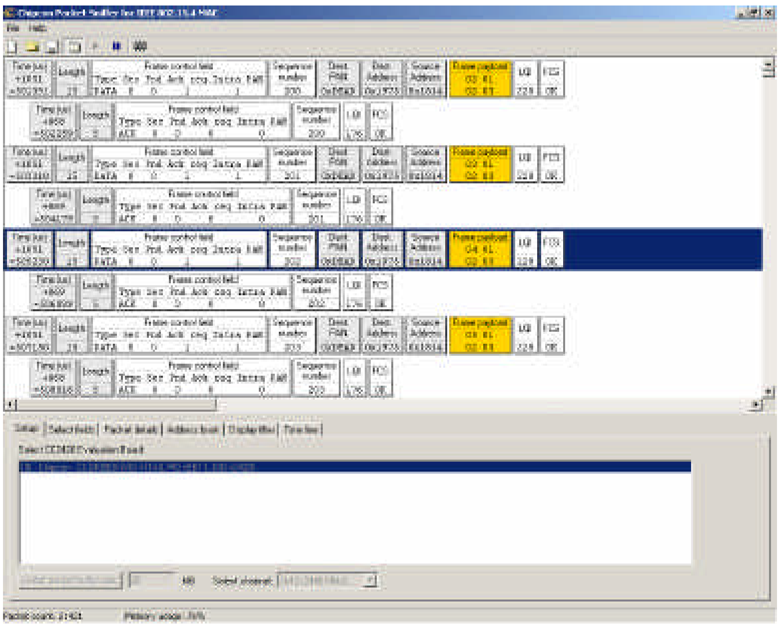

Fig 2: Timing behaviour of IEEE802.15.4 at maximum load

These assumptions lead to a net data rate of $\frac{256 Bits}{1.92 ms} = 133 kbit/s$.

Based on a gross data rate of 250 kbit / s, a utilization rate of 53.3 % is calculated.

Medium Traffic Load

However, SmartRF suite cannot handle this high data rate. At the given speed, it will loose some 4 or five frames after approx. 26 frames. This makes it impedable to monitor fame loss on the wireless channel.

Therefore, the maximum data-rate for SmartRF suite was chosen. This is a data volume of 256 Bits each 26.878 ms, which corresponds to $\frac{256Bits}{26.9ms} = 9.5kbit/s$.

2.4 IEEE802.15.4 characteristics without interference

The IEEE802.15.4 are dislocated very close to each other to achieve maximum link quality (cf. fig.3). However, it must be taken into account that the PCB antenna show a very strong dependency of the angle. This may lead to non-reproducible results in some cases, as especially in the near-field, the relative deviations may be significant.

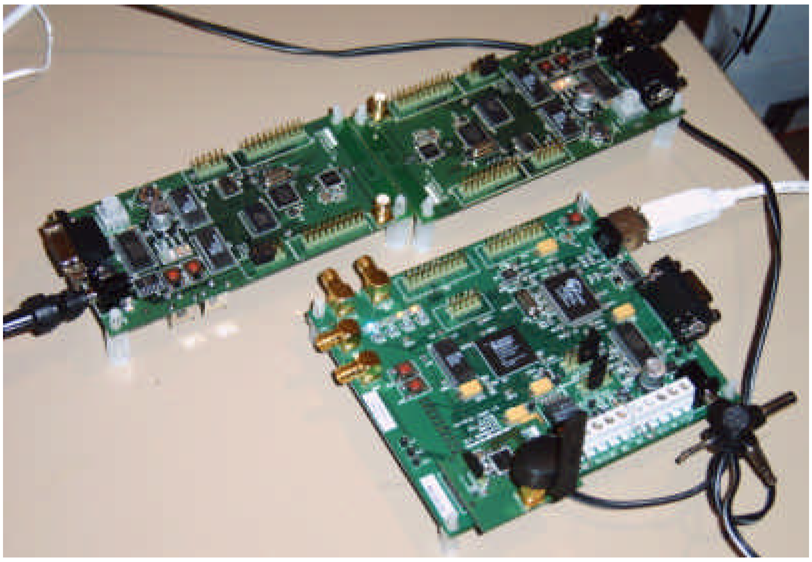

Fig 3:Test equipment with ChipCon IEEE802.15.4 boards

Figure fig. 4 shows the results as measured with the help of SmartRF Studio.

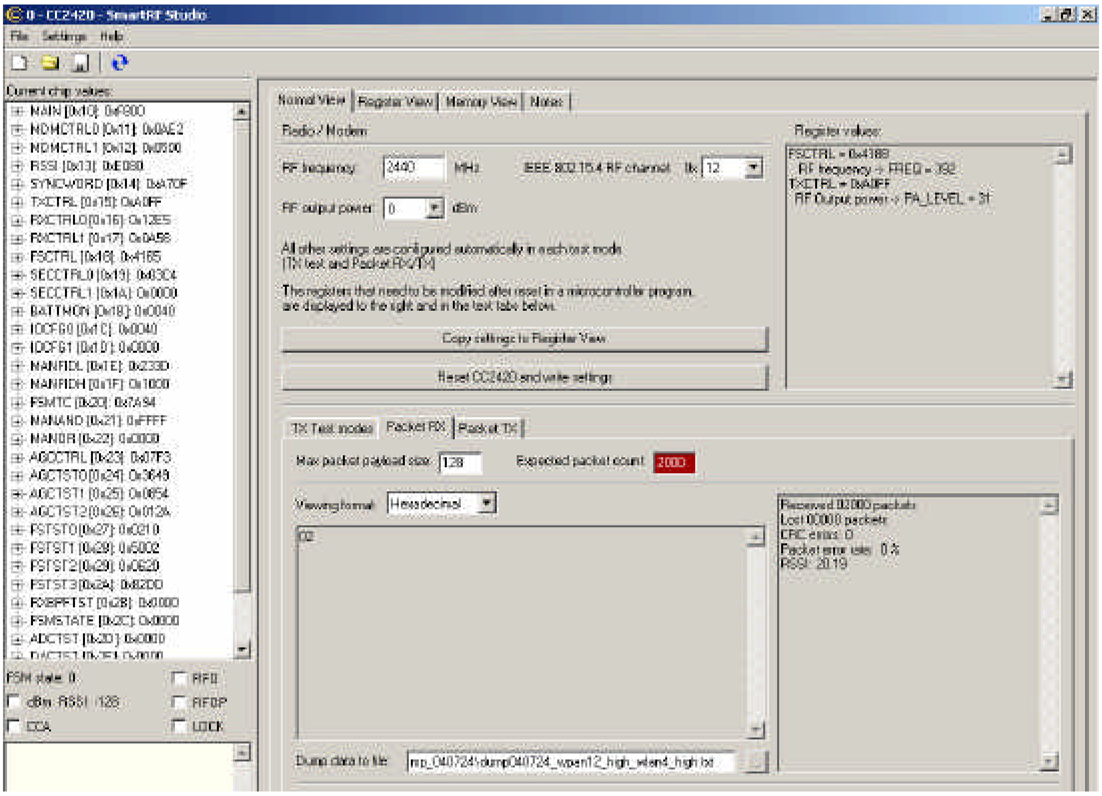

Fig 4:Test results as being observed with ChipCon's SmartRF Studio

Typically, some 2000 frames were observed, one half of them being data frames and the other half being acknowledgements. Not a single frame was lost during the tests, as long as no interference was applied. No CRC errors occurred. RSSI (Received Signal Strength Indicator) was determined as 20.2. However, the values of RSSI strongly depend on the actual positioning of the boards.

3 IEEE802.15.4 vs. IEEE802.11

3.1 IEEE802.11 test environment

The following devices were used:

- WLAN Access Point DrayTek Vigor2500
- Notebook with a Pentium III 750 MHz processor under MS Windows XP Home Edition. Two WLAN cards were in use for the given tests.
  - WLAN Client Level One WPC-0101 PC Card
  - WLAN Client Orinoco Gold from Agere Systems-

All stations run IEEE802.11b protocol with a sustained data rate of 11 Mbps.

For this test scenario, two WLAN stations are dislocated in the very surrounding to the WPAN, as it is shown in fig. 5.

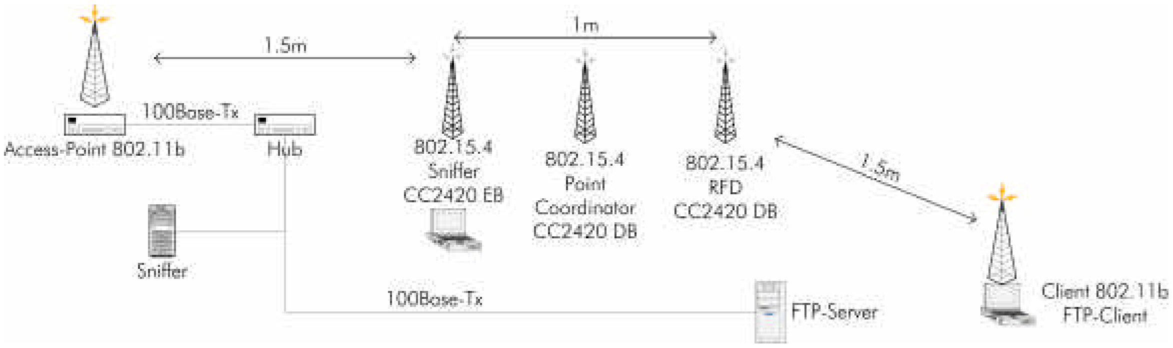

Fig 5: Environment for IEEE802.11b DSSS and IEEE802.15.4 compaibility tests

3.2 IEEE802.11 frequency characteristics

In Europe, IEEE802.11b comes with 13 channels with a distance of 5MHz each. However, the required bandwidth accounts for some 22 MHz per channel.
Figure 6 shows the frequency characteristics of a IEEE802.11 system.

Table 2 shows the channel distribution of IEEE802.11 DSSS-channels.

channel	1	2	3	4	5	6	7	8	9	10	11	12	13
mid frequency [MHz]	2412	2417	2422	2427	2432	2437	2442	2447	2452	2457	2462	2467	2472

Table 2: Channels of IEEE802.11 DSSS systems

It becomes clear that both systems, i.e. IEEE802.11b and IEEE802.15.4 have a small offset of 2MHz. However, due to the bandwidth requirements, channels may severely overlap.

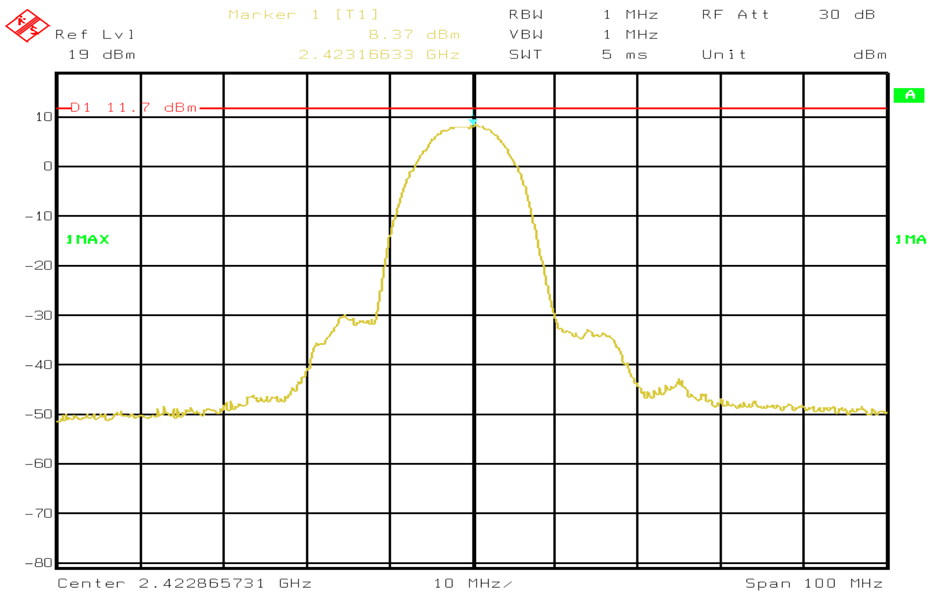

Fig 6: Frequency behaviour of a IEEE802.11 DSSS-transmission (courtesy of Tenovis)

3.3 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.
The load on the transmission channel can be estimated as follows:

	1446 Byte per FTP-Data
=	1514 Byte per Ethernet packet
=	1.101 ms (at a data rata of 11 Mbit / s)
+	0.192 ms (PLCP Header and PLCP Preamble)
=	1.293 ms per packet

Each FTP packet is acknowledged by a TCP-acknowledgement with

	66 Bytes per Ethernet packet
=	0.048 ms (at a data rata of 11 Mbit / s)
+	0.192 ms (PLCP Header and PLCP Preamble)
=	0.240 ms per packet

Additionally, each packet on the wireless medium receives a separate acknowledgement on the MAC layer, with a length of 10 Bytes.

	10 Bytes per Ethernet packet
=	0.007 ms (at a data rata of 11 Mbit / s)
+	0.192 ms (PLCP Header and PLCP Preamble)
=	0.199 ms per packet

This leads to a activity time of 1.293 ms + 0.199 ms + 0.240 ms + 0.199 ms = 1.931 ms for each data packet. Assuming 290 packets / s, 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.
  It is defined in [6] that aSIFSTime = 10 µs and aSlotTime = 20 µs, with DIFS = aSIFSTime + 2* aSlotTime = 50 µs. Considering 290 packets / s, interframe spaces account for
  290 * (2*10 µs + 50 µs) = 20.3 ms.
- processing time at the client and the server computer.

3.4 IEEE802.15.4 characteristics with IEEE802.11 interference

3.4.1 Worst case 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. 7) that more than 92 % of all WPAN-frames are destroyed by the interfering WLAN-frames. This means that there remain some unused time slots for IEEE802.15.4 traffic.

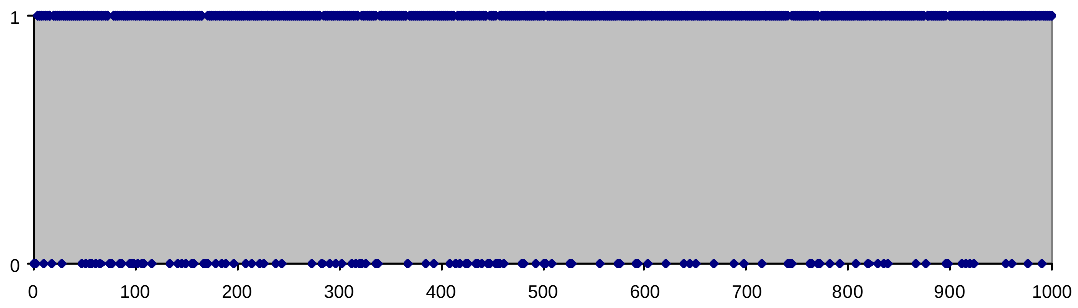

Fig 7: Loss of IEEE802.15.4 frames with a high activity IEEE802.11 DSSS overlapping channel: The x-axis shows the number of the fr4ame; a "0" on the y-axis indicates a successful transmission, a "1" stands for a frame loss

When looking closer to this diagram (cf. fig. 8), the bursty character of the interference can be seen.

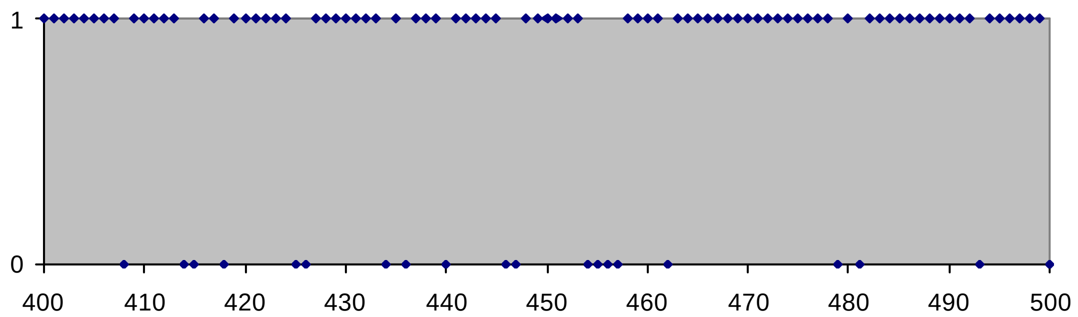

Fig 8: Loss of IEEE802.15.4 frames with a high activity IEEE802.11 DSSS overlapping channel: Extract from fig. 7

3.4.2 Channel selection test results

In the next tests, the channel selection of the WPAN system was kept constant at channel 16 (2440 MHz), where the WLAN channel was changed for different runs. It can be seen from fig 9, that the interference level is reduced with an increasing distance of the channels. If the WLAN system transmits on channel 4 with a center frequency of 2427 MHz and covering a frequency band between 2416 MHz and 2438 MHz, no more influence on the WPAN can be identified.

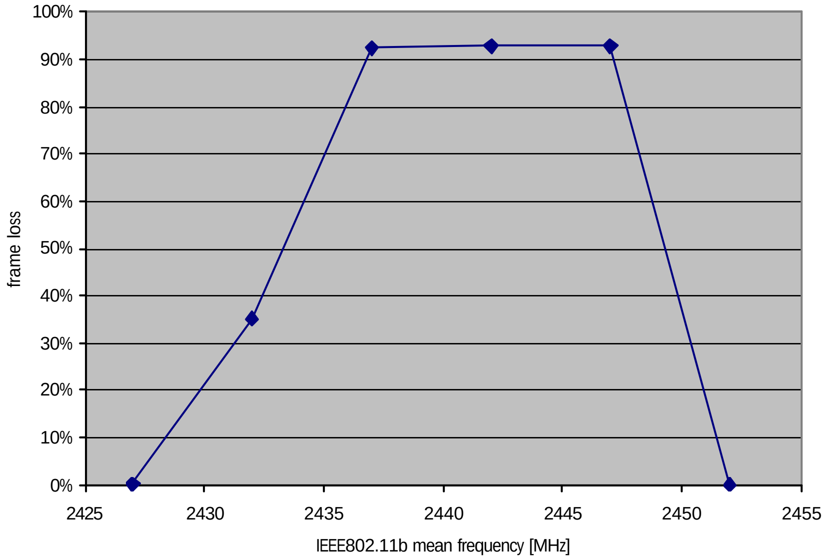

Fig 9: Loss of IEEE802.15.4 frames with a high activity IEEE802.11 DSSS; varying 802.11 channel, 802.15.4 channel kept constant at 2440 MHz

3.4.3 Frame length test results

The probability of collisions with the interfering IEEE802.11b frames increases with the increase in with the increase in frame length of IEEE802.15.4 length of the IEEE802.15.4 frames. However, as can be intercepted from fig- fig 10, 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.

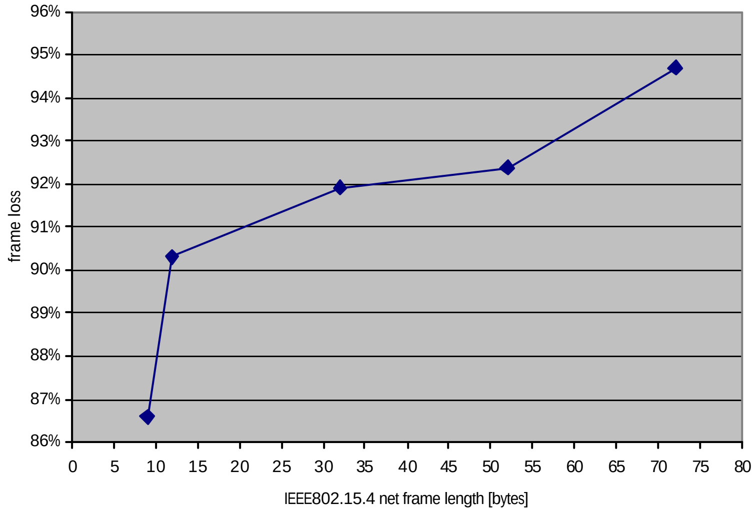

Fig 10: Loss of IEEE802.15.4 frames with a high activity IEEE802.11 DSSS;varying the IEEE802.15.4 frame length; the 802.11 channel is kept constant at 2437 MHz, the IEEE802.15.4 channel is at 2440 MHz

3.5 IEEE802.11 characteristics with IEEE802.15.4 interference

3.5.1 Preliminary remarks

One may assume that the interference of WPAN signals on WLAN transmission is low.

- The bandwidth of the WPAN signal is 5 MHz in comparison to the 22 MHz of the WLAN signal. Thus, the WPAN signals appear as a narrow band interference which can be sufficiently suppressed by IEEE802.11b spread spectrum technology.
- Additionally, the output power of IEEE802.15.4 antenna is limited to 0 dBm (1 mW) in comparison to 20 dBm (100 mW) of IEEE802.11. However, EIRP is limited for WLAN systems. As a consequence, most WLAN stations work with a maximum transmission power of 14,8 dBm (30 mW) to allow the use of anisotropic antenna.

3.5.2 Test results

The tests were performed with Orinoco WLAN card because a free client tool for administration and analysis is available for download (ORiNOCO Client Manager).
The WPAN systems runs on channel 12 with the highest available data rate.
The WLAN Client Manager delivers the results shown in fig. 11 and 12.
Fig. 11 is a screenshot of the Orinoco Client Manager tool, fig. 12 is an Excel based analysis of the data logger included in this tool. Using the data logger allows a more detailed control of the measurements. It is set to 0.1 s for this test.
However, both tests give a snapshot of the situation at the time of measurements, which explains the large variance of noise level.

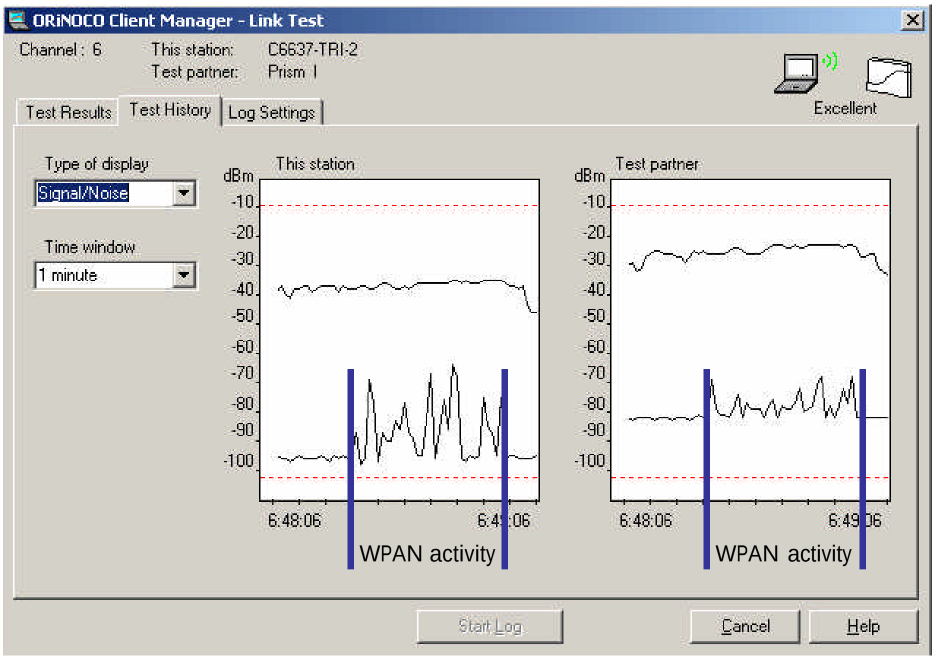

Fig 11: Increased noise level of IEEE802.11 in times of IEEE802.15.4 activity. This station is the Notebook with the Orinoco WLAN card very near to the IEEE802.15.4 (< 10 cm), the test partner is the router in a distance of approx. 50 cm. The upper curve shows the signal level, the lower curve the noise level.

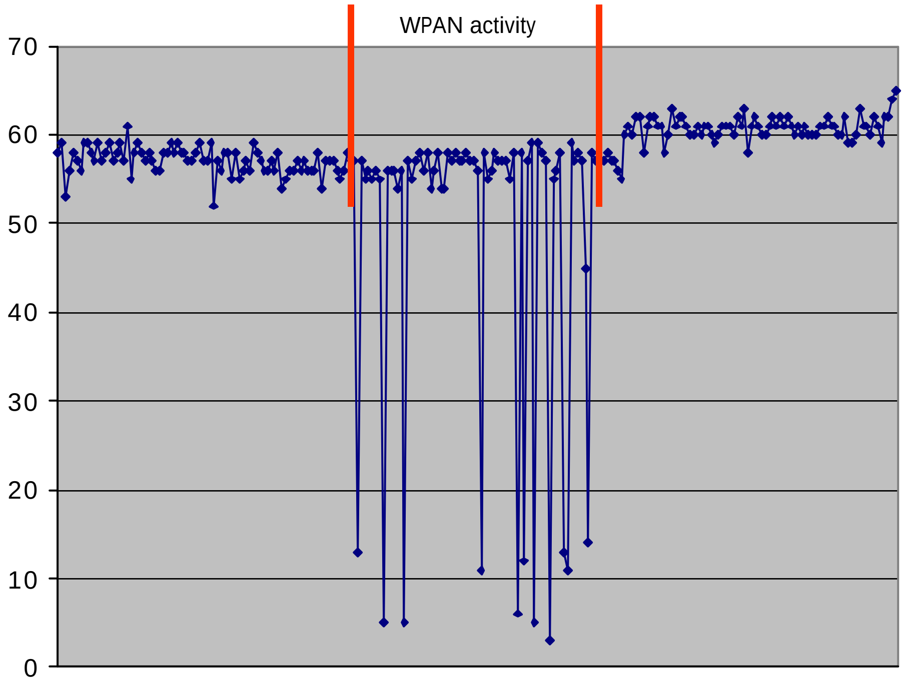

Fig 12: Reduced signal to noise ratio of IEEE802.11 in times of IEEE802.15.4 activity.

4 IEEE802.15.4 vs. Bluetooth

4.1 Test environment

Four Bluetooth stations are used for this first test.

- Two notebooks with a Pentium III 700 MHz processor under MS Windows XP Home Edition V2002 SP1.
- A desktop PC with a Pentium IV 2.8 GHz processer under MS Windows XP Profeesional Edition V2002 SP1.
  All PC are provided with Acer Bluetooth USB-Dongles BT-500 Class 1, 2 and 3, with a compatible product being used from Allnet (WBT-300). They run with highest available power (30 mW).
- A PDA with integrated Bluetooth connectivity. A Fujitsu-Siemens Pocket Loox 600 running Microsoft Pocket PC V3.0 is used.

The notebooks and the PDA are dislocated very close to the ZigBee equipment (cf. fig.13). The desktop dongle is approx. 0.75 m away – under the desk.

Fig 13: Test equipment with ChipCon IEEE802.15.4 boards and Bluetooth station

Fig 14:Screenshot of the Bluetooth environment of the desktop PC

4.2 Bluetooth frequency characteristics

Bluetooth, as specified in [3] uses Frequency Hopping Spread Spectrum (FHSS) technology. All 625 µs a new frequency is chosen out of 79 frequencies with a distance of 1 MHz. The only exception to this rule comes with superframe when the frequency remains constant for the duration of three or five frames (cf. fig 15).

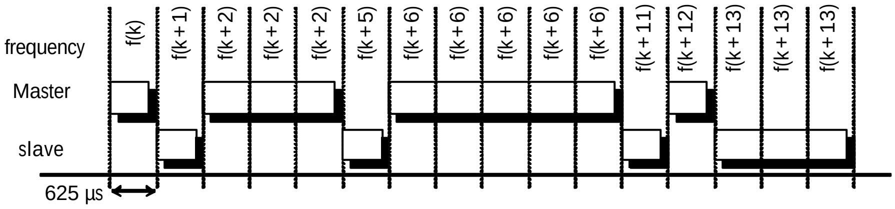

Fig 15: Frequency Hopping of Bluetooth systems

The basic sequence of frequencies can be given as for example:

$b(i) = 0, 54, 70, 45$

The transmission frequency of this basic sequence is then determined through:

$f_0(i) = 2402 + b(i)$ [GHz]

And the transmission frequency of the k-th frequency pattern is described as

$f_k(i) = 2402 + (b(i) + k) \bmod 79$ [GHz]

4.3 Bluetooth traffic characteristics

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.

4.4 Test results

Fig. 16 shows the result of this test. 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.

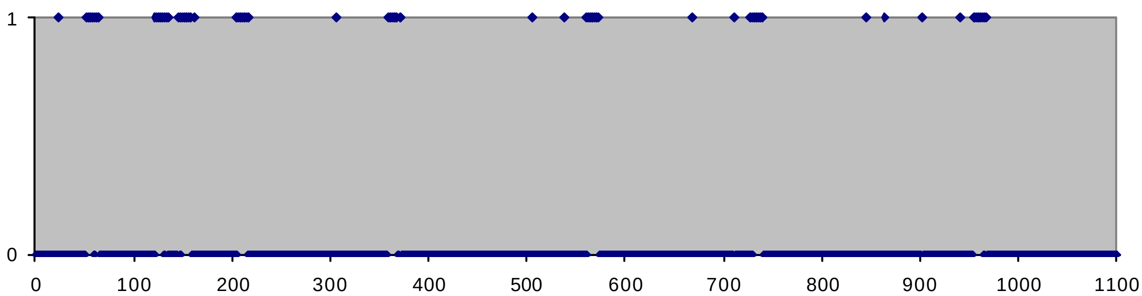

Fig 16: Loss of IEEE802.15.4 frames with Bluetooth interference

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.

5 IEEE802.15.4 vs Microwave Oven

5.1 Test environment

He 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 (cf. Fig. 17).

Fig. 17: Test environment with microwave oven; of course, the door was closed during operation.

5.2 Frequency characteristics

The 2.4 GHz ISM band was opened as it is the frequency where microwave ovens work. However, microwave ovens should be covered by a Faraday cage as to keep energy loss and adverse health effects at a minimum.
Experience shows that the influence of house-hold microwave ovens on Bluetooth and IEEE802.11b systems is negligible. However the emitted power of IEEE802.15.4-systems is significantly lower. Consequently, the microwave issue was revisited.

5.3 Test results

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 were 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 (cf. fig. 18).
- Running the microwave oven at a distance of ~1 m, no influence on the IEEE802.15.4-performance was left.

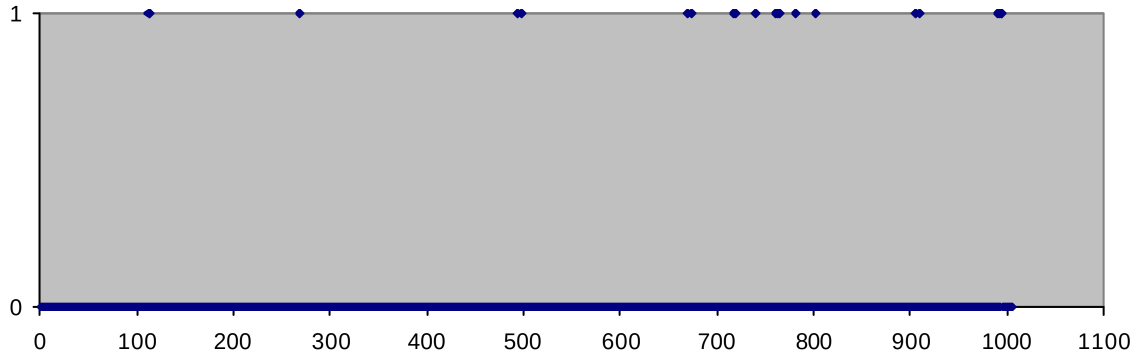

Fig 18: Loss of IEEE802.15.4 frames when used on top of a microwave oven

6 Conclusions

Albeit its low transmission power and its simple modulation technique, IEEE802.15.4 shows a robust behaviour against interference of other 2.4 GHz systems.
The results shown in the report are worst-case and thus should not deceive.
It is well possible to run IEEE802.11 and IEEE802.15.4 in parallel, when reliable transmission techniques (e.g. acknowledgement of frames) are applied.

- In worst case conditions for frequency overlap, local distance and high traffic load for interference, more than 90 % of the IEEE802.15.4 are lost on its way. However, even under these conditions some time slots remain for a successful transmission.
- It requires a distance of only two IEEE802.11-channels to allow a negligible interference on IEEE802.15.4-systems.

It is well possible to run Bluetooth and IEEE802.15.4 in parallel.

- However, it must be taken into account that some subsequent frames may be lost.

It is well possible to run IEEE802.15.4 in the environment of conventional micro-ovens.

- However, it must be taken into account that single frames may be lost.

7 Sources

[1] http://www.chipcon.com
[2] http://www.compotek.de
[3] http://www.bluetooth.org
[4] http://www.dectweb.com
[5] http://www.freescale.com
[6] http://grouper.ieee.org/groups/802/11/index.html
[7] http://www.ieee802.org/15/pub/TG4.html
[8] http://www.zigbee.org
[9] Sikora, A., "wireless personal and local area networks", J.Wiley & Sons, 2003, ISBN 0-470-85110-4.

Steinbeis-Transfer Centre

Steinbeis-Transfer Centre for Embedded Design and Networking (stzedn) is a R&D company in the Steinbeis network. It is located at the University of Cooperative Education Loerrach. Its highly qualified engineers develop secure wired and wireless connectivity solutions, preferably for embedded systems. The nucleus for stzedn is its TCP/IP-stack emBetter, which is unique in its portability, efficiency and performance.
stzedn is a Design Alliance partner of Freescale semiconductor [5] and a system partner of CompoTek [2].
More information can be found at http://www.ba-loerrach.de/stzedn.