Feasibility Study on Application of Impulse-UWB for Control Channel in Cognitive Radio Networks

Michael Döring, Anatolij Zubow and Adam Wolisz
{doering, zubow, wolisz}@tkn.tu-berlin.de

***Abstract*—Cognitive Radio (CR) will enhance the efficiency in spectrum usage by re-using temporally unused licensed spectrum. A promising transmission scheme to utilize even very fragmented and fast changing spectrum is Non-Contiguous OFDM (NC-OFDM). Unfortunately, NC-OFDM requires tight synchronization between sender and receiver, i.e. the receiver needs perfect up-to-date knowledge about the set of subcarriers being used by the NC-OFDM sender. Therefore, a reliable and always available Control Channel (CC) is crucial for signaling the spectrum allocation information. Although, underlay Impulse-Radio Ultra-WideBand (IR-UWB) meets the theoretical requirements for such a CC in CR networks, i.e. communication range of up to 1 km on a sufficient high data rate, there is a lack of practical studies of IR-UWB in real world environments, especially with respect to co-existence with NC-OFDM as in the envisioned CR multi-technology station.**

In this paper we present results of measurements in our state-of-the-art IR-UWB testbed. We show that IR-UWB can reach the required communication range of a few hundreds of meters in unobstructed as well as slightly obstructed Line-of-Sight propagation only. Although, IR-UWB is a wideband technology we show that it is severely affected by narrowband interference from close proximity sources which is typically the case in the envisioned multi-technology stations. Such a mutual disturbance can be mitigated by increasing the spatial separation between both air interfaces, orthogonalization in time or using only those parts of the radio spectrum for NC-OFDM which are outside the main IR-UWB transmission mask.

***Index Terms*—Cognitive Radio, Control Channel, IR-UWB, narrowband interference, testbed measurements**

I. Introduction

Cognitive Radio (CR) is a promising technology to overcome the scarcity of wireless spectrum availability. Even in spatial locations where all frequencies are exclusively licensed to certain entities, it has been shown that this licensed spectrum is very often underutilized [1]. Therefore, if the licensed or Primary User (PU) is not present, secondary usage of this spectrum by a Secondary User (SU) will boost the efficiency in spectrum usage enormously.

To utilize even very fragmented spectrum, Non-Contiguous OFDM (NC-OFDM) transmission technique can be applied. One of the main challenges of NC-OFDM is the required synchronization between sender and receiver, i.e., the secondary receiver needs perfect and up-to-date knowledge about the set of subcarriers (frequencies) being temporary used by the sender. Otherwise, the receiver is either not able to construct the proper preamble for the allocated non-contiguous spectrum and hence, the detection of the packet transmission will fail or an incorrect set of subcarriers is used for decoding. This means, a separate always available, low latency Control Channel (CC) is necessary to signal the allocated subcarriers to the receiver side. Moreover, the signaling needs to be very frequently because of the spectrum agility of NC-OFDM.

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Such a CC requires only a small but guaranteed bitrate, large enough to reference the scattered spectrum (subcarriers) in use. Furthermore, the update interval must be within the channel coherence time and below the maximum evacuation time to leave the primary spectrum. In a practical system the required bitrate for signaling the spectrum allocation is pretty low, i.e. in the order of a few 10 kbit/s[1] and depends on several PU properties as e.g. occurrence, quantity and channel width.

A candidate wireless technology for the CC could be Impulse-Radio Ultra-WideBand (IR-UWB) [2]. This technology allows transmission below the noise floor of other wireless transmission techniques and can therefore be used in parallel without interfering with PUs and without requiring additional dedicated spectrum resources (see Fig. 1). Other wireless technologies for the CC might be also conceivable, especially when operating in unlicensed ISM bands. But these technologies might not always meet the above CC requirements. In particular the widely use of random access schemes leads to unbounded latencies in crowded ISM bands (e.g. IEEE 802.11).

Usually IR-UWB technology is used in short range communication with high bitrates, whereas its use for medium and long range communications with low bitrates is challenging but possible as some theoretical work shows (see Table I and [3]). Because of a lack of experimental results we believe that the prior mentioned advantages of using IR-UWB for CC make it worth to conduct experiments using a commercial state-of-the-art IR-UWB transceiver to investigate IR-UWB behavior in a realistic (urban) outdoor scenario. Moreover, we believe it is important to analyze whether the two wireless technologies, IR-UWB and NC-OFDM as envisioned in this paper, can co-exist together in a multi-technology CR transceiver station without mutual interference. We have chosen OFDM for the co-existence analysis, because it is the successor technology in wireless communication.

Contributions: First, with the help of measurements in our IR-UWB testbed, we found out that under real conditions IR-UWB can achieve the required communication range of a few

[1] Take IEEE 802.22 as an example: 2048 subcarrier with an update interval of 6.25 Hz (based on the superframe duration of 160 ms) equals 12.8 kbit/s.

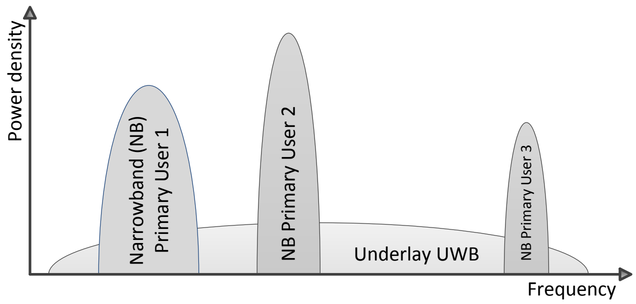


Fig. 1. In the underlay dynamic spectrum access model, a SU can transmit on a spectrum band regardless of whether the PU is active or not, but at a low power on each band to limit interference [4].

TABLE I
SIMULATION RESULTS TAKEN FROM NASCIMENTO AND NIKOOKAR [3] OF ACHIEVABLE RANGE-DATA RATES CONSIDERING THREE DIFFERENT PATH LOSS MODELS AND TWO LEVELS OF M-ARY PULSE AMPLITUDE MODULATION (PAM) AND PULSE POSITION MODULATION (PPM) MODULATIONS AT A BER EQUAL TO 10^{-6}.

Modulation	Ranges in meter for different bitrates 10 kbps	100 kbps	550 kbps	1000 kbps
	Free space path loss model			
2-PAM	730	231	98	73
64-PPM	1018	322	137	102
	Lognormal shadowing path loss model (outage probability of 0.01%)			
2-PAM	165	52	22	16
64-PPM	228	72	31	21
	UWB dependent two-ray path loss model			
2-PAM	850	422	133	110
64-PPM	1016	530	149	133

hundreds of meters in Line-of-Sight (LOS) only. Some form of minor propagation obstructions (e.g. leaves of trees) can be tolerated, whereas in a pure Non-Line-of-Sight (NLOS) environment long-range communication is impossible. Second, although IR-UWB is a wideband technology it is severely affected by narrow-band interference in close proximity, which is the case in the envisioned multi-technology CR station.

The rest of the paper is organized as follows. In the next section we present the most important publications regarding this topic. In Sec. III the UWB technology is presented briefly. The problem statement is formulated in Sec. IV. In Sec. V we present the results of the several measurements series conducted with our IR-UWB testbed and discuss their practical implications in Sec. VI. Finally, Sec. VII summarizes our main findings and concludes the paper.

II. RELATED WORK

A general overview of the UWB technology and especially a theoretical view on the influence of narrowband interferers on UWB is extensively given by Arslan et al. in [2]. Nascimento et al. [3] evaluated the tradeoff between IR-UWB communication range and bitrate from the theoretical point of view. Masri et al. [5] evaluated the use of IR-UWB for CC in CR Ad-hoc networks by means of network simulations. To overcome the limited communication range they proposed to forward control messages via multi-hop IR-UWB. By means of simulations Petracca et al. [6] studied the impact of an IR-UWB control

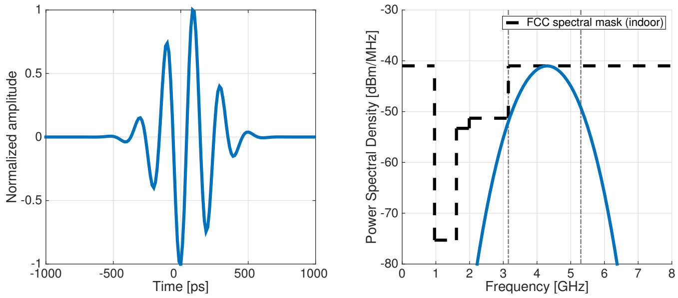


Fig. 2. UWB waveform example – 15th derivate of a Gaussian pulse – in time (left) and frequency domain (right) (adapted from: [9]).

channel on primary users (GSM). Manzi et al. [7] studied intensively the interference influence of IR-UWB on IEEE 802.11a/b WLAN by means of experiments and simulations. Finally, Şahin et al. [8] proposed to use IR-UWB in the data channel. To further reduce interference on PUs they suggest to perform even spectrum shaping in IR-UWB.

III. PRIMER ON IR-UWB

UWB is a rather simple wireless communication technology and was originally introduced in 1901 by Marconi to transmit Morse codes. As shown in Fig. 2 the pulses are very short in time, but occupy a very large bandwidth in the frequency domain. Signals with an instantaneous bandwidth exceeding 500 MHz or with a fractional bandwidth larger than 0.2 are considered as UWB [2]. The main advantages beside its very simple transceiver structure is, that radio frequency profiles are very low and the transmission is robust in the face of multipath. Because of the increasing spectrum scarcity the FCC approved in 2002 unlicensed operation in the frequency ranges from 3.1 GHz to 10.6 GHz with a very low transmit power of about -41.3 dBm/MHz. Following this decision the standardization group IEEE 802.15.3a was formed to provide a high speed UWB-PHY. The groups split up in 2006 because no agreement between the main PHY technologies Multi-Band Orthogonal Frequency Division Multiplexing (MB-OFDM) and Direct Sequence UWB (DS-UWB aka. IR-UWB) could be found. Currently MB-OFDM is a successor technology for short-range high-speed wireless USB, while IR-UWB is today mainly used for ranging.

In UWB a trade-off between communication range and data rate exist. This trade-off was already analytically evaluated for long-range IR-UWB communication by Nascimento et al. [3]. Their results show that from theoretical point of view a communication range of up to 1 km with a data rate of 10 kbit/s using the free space path loss model is possible. By applying the lognormal shadowing path loss model a data rate of 10 kbit/s can be achieved in ranges up to 200 m.

IV. PROBLEM STATEMENT

This paper is a measurement study from an outdoor IR-UWB testbed. The research question is to find out whether IR-UWB meets the requirements for a CC in CR networks. In particular, we are interested in whether IR-UWB is able to provide a reliable, low latency, always available but low bitrate

TABLE II
SPECIFICATION OF TIMEDOMAIN P410 TRANSCEIVER.

Parameter	Value
Operating band	3.1 - 5.3 GHz
Center frequency	4.3 GHz
Transmit power	-12.64 dBm
Noise figure	4.8 dB
Dynamic range (PII=10)	60 dB
Transmit pulse repetition rate	10.1 MHz
Pulse Integration Rate (PII)	10 (1024 pulses per bit)

($\approx$ 10 kbit/s) communication over the required communication range of a few hundred of meters outdoors (small cells). Moreover, we are interested whether the envisioned multi-technology station equipped with two air interfaces, IR-UWB and NC-OFDM, is feasible, i.e., there is no significant mutual disturbance between both technologies.

V. EVALUATION OF IR-UWB FOR CONTROL CHANNEL USAGE

We have performed a variety of experiments in our outdoor IR-UWB testbed to investigate the suitability of the IR-UWB technology as CC in CR networks. First, we measured the maximum communication range outdoors. Second, we studied whether the two wireless technologies, IR-UWB and NC-OFDM, can co-exist in a multi-technology station.

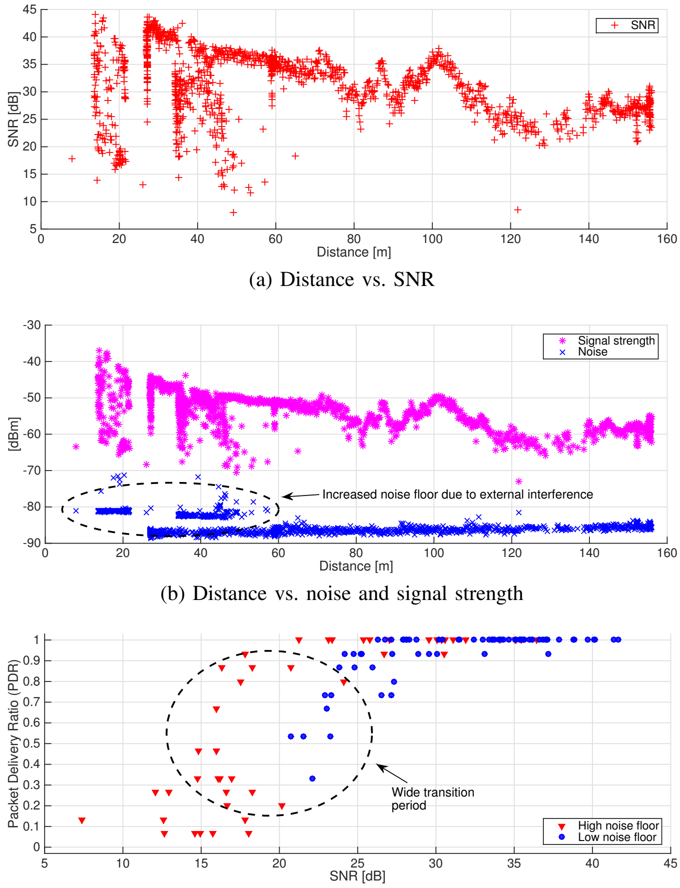
A. IR-UWB Hardware

The state-of-the-art IR-UWB transceiver for long range data communication and ranging, the TimeDomain P410 [10], is used in our experiments. The most important parameters are summarized in Table II. The advantage of the coherent receiver is that increasing the number of pulses per bit results directly in a Signal-to-Noise Ratio (SNR) gain and therefore in higher communication ranges, but at the cost of decreased data throughput. This means the Pulse Integration Rate (PII) affects the communication range significantly. The P410 is using a low duty cycle transmission, with coherent signal processing and a fixed pulse rate of 10 MHz, but different PII in the range of 4 (16:1) to 10 (1024:1) pulses per bit. According to the vendors specification for a PII of 4 the maximum communication range is 35 m with a peak data rate of 632 kbit/s is feasible. For the highest PII of 10 the maximum range is 354 m with a peak data rate of 9.86 kbit/s [10], which is still enough to exchange NC-OFDM subcarrier allocation information with a fair resolution (e.g. 1024 frequency bins) at a suitable update rate (e.g. 6.25 Hz).

B. SNR, Noise and Signal Strength Measurements in LOS

With unobstructed Line-Of-Sight (LOS) propagation very long links are feasible with IR-UWB. The P410 datasheet claims that in this case links of 300 m and more are achievable.

Methodology: The evaluation was carried out on the campus of the Technische Universität Berlin (TUB). The IR-UWB transmitter was placed on the edge of the roof of our building (approx. 25 m above the ground) and had direct LOS with the receiver located at the ground floor. We ensured that always



(a) Distance vs. SNR

(b) Distance vs. noise and signal strength

(c) SNR vs. PDR

Fig. 3. LOS measurements.

an unobstructed LOS propagation between transmitter and receiver existed. Further, the PII was set to the most robust value, which means that 1024 IR-UWB pulses are transmitted per symbol, which equals one bit. The resulting data rate is as stated before around 10 kbit/s which meets our requirements for the CC. The SNR, noise floor and signal strength are evaluated to investigate the influence of distance onto these parameters. The values presented in the plots were calculated from the channel impulse response as described in the API documentation [11, p. 49ff].

Results: From Fig. 3 we can observe that under LOS conditions links of more than 150 m are feasible. If LOS can be ensured even longer links might be established, which is unfortunately not the case on our campus. Moreover, we can observe that there is no clear relationship between link length and SNR. In our experiments we found lots of short links ($< 60\,m$) having an unusual low SNR. However, the propagation characteristics are not solely responsible for the large variations in the SNR. Indeed from Fig. 3a and 3b we see that there are lots of short links suffering from an unusual high noise floor which is about 8 to 17 dB higher than usual (about -88 dBm). Local sources of interference like WLAN or other wireless technologies which are widely used on our

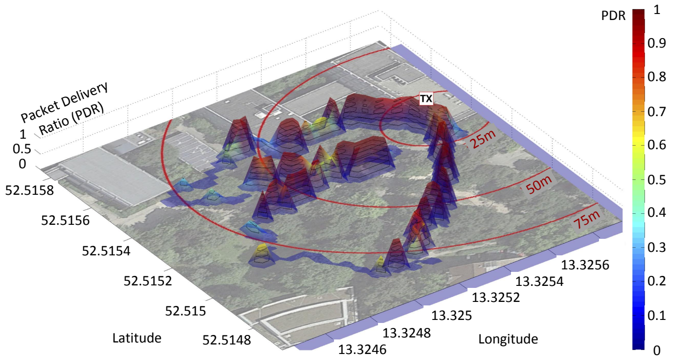


Fig. 4. Measured Packet Delivery Ratio (PDR) at IR-UWB receiver at different spatial locations on university campus (TUB).

campus may be responsible for that. Hence, their impact is studied in great detail in Sec. V-D.

Finally, the relationship between SNR and Packet Delivery Ratio (PDR) is given in Fig. 3c. We can identify a bi-modal distribution which is due to the different noise floor levels. The weak relationship between SNR and PDR makes the SNR a poor indicator for the link quality. Note, that each point in Fig. 3a and 3b represents a received packet from which SNR, noise and signal power is calculated.

C. Packet Delivery Ratio Measurements

As mentioned in Sec. IV the communication range of the CC for CR should correspond to the communication range of the used data channel. Therefore, the objective of this section is to study the propagation characteristics of the IR-UWB communication system in a real-world outdoor environment. Here we were especially interested in investigating the influence of obstructed LOS (oLOS) on the communication link. In the P410 datasheet it is stated that Non-LOS (NLOS) is working for very short distances only, therefore we want to investigate the influence of minor obstacles as for example leaves of trees.

Methodology: The methodology was similar to the previous experiment, but the receiver was further mounted on a tripod in a height of 1.20 m and was moved in a random walk over the campus. For every point in space, every received IR-UWB frame was GPS tagged and time stamped. The most robust modulation and coding, which means the most robust PII was used all time. As performance metrics the Packet Delivery Ratio (PDR) was measured.

Results: Fig. 4 shows the PDR at different spatial locations on our campus. It can be seen that a communication is only possible in unobstructed and slightly obstructed LOS. Minor shadowing from e.g. leaves of trees leads to a drop in the PDR. A communication with NLOS is only possible for very short ranges up to a few meters. Our results show that under real urban conditions with shadowing and obstacles like buildings, a communication over more than 75 m in general is not feasible.

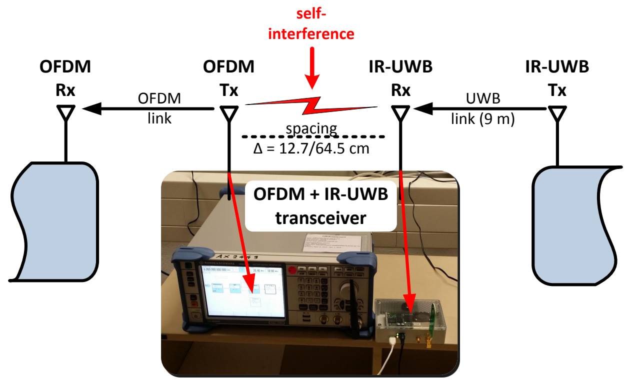


Fig. 5. Experimental setup with signal generator emulating the NC-OFDM transmission and the co-located IR-UWB receiver.

D. Co-existence of IR-UWB and NC-OFDM

As stated in Sec. IV we envision a multi-technology CR transceiver having two air interfaces: i) an IR-UWB for control signaling and ii) a NC-OFDM air interface for data transmission. The goal is to use the two interfaces simultaneously without mutual disturbance. Hence, in this section we study the self-interference between both wireless technologies with focus on the underlay IR-UWB transmission, because the influence of IR-UWB interference onto WLAN (OFDM) was already discussed extensively in [7].

Theory: The narrowband interference problem in IR-UWB systems is well studied in theory, e.g. [2, Chap. 11]. IR-UWB has a high probability to be affected by narrowband interference. Because of its ultra wide transmission band a large number of possible narrowband interferers will be in same frequency range. Further, the restricted transmission power leads to a limited dynamic range. Therefore, a single strong interferer can diminish the receivers performance seriously. The state-of-the-art IR-UWB transceiver in our testbed has a very wide bandwidth of about 2.2 GHz and a high dynamic range of about 60 dB. Hence, there is a possibility that the receiver is able to deal with narrowband interference to some degree. This issue is analyzed in the following.

Methodology: Fig. 5 shows the experimental setup. To mimic the envisioned multi-technology station two wireless links were set-up and used simultaneously, namely i) an UWB link and ii) a narrowband OFDM link. Without loss of generality the narrowband OFDM transmission, in this case IEEE 802.11 WLAN, is used to emulate the envisioned NC-OFDM wideband transceiver. In particular an 802.11a similar signal with a bandwidth of 20 MHz and a transmit power of 10 dBm is generated using a R&S SMBV100A vector signal generator [12]. The IR-UWB link was 9 m long, the transmitter is using the most robust modulation (PII=10) and the highest allowed transmission power (-12.64 dBm).

To investigate the impact of the OFDM transmission on the IR-UWB link the center frequency of the OFDM signal was swept from 1 GHz to 6 GHz with a step size of

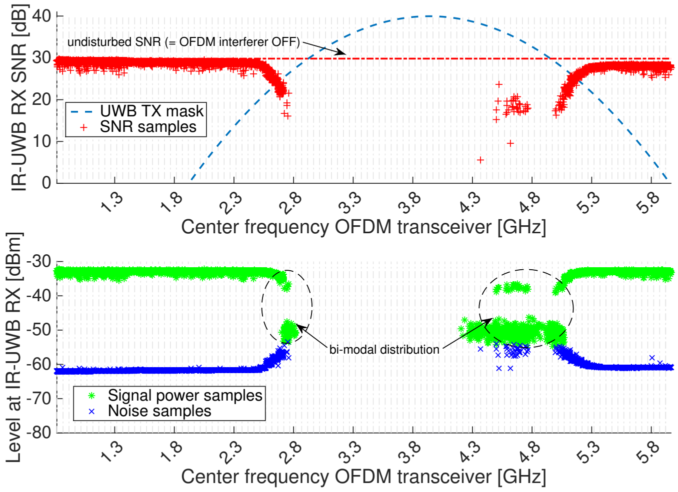
50 MHz. For each center frequency 40 IR-UWB frames were transmitted and timestamped at the IR-UWB receiver side for later offline processing. Two different measurement series with different spacings between the two air interfaces (OFDM TX and IR-UWB RX), namely, i) 64.5 cm which is a mockup for an outdoor setup and ii) 12.7 cm emulating an indoor multi-technology CR device, were conducted. The distance of 12.7 cm is chosen as a typical size of a compact IEEE 802.11 WLAN indoor access point case. The 64.5 cm is an example when base station and antennas share the same housing. Otherwise the distance between the antennas could be even larger.

Results: Fig. 6 shows the results for the two different air interface spacings. On the x-axis the center frequency of the OFDM narrowband transmitter is depicted. In each frequency bin (in the range of 1 - 6 GHz) the result of a complete measurement cycle is shown, i.e., each successfully received IR-UWB frame is marked by a red cross showing its SNR value. The blue dashed parabola is only for clarification and shows the transmit mask of the UWB transmitter. Moreover, both bottom plots show also the received signal power as well as the noise floor of each packet.

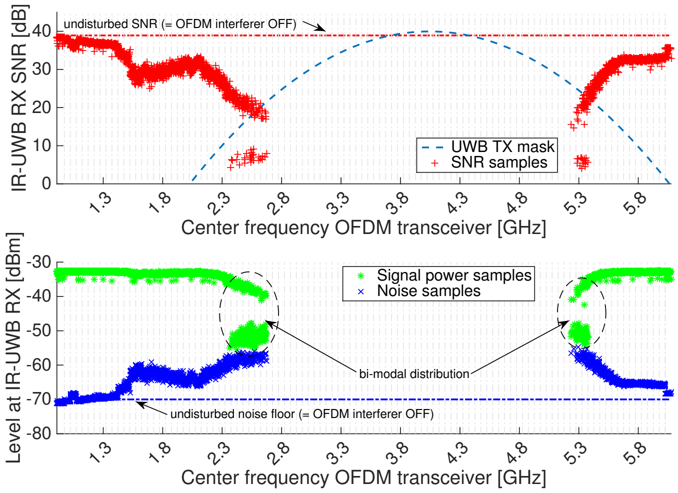
Fig. 6a shows the results where the spacing between the air interfaces was $\Delta = 64.5$ cm. Here we can see that as long as the OFDM transmission is not using frequencies which are within the frequency range of the UWB transmit mask, its impact on the UWB link is small. Nevertheless, any narrow-band OFDM transmission (here 20 MHz) within the UWB transmit mask causes a full outage on the UWB link, i.e., the PDR drops to zero. The used IR-UWB transceiver hardware has a dynamic range of 60 dB at maximum PII of 10. If we consider free space propagation the SNR is around - 50 dB. This means the IR-UWB link is jammed by the OFDM transmission completely.

In Fig. 6b we see the results for the typical multi-technology setup for the envisioned indoor multi-technology CR transceiver with a very small separation between the two air interfaces of $\Delta = 12.7$ cm. Here even narrowband OFDM transmissions outside the transmit IR-UWB mask have a severe impact on the performance of the IR-UWB link. An OFDM transmission with a much lower center frequency $f_c = 1.5$ GHz significantly influences the IR-UWB transmission, i.e., the SNR drops by more than 10 dB whereas the noise floor increases. The level of the noise floor adapts automatically with the received power, which means the reference level can be observed when the OFDM interferer is switched off. For some OFDM center frequencies we can observe a bi-modal distribution of the signal power which might be an indication of an insufficient dynamic range and therefore the saturation of the IR-UWB receiver. A better RF shielding, applying analog (notch) filtering before the pulse correlation [8] or pulse shaping [13] might improve the co-existence in this case.

The main challenge of any interference rejection technique is the requirement of the exact knowledge about the center frequency of the narrowband interferer. Theoretically, such information can be obtained by means of sensing or lookup in



(a) Air interface spacing of $\Delta = 64.5$ cm (outdoor base station)



(b) Air interface spacing of $\Delta = 12.7$ cm (indoor base station)

Fig. 6. SNR degradation on the IR-UWB link due to interference from narrow-band OFDM transmission for different spatial spacings.

databases as they are common in the CR context, but even if the complete knowledge about all the narrowband interferers is available, the high number of interferers make methods like notch filtering or pulse shaping practically impossible.

VI. Practical Implications

Our results have practical implications, which we want to illustrate using the example of TV White Spaces (TVWS). TVWS are spectrum bands in the frequency range below 1 GHz which are approved for dynamic re-use by SUs. Since this frequency band is very attractive because of its propagation properties several standards evolved. The main standards for secondary usage in TVWS are 802.22 [14], ECMA-392 [15] and 802.11af [16]. All standards focus on the protection of PUs and inter-standard co-existence. Heterogeneous co-existence is solved by means of spectrum sensing.

The performance of CR in TVWS can be significantly improved when using a separate CC. On one hand, the CC permits a very fast spectrum adaption and therefore a very high level of PU protection. On the other hand, SU co-existence schemes based on spectrum sensing are suffering from known problems as hidden node and are therefore unreliable. Here the CC is a reliable solution to distribute information about spectrum occupied by PUs and can further be used to coordinate spectrum allocation between SUs.

We believe that IR-UWB is an appropriate technology for the CC in TVWS. First, due to the used frequency band below 1 GHz we do not expect to have self-interference between IR-UWB (f_c = 4.3 GHz) and NC-OFDM using TVWS (ref. Sec. V-D). Second, when using TVWS for WLAN (e.g. 802.11af) the communication ranges of the control and data channel are comparable as long as (obstructed) LOS propagation exists (e.g. WLAN Access Points mounted on roof tops outdoors) (ref. Sec. V-B).

VII. Conclusions

A feasibility study on application of IR-UWB as an alternative technology for CC in CR networks was conducted. Results from our testbed show that IR-UWB is under certain conditions a suitable technology for CCs with requirements as always available, low latency and sufficient high data rate in CR networks. We have observed that at least a slightly obstructed LOS between IR-UWB transmitter and receiver is necessary to allow communication in ranges of 150 m and more. In the envisioned CR multi-technology setup, interference from very close narrowband communications can lead to full outage of the IR-UWB system, but such a mutual disturbance can be mitigated to some extent by e.g. increasing the spatial separation between both air interfaces, orthogonalization in time or using only those parts of the radio spectrum for NC-OFDM which are outside the main IR-UWB transmission mask.

Acknowledgment

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