On Using BOC Modulation in Ultra-Low Power Sensor Networks for Wildlife Tracking

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***Abstract*—Localization and tracking of small animals in the wild using sensor networks require nodes with ultra-low power consumption, which are particularly challenging to design. Here, we target the tracking of bats in their natural habitat and have to limit the weight of the mote to 2 g. To optimize the energy consumption in this scenario, the combination of data communication and ranging is essential. The limitations of the platform and the specific use case ask for a dedicated signal design. We start exploring the use of Binary Offset Carrier (BOC), which is known to be well suited for localization. In this paper, we concentrate on the data communication part of the system. We develop a BOC transceiver in Software Defined Radio (SDR) and perform simulations as well as lab measurements to evaluate its performance and compare it to Binary Phase-Shift Keying (BPSK), which is often used in low-power sensor systems. Most importantly, we conducted realistic field measurements to study the effects of multipath fading and shadowing. Our results clearly show that BOC is perfectly suited for ultra-low power communication in forest environments.**

I. INTRODUCTION

In wildlife monitoring, Wireless Sensor Networks (WSNs) provide the most successful methods to study individuals by attaching sensor nodes and gathering a huge amount of data over long period of time [1]–[3]. In the BATS[1] project, we aim to support biologists studying the social and foraging behavior of bats [4]. Our target species are mouse-eared bats (*Myotis myotis*) that typically weigh about 20 g and, thus, can carry a sensor node of at most 2 g including a battery. Bats that are equipped with ultra-low power sensor nodes continuously exchange information of the contacts between each other and appear in communication range of stationary base nodes on an irregular basis. If in communication range of at least one of the stationary base nodes, the bats are tracked based on periodically emitted localization signals and also these mobile sensor nodes are supposed to upload collected contact and system information. The very restricted weight of the mobile sensor node provides limited energy budget and computational power. Hence, robust and ultra-low power techniques are required to minimize the energy consumption of RF communication and the localization signal.

In energy constraint wireless communication, low order modulations with low bit-error-rate (BER), i.e., high Packet Delivery Ratio (PDR), are usually preferred to minimize overall energy consumption. The best known example is Binary Phase-Shift Keying (BPSK) [5]. The energy consumption of wireless sensor nodes can be minimized by selecting appropriate modulation and integrating it with Error Correcting Codes (ECCs) based on operating parameters such as inter-node distance [6]. However, the optimal system configurations cannot be chosen due to the high mobility in our scenario. Energy-efficient adaptive modulation [7] can be an excellent choice in such a case, but the extra energy required for adaptation and reconfiguration should also be considered – particularly in a such a dynamic environment.

Transmitting additional communication information separately in WSNs directly affects the total lifetime of the network because of the increased energy consumption [8]. We thus focus on combining the localization and the data communication signals in order to reduce the number (or length) of the necessary transmissions. The use of Binary Offset Carrier (BOC) modulated signals can incorporate data transmission along with accurate localization and tracking [9]. BOC modulation is primarily used in the Global Navigation Satellite Systems (GNSSs), for spectral separation between Galileo positioning system and Global Positioning System (GPS) to share the same frequency bands [10]. However, in contrast to GNSS continuous signals, short burst signals are needed in our scenario due to the limited battery resources.

In this paper, the focus lies on the data communication only. In our deployment scenario, the system will face highly varying channel quality because of fast movement of bats and rapidly changing environment making the communication highly unreliable. Moreover, the hunting areas of the bats where stationary base nodes will be deployed is a foliage environment causing shadowing effects by obscuring the line-of-sight (LOS) signal. Therefore, we investigate the performance of BOC using our new Software Defined Radio (SDR) implementation in heterogeneous environments including fading, multipath, and shadowing effects. We have performed simulations and conducted a large number of field measurements to show the feasibility of BOC for wildlife monitoring.

Our main contributions can be summarized as follows:

- We study the use of BOC modulation in ultra-low power mobile sensor nodes for wildlife monitoring.
- We implement BOC modulation in SDR and compare it with BPSK to demonstrate its feasibility.
- We perform an extensive set of field measurements for the experimental study of BOC in the BATS scenario.

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[1] Dynamically adaptive applications for bat localization using embedded communicating sensor systems, http://www.for-bats.org/

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II. RELATED WORK

In general, the physical layer plays an important role in overall energy consumption of WSNs. Chouhan et al. [6] provides an integrated energy analysis of different modulations with ECCs, like Reed-Solomon, by evaluating the energy consumption per information bit. More precisely, they optimize the energy consumption by studying the tradeoff between the overhead introduced by using ECCs and the increased robustness. It was found that with lower signal-to-noise ratio (SNR) there is always a crossover point from where on it is more efficient to use ECCs. This crossover point depends on the employed modulation scheme as well as the ECC.

When applying these results in the BATS scenario, we, however, face the problem that the optimal energy configuration changes over time due to movement and time varying channel conditions. Therefore, the use of an energy-efficient adaptive modulation [7] is an attractive option. Based on perfect knowledge of the received SNR, the system selects the most energy-efficient modulation. While this system can offer great improvements regarding energy consumption, it requires a feedback loop from the receiver to the transmitter to report about current channel conditions. Therefore, the energy required for the feedback and reconfiguration also has to be considered. Moreover, the constraint weight of our mobile sensor node does not allow to implement multiple modulation schemes together.

For position information, GPS is considered to be the most popular technique in WSNs. Even though GPS has been successfully used in wildlife monitoring [11], these systems are power hungry and not accurate enough to measure distances of several meters. Currently, the ICARUS project [12] aims to develop tags weighing 5 g with GPS to track large-scale movements of small animals or birds from space. For energy efficient operation, these tags are only active when triggered by the International Space Station.

Since the main design goal of GPS was not to support energy efficient receivers, localization and tracking techniques based on a dedicated infrastructure have been investigated. The most popular techniques for WSNs are based upon Angle Of Arrival (AOA), Time Of Arrival (TOA) as well as Time Difference Of Arrival (TDOA) and Received Signal Strength (RSS) [13]. Most of the TOA and TDOA estimation methods require highly precise clocks and are not suitable in scenarios like the BATS project because of multipath channels [14] as well as the tight clock synchronization problems. Similarly, simple RSS based localization estimates are unstable due to shadowing and fading and, thus, introduce large errors in the range estimate.

To overcome the issues of RSS based techniques, the phase difference of Radio Frequency IDentification (RFID) tags are exploited for accurate localization [15]. To further improve the accuracy, the authors propose combination of phase difference with RSS-based techniques.

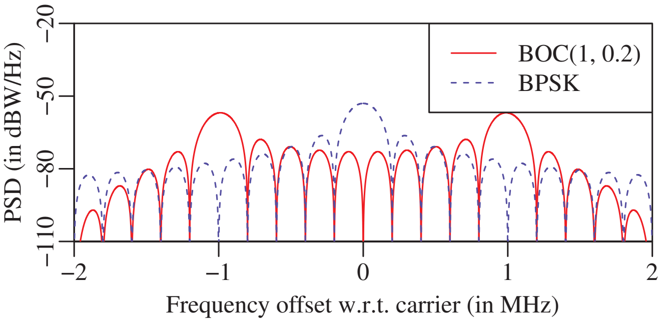

Figure 1. Power spectral density of BPSK and BOC signals.

Studying the energy consumption in systems that support data communication and ranging, it is evident that the main problem is that energy is spend twice since there is a dedicated signal for localization and another one for communication. To optimize energy consumption, a combined localization and data communication system based on BOC modulation has been proposed [9]. BOC modulation is primarily used in GNSSs. Therefore, the range estimation error for GNSS has been investigated in [16]. The author concludes that the ranging performance of BOC modulated signal is superior to BPSK due to higher robustness against multipath effects and code-tracking errors.

Recently, experimental study to investigate the multipath benefits of different variants of BOC over BPSK has been performed [17]. The authors gather live data from satellites by using an SDR receiver in different types of environments. It is shown that the performance of BOC modulated signals is better than BPSK in challenging multipath environments. Also, error-free comparison of multipath was not always possible due to mismatch in satellites geometry.

In this paper, we go one step further and provide experimental study of BOC modulation in ultra-low power sensor nodes and investigate the performance of BOC in wildlife monitoring.

III. BINARY OFFSET CARRIER MODULATION

The BOC modulation was first used in GNSSs for the spectral isolation of the signals that use same carrier frequency, but was soon found to provide better overall performance as well [10]. BOC modulation is a square sub-carrier modulation in which the data with a chip frequency (also called code rate) f_c is multiplied by a rectangular sub-carrier with frequency f_s. The sub-carrier multiplication before RF transmission of the signal, splits the signal spectrum into two parts. Therefore, in contrast to BPSK, which offers Power Spectral Density (PSD) with maxima at the center frequency, the PSD of BOC modulation has its maxima offset to the center frequency and minima in the channel center as shown in Figure 1. The PSD of BPSK and BOC are shown for the same code rate.

Typically, BOC modulation is defined by two parameters that are related to a reference frequency f_r. In general, the reference frequency f_r is normalized to the system master clock and is used for the generation of sub-carrier frequency, data and RF so that their zero crossings are aligned. The actual sub-carrier frequency f_s and code rate f_c are related with the two parameters as $f_s = a \cdot f_r$ and $f_c = b \cdot f_r$, respectively. Here, f_s has a period of $2T_s$ and f_c supports the time duration equal to nT_s, where n can be readily calculated by $n = 2f_s/f_c$ and is restricted to be an integer. The principal PSD shape of the BOC depends upon the n even or odd. The normalized baseband PSD for BOC modulation is derived from the autocorrelation of the time domain signal and its Fourier transform [10] and is given by:

$$S_{BOC(f_s,f_c)}(f) = f_c \left(\frac{\sin\left(\frac{\pi f}{2f_s}\right) \sin\left(\frac{\pi f}{f_c}\right)}{\pi f \cos\left(\frac{\pi f}{2f_s}\right)} \right)^2, \quad \text{for} \quad n = \frac{2f_s}{f_c} \text{ even} \tag{1}$$

$$S_{BOC(f_s,f_c)}(f) = f_c \left(\frac{\sin\left(\frac{\pi f}{2f_s}\right) \cos\left(\frac{\pi f}{f_c}\right)}{\pi f \cos\left(\frac{\pi f}{2f_s}\right)} \right)^2, \quad \text{for} \quad n = \frac{2f_s}{f_c} \text{ odd} \tag{2}$$

There are always $n - 2$ side lobes between the two main lobes (here referred as sidebands). The BOC modulation generalizes the Manchester scheme having more than one crossings per symbol. In case $f_s = f_c$, i.e., $n = 2$, yields BOC modulation equivalent to Manchester scheme. For $n = 1$, the PSD of BOC modulation is same as a conventional BPSK.

The signal processing required by the BOC receiver is same as a BPSK receiver since the receiver considers the BOC signal similar to a BPSK signal centered around the sidebands. However, BOC provides several benefits regarding implementation and performance. In BOC, the two sidebands can be combined coherently for best receiver and ranging performance. For low power and low complexity devices, filtering can be used to select one of the two sidebands and process it like a BPSK signal. Using only one of the sidebands lowers the performance up to approximately 3 dB in comparison to BPSK because of the fact that each sideband consists half of the signal power. However, also low complexity systems still benefit from using BOC due to the combined data and ranging signal. Moreover, if one of the sidebands is affected by noise or interference, the other sideband can still be used to decode the required information.

In our mobile sensor node, the limited battery cannot provide the demanded current of several mA to the transceiver directly. Therefore, an ultra-low power protocol by combining the duty cycling with wake-up receiver is used [3]. As the wake-up cycle cannot be faster than 10 Hz due to hardware constraint, very short burst BOC(1,0.2) signals having $n = 10$ are used. The short burst signals are able to support Time Division Multiple Access (TDMA) scheme avoiding collisions from multiple mobile sensor nodes. Moreover, BOC parameterized similar to GNSS with a data rate of 1 bit per 20 ms provides a way too low data rate for such short signal bursts.

(a) LOS (b) Foliage

(c) Single obstruction (d) Hardware setup

Figure 2. Field measurement sites and hardware setup.

IV. EXPERIMENTAL SETUP

This section provides an overview of our BOC implementation in SDR, and discusses the simulations and measurements setup. Furthermore, a description of types of environments used to record the data is presented. Finally, the types of measurements performed at each location are described.

A. Implementation

We have implemented a BOC(1,0.2) transceiver based on GNU Radio, a real-time signal processing framework to use with SDR platforms. In our experiments, we use a data rate of 200 kbit/s with a chip rate of 2 Mc/s. The transceiver sends bursts of 12 B that includes 1 B for preamble and 1 B for start of frame delimiter. Moreover, each frame contains 8 B of data and 2 B for Cyclic Redundancy Check (CRC). Such a burst translates into 480 µs and fulfills the requirement of BATS downlink data communication time slot.

On the receiving side, the system is tuned at one of the sub-carrier frequencies and uses the start of frame delimiter to synchronize. Thus, identical processing as a BPSK signal is performed on the selected sideband. Additionally, in order to compare the performance of BOC with BPSK in simulations, both of the BOC sidebands are combined in-phase to present the best case. With this implementation, the transmissions are simulated for an Additive White Gaussian Noise (AWGN) channel model. Furthermore, we performed over the air measurements using Ettus N210 and B210 USRP devices[2] connected to laptop computers.

B. Environment Description

The field measurements were performed in three different types of environments near Paderborn, Germany (cf. Figure 2).

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[2] http://www.ettus.com/

We took care to select areas that are similar to the target environment. The measurement sites along with hardware setup are shown in Figure 2. These environments are categorized into three types:

(a) LOS area: Situated away from the residential area to ensure good testing environment. The nearest building is about 800 m away and the side fields are a few hundred of meters far apart. The ground mainly consists of soil with some parts covered with grass. Since there are no obstructions in between, the site provides perfect LOS.

(b) Foliage area: Similar to a dense forest environment. The area contains of a mixture of different trees dominated by large ones. The large trees are approximately 15 m tall and are spaced with a distance of around 3 m. The ground is a rich cushion of detritus and a significant amount of low-level branches exist throughout the area.

(c) Single obstruction area: This area consists of very few but large trees with height of 10 m spaced with a distance of around more than 25 m. The spot has a diameter of approximately 6 m including the leaves on grass ground.

C. Measurement Setup

We are interested in understanding the performance of the data communication and the reliability of short BOC signals in our application scenario. Furthermore, we consider the mobility of bats that could cause a highly unreliable and time varying channel. Moreover, as the ground nodes will be deployed in the forest, we expect considerable shadowing along with multipath effects.

For field measurements, we use an omni-directional antenna with a gain of 3 dB, which is mounted at a height of 0.5 m from the ground. The carrier frequency is 868 MHz. In our case, the mobile sensor nodes that are situated on the bats have a transmission power of around 10 dBm. Therefore, the transmit power calculated for field measurements is in the range of 10 dBm. This is achieved by adjusting the transmitter gain and amplitude of the transmitted signal. However, it needs to be noted that the USRPs are not calibrated, so, we focus more on relative power values rather than absolute ones. Moreover, a smart phone GPS is used to record the positions during the field measurements. The GPS coordinates are then verified by a map and the average accuracy is found to be of several meters. All results are processed offline.

The field measurements in the LOS and foliage environment were performed to study the range and impact of environment on signal reception rate. Two types of field measurements are performed in each of these environments: *Static* – We perform measurements at different distances, while keeping the system static during each individual measurement. *Mobile* – We perform measurements while moving the transmitter at a human walking speed of 4 km/h–5 km/h on a circle around the receiver to keep the distance constant during a measurement.

We repeated the experiment in the foliage environment at a communication distance of 100 m–130 m using an e-bike at different speeds to match typical behavior of hunting bats [18].

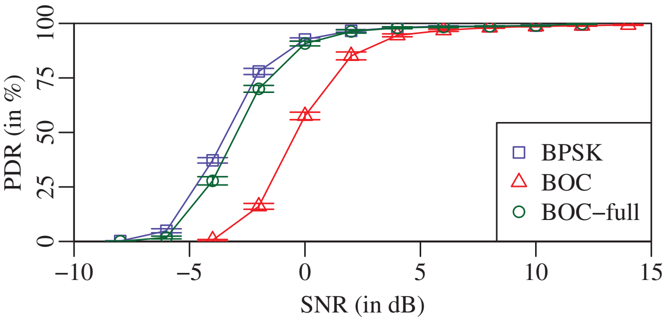

Figure 3. Simulated packet delivery ratio of BOC compared to BPSK over an AWGN channel.

The final field measurements were conducted in the single obstruction area to understand the shadowing effect caused by trees. We measured the received power across a tree, which covers the whole first Fresnel zone between the transmitter and receiver.

V. RESULTS AND DISCUSSION

As a main metric, we studied the PDR for different distances and, thus, SNRs. We first investigate the performance in simulation to validate our model and implementation before we study the system in a lab setup and, finally, in the wild.

A. Simulations

We first analyze the performance of BOC by comparing it to BPSK over an AWGN channel. Figure 3 shows the comparison of simulated PDR with 95 % confidence intervals for different SNRs. The simulations are repeated between 30 to 60 times to obtain the confidence intervals. As expected, processing only a single sideband of BOC performs approximately 3 dB worse than BPSK. In simulation, we also combine the two sidebands of BOC (labeled as BOC-full in Figure 3) to present the best case. We see that combining the two sidebands of BOC compensates the loss only partially and the system still suffers from around 0.5 dB of loss. It is due to the fact that each sideband is affected by noise separately and combining the two sidebands also increases the noise in comparison to BPSK. Our simulations results are fully in line with the results stated in original BOC model in [10] and, thus, validate the implementation in GNU Radio.

B. Lab Measurements

For more realistic comparison, over the air transmissions were conducted in a lab environment for BPSK and BOC (using only one sideband for demodulation). The lab measurements over the air were conducted using exactly the same parameters as in the simulations.

The resulting PDR for different SNR values is plotted in Figure 4. Since the exact absolute power values cannot be perfectly estimated, we shifted the curves to match the simulation results. It can be seen that the shapes of the curves perfectly match the simulation results. The lab measurements thus verify error-free over the air transmissions for field measurements.

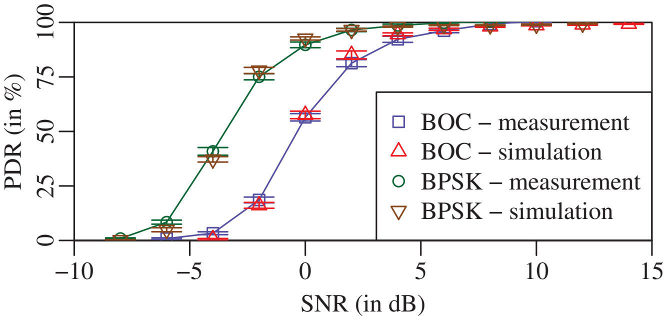

Figure 4. Experimental study of the packet delivery ratio over the air in a lab environment; for validation, overlaid with the simulation results.

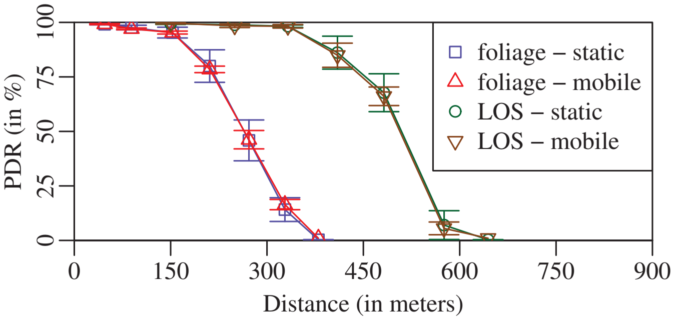

Figure 5. Packet delivery ratio in the different field measurement sites. Here, we plot the PDR over communication distance.

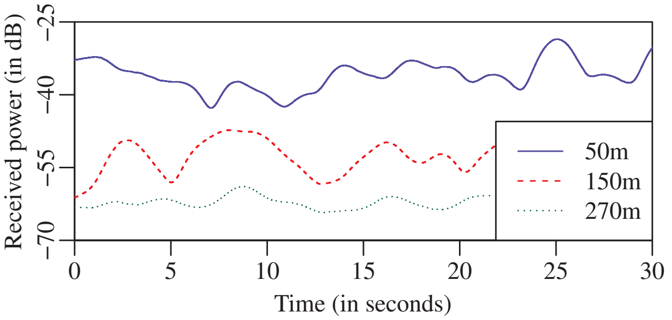

Figure 6. Relative received power for various distances between transmitter and receiver in a foliage environment.

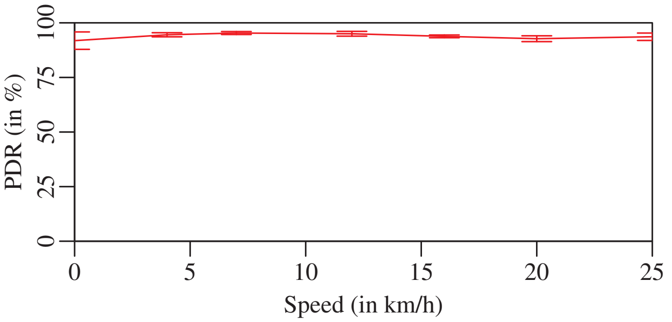

Figure 7. Packet delivery ratio for different average speeds of the transmitter in a foliage environment.

C. Field Measurements

We start our analysis of field measurements by focusing on the impact of environment on the reception quality. Hence, static measurements are conducted in LOS and foliage environments. The communication range of our transmission is then reported in terms of PDR. We also performed these experiments at walking speed to understand multipath and fading effects on PDR in both environments.

Figure 5 shows the resulted PDR with also 95 % confidence intervals for different distances in LOS and foliage area. The confidence intervals are obtained by repeating the measurements between 10 to 30 times. It can be noticed that there is no effect on the PDR if the transmitter is in continuous motion at walking speed and matches the PDR results of static measurements. The system is able to successfully reach a PDR of about 90 % for distances of around 350 m and 150 m in LOS and foliage area, respectively. The results clearly show the impact of environment on our system range. Even though confidence intervals for static and mobile measurements are obtained by repeating the measurements for equal number of times, the confidence intervals for static measurements are comparatively larger than that of the mobile measurements. This is because of the fact that every static measurement is conducted at specific physical positions whereas the mobile measurements are always repeated over the same arc of the circle around receiver.

The confidence intervals of our results can be further analyzed by studying the received signal power during a measurement. Figure 6 shows the variation of relative received power for a single mobile measurement at various distances in a foliage environment. Each time sample corresponds to physically different position because of the continuous movement of transmitter around receiver. The variation in the received signal power (up to 15 dB for a distance of 50 m between transmitter and receiver) during a measurement can be well explained by the uneven distribution of obstructions such as trees. Also the measurement at each distance is conducted only on the arc of circle around receiver where enough space was available to move.

The value of received power depends upon whether a tree was present exactly in front, blocking the strong copy of received signal at a particular physical position, or if we experience direct LOS. At higher distances such as 270 m, the variation in the phenomenon becomes less pronounced because the shadowing becomes a dominant factor and the received signal power approaches the noise floor.

Since the foliage environment is densely populated with trees and low level branches, achieving a speed equivalent comparable to the hunting speed of bats is almost impossible. Therefore, to understand the fast movement effects on reception, we selected a part of foliage area with a distance of around 100 m–130 m away from the receiver. Measurements with a transmitter moving speed of maximum up to 25 km/h were conducted using an e-bike. Figure 7 depicts the PDR at different average speeds of the transmitter. It is expected that, at higher speed the communication process will be affected

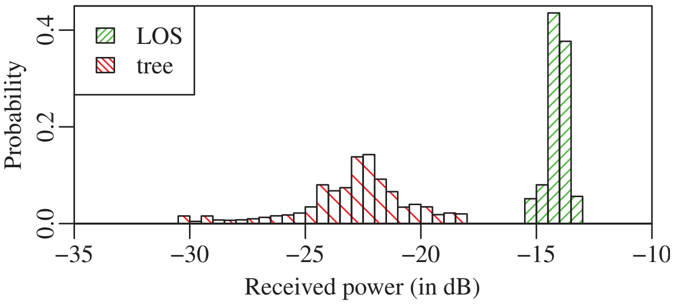

Figure 8. Probability distribution of relative received power.

because of rapidly changing channel parameters and other factors such as multipath and fading. However, it is interesting to see that even reaching up to a speed of 25 km/h does not affect the signal reception.

Finally, we conducted measurements to understand the shadowing effect in a single obstruction area. For this shadowing measurement, the distance of tree from the transmitter is kept same as from the receiver. A tree that is covering even the whole first Fresnel zone between transmitter and receiver does not affect the PDR for the chosen distance. We measured the relative received power of the signal when the whole Fresnel zone is free and when covered completely by a tree.

Figure 8 shows how a tree affects not only the received power but also the distribution of the received power for a communication distance of 20 m. Moreover, repeating the measurement at the same distance lead to slightly different distribution which can be well explained by the reception of different attenuated signal copies with varying power from the tree and ground.

VI. CONCLUSION

In this paper, we studied the performance of combined transmission of data and localization signals for ultra-low power WSNs. We evaluated the feasibility of using BOC modulated signals compared to typically used BPSK signals. In particular, we performed lab and field measurements in different environments to assess the quality of the received signal in terms of PDR. With a transmission power in a range of 10 dBm, the PDR reaches up to more than 90 % for distances less than 350 m and 150 m in LOS and foliage environment, respectively. It is also worth mentioning that the PDR is not affected, if the transmitter is moving with a speed up to 25 km/h. Moreover, shadowing because of the obstruction of trees does not affect the PDR at smaller distances but only the received power and its distribution. Our future work is focusing on combining both BOC spectra in real scenarios for improved reception quality.

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