Receiving More than Data - A Signal Model and Theory of a Cognitive IEEE 802.15.4 Receiver

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Abstract. In standard medium access, transmitters perform spectrum sensing. Information about concurrent interferers is gained mainly during this sensing period. Especially during transmission respectively reception there is a blind gap where transmitter and receiver have limited capabilities to detect interferer. Standard radio receiver devices for IEEE 802.15.4 provide solely data output and no cognitive capabilities. Particularly mobile interferer create problems when moving gradually into reception range. First, they create small interference before actually causing collision later, when approaching. However, small interference is not yet detectable by todays transceivers. As a solution, we provide a signal model and an architecture for an extended cognitive IEEE 802.15.4 receiver as a basis for advanced signal processing for interference detection. The results of our theoretical analysis verify that the received signal contains signal marks of the interferer and therefore holds more information than transmitted data. Our theory is evaluated by simulations and experiments with a pair of IEEE 802.15.4 transmitter and an extended cognitive receiver.

Keywords: Spectrum sensing · Interference · Signal model · IEEE 802.15.4

1 Introduction

The number of devices with wireless interfaces increases continuously with numerous devices operating in the scarce spectrum available for unlicensed ISM bands. Spectrum utilization in ISM bands is very heterogeneous with many standards competing within the same frequency range. For 2.4 GHz we have IEEE 802.11 (WLAN), IEEE 802.15.1 (Bluetooth), and IEEE 802.15.4 (in some literature named Zigbee) suitable for low power and also for mobile devices. In addition, several proprietary wireless transmissions operate in that frequency range. Therefore, concurrent transmission with interference occurs regularly. Concurrent transmission takes place when at least two wireless transmitters utilize the same or parts of frequency spectrum and a receiver is in reception range. During concurrent transmissions signals interfere with each other on the receiver side.

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Strong interference degrades the performance of a wireless system as transmission errors occur. With competing devices using the same standard the term collision is used preferably. Wireless standards like IEEE 802.15.4 apply schemes like carrier sensing (CS) or collision avoidance (CA) to avoid collisions and interference [1]. CS is performed prior start of transmission but the transceiver is "blind" during the transmission itself.

Although this is a general problem for wireless transmissions, we will focus on a solution for IEEE 802.15.4 within this paper. A pair of standard IEEE 802.15.4 transceivers is not able to detect and identify reliably interference during transmission and reception. To the best of our knowledge we are the first to propose a cognitive receiver for IEEE 802.15.4 to enable spectrum awareness during transmission. The contributions are as follows: We provide a theoretical analysis of quadrature demodulated signals and interferences. We introduce a new model for an extension of the physical layer (PHY) of an IEEE 802.15.4 transceiver towards a cognitive receiver. It serves as a basis for future signal processing capabilities e.g. to enable comprehensive interference detection. We provide both, simulation and experimental results of our implementation with GNU Radio. The results of the evaluation show that we have reached a further step towards a cognitive receiver.

The rest of this article is organized as follows: Section 2 will introduce related work and demonstrate the need for new approaches. We will analyze the problem of concurrent interference and its impact as signal marks in the received signal in Section 3. Section 4 evaluates the theory by simulations. The paper concludes with a short summary and presents future work in Section 5.

2 Related Work

The goal of our approach is to increase the spectrum awareness during transmission. We will introduce recently published approaches for advanced spectrum sensing prior to and during an ongoing transmission and discuss it in relation to our work.

Akyildiz et al. describe in [2] that spectrum sensing is an important requirement to exploit unused frequencies. The authors distinguish between in-band and out-of-band sensing. In contrast to our work in-band sensing in [2] is only considered prior to transmission. Therefore, a trade-off between sensing and transmission has to be found in order to gain reasonable interference avoidance and transmission period. On the other hand out-of-band sensing is able to sense other frequency bands during an ongoing transmission, but not in the band that is currently utilized for transmission. A comprehensive summary of spectrum sensing schemes is given by Yücek and Arslan in [3] and Ariananda et al. in [4]. The sensing schemes under investigation achieve a variety in performance and accuracy. Schemes providing more detailed spectrum awareness are usually more complex and time-consuming. The three most prevalent schemes are energy detection, cyclostationary feature detection and matched filters. All schemes perform sensing prior to a transmission and not during the transmission. To ensure spectrum awareness during transmission in all these solutions a third radio for sensing is required whereas in our approach one pair of transceivers is sufficient.

Another solution to perform spectrum sensing during transmission is cooperative spectrums sensing. A survey on cooperative spectrum sensing in order to increase spectrum awareness is given by Akyildiz et al. in [5]. With cooperation of multiple and spatially separated sensing devices the spectrum awareness can be significantly improved. On the other hand this yields in more operational effort due to multiple sensing devices and additional overhead caused by exchange of sensing information. Cooperative sensing cannot be implemented with a single pair of transmitter and receiver.

In the past new approaches for spectrum sensing even during transmission were introduced. In [6] the authors propose to divide the transmission band into subbands, whereas a redundant subband is continuously used for spectrum sensing. This reduces bandwidth efficiency as a redundant frequency range with no data transmission being required. Another approach to achieve spectrum awareness during ongoing transmission is to utilize multicarrier waveforms and to analyze subcarriers at the receiver. In [7] Farhang-Boroujeny suggests to measure and to compare the energy of each received subcarrier in order to detect concurrent transmissions. It allows in-band concurrent transmitter detection even during ongoing transmissions, but requires wideband multicarrier transmission which is not available for IEEE 802.15.4 devices. As energy detection is proposed, again it is not possible to identify any specific signal marks from other interferer. With recent advances in full-duplex wireless communication [8] schemes like simultaneous transmit-and-sense seem to be achievable in the future. However, to the best of our knowledge current results have not yet exceeded the status of preliminary experiments [9] and analytical examination of the advantages [10]. Furthermore, our approach does not require any additional and complex antenna configuration within transmit and receive path.

In conclusion, several techniques and schemes to provide spectrum awareness have been introduced in the past. *Spectrum sensing schemes prior transmission* provide information about signal marks from interferer only during execution, but not during subsequent transmission. *Spectrum sensing schemes during transmission* either require redundant subbands for sensing, multicarrier waveforms or complex antenna circuitry and configuration. In the following sections, we will describe how small signal interference changes the received signal and how to build a radio receiver for IEEE 802.15.4 that receives more than data.

3 Problem and Analysis

As introduced in Section 1 the increasing utilization of wireless systems will result in a heterogeneous and dynamic radio environment. In such a radio environment concurrent wireless transmissions using the same frequency range will interfere with each other. Many of these radio transceivers are mobile today. A mobile and transmitting transceiver appearing in the scene interferes with small power first and with closer distance it finally disrupts the transmission of other systems and causes collisions. Hence, it is important to detect such interferer reliably in advance before collisions occur.

Today's wireless systems like IEEE 802.15.4 [1] transceiver use Carrier Sense Multiple Access Collision Avoidance (CSMA/CA) among each other in heterogeneous radio environment. Transceivers perform carrier sensing (a simple energy detection) immediately prior to transmission. If no other transmission is detected during spectrum sensing the transmitter starts its own transmission. After the receiver has decoded the data frame, it is checked for transmission errors by calculating the cyclic redundancy check (CRC). Occurring bit errors are detected reliably with CRC but the reason cannot be identified. In conclusion, spectrum awareness can only be provided during the spectrum sensing period (SS) as illustrated in Figure 1 by the white background. During the transmission and reception there is a "blind gap" illustrated as grey background that we will quantify in the following. In the IEEE 802.15.4 standard the measurement duration for carrier sensing is specified to be $128us$ (measurement duration of 8 symbols [1] p.54). With maximum transmission duration of 4.2 ms this yields in a spectrum awareness of only 3% of the total time interval. With minimum transmission duration (by sending acknowledgement frames) spectrum awareness is increased to not more than 25% of the total time interval.

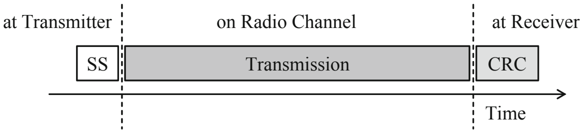

Fig. 1. Limited Spectrum Awareness during Transmission

The aim of our work is to show that it is possible to receive more than just data in order to improve spectrum awareness during transmission. We propose to analyze the received and demodulated signal of single received frames or even parts of these frames, for marks of another concurrent interfering signal. Our theoretical analysis shows that the received signal includes information about interference occurred during an ongoing transmission. Therefore, we propose to add cognitive capabilities to the receiver. This is the basis for future work on signal processing of the received signal. First preliminary results from experiments analyzing the received signal at the receiver and a conceptual hardware setup are published in [11,12]. Our previous work shows an implementation with a basic modulation scheme (MSK) and a preliminary study to integrate it into a standard receiver. The work did not provide a signal model and no theoretical analysis of the received and demodulated signal.

In our approach we assume that the interfering signal is still not large enough to cause a collision and transmission errors. This assumption is reasonable as especially in a heterogeneous environment with mobile devices a radio transceiver needs to be very sensitive to concurrent radios to avoid interfering with their transmissions. It is important to detect the signal of a concurrent radio on an overlapping frequency band as soon as possible to adapt transmission parameters accordingly in advance of a collision. After this initial explanation we will describe the digital demodulation process and provide mathematical expressions for an Offset Quadrature Phase Shift Keying (OQPSK) modulated signal. The theoretical analysis and model were validated by simulations and experiments with a real IEEE 802.15.4 radio link. Furthermore, our concept was adapted to IEEE 802.15.4 transmission without affecting standard compliant data transfer. For simplicity, the presented mathematical analysis does not consider noise in the environment. However, the experimental results in 4 show that the analytic results hold also for noisy signals.

3.1 Quadrature Demodulation of an OQPSK Modulated Signal with Interference

The Offset Quadrature Phase Shift Keying (OQPSK) signal can be written as [14]:

$$s_{OQPSK}(t) = a_c[m_I(t)\cos(\omega_c t) + m_Q(t)\sin(\omega_c t)] \tag{1}$$

OQPSK utilizes half-sine pulse shaping, $m_I(t)$ and $m_Q(t)$. Where in-phase (I) and quadrature component (Q) are misaligned by half a symbol duration. The demodulation of such a OQPSK signal with a quadrature demodulator follows several stages as depicted in Figure 2. Equation (2) to (4) show the result of each stage in detail. First, the received OQPSK modulated and real signal $s_{recO}(t)$ is converted with Hilbert transform into a complex signal $S_{recO}(t)$.

$$S_{recO}(t) = a_c[m_I(t)\cos(\omega_c t) + jm_Q(t)\sin(\omega_c t)] \tag{2}$$

Second, the complex signal is quadrature demodulated, resulting in $S_O(t)$.

$$\begin{aligned} S_O(t) =& S_{rec}(t) \times e^{-j\omega_c t} \\ =& a_c[m_I(t)\cos(\omega_c t) + jm_Q(t)\sin(\omega_c t)] \\ & \times [\cos(\omega_c t) - j\sin(\omega_c t)] \\ =& a_c[\underbrace{m_Q(t) + (m_I(t) - m_Q(t))\cos^2(\omega_c t)}_{I_{SO}(t)} \\ & + j\underbrace{(m_Q(t) - m_I(t))\cos(\omega_c t)\sin(\omega_c t)}_{Q_{SO}(t)}] \end{aligned} \tag{3}$$

Third, the phase angle of the demodulated signal $\varphi(t)$ is determined with *arc tangent* function. Finally, bit decision is made based on the determined phase angle $\varphi(t)$.

$$\varphi(t) = \arctan\left(\frac{Q_s(t)}{I_s(t)}\right) \tag{4}$$

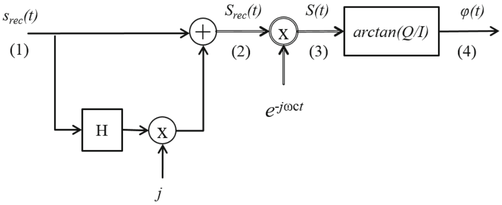

Fig. 2. Limited Spectrum Awareness during Transmission

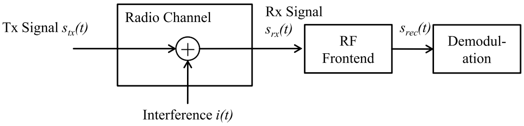

Fig. 3. Reception of a transmitted signal with superimposed interference from a concurrent transmitter

If another concurrent radio signal $i(t)$ interferes with the transmitted OQPSK modulated signal $s_{OQPSK}(t)$, it is superimposed as shown in (5) and Figure 3.

$$s_{recOI}(t) = s_{OQPSK}(t) + i(t) \tag{5}$$

With concurrent transmission, (2) and (3) are extended by additional components ($Interference$) as shown in (6) and (7). $\hat{S}$ and $\hat{I}$ are the Hilbert transformed signal components of the OQPSK and the interfering signal.

$$S_{recOI}(t) = [S_{OQPSK}(t) + I(t)] + j[\hat{S}_{OQPSK}(t) + \hat{I}(t)] \tag{6}$$

$$\begin{aligned} S_{OI}(t) =& S_{rec}(t) \times e^{-j\omega_c t} \\ =& S_{OQPSK}(t) \times e^{-j\omega_c t} + I(t) \times e^{-j\omega_c t} \\ =& \underbrace{\left[\underbrace{I_{Soqpsk}(t)}_{OQPSK\ only} + \underbrace{I(t)\cos(\omega_c t) + \hat{I}(t)\sin(\omega_c t)}_{Interference} \right]}_{I_{SOI}(t)} \\ &+ j \underbrace{\left[Q_{Soqpsk}(t) - I(t)\sin(\omega_c t) + \hat{I}(t)\cos(\omega_c t) \right]}_{Q_{SOI}(t)} \end{aligned} \tag{7}$$

Finally, inserting the corresponding $I_s(t)$ and $Q_s(t)$ component into (4) results in the phase angle of the demodulated signal that additionally contains signal marks of the interfering signal. In order to extract the influence of interference, we introduce an extension of a traditional receiver which is presented in the next section.

3.2 Interference Extraction out of Received OQPSK Modulated Signal

To extract the influence of the interference signal we apply a method which is known from interference cancellation technique [14]. But, here we apply it the other way around. We extract the interference signal components from the demodulated signal as shown in Figure 4 and Equation (8).

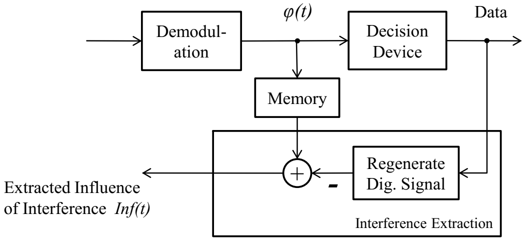

Fig. 4. Interference Extraction

$$\varphi_{int}(t) = \underbrace{\varphi_s(t)}_{received} - \underbrace{\varphi_{OQPSK}(t)}_{regenerated} = Inf(t) \tag{8}$$

Remember that we consider cases where the interference is still not large enough to cause transmission errors. Demodulated and decoded data is used to regenerate the demodulated signal $\varphi_{OQPSK}(t)$ as it supposed to be like without impact of interference. This regenerated signal $\varphi_{OQPSK}(t)$ is subtracted from the actual received and demodulated signal $\varphi_s(t)$ including the interference. Inserting the in-phase $I(t)$ and quadrature $Q(t)$ components from (7) (*received*) and (3) (*regenerated*) into *arc tangent* of (4) and successively into (8) results in a rather more complex expression. Corresponding signal marks from the interfering signal are hardly observable within this complex term. Therefore, we further simplify this expression by applying an approximation. Considering an interfering signal with signal strength that is much smaller than our actually transmitted and received signal, we use the approximation that:

$$\lim_{x \to 0} \tan x \approx x \tag{9}$$

Instead of (8) the approximated influence of interference $\widetilde{Inf}(t)$ is expressed as:

$$\varphi_{int}(t) \approx \tan\left(\varphi_{int}(t)\right) = \widetilde{Inf}(t) \tag{10}$$

This approximation and (8) results in the following term:

$$\begin{aligned}\tan\left(\varphi_{int}(t)\right) &= \tan\left(\varphi_s(t) - \varphi_{OQPSK}(t)\right)\\ &= \frac{\tan\left(\varphi_s(t)\right) \cdot \tan\left(\varphi_{OQPSK}(t)\right)}{1 + \tan\left(\varphi_s(t)\right) \cdot \tan\left(\varphi_{OQPSK}(t)\right)} \qquad \text{(11a)}\end{aligned}$$

At first glance this does not seem to be a true simplification, but the *tangent* suspends the *arc tangent* from (4). As shown in the following section these assumptions will simplify the expression of $Inf(t)$.

3.3 Influence of Interference

We consider a sinusoidal signal to show the influence of the superimposed interfering signal.

$$i_{cos}(t) = a_i \cos(\omega_i t + \varphi_i) \tag{12}$$

If this interference signal is inserted in (7), we get:

$$\begin{aligned} I_s(t) =& I_{Soqpsk}(t) + a_i \cos(\omega_i t + \varphi_i) \cdot \cos(\omega_c t) \\ &+ a_i \sin(\omega_i t + \varphi_i) \cdot \sin(\omega_c t) \\ =& I_{Soqpsk}(t) + a_i \sin\big((\omega_i - \omega_c)t + \phi_i\big) \qquad (13a) \\ Q_s(t) =& Q_{Soqpsk}(t) + a_i \cos\big((\omega_i - \omega_c)t + \phi_i\big) \qquad (13b) \end{aligned}$$

With (11) and further trigonometric identities and successive simplifications this yields in (14).

$$\begin{aligned} \widetilde{Inf}(t) =& \frac{c_4 c_3 \cos\big(\beta\big) + c_4(c_2 - c_3)\cos\big(\alpha\big)\cos\big(\alpha - \beta\big)}{c_4 c_3 \sin\big(\beta\big) + c_4(c_2 - c_3)\cos\big(\alpha\big)\sin\big(\alpha - \beta\big) + c_1\big(c_2\cos(\alpha)\big)^2 + c_1\big(c_3\sin(\alpha)\big)^2} \\ c_1 =& a_c \ , \ c_4 = a_i \ , \ c_2 = m_I(t) \ , \ c_3 = m_Q(t) \\ \alpha =& \omega_c t \ , \ \beta = \big((\omega_i - \omega_c)t + \phi_i\big) \end{aligned} \tag{14}$$

The resulting term of $\widetilde{Inf}(t)$ includes signal components and therefore marks of the superimposed sinusoidal interference. It is influenced by its amplitude a_i, frequency ω_i and phase ϕ_i. Corresponding examples of such signals are depicted in Figure 5. The upper signal presents the demodulated signal with interference. The second signal presents the demodulated signal without interference, respectively the regenerated demodulated signal. The example of an extracted influence of interference in the third graph is a result of a sinusoidal interference with a SIR of 14 dB and a frequency of 50kHz. The extracted influence of interference shows significant signal marks caused by the interfering signal. The width of the sinusoidal cycles is dependent on the frequencies of the transmitted and interfering signal, ω_c and ω_i. Amplitude of the interfering signal determines the amplitude values of the extracted influence of interference. This is because the amplitude of the interference a_i respectively c_4 is not part of the last two sinusoidal terms of denominator of Equation (14) and these components stay constant if c_4 varies. Whereas the transmitted symbols corresponding to $m_I(t)$ and $m_Q(t)$ and the phase of interfering ϕ_i determines the phase shifts.

The results in this section show that the extracted influence of an interfering signal after demodulation contains signal marks corresponding to the interfering signal. The presented signal model is validated in the next Section 4 with baseband simulation and experiments with an OQPSK modulated signal and a superimposed OQPSK modulated interfering signal.

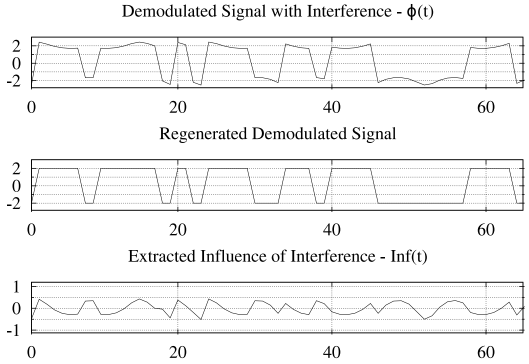

Fig. 5. Interference Extraction with sinusoidal interference for 64 demodulated bits

4 Evaluation

We have implemented an extended IEEE 802.15.4 receiver with software defined radios (SDR) composed of an USRP2 [15] and signal processing with GNU Radio [16]. USRP2 is a hardware frontend for GNU Radio applications responsible for up- and down-conversion of RF signals and furthermore for digital-to-analog and analog-to-digital conversion. Our extended IEEE 802.15.4 receiver is completely implemented in GNU Radio. Signal processing relevant to IEEE 802.15.4, i.e. demodulation and decision device, is based on the work of Schmid, presented in [17]. The interference extraction is implemented according to Figure 4. The received IEEE 802.15.4 signal is A/D-converted with a sampling frequency of 4 MS/s. After demodulation including clock recovery the sample rate of the digital signal is 2 MS/s corresponding to the chip rate 2 MChips/s of a standard IEEE 802.15.4 transmission. An IEEE 802.15.4 transmitter is set up accordingly.

4.1 Baseband Simulation with OQPSK

First, GNU Radio simulation was employed to show that even an OQPSK modulated interfering signal generates significant signal marks in the extracted influence of interference $Inf(t)$. Therefore, a second interfering OQPSK modulated signal was generated and superimposed in baseband on the original signal. Considering (5) this yields in:

$$s_{rec}(t) = s_{OQPSK-Tx}(t) + s_{OQPSK-Interferer}(t) \tag{15}$$

A carrier frequency offset of 50kHz compared to the original Tx-signal was chosen to simulate another concurrent OQPSK transmitting radio device. The resulting signals are depicted in Figure 6, again with an SIR of 14dB. The occurring signal marks caused by the interfering OQPSK signal are dependent on the transmitted data of the original transmitter and the interferer. For this simulation the interfering transmitter signal is modulated with random data. If the data is incidentally similar to the data transmitted by the original transmitter the amplitude of the influence of interference is close to zero, see the start of the depicted signal $Inf(t)$. Compared to the extracted influence of interference of a sinusoidal interference the signal shape shows more complex variations. This is due to the dependency the in-phase and quadrature part of the interfering signal are varied by its OQPSK modulation. Nevertheless, baseband simulation showed that even with a more complex interfering signal observable signal marks occur in the extracted influence of interference.

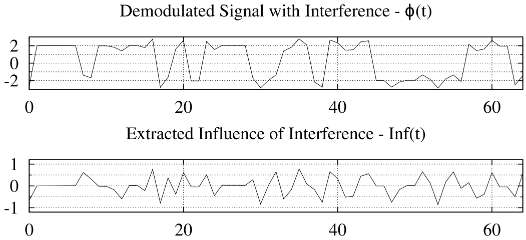

Fig. 6. Interference Extraction with OQPSK interference for 64 demodulated bits

4.2 Measurement with an Extended IEEE 802.15.4 Receiver

Finally, the extended IEEE 802.15.4 receiver was evaluated in a real and therefore noisy radio environment with mobile IEEE 802.15.4 interferer as depicted in Figure 7. Distance between IEEE 802.15.4 transmitter and extended receiver was fixed to 3 m. Distance between the concurrent and interfering IEEE 802.15.4 transmitter and the extended receiver was varied from 5 to 1.5 m. At a distance of 1.5 m between receiver and interferer single chip errors start to occur and therefore risk of an upcoming collision arises.

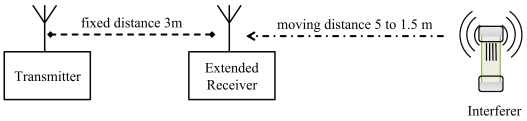

Fig. 7. Measurement setup for moving interferer

Short frames comparable to an acknowledgement frame were transmitted within the experiment. A section of the extracted influence of interference for

256 chips is depicted in Figure 8. An initial measurement without interfering signal was conducted first. No significant signal marks are present except noisy variations of the amplitude. Subsequently the distance between interferer and extended receiver was shortened from 5 m to 1.5 m. At the beginning of each section depicted in Figure 8 no interference is present. Next to the 50th chip in both plots the interferer starts its transmission and therefore superimposes its signal. At this point in time the amplitude of the extracted influence of interference increases by approximately 10dB (5m) and 20dB (1.5m) respectively. Even if the interferer is 5 m away from the extended receiver the occurring signal marks are observable in $Inf(t)$.

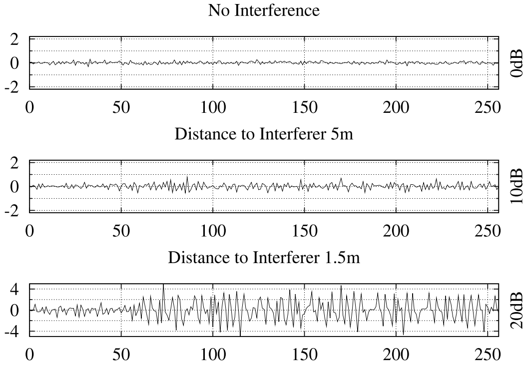

Fig. 8. Extracted Influence of interference $Inf(t)$ for 256 demodulated chips for different distances between cognitive receiver and interferer

The conducted simulations and experiments show that concurrent and interfering transmission generate signal marks within the received and demodulated signal. With an extended receiver we will be able to receive more than data. Note again, that no additional third radio is required in our approach.

5 Conclusion

In this paper we have motivated the need of spectrum awareness during transmission. We have shown with theoretical analysis, simulation and experiments that signal marks from concurrent interfering signals are observable in the received and demodulated signal. Once the receiver observes these signal marks and is able to assign them to a corresponding interfering source, the receiver will be able to inform the transmitter that concurrent transmission occurred. This information might be transmitted within a corresponding acknowledgement frame. Implementing such protocol will be part of our future work. Our proposed signal model and theory of an extended cognitive receiver is the basis for advanced signal processing to detect and identify interfering transmitter. Next, we will implement such signal processing and investigate its performance to detect and identify different kind of sources of interference. We plan to analyze the extracted influence of interference with signal processing like performing an FFT, analyzing the distribution of the amplitude values (i.e. determing m-order moment) or others. Additionally, we will evaluate our approach in terms of the occurrence of single bit errors and in case of multiple interferer. Finally, we will implement the interference extraction into a mobile IEEE 802.15.4 transceiver with a small-scale SDR extension. An additional RF-frontend performs the down-conversion into baseband and ADC, whereas the signal processing in Figure 4 is implemented into a small FPGA. The conceptual setup is described in [12].

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