Interference Measurements on Performance Degradation between Colocated IEEE 802.11g/n and IEEE 802.15.4 Networks

Marina Petrova, Lili Wu, Petri Mähönen and Janne Riihijärvi
Department of Wireless Networks, RWTH Aachen University
Kackertstrasse 9, D-52072 Aachen, Germany
email: mpe@mobnets.rwth-aachen.de

***Abstract*— We have made detailed measurements, on the impact of modern Wireless LAN technologies on the IEEE 802.15.4 in the 2.4 GHz ISM band. We have specifically focused on IEEE 802.11g and pre-standard IEEE 802.11n products as potential interferers. Our measurements show that high levels of network traffic interference from either of these technologies has disastrous impact on the performance of IEEE 802.15.4. Our results also indicate that these interference effects are especially difficult to avoid in the (pre-standard) 802.11n case due to the significantly increased channel bandwidth compared to previous Wireless LAN technologies. Widespread adoption of IEEE 802.11n especially in applications involving high data rates (such as backbones for wireless mesh networks) could thus have serious impact on the usability of IEEE 802.15.4 as well as other low-power 2.4 GHz ISM band technologies. This indicates that low-power building automation, consumer electronics and sensor networks may be vulnerable to the interference from the future IEEE 802.11n high-data rate WLAN deployments.**

I. INTRODUCTION

During the past couple of years the IEEE 802.15.4 [1] has become a widely used technology for several low-power wireless sensor and embedded networking applications. Widespread adoption of the Zigbee standard would further strengthen the position of the IEEE 802.15.4, ensuring almost ubiquitous deployment into homes and businesses alike. With all its advantages, the use of IEEE 802.15.4 is not free from problems. Most critical of these is perhaps the problem of coexistence in the all the time more crowded 2.4 GHz ISM band (as we shall observe later, IEEE 802.15.4 supports the use of other frequency bands as well in limited fashion, but these bring other restrictions into play).

At present the 2.4 GHz ISM band is undoubtedly one of the most highly occupied pieces of the unlicensed spectrum. The widespread adoption of IEEE 802.11b together with the introduction of Bluetooth into several common cellular phones and other handheld and portable devices have started the proliferation of 2.4 GHz technologies. More recently Wi-Fi evolutions, namely IEEE 802.11g, have continued this trend. Very recently, first pre-standard compliant versions of the next-generation Wi-Fi systems (IEEE 802.11n) have also begun to emerge. This has potentially a disastrous effect on the usability of other 2.4 GHz ISM band technologies due to very high bandwidths of IEEE 802.11n systems.

In this paper we will study the effects of active IEEE 802.11g and IEEE 802.11n devices on the IEEE 802.15.4 connections conducting an extensive measurement campaign. The measurements and analysis of the pre-802.11n products is relevant and important as there is still possibility to affect the final IEEE 802.11n standard from the coexistence point of view. We refer the reader to [2], [3], [4], for results on the case of IEEE 802.11b as the interfering technology. One of the aim of this paper is to show that there maybe severe limitations how to deploy IEEE 802.11g/n and IEEE 802.15.4 networks into the same locality. The networks deployment will not be free due to interference limitations, and this needs to be taken into account by the network designers.

We begin with a short introduction to the relevant technologies in Section II. After this, we present our measurement setup in detail in Section III. The measurement results are then presented and analyzed at length in Section IV before drawing the conclusions in Section V.

II. OVERVIEW OF THE IEEE 802.15.4 AND IEEE 802.11N

A. IEEE 802.15.4

The IEEE 802.15.4 [1] is a part of the IEEE family of standards for physical and link-layers for wireless personal area networks (WPANs). The IEEE 802.15.4 standard is designed to address applications with low throughput and relaxed latency requirements while favoring a low-cost and low-power design. These features enable applications in the fields of industrial, agricultural, vehicular, residential, and medical sensors and actuators, which cannot make use of current wireless technologies or are using proprietary solutions. The standard defines two types of devices: a 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 based on direct sequence spread spectrum (DSSS) The low-band 868/915 MHz PHY known as uses binary phase shift keying (BPSK) modulation whereas the 2.4 GHz PHY (high-band) uses offset quadrature phase shift keying (O-QPSK) modula-

Proceedings of the Sixth International Conference on Networking (ICN'07)
0-7695-2805-8/07 $20.00 © 2007 IEEE

tion. Both modulation modes offer an extremely good bit error rate (BER) performance at low Signal-to-Noise Ratios (SNR).

The IEEE 802.15.4 physical layer offers a total of 27 channels, one in the 868 MHz band, 10 in the 915 MHz band, and, finally, 16 in the 2.4 GHz band. The nominal radio bit rates on these three frequency bands are 20 kbps, 40 kbps, and 250 kbps, respectively. For more details on the physical layer design we refer the reader to [1]. In this paper we are focusing on measurements in the 2.4 GHz frequency band as that is the area where inter-technology problems between IEEE 802.15.4 and IEEE 802.11g/n are of a great concern when it comes to interchannel interference. Without a proper channel configurations the WLAN technologies may cause serious performance degradations to the nearby sensor deployments.

B. IEEE 802.11n

In September 2003 the IEEE 802.11 working group formed the Task Group n (TGn) with a goal of developing a wireless standard that will provide usable throughput of at least 100 Mbps. Just as a comparison, the theoretical maximum throughput for standard-based 802.11a and 802.11g products is 54 Mbps, and the highest usable throughput achieved is typically between 25-30 Mbps.

The current pre-standard work in IEEE 802.11n group is strongly affected by two large industry consortia namely the Enhanced Wireless Consortium (EWC) and the World-Wide Spectrum efficiency group (WWiSE). However, the latest pre-standard release was generating a large amount of comments and correction suggestions. Hence the full standard of IEEE 802.11n is expected to be ratified by the second quarter of 2007 at earliest, or even later.

The IEEE 802.11n standard promises an immense increases in aggregate wireless throughput and range through the use of MIMO (multiple input, multiple output) spatial multiplexing techniques coupled with OFDM technique presently implemented in the legacy IEEE 802.11a/g devices. MIMO can provide many benefits, thanks to the ability to process spatially different signals simultaneously. Using multiple antennas, MIMO technology offers the ability to coherently resolve information from multiple signal paths using spatially separated receive antennas. In that way, MIMO offers the opportunity to spatially resolve multipath signals, providing diversity gain increases receiver's ability to recover the sent information. According to the both 802.11n proposals the minimum required MIMO antenna configurations is 2×2, where both the sender and the receiver have two transceivers active.

Another valuable feature of MIMO technology is the Spatial Division Multiplexing (SDM). SDM spatially multiplexes a number of independent data streams, transmitted simultaneously within one frequency channel. MIMO SDM can significantly increase data throughput as the number of resolved spatial data streams is increased.

The significant increase in the PHY transmission rate in IEEE 802.11n technology is also due to the use of wider channel bandwidth. The current draft standard and the products on the market support both 20 MHz and 40 MHz channels. The 40 MHz channels provide more than two times the usable channel bandwidth of two IEEE 802.11 legacy channels. The 20 MHz channels are to be used where the spectrum availability is limited. According to the WWiSE the 20 MHz channels are divided into 56 subcarriers just like in the IEEE 802.11a, and the 40 MHz channels into 112 subcarriers. The 40 MHz channels are optional and are only supported in the 5 GHz frequency band. However, in the EWC proposal, the 40 MHz channel is compulsory and divided into 128 subcarriers.

While the 40 MHz wide channel brings an increase in the data rate for the IEEE 802.11n users, it is very probable that the IEEE 802.11n will endanger the IEEE 802.15.4 low-power sensor networks deployments. We expect that the way wireless administrators allocate channels in the 2.4 GHz band will need to change dramatically once IEEE 802.11n products gain wider acceptance. In order to estimate the effects the new wireless technology has on the concurrent IEEE 802.15.4 transmissions we performed several measurements using off-the-shelf hardware. The details on the measurement setup and our findings are presented in the following sections.

III. MEASUREMENT SETUP

The purpose of the measurement campaign is to examine the interference of IEEE 802.11g/n on IEEE 802.15.4 devices as mentioned above. This work is partially inspired by the true needs of the industry. Especially companies providing automation and entertainment solutions based on IEEE 802.15.4 have an interest on understanding better the interference effects the IEEE 802.11n devices might have on their networks.

The setup of the measurement include IEEE 802.11g/n access point (AP) (Linksys WRT300N), and a laptop equipped with an 802.11g/n PCMCIA adapter (Linksys WPC300N). Another computer was connected to the IEEE 802.11 AP as the traffic generater. For IEEE 802.15.4 testing we were using two TelosB nodes which have the standard compliant CC2420 radio chip , working in 2.4 GHz ISM frequency band [5]. The measurement setup was continuously monitored with Agilent E4440A spectrum analyzer. We were specifically measuring the spectral power of the interfering traffic.

The IEEE 802.11g/n AP and the client laptop were used to generate background traffic. The network performance measurement tool, Iperf [6], was employed to generate traffic in the wireless LAN link. The TelosB nodes use TinyOS [7] as operating system. During the measurements one TelosB node was programmed to transmit certain number of packets with different payload sizes at a fixed time interval between the packets. The other TelosB node counted the number of correctly received packets for each measurement. The criteria applied for evaluating the quality of IEEE 802.15.4 transmission is the packet delivery ratio (PDR).

Figure 1 illustrates the channel assignment and the PSD (Power Spectrum Density) mask of IEEE 802.15.4 and IEEE 802.11g/n. For IEEE 802.11n, a 40 MHz channel with the central frequency at 2452 MHz (WLAN channel 9) was used in the measurements, whereas for 802.11g, a 20 MHz channel

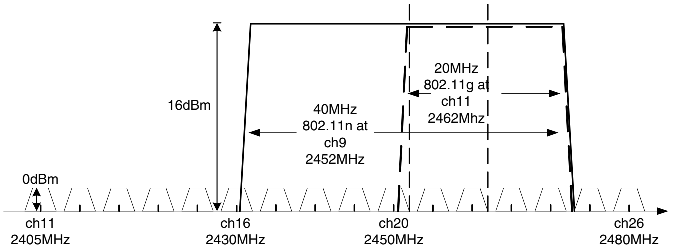

Fig. 1. IEEE 802.15.4 and IEEE 802.11g/n channel allocation and PSD mask.

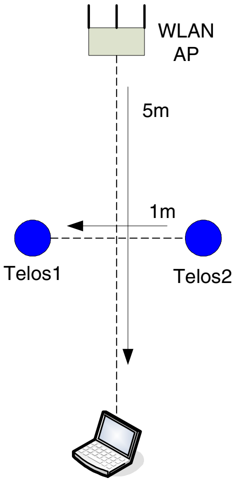

Fig. 2. Setup 1: UDP background traffic from IEEE 802.11 AP to laptop, TelosB (IEEE 802.15.4) nodes located in the middle of wireless LAN nodes.

centered at 2462 MHz (WLAN channel 11) was selected. The IEEE 802.11n and 802.11g devices have a maximum transmission power of 16 dBm, while the TelosB nodes the maximum transmission power of 0 dBm. During the measurements, the transmission power of both radio technologies was set to maximum level.

The measurements were done in two different setups. The topology of the setup 1 is shown in Figure 2. In this setup the wireless AP and the wireless client were located 5 meters away. The sensor nodes were set 1 meter apart and located perpendicular to the WLAN link. This scene was used to compare the impact of IEEE 802.11g/n with different traffic loads on IEEE 802.15.4 transmission.

The setup 2, shown in Figure 3, was established to examine the effect of different orientations of IEEE 802.11n transmission on IEEE 802.15.4 devices. Measurements were processed at 5 points, where the orientation of 0° indicated that the laptop was placed in the same line with the TelosB nodes and the wireless AP. It is important to note that the laptop is the only device changing the position. In order to get quantitative observation of the signal strength, the spectrum analyzer is located close to the receiver TelosB node to monitor the spectrum strength of the background traffic.

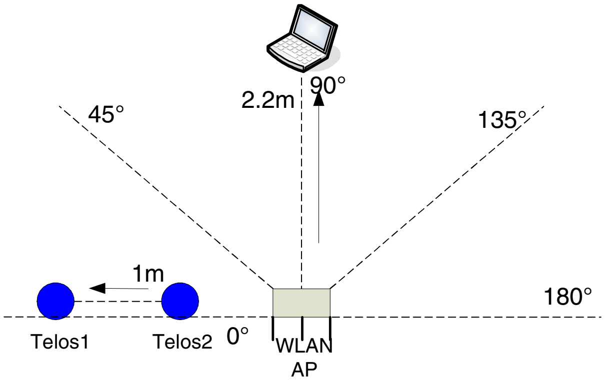

Fig. 3. Setup 2: UDP background traffic from IEEE 802.11 AP to laptop, the position of IEEE 802.11 laptop changes in different measurement. A spectrum analyzer was located near Telos1 to monitor interference signal strength.

IV. COEXISTENCE BETWEEN THE TWO TECHNOLOGIES

As presented in the previous section, the IEEE 802.11g/n devices were used to generate background traffic, source of interference, during the measurements. UDP traffic with 1472 bytes payload size (MTU 1500 bytes) was sent from the IEEE 802.11n/g AP with different offered data rate. On the sensor side, two payload sizes were used, 26 bytes and 116 bytes. The interval of sending packets is 16 ms. The combination of maximum payload size and the transmission interval has been tuned to fit in the channel capacity of IEEE 802.15.4, so that when there is no interference in the channel, the PDR value is up to 100%.

In each measurement, the TelosB sender node transmitted 2000 packets. On the receiver side, the number of correctly received packets was counted. During the measurement, the IEEE 802.11 channels were set as shown in Figure 1. The channel of the TelosB nodes was changed after each measurement. In this way, the IEEE 802.15.4 channels which are overlapping and neighboring to the IEEE 802.11 channel can be measured. In order to reduce the effect of unpredictable interference during the measurement, each measurement was repeated at least 5 times, and the average values are shown in the results.

A. Setup 1 results

In this scenario we tested the impact of IEEE 802.11n/g transmissions with different offered traffic load. For IEEE 802.11g, 30 Mbps is close to the maximum theoretical UDP throughput [8]. With the IEEE 802.11n adapters, we were able to reach 150 Mbps UDP throughput in a 40 MHz channel.

Figure 4 shows the average PDR of IEEE 802.15.4, with 26 bytes payload size and 16 ms packet interval, under different IEEE 802.11g/n traffic loads.

In the IEEE 802.15.4 channels which are overlapping with IEEE 802.11 channels (40 MHz for 802.11n and 20 MHz for 802.11g), a higher IEEE 802.11g/n traffic load will result in a lower PDR between the sensor nodes. Especially when the background traffic is approaching the maximum value,

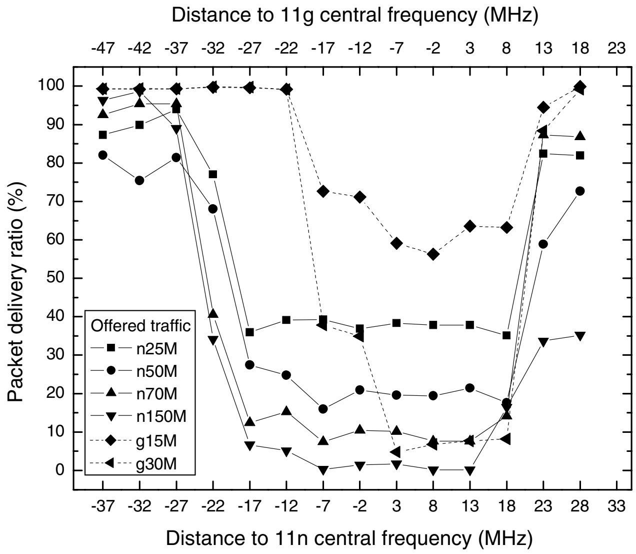

Fig. 4. Setup 1 results: packet delivery ratio of 2000 packets (26 bytes payload size) from Telos2 to Telos1 in different IEEE 802.15.4 channels. The background IEEE 802.11g/n UDP traffic had various offered data rate.

the PDR of IEEE 802.15.4 in the overlapping channels is close to 0%. The highest value of the PDR achieved is only around 60% when the interferer is IEEE 802.11g with 15 Mbps offered traffic. In real wireless sensor network scenarios where competing traffic, collisions, and interference from the same technology exist, we can expect further dramatic drop in PDR, thus the requirements of applications on the link quality cannot be fulfilled. In a separate measurement with moderate IEEE 802.11n traffic (512 kbps), the PDR of IEEE 802.15.4 was close to 100%. The results indicate the communication between IEEE 802.15.4 nodes suffers heavily in the overlapping channels if there are IEEE 802.11g/n transmissions nearby with middle or high traffic load.

An interesting observation from the figure is that in the IEEE 802.15.4 channels outside the IEEE 802.11n channel (e.g. at -22 MHz from IEEE 802.11n central frequency), the effect of interference is still obvious. This is caused by the interaction of IEEE 802.11 energy outside its frequency band and the CCA (Clear Channel Assignment) mechanism used in IEEE 802.15.4. This issue will be further studied in Section IV-B.

The same measurement was done also with a IEEE 802.15.4 payload size of 116 bytes. The results present the similar effect as with 26 bytes payload. A comparison of PDR of the IEEE 802.15.4 packets in one overlapping channel (channel 21) under different IEEE 802.11g and IEEE 802.11n traffic loads is shown in Table I. As expected, under the same background interference, smaller packets generally result in higher PDR.

TABLE I

COMPARISON ON PDR OF TWO IEEE 802.15.4 PAYLOAD SIZES IN ONE OVERLAPPING CHANNEL.

Payl.	g15M	g30M	n25M	n50M	n70M	n150M
26B	63.6%	7.7%	37.9%	21.4%	7.7%	0.2%
116B	36.8%	11.1%	5.1%	8.5%	0.8%	0.5%

B. Setup 2 results

In [9] beam forming is presented as an option for 802.11n sender and receiver. Beam forming is a technique that the transmitter can make use of the knowledge of the MIMO channel to improve range of a wireless system and thus improve throughput. In the setup 2 (Figure 3), the goal of the measurement is to study the impact of directionality of IEEE 802.11n on IEEE 802.15.4 transmission.

In each measurement, UDP traffic (1472 bytes payload size) of 70 Mbps offered load was sent from IEEE 802.11n AP to the IEEE 802.11n laptop. The position of the IEEE 802.11n AP and the sensor nodes were fixed throughout the whole measurement. The IEEE 802.11n laptop was located in one of the five points for each measurement as shown in Figure 3.

Figure 5 shows the results of measurement. The difference in PDR for different background traffic clearly shows the effect of directionality of 802.11n transmission. In this measurement, when the IEEE 802.11n traffic was at 90°, we noticed the highest PDR at the receiving TelosB node. The second best IEEE 802.11 PDR can be observed when the IEEE 802.11n traffic is at 180°. When the IEEE 802.11n nodes were inline with IEEE 802.15.4 nodes, namely at 0°, both the overlapping IEEE 802.15.4 channels and the neighboring channels were heavily affected by the IEEE 802.11n traffic. The PDR results of IEEE 802.15.4 fit very well to the spectrum measurement shown in Figure 6. For example, the two lowest average interference level in the spectrum measurement correspond to the two highest PDRs in IEEE 802.15.4 transmission. Moreover, we can clearly see from the spectrum measurement that the difference of in average signal strength can reach up to 15 dBm, dependent on the orientation of IEEE 802.11n receiver. Such a phenomenon was not observed in another measurement with IEEE 802.11g, in the same topology. The effect of beam forming in IEEE 802.11n observed in the measurements can be utilized in deploying IEEE 802.11n systems and IEEE 802.15.4 networks to minimize the interference between the two technologies.

In this setup, we also show the impact of the interference from IEEE 802.11n device in the non-overlapping IEEE 802.15.4 channels, i.e. channel 25 and 26. From the spectrum measurement we can observe the signal strength is still rather high outside IEEE 802.11n channel. In the IEEE 802.11n PHY specification [9] a 20 dB drop is defined for the PSD mask at ± 21 MHz to the central frequency of the channel. Considering the transmission signal power level of the TelosB nodes and IEEE 802.11 devices as shown in Figure 1, it is still possible in close range, that a IEEE 802.11n transmission corrupts the packets from IEEE 802.15.4 devices in non-overlapping channels. A possible reason for this is the CCA mechanism used by the TelosB nodes. According to the specification [1], IEEE 802.15.4 PHY shall provide at least one of the three CCA modes: energy above threshold, carrier sense only, and carrier

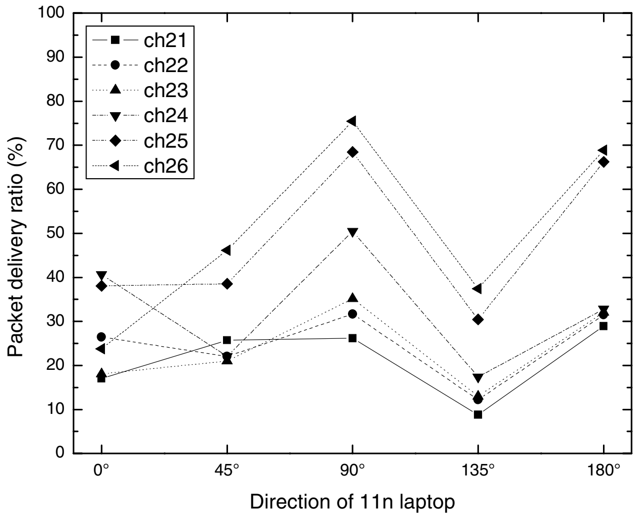

Fig. 5. Setup 2 results: packet delivery ratio of 802.15.4 transmission, when IEEE 802.11n laptop was located at different positions. The UDP traffic from IEEE 802.11n AP to laptop had 70 Mbps data rate.

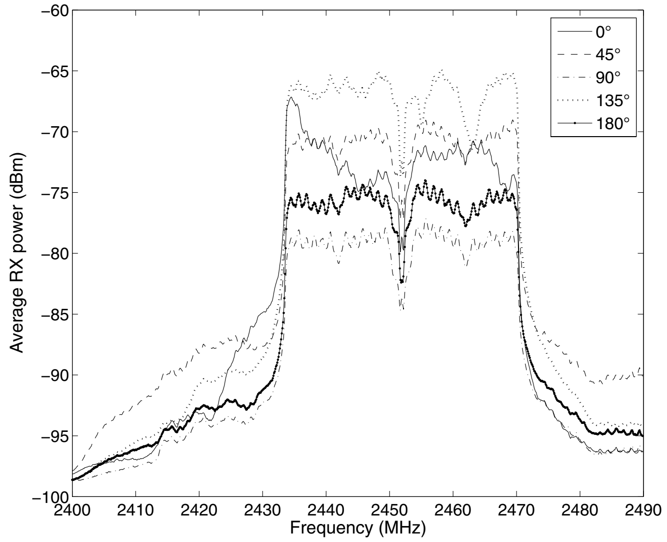

Fig. 6. Average spectrum strength at Telos1 node in Setup 2 for different positions of IEEE 802.11n laptop.

sense with energy above threshold. The third CCA mode means CCA shall report a busy medium upon the detection of a signal with the modulation and spreading characteristics of IEEE 802.15.4 with the energy above the energy detection (ED) threshold. The radio chip CC2420 [5] supports the first two CCA modes defined in the IEEE 802.15.4 specification but the third CCA mode is modified and defined as a clear channel, i.e., the energy is below the threshold and the channel is not receiving valid IEEE 802.15.4 data. The ED/carrier sense (CS) threshold is programable, and its typical value is -77 dBm. The third CCA method is the default mode used in TinyOS (defined as const value in CC2420 control module), and it was used in the measurement. Since the location of the sender IEEE 802.15.4 node was close to the IEEE 802.11 AP in the measurement, we can presume one reason for losing packets at IEEE 802.15.4 receiver in non-overlapping channels is that the packets were not sent by the sender when the interference level is higher than the ED/CS threshold.

To verify this assumption another measurement was done in setup 2. In this case, the IEEE 802.11n laptop was fixed at 90° position. The background traffic kept the same, UDP traffic of 70 Mbps. Three different ED/CS thresholds were tested: -77 dBm, -65 dBm, and -55 dBm. Also two packet payload sizes (26 and 116 bytes) were used in the measurement. Figure 7 presents the measurement results. The effect of changing ED/CS threshold is clear. When the threshold is set to the default value -77 dBm, IEEE 802.15.4 channels outside the 802.11n band are also affected. If the threshold is -65 dBm the interference to the IEEE 802.15.4 can no longer be detected for both packet sizes. The result confirms our assumption on the interaction of interference level and the CCA mechanism employed by IEEE 802.15.4 devices. We can conclude in this scenario that the impact of IEEE 802.11n transmission on the IEEE 802.15.4 non-overlapping channels is not directly caused by the channel error, but mainly the consequence of high sensitive CCA threshold setting. The PDRs in the overlapping channels were also improved, this indicates the low PDR values in these channels are only partially caused by the transmission errors in the channel with high interference. The last test was made with the threshold set to -55 dBm for IEEE 802.15.4 packets with 26 bytes payload. This time, the PDRs in the overlapping channels were further improved than the threshold of -65 dBm, although the improvement is not as obvious as between the last two measurements. We can conclude from this measurement that in certain network environments with interference from other radio technologies, if the IEEE 802.15.4 devices can adaptively set the CCA ED threshold based on the noise level, the performance in the overlapping and neighboring channels can be improved. An example of using the adaptive CCA threshold scheme is at a sensor network gateway, which connects IEEE 802.15.4 and IEEE 802.11 network. In IEEE 802.15.4 networks, increasing the CCA ED/CS threshold may on one hand improve the channel utilization, and on the other hand it will increase the number of collisions in the network. In [10], the authors present the choice of carrier sense range in wireless networks, and observe that the optimal carrier sense threshold depends on the degree of channel contention, packet size and other factors affecting bandwidth-(in)dependent overhead. The authors also take into account MAC layer overhead. When interference from other radio technology is also introduced in wireless networks, the selection of CCA ED/CS threshold becomes more complicated, and need to be further studied.

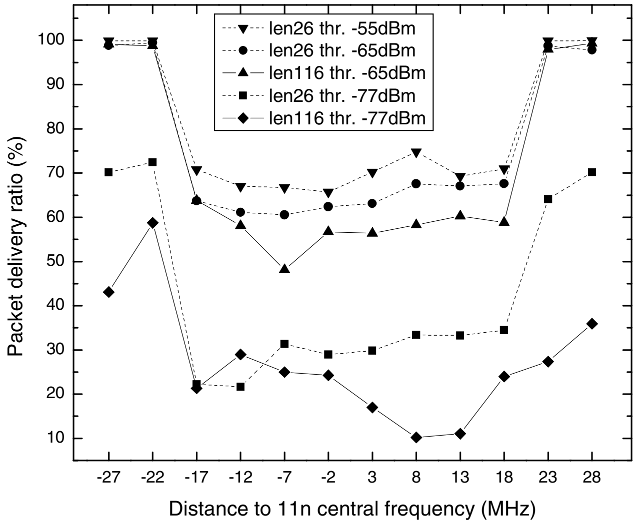

Fig. 7. Comparison of packet delivery ratio of IEEE 802.15.4 transmission, when different CCA thresholds were set. The positions of IEEE 802.11n nodes were fixed, and the traffic was 70 Mbps UDP.

V. CONCLUSIONS

The overall goal of this paper was to determine, qualitatively, the effects of the new high-speed IEEE 802.11n WLAN technology on the already wide-spread IEEE 802.15.4 low-power devices, which are operating in the same 2.4 GHz frequency band. We analyzed through measurements the co-existence impact the pre-IEEE 802.11n off-the-shelf devices have on the IEEE 802.15.4 compatible sensor nodes (TelosB). Our measurements were organized in two setups. The setup 1 was used to test the effects of the different IEEE 802.11g/n background traffic loads on the packet delivery ratio (PDR) between two TelosB nodes. In setup 2 we studied the influence of the IEEE 802.11n directionality on the communication between two TelosB nodes. All measurements were performed in a overlapping and non-overlapping channel operation between the two technologies.

We can conclude, based on our results, that in an environment with a middle or high IEEE 802.11n traffic load it is very difficult to guarantee the quality of the nearby operating IEEE 802.15.4 based sensor networks. If no care is taken about the operational channels of the two technologies, the IEEE 802.11n itself will have a negative effect on the performance of the IEEE 802.15.4 transmission, resulting in a very poor PDR. We have observed that even outside of the operating channel the IEEE 802.11n power is high enough to seriously interfere the IEEE 802.15.4 channels. This is due to the highly sensitive CCA (Clear Channel Assignment) threshold settings in the IEEE 802.15.4 devices. If this threshold can be set dynamically, according to the current interference level, there can be improvements in performance of the IEEE 802.15.4 communications both in the overlapping and non-overlapping channels (with IEEE 802.11n).

Furthermore we observed that the beam-forming in the IEEE 802.11n has an impact on the performance of a IEEE 802.15.4 link. Depending on the IEEE 802.15.4 traffic flow orientation in regard to the interfering IEEE 802.11n communication , the PDR between the TelosB nodes can be higher or lower.

At the end we believe that such measurement studies are relevant for the further finalization of the IEEE 802.11n standard when it comes to the coexistence issues with the other technologies operating in the 2.4 GHz band. On the other hand these findings are very important for the industry deploying sensor networks in order to be able to guarantee and maintain the performance of their networks in different interference environments.

ACKNOWLEDGMENT

We would like to thank DFG and RWTH Aachen University for the partial funding through UMIC excellence cluster. Additionally we would like to acknowledge the support of the European Commission (WASP and RUNES projects).

REFERENCES

[1] *Part 15.4: Wireless Medium Access Control (MAC)and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (LR-WPANs)*, no. 802.15.4. IEEE, 2003.

[2] M. Petrova, J. Riihijärvi, P. Mähönen, and S. Labella, "Performance study of IEEE 802.15.4 using measurements and simulations," in *Proc. of IEEE WCNC, Las Vegas '06*, April 2006.

[3] C. Won, J. Youn, H. Ali, H. Sharif, and J. Deogun, "Adaptive radio channel allocation for supporting coexistence of 802.15.4 and 802.11b," in *Proc. of IEEE VTC '05*, September 2005.

[4] *Compatibility of IEEE 802.15.4 (ZigBee) with IEEE 802.11 (WLAN), Bluetooth, and Microwave Ovens in 2.4 GHz ISM-Band, Test Report v.03*. Steinbeis-Transfer Centre, Embedded Design and Networking, University of Cooperative Education Loerra, September 2004.

[5] *CC2420 Data Sheet 1.4*. Chipcon, 2006.

[6] *The Iperf tool*, http://dast.nlanr.net/Projects/Iperf/.

[7] *TinyOS*, http://www.tinyos.net/ [last visited 19.11.2006].

[8] *White Paper: 802.11 Wireless LAN Performance*. Atheros Communications, 2003.

[9] *HT PHY Specification V1.27*. Enhanced Wireless Consortium, 2005.

[10] X. Yand and N. Vaidya, "On physical carrier sensing in wireless ad hoc networks," in *Proc. of IEEE INFOCOM '05*, March 2005.