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Reliable Communication in Distributed Sensor Networks

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Reliable Communication in Distributed Sensor Networks

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Abstract

Sensor networks have gained considerable attention in the past due to their self-organized operation. In this PhD thesis, we target those heterogeneous sensor networks in which backbone (or ground) nodes establish a core network to deliver data to a sink, whereas mobile nodes transmit both localization and encounter information to this backbone network. In the case of errors, the transmitted information is lost and thus needs to be retransmitted. Considering extremely energy-constrained nodes (having weight of less than 2 g), such retransmissions are quite expensive. Hence, we focus on improving the energy-efficiency and communication reliability in such ultra-low power sensor networks. We begin this thesis by investigating the potential of using a square sub-carrier modulation alongside Binary Phase-Shift Keying (BPSK) to transmit localization and data information simultaneously at a single carrier. To assess the performance in both simulations and practical experiments, we develop the whole system in a Software Defined Radio (SDR)-based platform. Our results show that the sub-carrier modulation performs only marginally worse than the BPSK, however, using both of them together saves energy at the mobile node. We then turn our attention towards improved communication reliability. For that, we exploit the distributed nature of the ground network and use it as a distributed antenna array to apply diversity combining. In order to employ receive diversity efficiently, we propose the concept of selective sample forwarding. We build upon our SDR-based implementation and experimentally show that the proposed approach improves the Packet Delivery Rate (PDR) by more than 10 % in comparison to not using diversity combining at all. Finally, we address the cost of forwarding the received information through the ground network to a central sink, where diversity combining is applied. We explore a tree-based algorithm that realizes diversity combining early in the network at local ground nodes rather than at the sink. Our results demonstrate that the proposed algorithm outperforms the naïve centralized solution in terms of energy-consumption, channel utilization, and data rate required in the ground network.

Kurzfassung

Sensornetzwerke haben in der Vergangenheit aufgrund ihres selbstorganisierten Betriebs große Aufmerksamkeit erlangt. Diese Dissertation befasst sich deshalb mit heterogenen Sensornetzwerken, in denen Backbone- oder Boden-Knoten ein Kernnetzwerk bilden, über das Daten an eine Senke geliefert werden und mobile Knoten Lokalisierungs- und Nachbarschafts-Informationen zu diesem Backbone-Netzwerk senden. Im Fehlerfall gehen die übertragenen Informationen verloren und müssen daher erneut übertragen werden. In Anbetracht extrem energiebeschränkter Knoten sind solche Neuübertragungen äußerst teuer. Daher konzentrieren wir uns auf die Verbesserung der Energieeffizienz und der Zuverlässigkeit der Kommunikation in solchen Sensornetzwerken. Wir beginnen mit der Untersuchung einer quadratischen Sub-Carrier-Modulation zusammen mit Binary Phase-Shift Keying (BPSK) zur gleichzeitigen Übertragung von Lokalisierungsinformationen und Daten auf einem einzelnen Träger. Um die Leistung sowohl in Simulationen als auch in praktischen Experimenten zu bewerten, entwickeln wir das gesamte System auf einer Software Defined Radio (SDR)-basierten Plattform. Unsere Ergebnisse zeigen, dass die Sub-Carrier-Modulation nur geringfügig schlechter abschneidet als BPSK. Wenn jedoch beide zusammen verwendet werden, wird Energie am mobilen Knoten eingespart. Anschließend richten wir unsere Aufmerksamkeit auf eine verbesserte Zuverlässlichkeit der Kommunikation. Dafür nutzen wir die verteilte Struktur des Bodennetzes aus und verwenden es als verteiltes Antennenarray, um Diversity Combining anzuwenden. Um diese Technik effizient einsetzen zu können, schlagen wir das Konzept der selektiven Sampleweiterleitung vor. Wir bauen auf unserer SDR-basierten Implementierung auf und zeigen experimentell, dass der vorgeschlagene Ansatz die Packet Delivery Rate (PDR) um mehr als 10 % verbessert. Abschließend befassen wir uns mit den Kosten der Weiterleitung der empfangenen Informationen an eine zentrale Senke, bei der Diversity Combining angewendet wird. Wir untersuchen einen baumbasierten Algorithmus, der Diversity Combining zu einem früheren Zeitpunkt im Netzwerk an lokalen Bodenknoten realisiert. Unsere Ergebnisse zeigen, dass unser Algorithmus in Bezug auf Energieverbrauch, Kanalauslastung und erforderlicher Datenrate die naive, zentralisierte Lösung übertrifft.

Contents

Chapter 1

Introduction

IN the modern era of science and technology, wireless communication has paved the way to constantly connect people and things around us. We can now gather data from places which are either impossible or very difficult for humans to reach directly. Similarly, we are also able to study natural habitat of living organisms over a long period of time without any human intervention. One of the pivotal concepts that has made this all possible is the Internet of Things (IoT).

It was over a decade ago when US National Intelligence Council (NIC) considered IoT as one of the leading technologies that will possibly impact US national power by 2025 [1]. In their report, NIC highlighted the potential opportunities of IoT in everyday things and its indispensable contribution to the economy. To date, we have witnessed thousands of IoT applications in logistics, healthcare, smart environment, and many other domains, benefiting us in different ways and improving our lifestyle [2]–[5]. The basic idea behind IoT is to use Radio Frequency IDentification (RFID) tags, mobile phones, sensors, etc., which interact with each other for the pervasive presence of objects or things around us.

1.1 Wireless Sensor Networks

Sensors based networks have played a key enabling role in IoT because of their self-organizing ability and energy-efficient operation [6]–[8]. They have become a practical tool over the last two decades supporting a wide range of applications [9]–[12]. Wireless Sensor Networks (WSNs) were initially the focus of military and heavy industrial applications, however, they soon gained the attention of many other fields such as environmental monitoring, healthcare, smart environment, etc. Due to widespread use of sensor networking, its application domains now go beyond these applications; particularly wildlife monitoring has become a major field [13], [14]. Unlike other networks, WSNs usually exhibit particular characteristic of collecting sensed data to monitor and analyze the behavior of objects or an environment. Regardless of the scenario, the primary task of WSNs is to provide energy-efficient and cost-effective method to gather this information. Nevertheless, with an ever increasing demand of applications that involve very strict environmental conditions, the energy and size limitations are now even higher [15]. For example, when tracking and monitoring very small animals or birds that are equipped with sensor nodes weighing less than few grams [16]–[18], the energy budget available at the sensor node is now very limited. Most of the times, these miniature nodes are attached to the targeted object which cannot be directly connected to a continuous power supply. Also, energy harvesting is often prohibitive for these miniature nodes because of the size and weight constraints [19].

WSNs have many different characteristics and architectures [20], [21]. Most of the WSNs are autonomous as they perform their designated tasks without any human intervention. Moreover, if all nodes in the network have similar capabilities in terms of available energy budget, processing power, and communication, then it is called a homogeneous sensor network, else the network is heterogeneous. Regardless of the network nature, the main target of WSNs is to communicate reliably, and in an energy-efficient manner. Furthermore, a WSN can be flat or hierarchical. In the flat sensor networks, all nodes are grouped together to perform same task and are connected to a common sink via single-hop or multi-hop topology. While in the hierarchical sensor networks, different nodes are grouped together for the purpose of communication, and to perform different tasks. Finally, a sensor network can be composed of static nodes, mobile nodes, or both.

In this thesis, the network topology and data processing follows the scheme illustrated in Figure 1.1. The mobile node is a miniature chip having less storage capacity, restricted processing power, and very limited energy available at the node. Whereas, the stationary ground nodes are typically less energy-constrained and

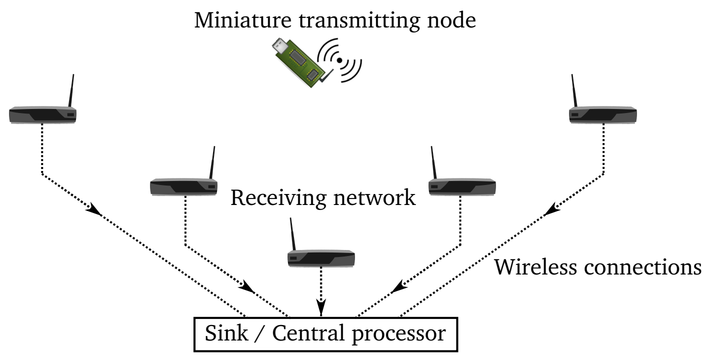


Figure 1.1 – Multiple receiving ground nodes detect a signal from a mobile sender and forward it to a sink for further processing.

interconnected by means of wireless communication supporting higher data rates. These ground nodes are also connected to a centralized sink via a wireless multi-hop network. Hence, it can be considered as a hierarchical heterogeneous sensor network. The miniature mobile node collects the required information (e.g., about the surrounding environment) and transmits it to the ground nodes which further forward it to the sink for final processing. Additionally, the mobile node also generates a localization signal for tracking purposes. Since the mobile node has a very small size, it results in a tight energy budget and, thus, the transmissions towards ground network are very low powered. These transmissions are highly affected not only because of the multi-path fading and shadowing in the wireless channel but also due to the mobility of transmitting nodes. Therefore, it is important to investigate solutions that can help in reliably passing the information from these miniature mobile nodes to the receiving network.

1.2 Research Questions

Due to the weight and size constraints on the mobile node, the available energy budget is quite limited. Therefore, the very first research question is: how to reduce the energy consumption at the mobile node? Are there any energy-efficient methods available in the literature? If yes, is it possible to incorporate these state-of-the-art methods in this miniature node? As performing data communication and ranging at the node require dedicated signals, the energy consumed is twice. To optimize the energy consumption, a simple principle is to completely switch the node off when not communicating. This idea has been investigated in-depth using smart duty-cycling [22], wake-up receiver [23], and, most recently, combinations thereof [24], [25]. However, these solutions are still not sufficient because of the extremely reduced size of mobile nodes. Therefore, it is important to find potential solutions that can further reduce the energy consumption at the mobile node, and prolong its lifetime.

Apart from the energy-efficiency, another research question is: how to reliably pass information from one or many mobile nodes to a receiving network (i.e., ground network in our case)? The transmissions towards the ground network are highly affected. First, because the environment involves challenging multi-path effects and shadowing due to a massive number of obstacles, e.g., buildings and trees. Second, the mobility of transmitting nodes results in a time-varying channel which aggravates the communication reliability. In case of information loss, repeated transmissions or Automatic Repeat-Request (ARQ) mechanisms are prohibitive due to the very tight energy budget of the mobile nodes [26]. Forward Error Correction (FEC) using fountain codes improves the communication reliability [27], however, it is still not sufficient. Therefore, to ensure reliability in harsh time-varying channel conditions, novel solutions are required.

Since a transmission from a mobile node is broadcast over a ground network, it will possibly be received by several ground nodes. One unique solution in this scenario is to use ground network as a distributed antenna array and apply diversity combining techniques for improved reception. However, applying diversity combining in distributed systems is not that straight forward and gives rise to several research challenges. First, efficient forwarding of received information to a central node is required through a limited bandwidth link. Second, ground nodes have to be tightly synchronized to align the start of all signal copies received at different nodes. The next challenge is to precisely track the phase and frequency offsets for the constructive combining of signals from different nodes. Finally, optimal placement of ground nodes or, alternatively, minimal transmit power required for reliable communication needs to be investigated.

It can be noted that diversity combining techniques are eventually applied at a central (sink) node. Hence, the last research question is: What is the cost (in terms of time delay, energy consumption, required data rate, etc.) of forwarding the received information to the central sink through the ground network? Can this cost be reduced? In this scenario, an efficient solution is to apply diversity techniques early in the network at local ground nodes rather than at the centralized sink. To achieve this, several data aggregation algorithms have been proposed that focus on collecting the received data samples at a local network node and apply diversity combining locally before forwarding the decoded data to the sink as a single data message [28]–[30]. However, the typical target of these state-of-the-art algorithms are stationary homogeneous sensor networks or heterogeneous sensor networks in which the communication protocol and architecture are different than the considered WSN. In contrast to the literature, we consider a sensor network in which the energy budget is only limited at the transmitting node, which is, at the same time, highly mobile and experiences challenging channel conditions. Therefore, to perform diversity combining efficiently at local nodes (in the receiving network), unique solutions are required.

1.3 Structure of the Thesis

To address all the research questions discussed above, we focus on a wildlife application scenario (in Chapter 2) that involves a similar sensor network architecture as the one described in Section 1.1. Every follow-up chapter of this PhD thesis then provides a unique contribution.

As the first contribution of this thesis, in Chapter 3, we optimize energy consumption of the mobile node by developing a novel Software Defined Radio (SDR)-based Binary Offset Carrier (BOC) transceiver to perform data communication and ranging simultaneously at a single carrier. Our used BOC variant supports higher data rate in comparison to its traditional variants used in satellite communications and, hence, perfectly fits within the context of WSNs. Using BOC not only saves energy but also allows to incorporate state-of-the-art concepts (e.g., wake-up receiver, duty cycling) to further minimize the energy consumption of the mobile node.

Since a transmission from a mobile node will possibly be received by several ground nodes, we propose to use ground network as a distributed antenna array in Chapter 4 as the next contribution of this thesis. With that, we employ receive diversity techniques in the ground network and, hence, combine signal copies that belong to the same transmission for improved reception quality. We also target several research challenges that arise while realizing diversity combining techniques in distributed sensor networks and present solutions to overcome them. We develop the whole system model in an SDR-based platform and evaluate the performance by means of simulations, lab measurements, and outdoor experiments.

The final contribution of this thesis focuses on realizing diversity combining in the ground network in a distributed fashion. We propose a variant of tree algorithm in Chapter 5 in order to apply diversity combining early in the network at local ground nodes rather than at a centralized sink. The proposed algorithm not only reduces the data rate required in the ground network but also improves the performance in terms of energy-efficiency and channel utilization.

1.4 Publications

This PhD thesis is based on the following publications:

- M. Nabeel, B. Bloessl, and F. Dressler, “On Using BOC Modulation in Ultra-Low Power Sensor Networks for Wildlife Tracking,” in *IEEE Wireless Communications and Networking Conference (WCNC 2016)*, Doha, Qatar: IEEE, Apr. 2016, pp. 848–853, © 2016 IEEE.

  In this conference publication, my contribution was to develop a novel SDR-based BOC transceiver supporting higher data rate applications, and investigate its suitability in ultra-low power sensor networks by performing an extensive set of simulations as well as real-world experiments.

- M. Nabeel, B. Bloessl, and F. Dressler, “Low-Complexity Soft-Bit Diversity Combining for Ultra-Low Power Wildlife Monitoring,” in *IEEE Wireless Communications and Networking Conference (WCNC 2017)*, San Francisco, CA: IEEE, Mar. 2017, © 2017 IEEE.

In this conference publication, my contribution was to propose and exploit the distributed nature of ground nodes and use them as a distributed antenna array to employ receive diversity. To optimize link utilization in the ground network, I also investigated the performance of low-complexity soft-bit diversity techniques in simulations and through SDR-based experiments.

- M. Nabeel, B. Bloessl, and F. Dressler, "Selective Signal Sample Forwarding for Receive Diversity in Energy-Constrained Sensor Networks," in *IEEE International Conference on Communications (ICC 2017)*, Paris, France: IEEE, May 2017, © 2017 IEEE.

  In this conference publication, my contribution was to propose a novel system that only forwards selected complex signal samples of the received packets to the network sink where diversity combining is applied. The proposed system achieved maximum diversity gain in comparison to soft-bit combining while keeping the data rate in the ground network at an acceptable rate.

- M. Nabeel, B. Bloessl, and F. Dressler, "Efficient Receive Diversity in Distributed Sensor Networks using Selective Sample Forwarding," *IEEE Transactions on Green Communications and Networking*, vol. 2, no. 2, pp. 336–345, Jun. 2018, © 2018 IEEE.

  In this journal article, my contribution was to perform an extensive set of simulations and lab measurements, and explore the application performance of selective sample forwarding approach. Additionally, I also proposed a model that helps in efficient deployment of distributed diversity systems by selecting optimal receiver positions or by minimizing the transmit power while maintaining reliable communication.

- M. Nabeel, V. K. Singh, and F. Dressler, "Efficient Data Gathering for Decentralized Diversity Combining in Heterogeneous Sensor Networks," in *IEEE Wireless Communications and Networking Conference (WCNC 2019)*, Marrakech, Morocco: IEEE, Apr. 2019, © 2019 IEEE.

  In this conference publication, my contribution was to propose a variant of tree algorithm for applying diversity combining locally at ground nodes. I performed an extensive set of simulations to investigate its performance and to compare it with a variant of cluster algorithm and the naïve centralized solution.

During my studies, I also authored the following publication:

- M. Nabeel, M. S. Amjad, and F. Dressler, "Preamble-Less Diversity Combining: Improved Energy-Efficiency in Sensor Networks," in *IEEE Global Telecommunications Conference (GLOBECOM 2018)*, Abu Dhabi, UAE: IEEE, Dec. 2018.

Finally, I also shared results of my research with other researchers from the project. In collaboration, I have co-authored the following publications:

- N. Duda, T. Nowak, M. Hartmann, M. Schadhauser, B. Cassens, P. Wägemann, M. Nabeel, S. Ripperger, S. Herbst, K. Meyer-Wegener, F. Mayer, F. Dressler, W. Schröder-Preikschat, R. Kapitza, J. Robert, J. Thielecke, R. Weigel, and A. Kölpin, "BATS: Adaptive Ultra Low Power Sensor Network for Animal Tracking," *Sensors*, vol. 18, no. 10, pp. 3342–35, Oct. 2018.
- F. Dressler, M. Mutschlechner, M. Nabeel, and J. Blobel, "Ultra Low-Power Sensor Networks for Next Generation Wildlife Monitoring," in *11th IEEE International Conference on Communication Systems and NetworkS (COMSNETS 2019)*, Bangalore, India: IEEE, Jan. 2019.

Chapter 2

Fundamentals

TODAY, everything in this world is connected to each other by means of wireless communications. However, unlike wired systems, the performance of a wireless communication system is usually much more unpredictable due to the underlying wireless channel environment. Therefore, to achieve a reasonable performance, optimization of wireless communication systems is the main focus of researchers since many decades.

In this chapter, first we explain the characteristics of a typical wireless channel and the challenges it imposes on a wireless communication system due to its dynamic and unpredictable behavior. We then focus on the design of a general wireless system and study few of the available techniques that help in improving the communication performance. We also discuss the implementation of the wireless systems in the Software Defined Radio (SDR) platforms and its advantages. Finally, in the last part of this chapter, we describe our targeted wildlife application scenario that includes ultra-low power communication, and highlight the challenges involved that are focused in this PhD thesis.

2.1 Wireless Communication Systems

A wireless communication system typically includes three main blocks, i.e., a transmitter, a receiver, and a channel as shown in Figure 2.1. The transmitter sends the intended information $x(t)$ to the receiver over-the-air (i.e., channel) in form of radio waves. While propagating through the channel, the radio waves are either diffracted, deflected, or scattered because of the obstructions and the nature of the environment [39], [40]. As a result, the characteristics of a radio wave signal such as its amplitude and phase are affected. The resulting signal $y(t)$ at the receiver can thus be written as

$$y(t) = h(t) * x(t) + n(t). \tag{2.1}$$

Here, $h(t)$ represents the attenuation caused by the wireless channel, whereas $n(t)$ refers to the thermal noise and is normally modelled as an Additive White Gaussian Noise (AWGN). This equation is widely used in signal theory to analyze the behavior of a signal in a wireless channel.

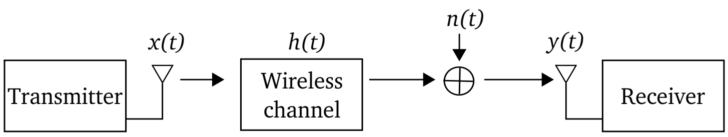


Figure 2.1 – A general wireless communication system.

In practical systems, the received signal power P_r (in dB) is estimated by

$$P_r = P_t + G_t + G_r - L_{FSPL} - L_{Fading}. \tag{2.2}$$

Here, P_t denotes the transmit power while G_t and G_r refer to transmit and receive antenna gains, respectively. Whereas, L_{FSPL} shows the deterioration in signal power due to its propagation in free-space. This power-loss is known as a Free Space Path Loss (FSPL), and it depends upon the frequency used for transmission and the distance a signal covers. If d is the distance and λ is the signal wavelength, then FSPL can be calculated as

$$FSPL = \left(\frac{4\pi d}{\lambda}\right)^2. \tag{2.3}$$

Finally, L_{Fading} denotes the loss in signal power due to fading. Fading in wireless communications refers to the variation in the signal amplitude over frequency and time [41]. Unlike additive noise, the fading is a non-additive signal disturbance in a wireless channel. If fading is caused by obstacles present in the environment then it is called shadowing and is often modelled by a log-normal distribution [42]. Since FSPL and shadow fading increase with distance, they are also termed as large-scale fading.

However, if a signal is scattered and takes multiple paths to reach a destination then it is referred to as multi-path fading. In multi-path fading, there are rapid fluctuations in signal power due to constructive or destructive interference of multiple signal copies over very short distances, hence, it is known as small-scale fading. In a Non Line-of-Sight (NLOS) environment, the multi-path fading often follows a Rayleigh distribution which can be obtained by the sum of two quadrature Gaussian distributions [40]. The Probability Density Function (PDF) of the Rayleigh distribution for the average received signal power σ^2 is computed as

$$P(x) = \frac{x}{\sigma^2} exp\left(-\frac{x^2}{2\sigma^2}\right), \qquad \text{for} \quad x \geq 0. \tag{2.4}$$

Moreover, if a signal is transmitted or received by a non-stationary transceiver, the signal experiences additional variations in its amplitude and phase over time due to the movement of the transceiver. In such a time-varying channel, it is crucial to estimate the channel again in case the signal-length is longer than the coherence time. The coherence time T_c is a time duration in which the state of the channel remains nearly constant. It is dependent upon the transceiver speed v and is approximately given by [40]

$$T_c = \frac{9\lambda}{16\pi v}. \tag{2.5}$$

With all these channel effects, the received signal power is highly affected. To make the signal more robust against these channel effects as well as interference from the other signals at the same frequency band, advanced signal processing techniques are used at the transmitter and the receiver. In the next section, we study the structure of a transmitter and a receiver in detail, and discuss the steps involved to process the signal efficiently against these adverse channel effects.

2.2 Transceiver Design

Figure 2.2 shows the block diagram of a typical digital transceiver. At the transmitter, first, baseband signal processing is performed on the binary input data stream. In the signal processing block, the most important steps involve coding and digital modulation. Coding is usually performed for error detection and correction by adding extra bits (i.e, channel coding), for data compression by removing redundant or unnecessary bits (i.e, source coding), and/or for secure communication (cryptographic coding). Whereas, in order to perform digital modulation, the incoming bit stream is converted into symbols based on the modulation order and, then, mapped onto the corresponding constellation points. Digital modulation techniques help in controlling the bit-energy and data rate for transmission. The baseband processing can also perform other tasks such as interpolation, pulse shaping (to reduce the intersymbol intereference (ISI)), etc. The resultant signal is then fed into the Digital-to-Analog Converter (DAC) to convert it into analog domain. Afterwards, in the Radio Frequency (RF) front end block, up-conversion is performed by multiplying the signal with a carrier frequency before filtering and, finally, transmitting the encoded information via an antenna.

At the receiver side, a reverse procedure is followed to recover the actual data. However, since the signal is also affected by several channel effects while propagating from the transmitter to the receiver, the baseband signal processing at the receiver

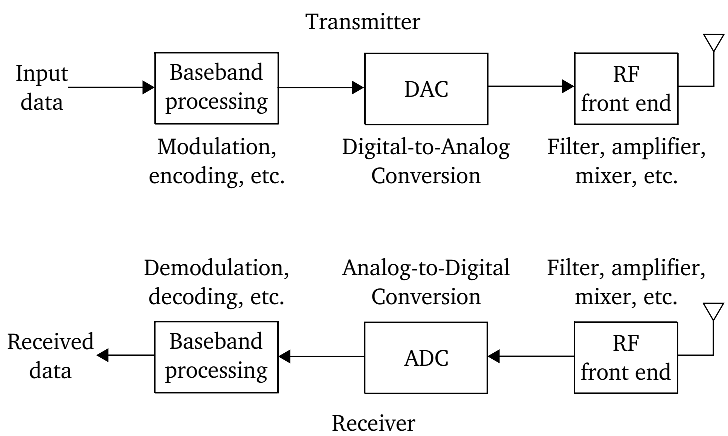


Figure 2.2 – Block diagram of a typical digital transceiver.

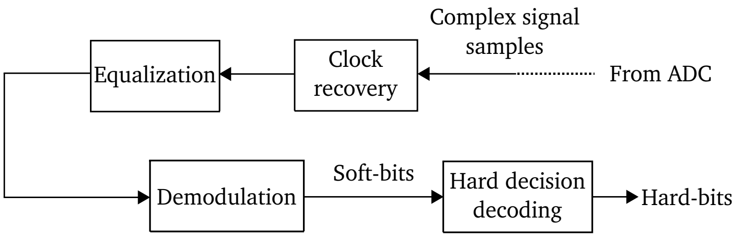


Figure 2.3 – Basic operations performed in baseband processing block at the receiver.

is more complex as it tries to revert all the channel effects as well. On reception of the signal at a receiver, the received data is first amplified, filtered, and then down-converted by multiplying the same carrier frequency before converting the data into digital domain by an Analog-to-Digital Converter (ADC). To obtain the actual transmitted data, baseband signal processing is performed and, finally, hard decision decoding is applied.

To understand the signal processing at the receiver in more detail, we further study the important steps performed in the baseband processing block also shown in Figure 2.3. Apart from the mentioned blocks, a receiver can also perform decimation and different types of filtering, e.g., matched filter to maximize the received Signal to Noise Ratio (SNR). After obtaining the complex baseband signal samples, the receiver estimates, and compensates for the symbol timing, sampling clock offset, and frequency offset to synchronize its clock with the transmitter, and eventually to coherently decode the received data. The estimation is usually performed with the help of a training data. The training data also helps in detecting the signal by correlating it with the received samples and in estimating the channel quality. To revert the channel effects on the signal, equalization is performed by multiplying the inverse of estimated channel with the received complex signal samples. The resulting samples are then further processed (e.g., differential demodulation in case of Differential Phase-Shift Keying (DPSK)) to obtain soft-bits. Finally, these soft values are mapped to nearest constellation points to obtain hard-bits and for final decoding.

2.3 Modulation Techniques

Since lower-order modulations are relatively simple to process [39], they are well suited for low-power communications. Therefore, in this thesis, we particularly focus on the BPSK modulation. In BPSK modulation, the modulator represents the binary values, i.e., 0 and 1, with phases that are obtained by switching the phase of a constant amplitude carrier signal between two values. For a better detection of the

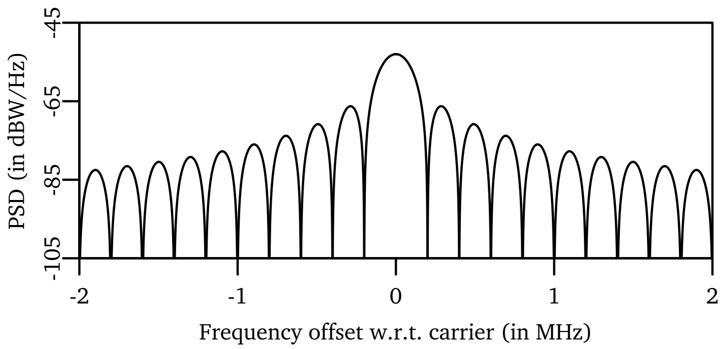


Figure 2.4 – Power spectral density of a BPSK signal with a code rate of 0.2 Mchip/s.

BPSK symbols at a receiver, the two phases are separated by 180°. Because of the maximum separation between the phases, BPSK is considered as one of the most robust modulation schemes. However, as a drawback, BPSK is able to modulate one bit per symbol only, hence, it is not suitable for applications which involve very high data rates.

Figure 2.4 shows the normalized Power Spectral Density (PSD) of a BPSK signal. This normalized PSD with code rate f_c can be obtained by [43]

$$S_{BPSK}(f) = f_c \left(\frac{\sin\left(\frac{\pi f}{f_c}\right)}{\pi f} \right)^2 . \tag{2.6}$$

It can be noted that the PSD of BPSK has its maxima at the center frequency. The null-to-null bandwidth of BPSK is twice the code or bit rate, while 90 % of the signal energy is contained within the bandwidth of approximately 1.6 times of the bit rate [40].

BPSK modulation can be coherent or non-coherent. In the case of coherent BPSK, a low level pilot carrier signal is transmitted along with the modulated data. The BPSK receiver uses this pilot signal to estimate the carrier phase and frequency for the coherent demodulation of the transmitted information. Since coherent BPSK requires additional energy at the transmitter, it is not preferred in low-power systems.

Differential Binary Phase-Shift Keying (DBPSK) is a non-coherent form of BPSK as it does not require a coherent reference signal for the receiver. Non-coherent BPSK modulation is cheap and easy to implement, hence, it is widely used in wireless communications. In DBPSK systems, the input binary data is differentially encoded before modulating it using a BPSK modulator. A differentially encoded sequence is generated from a binary input data by complementing the modulo-2 sum of each symbol with its previous symbol. The phase of a binary symbol is changed if the incoming symbol is 0, else the phase remains unchanged in case the incoming symbol is 1. The original sequence is recovered at the receiver after demodulating the differentially encoded signal by a complementary process. Even though, in practical systems, DBPSK is much simpler to implement than a coherent BPSK signaling, the performance it achieves is also relatively lower [40]. The performance loss is due to the phase dependency of each bit on the previous bit.

2.4 Diversity Combining

To overcome the effects introduce by a wireless channel, a simple technique is to use diversity combining of independently fading signal paths (i.e., diversity branches). Diversity combining increases the robustness of wireless communication systems by using spatially separated antennas. These antennas can be mounted at the transmitter (referred to as a transmit diversity), receiver (referred to as a receive diversity), or both. In this thesis, we focus on receive diversity techniques. A general receive diversity system with n diversity branches is shown in Figure 2.5.

In the receive diversity, if the antennas used for diversity combining belong to a single receiver, they mitigate the effect of multi-path fading and the system is known as a micro-diversity system. If these antennas belong to spatially separate receivers that are placed to cover a large region, the system, in addition, becomes more robust against shadowing and interference, and is called a macro-diversity system. However, regardless of the receiver structure, the commonly employed receive diversity techniques include Selection Diversity (SD), Equal Gain Combining (EGC), and Maximum Ratio Combining (MRC).

SD is considered to be the simplest one of all these techniques: a branch with the highest SNR is selected and signals from rest of the branches are discarded. In presence of Rayleigh fading, the resultant signal power ratio p for n diversity

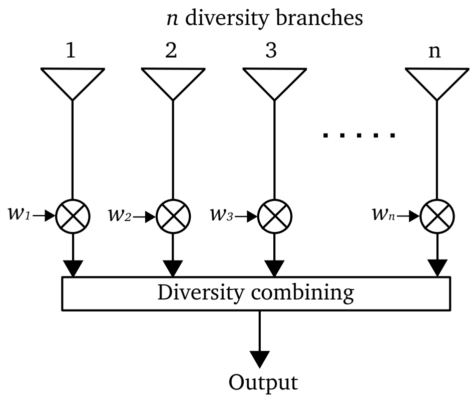


Figure 2.5 – Receive diversity combining.

branches is given by [44]

$$p = \sum_{i=1}^{n} 1/i \,. \tag{2.7}$$

It can be noted that adding the i^{th} branch in a SD system contributes only $1/i$ in the resultant power ratio, hence, diminishing the diversity advantage.

In contrast to SD, EGC does not discard signal from any diversity branch and provides higher diversity gain. Signals from all of the branches are phase-aligned and summed up by weighting the gain of each branch w_i as unity. The resultant signal power ratio for EGC is thus written as [44]

$$p = 1 + (n-1)\pi/4 \,. \tag{2.8}$$

In EGC, signal copies from all branches are combined after co-phasing, thus, the receiving branches are highly dependent on each other, and if one branch contains just noise or a distorted signal, it affects the overall performance. To overcome this problem, MRC weights the gain of each branch w_i relative to its received signal quality. MRC achieves full diversity gain if the weight of each branch is set relative to p_i/N, where p_i is the signal power in that branch while N denotes the average noise power [40]. As a result, the resultant signal power ratio is maximized and is given by

$$p = \sum_{i=1}^{n} p_i \,. \tag{2.9}$$

All these diversity combining techniques are usually realized at the complex signal samples received at the receiver. For a performance overview, we show a comparison in presence of Rayleigh fading in Figure 2.6. It can be seen that increasing number of branches only marginally contribute to the diversity advantage for SD. Moreover, the performance of EGC is slightly worse than MRC because of the blind

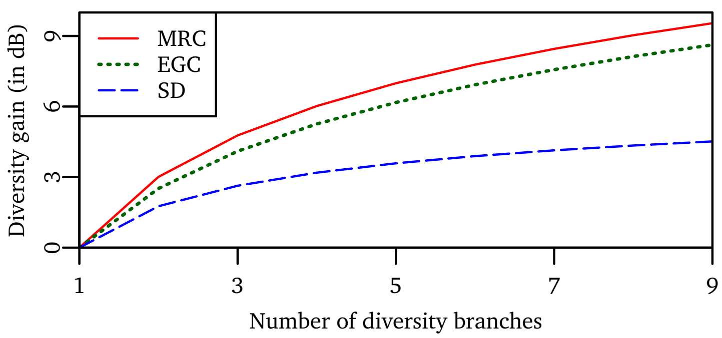


Figure 2.6 – Performance gain with different diversity techniques in Rayleigh fading channels.

addition of signal copies from different diversity branches. It is worth noting that the performance improvement of MRC/EGC over SD comes with an expense of increased signal processing required at each diversity branch for the phase alignment to combine signal copies constructively.

Even though SD is considered as the simplest diversity technique, its applicability in macro-diversity systems is not straight forward due to the additional exchange of information, e.g., received signal strength, between distributed receivers. As a replacement, one option is to apply diversity at soft decision bits in order to reduce the data rate requirements in distributed networks. Though signal level combining achieves maximum diversity gain, soft-bit combining degrades performance due to the loss of signal level properties [45].

Moreover, diversity can also be performed at hard-bits in order to further reduce the data rate requirements. Performing diversity at hard-bits uses different techniques such as Multiply-Detected Macro-diversity (MDM) [46] or Post-Detection Combining (PDC) [47], in which a decision for each bit is taken by a majority combiner. If the total branches are even in number and there is a tie to select a bit, a random selection is made. This certainly reduces the network load but at the expense of increased processing at local receiving nodes.

2.5 Software Defined Radio

In the past, radios have been built for specific purposes with predefined specifications. There were no possibilities of modifications and a change in technology usually required new hardware designing. The idea of programmable radios, i.e., SDRs, has revolutionized the current wireless communications testbeds [48], [49]. SDRs can be easily programmed and their functionalities can be modified for the required purposes without the need of a new hardware. Unlike old radios, SDRs are cost-effective, and provide ubiquitous platform for the implementation and demonstration of state-of-the-art as well new concepts conveniently. Nowadays, SDRs are widely used in both industry and academia for the purpose of learning, research, and to better understand the internals of wireless transceivers [50].

The most popular SDRs-platforms are either Field-Programmable Gate Array (FPGA)-based or General Purpose Processor (GPP)-based. The main difference between them is the way the physical layer is implemented. FPGA-based SDRs normally use hardware description languages, e.g., Verilog or VHDL, and are computationally faster than the GPP-based ones. Another advantage of using FPGA-based SDRs is that they can support high bandwidths and have deterministic timings. Because of their low-latency, they are well-suited for applications which involve strict timing constraints. Even though FPGA-based SDRs are fully programmable in theory, in practice, they offer limited flexibility in implementing the physical layer. Moreover, realizing complex signal processing algorithms on FPGAs is often challenging and require longer development time.

In contrast to FPGA, GPP-based SDRs are more flexible as they offer the possibility of rapid-prototyping and the physical layer is implemented in software on a simple Personal Computer (PC), which makes it very easy to modify. To reduce the number of computations in the PC, usually baseband signal processing is performed in the software, whereas, a hardware device is used for DAC/ADC and for the mixing of the baseband signal with a carrier frequency before transmitting or receiving via antennas. On the one hand, GPP-based SDRs are beneficial as they use high-level programming languages such as C++ or Python which are easier to write, compile, and debug, in comparison to hardware description languages. On the other hand, the disadvantage of using GPP-based SDRs is that they are computationally much slower than FPGA-based SDRs. Buffering of samples to process in a PC and transporting them between the PC and the device introduce latencies in the order of µs [51]. Nevertheless, since the physical layer in GPP-based SDRs is implemented on a PC, additional to real-world experiments, it allows its users to perform simulations by connecting transmitter and receiver in software. Simulations not only provide an easy switch between theory and practice but also help in testing the transceiver prior to practical experiments.

2.5.1 GNU Radio

In this PhD thesis, we have used GNU Radio[1] together with Ettus Universal Software Radio Peripheral (USRP)[2] devices, for the implementation and demonstration of our wireless system. GNU Radio is an Open Source signal processing framework (used as a software part of GPP-based SDR) that allows to implement signal processing algorithms in high-level programming languages, i.e., C++ or Python, on a simple PC [52]. In comparison to one of the most popular signal processing tools, i.e., MATLAB, GNU Radio provides an advantage of processing a sample stream in real-time rather than offline signal processing. Since GNU Radio is Open Source, it does not cost any licensing fees and, hence, actively used in the research community for rapid-prototyping and physical layer experimentation [53], [54].

The basic element of GNU Radio is a *block*. A block is usually implemented by a set of lines of codes written in C++ or Python that perform specific signal processing tasks such as filtering, modulation, etc. GNU Radio comes with a built-in block set which already implements most of the basic signal processing algorithms. In order to perform application-specific tasks, GNU Radio allows its users to implement custom

[1] `https://www.gnuradio.org/`
[2] `https://www.ettus.com/`

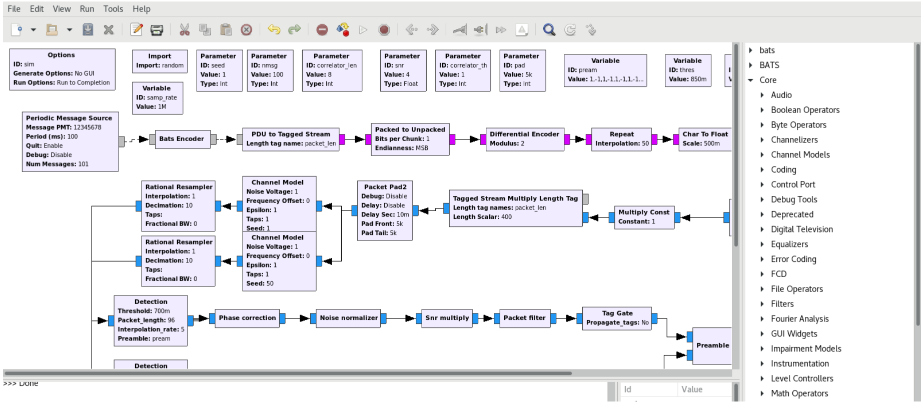


Figure 2.7 – Screenshot of GNU Radio Companion and a flow graph.

blocks in Out-of-Tree (OOT) modules. Multiple blocks are connected by means of connections to make a *flow graph*, which can also be interpreted as a representation of a complete transceiver. GNU Radio also comes with a user-friendly graphical user interface as shown in Figure 2.7. This allows to build, modify, and run flow graphs easily. Moreover, it can be comfortably connected with USRPs for over-the-air experiments. It is also worth noting that, unlike other SDR frameworks, GNU Radio can be interfaced with many other devices as well, e.g., HackRF One from Great Scott Gadgets and BladeRF from Nuand.

Since GPP-based SDRs are relatively slower in processing, GNU Radio copes with increased bandwidth demands of state-of-the-art technologies by starting each block in its own thread resulting in a load distribution between different cores and, hence, increasing the computations speed. Apart from real-time over-the-air experiments, GNU Radio also allows its users to easily perform simulations by connecting transmitter with the receiver through a wireless channel block in software. GNU Radio provides a built-in block set to simulate different types of channel models including AWGN and Rayleigh. These channel models also allow to set up values for hardware impairments such as clock drift and phase noise. Lastly, GNU Radio has graphical outputs to show different characteristics of a signal at the blocks output, for example, signal in time or frequency domain, while a flow graph is running. These graphical outputs are extremely helpful in debugging complex flow graphs.

2.6 BATS Project

To study the research questions discussed in the previous chapter in detail, we consider a particular wildlife application scenario. With that, our aim is twofold. First, we focus on an endangered species and help biologists studying the social behavior of that species. Such information helps in providing a better environment for the reproduction and survival of this endangered species. Second, we study the social behavior of this species by equipping them with a sensor node that is one order of magnitude smaller than the ones used in the literature. Hence, we practically address several related research questions and provide novel solutions to overcome them.

Our main target application is a wildlife monitoring within the scope of the BATS project [19]. In the BATS[3] project, we are working in an interdisciplinary team to support biologists studying the foraging behavior of mouse-eared bats (Myotis myotis) in their natural habitat. An overview of the BATS scenario is also shown in Figure 2.8. In brief, we are equipping bats that weigh about 20 g with a sensor node of only 2 g, which continuously records contacts information between individuals. The main aim of this thesis is to investigate solutions that offer energy-efficient and reliable extraction of this recorded information along with the accurate tracking of a flying bat.

This mobile node on the bat (referred to as a bat node) is composed of a radio transceiver (including a wake-up receiver), a microcontroller, and a battery. The transceiver cannot be switched on directly due to the limited size of the battery which does not provide the demanded current of several mA. To cope with this challenge, we use an ultra-low power protocol by employing a wake-up receiver on the node and combining it with the concept of duty cycling [24]. As a result, we get a wake-up cycle of 10 Hz allowing us to use Time Division Multiple Access (TDMA) with short time slots of less than 500 µs for all communications. Using short burst signals with TDMA helps in collision avoidance of multiple bat nodes in the same area. We use a packet size of 12 Byte containing 2 Byte each for training data and Cyclic Redundancy Check (CRC), and 8 Byte of payload (for the meetings information). A bat node modulates this packet with DBPSK and is able to transmit in a TDMA slot of 100 ms at 868 MHz with a data rate of 200 kBit/s.

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

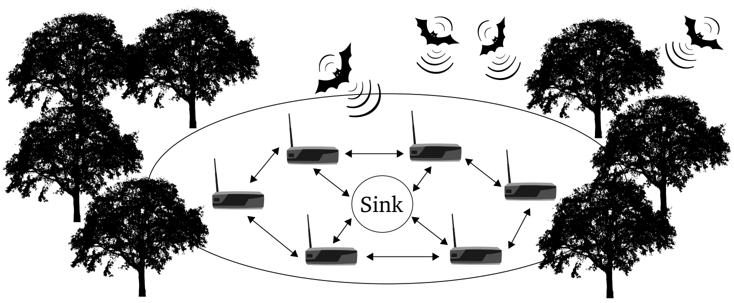


Figure 2.8 – An overview of the BATS project.

Moreover, we deploy a distributed ground network composed of static single antenna sensor nodes which do not have strict energy limitations in the hunting areas of bats. This ground network not only tracks the trajectories of a flying bat on its visit to the hunting ground but also extracts the contacts information saved on the miniature chip. The ground network nodes are deployed with an inter-distance of 30 m for accurate localization during flight maneuvers and are also connected to a central node via a wireless multi-hop network. This scenario is similar to the one shown in Figure 1.1, except that the receiving network here is deployed in a foliage environment and the communication channel is highly affected due to multi-paths, shadowing, and nocturnal movement of bats. The ground network periodically transmits a wake-up signal to trigger the wake-up receiver of the bat nodes in range, causing to transmit all saved information to the ground network. Furthermore, all nodes in the ground network continuously check for the detection of signal by correlating the known data with incoming samples. In presence of a transmitting bat, the signal is detected, decoded, and forwarded to the centralized node for further processing. Since the transmitter is highly energy-constrained, we mainly focus on improving the bat-ground communication without increasing the transmit power at the bat node.

Chapter 3

Binary Offset Carrier Modulation

In the previous chapter, we have learned that the bat node is light weight and the available energy budget is limited. Therefore, it is essential to provide solutions which minimize the energy consumption of the bat node, and at the same time, achieve high performance. To optimize the energy consumption in this scenario, one method is to use Binary Offset Carrier (BOC) modulation, and perform data communication and ranging simultaneously at a single carrier. BOC has been widely studied and used within the scope of Global Navigation Satellite Systems (GNSSs), however, its implication in ultra-low power sensor systems is still in its prime. Therefore, in this chapter, we focus on the experimental study of BOC to analyze its performance in Wireless Sensor Networks (WSNs).

This chapter is based on the following publication:

- M. Nabeel, B. Bloessl, and F. Dressler, "On Using BOC Modulation in Ultra-Low Power Sensor Networks for Wildlife Tracking," in *IEEE Wireless Communications and Networking Conference (WCNC 2016)*, Doha, Qatar: IEEE, Apr. 2016, pp. 848–853, © 2016 IEEE.

  In this conference publication, my contribution was to develop a novel Software Defined Radio (SDR)-based BOC transceiver supporting higher data rate applications, and investigate its suitability in ultra-low power sensor networks by performing an extensive set of simulations as well as real-world experiments.

3.1 Motivation

It is quite evident that to support data communication and ranging in a single system, the energy is spent twice as there is a dedicated signal for communication and another one for localization. We thus explore the options of combining data communication with the localization signals in order to reduce the number (or length) of the necessary transmissions. BOC is a square sub-carrier modulation which offers communication adjacent to another signal at a single carrier frequency without interfering with each other [55]. As lower-order modulations (e.g., Binary Phase-Shift Keying (BPSK)) are relatively simple to process [39], using BPSK along with BOC to perform localization and data communication at the same time can be an optimum choice to reduce energy consumption in energy-constrained wireless networks. BOC modulation was first developed and analyzed for GNSSs to provide spectral separation between Global Positioning System (GPS) and Galileo positioning system that share the same frequency bands [55]. Exploiting BOC in ultra-low power energy systems however imposes numerous research challenges in contrast to GNSS due to the limited battery resources which offer communication with only short burst signals. Therefore, it is essential to explore BOC modulation within the scope of WSNs and assess its performance in comparison to the conventional BPSK systems.

In this chapter, we focus on using BOC for the data transmission from bat node to the ground network. As stated in the previous chapter, due to the fast movement of bats in a forest environment, the transmitted signal faces adverse and highly varying channel conditions. Therefore, we develop the BOC transceiver in an SDR and investigate its performance in different heterogeneous environments. We have performed simulations, lab measurements, and conducted several field measurements to show the feasibility of BOC in our wildlife scenario.

Our main contributions in this chapter can be summarized as follows:

- First, we study and explore BOC modulation for its applicability in ultra-low power sensor systems.
- Next, we propose and develop an SDR-based BOC transceiver supporting higher data rate applications and validate our implementation by means of simulations and lab measurements. We also compare its performance with BPSK to demonstrate its feasibility.
- Finally, we perform an extensive set of measurements in the wild to analyze the experimental performance of BOC in our scenario.

3.2 Preliminaries

The overall energy consumption of WSNs is highly dependent upon the underlying physical layer. Since lower-order modulations (such as BPSK) are more robust and simple to implement because of their low-complexity [39], they are well suited for energy-constrained sensor networks. In the literature, efforts have been made to provide integrated energy analysis of different modulation schemes with Error Correcting Codes (ECCs), such as Reed-Solomon [56]. It has been noticed that there is always a trade-off between the increased robustness and the overhead introduced by using ECCs. Furthermore, there is always a crossover point at lower Signal to Noise Ratio (SNR), after which, it is more efficient to use ECCs. This crossover point is dependent upon the employed modulation and the ECC used.

Unfortunately, these results cannot be directly applied in ultra-low power systems with highly varying channel because the optimal energy configuration changes rapidly over time. Using energy-efficient adaptive modulation [57] seems to be an excellent solution in such a scenario. With that, the system continuously monitors the channel, and whenever there is a change in the channel quality, the most energy-efficient modulation is adapted accordingly. On the one hand, the system can provide huge improvements in terms of energy consumption on the physical layer. However, to monitor and exchange the current channel conditions, there is a requirement of a feedback loop from the transmitter to the receiver, which on the other hand increases required energy overhead. Furthermore, it cannot be implemented in energy-constrained networks due to the difficulty of supporting multiple modulations schemes together on a single miniature chip.

For position information, GPS is considered as one of the most successful methods and has been widely used in wildlife monitoring [58]. Currently, the ICARUS project [16] is developing very small tags with GPS to monitor large-scale movements of small animals or birds from space. These tags will be only active when triggered by the International Space Station for an energy-efficient operation. Even though GPS is popular in many applications, the main drawback of using GPS is that its accuracy is not high enough to measure small distances of several meters and it is also power hungry.

As the main design goal of GPS was to provide position information without focusing on energy-efficiency, several other tracking and localization techniques based on a dedicated infrastructure have been investigated. The most popular techniques in the literature are based upon Time Of Arrival (TOA) as well as Time Difference Of Arrival (TDOA), Angle Of Arrival (AOA), and Received Signal Strength (RSS) [59]. The TOA and TDOA estimation methods cannot be directly applied in scenarios like the BATS project because of the requirement of highly precise clocks for synchronization and multi-path channels [60]. Similarly, due to the presence of shadowing and fading, the RSS based localization estimates are unstable and introduce large errors. To overcome this problem, the phase difference of Radio Frequency IDentification (RFID) tags has been considered and exploited for accurate localization [61]. For further accuracy improvement, the combination of phase difference with RSS-based techniques is also proposed.

To optimize energy consumption in the BATS scenario, the concept of combined data communication and localization based on BOC has been proposed [62]. Since BOC was first used in GNSSs, its ranging performance in GNSS has been studied thoroughly in [43]. It is highlighted that the range estimation error of BOC modulated signal is improved in comparison to BPSK due to higher robustness against code-tracking errors and multi-path effects. Moreover, to further investigate the multi-path benefits of BOC over BPSK in practical environments, live data has been gathered from satellites using SDR receivers [63]. It is noted that BOC performs better than BPSK in challenging multi-path environments.

In this chapter, we go one step further and exploit BOC modulation for its applicability in ultra-low power sensor nodes and investigate its experimental performance in wildlife monitoring.

3.3 Binary Offset Carrier Modulation

As stated earlier, BOC modulation was primarily used in GNSSs to provide spectral isolation of the signals that use same carrier frequency, but was soon found less susceptible to multi-paths as well [55]. In BOC modulation, the data with a chip frequency or code rate f_c is multiplied by a rectangular sub-carrier with frequency f_s before the actual RF transmission, splitting the signal spectrum into two parts. Therefore, the Power Spectral Density (PSD) of BOC modulation has its minima at the center frequency and its maxima offset to the channel center. This unique PSD differentiates BOC from the conventional BPSK which has its maxima in the channel center. The PSD of BOC and BPSK for the same code rate is shown in Figure 3.1.

BOC modulation is usually represented by the two parameters f_s and f_c that are generated in relation to a reference frequency f_r. First, the reference frequency is normalized to the system master clock so that the zero crossings of data, sub-carrier frequency, and RF are aligned. Second, the actual sub-carrier frequency f_s and the code rate f_c are generated by $f_s = a \cdot f_r$ and $f_c = b \cdot f_r$, respectively. Here, f_s supports the time duration equal to $2T_s$ and f_c has a period of nT_s, where $n = 2f_s/f_c$ and is restricted to be an integer. The PSD shape of a BOC modulated signal depends whether the n is odd or even. To derive the normalized baseband PSD of BOC, the autocorrelation of time domain signal and its Fourier transform are used as [55]:

$$S_{BOC(f_s,f_c)}(f) = f_c \left(\frac{\sin\left(\frac{\pi f}{2f_s}\right) \cos\left(\frac{\pi f}{f_c}\right)}{\pi f \ \cos\left(\frac{\pi f}{2f_s}\right)} \right)^2, \qquad \text{for} \quad n = \frac{2f_s}{f_c} \ \text{odd}, \qquad (3.1)$$

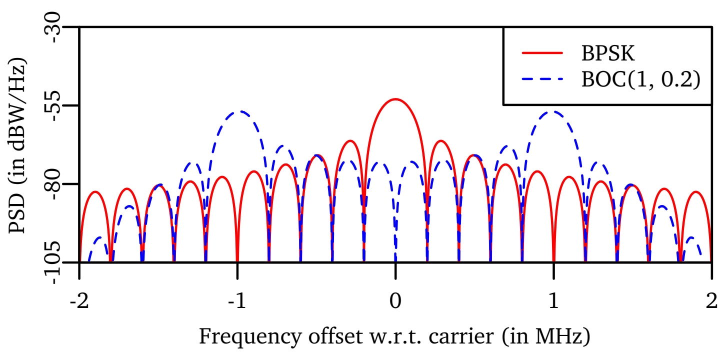


Figure 3.1 – Power spectral density of BOC and BPSK signals. (Reproduced from [31], © 2016 IEEE.)

$$S_{BOC(f_s,f_c)}(f) = f_c \left(\frac{\sin\left(\frac{\pi f}{2f_s}\right)\sin\left(\frac{\pi f}{f_c}\right)}{\pi f \, \cos\left(\frac{\pi f}{2f_s}\right)} \right)^2, \qquad \text{for} \quad n = \frac{2f_s}{f_c} \text{ even.} \tag{3.2}$$

In between the two main lobes of BOC PSD (here referred to as sidebands), there are always $n-2$ side lobes. If $n = 2$ (i.e., $f_s = f_c$), the BOC modulation becomes analogous to the Manchester coding scheme. Similarly, $n = 1$ yields BOC modulation equivalent to the conventional BPSK.

Since BOC signal is similar to a BPSK one with an exception that the signal is centered around the sidebands rather than the strict center, the complexity of BOC receiver is same as a BPSK receiver. However, BOC provides benefit regarding implementation as well as performance, e.g., the two sidebands can be coherently combined to improve ranging. Similarly, for low complexity receivers, only one of the two sidebands can be filtered to process it like a simple BPSK signal. Processing only a single sideband reduces the performance approximately 3 dB due to the fact that each sideband consists half of the signal power. Nevertheless, low complexity receivers still benefit from BOC due to the combined ranging and data signal. Furthermore, the other sideband can still be used to extract the data in case one of the sidebands is affected by noise or/and interference.

As discussed in the previous chapter, the wake-up cycle of a bat node is limited to a maximum of 10 Hz, therefore, we use short burst BOC(1,0.2) signals (i.e., $f_s = 1$ MHz and $f_c = 200$ kbit/s) having $n = 10$. These short burst signals also support the use of Time Division Multiple Access (TDMA) for collision avoidance of multiple bat nodes in the same area. GNSSs in contrast to our system use BOC with a data rate of 1 Bit per 20 ms which is a way too low data rate for short signal bursts.

3.4 Experimental Setup

In this section, first, we discuss our BOC implementation model in SDR. Second, we provide a detailed overview of our simulations and lab measurements setup. Furthermore, we also present a description of types of environments used for field measurements. Finally, the types of measurements performed at each of these locations are described.

3.4.1 Implementation

We have implemented a BOC(1,0.2) transceiver in GNU Radio with a chip rate of 2 Mchip/s and a data rate of 200 kbit/s. The transceiver periodically transmits a short burst of 12 Byte every 100 ms that contains 1 Byte each for preamble and start of frame delimiter, 8 Byte of payload, and last 2 Byte for Cyclic Redundancy Check (CRC). With that, one burst translates into 480 µs and fits within the downlink data communication time slot of BATS protocol.

To receive the transmitted BOC signal, the receiver is tuned to one of the sub-carrier frequencies and processing identical to a BPSK receiver is performed on the selected sideband. The system uses the start of frame delimiter to synchronize and also combines both sidebands in-phase to compare full-BOC performance with BPSK in simulations. The simulations are performed over an Additive White Gaussian Noise (AWGN) channel while over-the-air measurements are performed at 868 MHz carrier band by using Ettus B210 and N210 Universal Software Radio Peripherals (USRPs) connected to laptop computers.

3.4.2 Environment Description

To perform the field measurements, we chose three different types of sites that are similar to the target environments. These measurement sites are categorized into three types:

(a) Line-of-Sight (LOS) area: To ensure good testing environment, the target place is situated away from the residential area. The surrounded fields are a few hundred of meters far apart and the nearest building is about 800 m away. The ground mainly consists of soil and grass. To offer good LOS communication, no obstruction lies between the transmitter and the receiver.

(b) Single obstruction area: This area has very few but large trees spaced with a distance of around more than 25 m and, thus, distributed over a large region. The spot has a height of 10 m and a diameter of approximately 6 m including the spread bushes and leaves on a grass ground.

(c) Foliage area: This area is similar to a dense forest and is a mixture of different sizes of trees dominated by large ones. The large trees are around 15 m tall and are spaced with a distance of approximately 3 m. A significant amount of low-level bushes and branches exist throughout the ground of this area.

3.4.3 Measurement Setup

In our application scenario, the communication will take place in a forest, therefore, we expect considerable multi-path and shadowing effects. Moreover, mobility of bats can cause a highly unreliable and time-varying channel. Considering all these factors that affect the channel quality, we are interested in analyzing the reliability and the data communication performance of short BOC signals in the BATS.

For field measurements, we select a carrier frequency of 868 MHz and use omnidirectional antennas each with a gain of 3 dB mounted at a height of 0.5 m from the ground. Since the bat nodes are planned to have a transmit power in the range of 10 dBm, we adjust the transmit power of our USRPs accordingly by changing the transmitter gain and, thus, amplitude of the transmitted signal. However, it is also important to note that we focus more on relative power values, therefore, perfect calibration of USRPs is not required which will be really difficult otherwise. Moreover, to record the positions during the field measurements, we use a smart phone GPS with an average accuracy of less than 10 m which is enough for our experiments over hundreds of meters. The accuracy of GPS coordinates is verified by a map and the results are processed offline.

To study the range and reception rate of a BOC signal in different environments, first, we conducted two types of field measurements in both LOS and foliage environment:

(a) Static: In order to perform static measurements, we keep the system static during each individual measurement and then repeat it for different distances.

(b) Mobile: For mobile measurements, we move the transmitter at a human walking speed (i.e., 4 km/h–5 km/h) on a circle around the static receiver to keep the communication distance constant during a measurement.

Second, we performed measurements in the foliage environment by moving the transmitter at a communication distance of 100 m–130 m and at various speeds using an e-bike to match the typical behavior of a hunting bat [64]. Finally, to investigate the impact of shadowing caused by trees on the received signal power, we conducted measurements in the single obstruction area.

3.5 Results and Discussion

To analyze the performance, we consider Packet Delivery Rate (PDR) (i.e., packets successfully received from total transmissions) as a main metric and study it for different distances, and consequently SNRs. First, we validate our implementation model by performing simulations and comparing the results with the lab measurements and, then, we study the system in the wild.

3.5.1 Simulations

We first simulate the performance of BOC over an AWGN channel and then compare it with the conventional BPSK. Figure 3.2 shows the simulated PDR over different SNRs with 95 % confidence intervals that are obtained by repeating the simulations

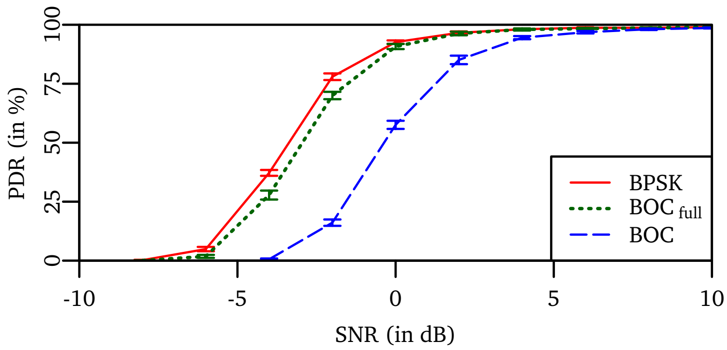


Figure 3.2 – Simulated packet delivery rate of BOC compared to BPSK over an AWGN channel. (Reproduced from [31], © 2016 IEEE.)

30 times. It can be seen that processing only a single sideband of BOC at the receiver leads to a performance loss of approximately 3 dB in comparison to BPSK. To present the best case, we also combine both sidebands of BOC in simulations (labeled as BOC_{full} in Figure 3.2). BOC_{full} performs much better than processing only a single sideband, however, the loss is still compensated only partially and the system still suffers from 0.5 dB of performance loss. The main reason of such a performance behavior is that each sideband is affected by noise separately and, hence, combining the two sidebands increases overall noise in comparison to BPSK. These results are perfectly in line with the results described in original BOC model in [55] and, thus, validate our implementation.

3.5.2 Lab Measurements

As a step further, we perform over-the-air measurements in a lab environment for a more realistic comparison of BPSK and BOC (using only one sideband for demodulation). For a fair comparison with simulations, we conducted the lab measurements with exact same parameters as in the simulations.

Figure 3.3 plots the obtained PDR for different received SNRs. Confidence levels are not shown for clarity and are similarly small as in Figure 3.2. Since we cannot estimate exact absolute powers, we shift all curves with a constant offset to match the simulation results. The shapes of the resulting curves perfectly match the simulation results and, thus, confirm error-free over-the-air transmissions.

3.5.3 Field Measurements

Since there is a possibility that a signal is affected differently in different environments, we first focus on understanding the impact of environment on the signal reception. For that, we conducted static measurements (i.e., the positions of trans-

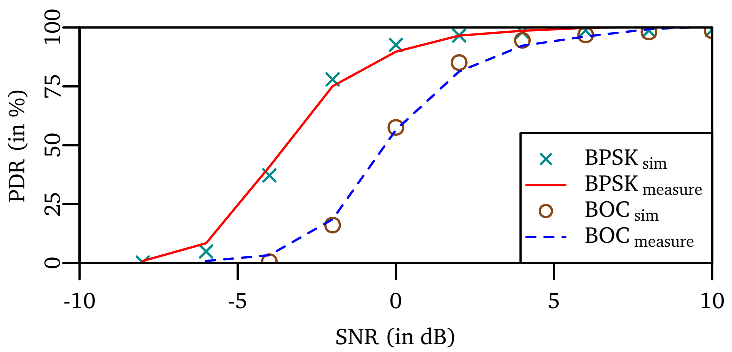


Figure 3.3 – Experimental study of the packet delivery rate over-the-air in a lab environment; for validation, overlaid with the simulation results. (Reproduced from [31], © 2016 IEEE.)

mitter and receiver are fixed during an experiment) both in LOS as well as foliage environment and report our performance in terms of PDR over different communication ranges. Further, to study the behavior of the signal in presence of multi-path fading and other channel effects, we also performed experiments with a mobile transmitter in both environments.

Figure 3.4 plots the resultant PDR over different distances in LOS and foliage area. The error bars show 95 % confidence intervals obtained by repeating the measurements 30 times. It is interesting to note that a continuous motion of a transmitter at a walking speed does not affect the resultant PDR as it matches the PDR results of static measurements. The system provides a PDR of more than 90 % for distances less than 350 m and 150 m in LOS and foliage area, respectively. Hence, the results clearly highlight the impact of environment on our system range. It can be also observed that the confidence intervals for static measurements are comparatively larger than that of the mobile measurements for the same number of repetitions. This

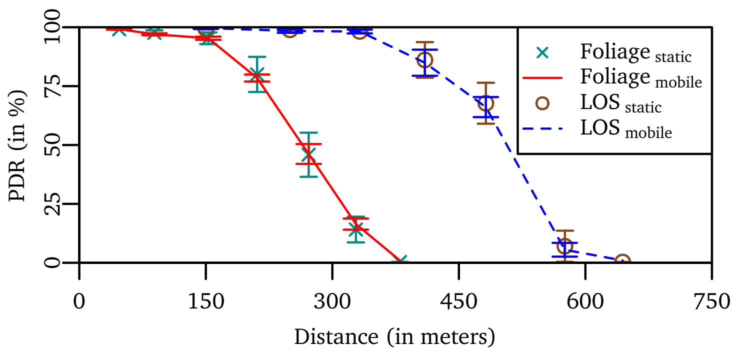


Figure 3.4 – Packet delivery rate in the different field measurement sites. Here, we plot the PDR over communication distance. (Reproduced from [31], © 2016 IEEE.)

happened because the mobile measurements are always repeated over the same path around a receiver, whereas the static measurements are repeated at specific physical positions of the transmitter while keeping its distance to the receiver constant.

To further analyze the confidence intervals, we study the received signal power in the foliage environment. The variation in the relative received power during a single measurement at various distances is shown in Figure 3.5. Since the transmitter is continuously moving around the receiver, each time sample corresponds to a physically different transmitter position. It should be also noted that the measurement at each distance is conducted only on the arc of circle around receiver where enough space was available to move. The drop in the received signal power is high if a tree was present exactly in front of the transmitter blocking the LOS signal at that particular position. Due to uneven distribution of obstructions such as trees, the variation in the received signal power is as much as up to 15 dB during a measurement. The variation in the phenomenon becomes less pronounced at higher distances especially 270 m because the shadowing becomes a dominant factor and the received signal power approaches the noise floor.

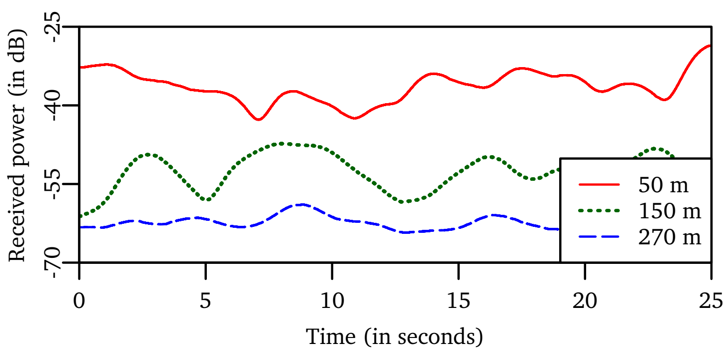


Figure 3.5 – Relative received power for various distances between transmitter and receiver in a foliage environment. (Reproduced from [31], © 2016 IEEE.)

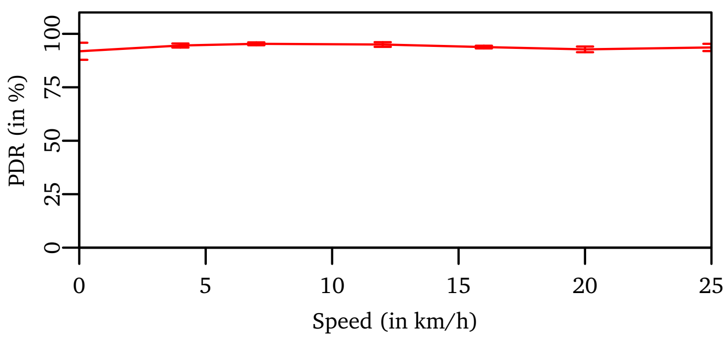


Figure 3.6 – Packet delivery rate for different average speeds of the transmitter in a foliage environment. (Reproduced from [31], © 2016 IEEE.)

It is really difficult to conduct measurements in the foliage environment with a speed that is comparable to a hunting speed of bats due to the low level branches and trees that are present throughout the area. Therefore, we carefully selected a part of foliage area where achieving a higher speed was possible to study the fast movement effects on a signal reception. We placed the receiver 100 m–130 m away from the selected area and conducted measurements with a transmitter moving speed of maximum up to 25 km/h using an e-bike. The resultant PDR at different average speeds of the transmitter is depicted in Figure 3.6. Surprisingly, even reaching up to a speed of 25 km/h does not affect the PDR despite the fact that at higher speeds the communication process is affected because of rapid change in the channel conditions.

Finally, to understand the shadowing effect more thoroughly, we conducted measurements in the single obstruction area. The transmitter and receiver are placed in a way that their distances from the tree remain same, hence, the tree lies exactly in middle of the communication distance. For the chosen distance, a tree that is covering the whole first Fresnel zone between transmitter and receiver does not affect the PDR. Therefore, we measured the relative received signal power with and without tree for a fixed distance in the same area.

Figure 3.7 shows the distribution of the relative received power for a communication distance of 20 m. A tree that is covering the whole first Fresnel zone affects not only the received power but also its distribution. Moreover, it is also worth noting that repeating the measurement at the same distance but different physical position gives rise to a slightly different distribution due to the presence of varying multi-path effects.

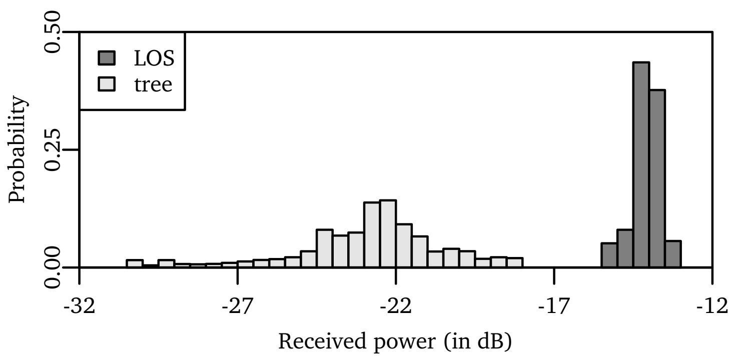


Figure 3.7 – Probability distribution of relative received power. (Reproduced from [31], © 2016 IEEE.)

3.6 Conclusion

BOC modulation has been popular since more than a decade and different BOC variants have been proposed to improve its performance, however, the target application remains GNSS. To the best of our knowledge, this is the first work that investigates the practical performance of BOC modulated signals within the scope of WSNs and, hence, gives rise to a new research direction. It is shown that BOC can be useful to transmit multiple signals simultaneously for saving energy in ultra-low power systems. The new application domain involves short burst signals with relatively higher data rate which is different from its traditional use in GNSSs.

In this chapter, we particularly focused on the combined transmission of localization and data signals for an energy-efficient communication in ultra-low power WSNs. We exploited BOC modulated signals and compared it with typically used BPSK signals. In order to investigate the performance in terms of PDR, we implemented the BOC transceiver in an SDR, and performed lab and field measurements in different environments. With a fixed transmit power, the system achieves a PDR of more than 90 % for distances less than 350 m and 150 m in LOS and foliage area, respectively. It is also noted that a transmitter moving up to a speed of 25 km/h does not affect the resultant PDR. Furthermore, it is shown that the shadowing from trees has no impact on PDR at smaller distances, however, it affects the received signal power and its distribution.

Chapter 4

Diversity Combining

RECEIVE diversity techniques[4] have been studied in the literature in-depth and such algorithms are massively deployed in, for example, cellular networks, in which all receivers are connected through optical fiber or in systems where antennas belong to a single receiver.

In this chapter, we propose to exploit the distributed nature of the ground network and employ receive diversity, i.e., we use the ground nodes as a geographically distributed antenna array. However, employing receive diversity in distributed sensor networks such as our ground network poses a number of research challenges. One of the main challenges to be addressed is the forwarding of all signal copies from all nodes in the network through limited data rate links and combining them constructively at a single point. Therefore, to optimize link utilization in the network, we study the performance of low-complexity soft-bit diversity combining for robust packet-based communication. As a novel concept, we also propose a system that only forwards selected complex signal samples belonging to a packet with high probability. Finally, we provide a unified framework for studying different diversity techniques in simulations, lab experiments, and field testing. Our results clearly indicate a substantial performance gain while keeping the data rate in the ground network in a feasible range.

This chapter is based on the following publications:

- M. Nabeel, B. Bloessl, and F. Dressler, "Low-Complexity Soft-Bit Diversity Combining for Ultra-Low Power Wildlife Monitoring," in *IEEE Wireless Communications and Networking Conference (WCNC 2017)*, San Francisco, CA: IEEE, Mar. 2017, © 2017 IEEE.

  In this conference publication, my contribution was to propose and exploit the distributed nature of ground nodes and use them as a distributed antenna array to employ receive diversity. To optimize link utilization in the ground network, I also investigated the performance of low-complexity soft-bit diversity techniques in simulations and through Software Defined Radio (SDR)-based experiments.

- M. Nabeel, B. Bloessl, and F. Dressler, "Selective Signal Sample Forwarding for Receive Diversity in Energy-Constrained Sensor Networks," in *IEEE International Conference on Communications (ICC 2017)*, Paris, France: IEEE, May 2017, © 2017 IEEE.

  In this conference publication, my contribution was to propose a novel system that only forwards selected complex signal samples of the received packets to the network sink where diversity combining is applied. The proposed system achieved maximum diversity gain in comparison to soft-bit combining while keeping the data rate in the ground network at an acceptable rate.

[4] In the follow up text, diversity will always refer to receive diversity unless explicitly specified

- M. Nabeel, B. Bloessl, and F. Dressler, "Efficient Receive Diversity in Distributed Sensor Networks using Selective Sample Forwarding," *IEEE Transactions on Green Communications and Networking*, vol. 2, no. 2, pp. 336–345, Jun. 2018, © 2018 IEEE.

  In this journal article, my contribution was to perform an extensive set of simulations and lab measurements, and explore the application performance of selective sample forwarding approach. Additionally, I also proposed a model that helps in efficient deployment of distributed diversity systems by selecting optimal receiver positions or by minimizing the transmit power while maintaining reliable communication.

4.1 Motivation

In chapter 2, we learned that the transmissions from a bat node to the ground network are heavily affected due to adverse channel conditions. Thus, the Packet Delivery Rate (PDR) of unreliably sent packets is expected to be rather low. Repeated transmissions as well as using Automatic Repeat-Request (ARQ) mechanisms is prohibitive due to the short contact times and the very tight energy budget of the bat nodes. In a previous work [27], the use of Forward Error Correction (FEC) using fountain codes has been investigated to improve the communication reliability, which is still not at a sufficiently high level. Therefore, novel solutions are needed to overcome these limitations.

In this chapter, we exploit the fact that the ground network is rather dense as it was designed to allow tracking of bats through triangulation. Such a scenario provides a natural system to apply diversity techniques for improved performance by using multiple ground nodes as distributed single antenna receivers. We thus envision to use the ground network as a distributed antenna array on physically separated receivers. This idea is similar to a macro-diversity in cellular networks [65], where architectural requirements and communication protocols are different compared to the BATS project.

Since more than half a century, diversity combining is considered as one of the most promising techniques to increase the robustness of wireless communication systems [44]. It is often realized by employing multiple antennas at the transmitter (referred to as a transmit diversity) or receiver (referred to as a receive diversity). With a same radiated power, transmit diversity often performs poorer than the receive diversity [66]. Therefore, it is not efficient to employ transmit diversity on our transmitter (i.e., bat node) as it is energy-constrained. Moreover, as the bat node is also size-constrained, it does not allow to mount multiple antennas on the transmitting side. Hence, using distributed receivers of the ground network as a distributed antenna array to realize receive diversity is an optimal solution in such a case. In receive diversity, uncorrelated copies of the transmitted signal are received at several antennas, which are then aligned, co-phased, and added constructively. This helps in improving the received signal strength without the need of increase in transmit power. In most cases, the Signal to Noise Ratio (SNR) of the resultant signal is higher than the SNR of any individual copy received [67].

The concept of receive diversity was initially proposed for systems that use multiple antennas at a single receiver but, later, extended to systems with distributed receivers, e.g., cellular networks [65]. By using distributed receivers as a distributed antenna array to employ receive diversity not only overcomes fading but also makes the system more robust against interference and shadowing [68], [69]. However, this increased robustness comes at the expense of additional hardware and extra processing required at each receiver. Furthermore, this also gives rise to several research challenges. Once of the main challenges include the passing of information in the network through links that offer only limited data rate [70].

To optimize link utilization in the network, one option is to do most of the signal processing locally at nodes and forward only hard-bit information [71]. Realizing diversity on bits greatly reduces the system complexity [45]. Signals received on different receivers (or branches) are processed separately and combining is performed when they are already converted into bits [47]. Such a diversity system does not require any phase alignment and is usually implemented for Differential Phase-Shift Keying (DPSK) with differential detection. However, this solution is not optimum because of losing soft information, therefore, another option is to realize diversity on soft-bits. Forwarding soft-bit information rather than hard-bit slightly increases the network load but provides higher diversity gain. Nevertheless, the performance of diversity combining at bits is still worse than the conventional diversity combining [45], [47]. Transmitting all complex samples rather than bit samples to realize conventional diversity combining is prohibitive in the wireless ground network due to link limitations.

In this chapter, we propose a framework that exploits signal level receive diversity in a distributed network by forwarding only selected complex signal samples to the central server. The core idea is to identify the possible start of a packet and then forward signal samples corresponding to a maximum sized packet. We address all issues arising from practical diversity combining at distributed nodes including receivers' positions and phase correction of received signal copies before combining. Taking a different perspective, we also discuss the efficient node placement and adapt parameters like transmit power to maximize diversity gain. In order to demonstrate the effectiveness and efficiency of our approach, we implemented the proposed system in GNU Radio SDR platform. This allows to assess the general system behavior in simulation using different channel models (noise, path loss, fading, shadowing) as well as in lab experiments using Ettus Universal Software Radio Peripherals (USRPs). We compare multiple diversity combining techniques when performed at signal level (i.e., received complex signal samples) and soft-bits (i.e., single sample corresponds to a bit) in an unified framework to evaluate the performance. We also consider the performance of single receivers that decode the signal separately as a baseline. Our results clearly show the advantages of signal level diversity combining in a distributed environment with only a marginal trade-off in system complexity. Furthermore, when applying any type of diversity, it is frequently assumed that all branches provide equal noise power [44]. However, the use of automatic-gain-control (AGC) breaks this assumption and can degrade the performance [72], [73]. Therefore, we also analyze the system performance for unequal gain receivers. Our study also shows how receive diversity allows to reduce the transmit power of the bat nodes while maintaining the same level of reliability, thus, increasing the lifetime of the bat node [74]. Finally, we carry out an extensive set of experiments in the wild to study the practical application performance.

Our core contributions of this chapter can be summarized as follows:

- We propose to use a distributed sensor network as a distributed antenna system for applying receive diversity algorithms.
- We also propose a novel technique for selecting relevant signal samples to be forwarded to a central receiver applying diversity algorithms at signal level.
- We develop the complete system in an SDR-based platform and perform an extensive set of simulations, lab measurements, and outdoor experiments to evaluate the performance.
- Our results clearly show that the proposed selective signal sample forwarding approach achieves full diversity gain while keeping the data rate in the ground network at an acceptable rate.

4.2 Preliminaries

Space diversity exploits multiple antennas sufficiently far apart to mitigate fading in wireless communications without any modification on the physical layer. Commonly used diversity techniques involve Maximum Ratio Combining (MRC), Equal Gain Combining (EGC), and Selection Diversity (SD) [44]. SD is considered to be the simplest one of all these techniques: the branch with highest SNR is selected. In EGC or MRC, signals from all of the branches are phase-aligned and summed up by weighting the gain of each branch as unity or according to their individual SNR, respectively. Using MRC, inaccurate SNR estimation results in poor weight selection which degrades diversity performance. A detailed comparison of these techniques when using multiple antennas at a receiver is presented in [67]. By combining SD and EGC, a hybrid diversity technique is also proposed, in which performance close to MRC is achieved with only incremental complexity [75], [76]. Since this conventional diversity aligns the phases of all branches before converting the signal into bits, the complexity of system is much higher. Hence, such a system leads to a higher computational demand.

Some practical applications offer insufficient spacing between antennas due to their limited size devices and, hence, give rise to correlated fading among different diversity branches. Therefore, the asymptotic error performance in correlated fading scenarios is analyzed in [77]. The results are further extended for a complex fading model such as Nakagami [78]. Later, the impact of interference on the outage probability of diversity combining is analyzed in [79].

If the antennas used for diversity combining belong to spatially separate receivers that are placed to cover a large region, the system, in addition, becomes more robust against shadowing and interference [68]. As a drawback, this also requires more complex signal processing at the receivers, as, for example, the frequency offset has to be corrected in each diversity branch before coherent combination of the signals is possible. However, because of the distant antennas, the channel between branches becomes highly uncorrelated and favors a high diversity gain.

The idea to exploit diversity with distributed receivers, e.g., in cellular networks, is well studied in the literature [65], [71]. Simple techniques such as SD or diversity at soft-bit level is usually recommended in such systems because of the link limitations between receivers. Performing diversity with soft values rather than hard decision bits improves system performance [45]. It has also been shown that in the presence of impulsive noise, diversity at bits outperforms [47]. However, the diversity gain is still not fully achieved because of the conversion of signal into soft values. The theoretical performance of traditional MRC in macro-diversity systems is analyzed in detail in [80] while practical performance in some limited test environment is studied in [81]. Therefore, there is a need of in-depth practical considerations.

Some wireless networks comprise nodes with a limited energy budget and processing capabilities. While it is difficult to realize diversity combining directly on these nodes, they can act as relays to a stronger node by applying simple schemes such as Amplify-and-Forward (AF) and Decode-and-Forward (DF), improving the performance through cooperative diversity [82]. This approach shows that the idea of cooperative diversity suits well within the scope of Wireless Sensor Networks (WSNs), albeit it also comes with new practical research challenges due to the limited energy available and even stricter data rate offered between nodes [70]. Earlier works in the sensor networking domain that target combining multiple copies of the same signal to improve reception quality involve Hybrid Automatic Repeat

Request (HARQ) systems [83]. They focus on fusion of retransmitted signal with the previous transmissions rather than combining the signal copies received at different distributed nodes. Apart from that, analytical performance of combining decisions in sensor networks in presence of Rayleigh fading channel has been explored in [84]. Moreover, diversity combining also helped in improving the performance of animal monitoring through WSNs [85]. However, the presented results are for only SD with no insights or comparisons of different diversity combining techniques. In recent years, diversity combining is used to enhance the physical layer performance of Body Area Networks (BANs) [86], [87].

Furthermore, while performing diversity combining, it is usually assumed that all branches exhibit same noise power. However, since the implementation of AGC is needed to cover dynamic range of the input signal at the receiver (especially in distributed systems), gains differ between branches. In conventional diversity systems, unequal gain branches highly degrade the overall performance [72], [73]. Since our network is distributed in nature, it is important to analyze the effect of unequal branch gains on overall diversity performance.

Apart from the diversity combining strategy, also the position of receivers is important to maximize performance and to optimize the coverage area [68]. Cooperative diversity helps reducing the number of nodes that are required to cover a specific region [88]. However, the factors affecting the coverage areas are not discussed in the literature.

In this chapter, we cover the missing literature gap and compare conventional diversity techniques with the combining at soft-bits in an unified framework with practical experiments. Even though the literature shows that it is possible to apply diversity in WSNs, the communication protocol and architecture are different from the BATS project (e.g., the energy budget is only limited at the transmitting node, which is, at the same time, highly mobile and experiences challenging channel conditions). Since the literature is rich of mathematical and theoretical analyses of basic diversity combining techniques, this chapter focuses on the practical aspects within the application of ultra-low power WSNs. Moreover, we also present a detailed description of coverage areas along with practical considerations with regard to diversity combining in distributed systems.

4.3 Receive Diversity in Distributed Sensor Networks

In a packet-based communication, the packet structure usually involves a preamble, i.e., training data, payload, and a Cyclic Redundancy Check (CRC). A receiver continuously performs correlation of the incoming samples with the known preamble to detect the transmitted signal. In the case of detection, the signal is processed and fed into timing recovery module to optimize the sampling instants and obtain soft-bit values. These soft values are then converted into hard decisions by mapping them to the nearest decision points and, finally, the CRC is used to check correct decoding.

When diversity combining is employed at antennas belonging to a single receiver, detected complex signal samples from different antennas are co-phased and summed before converting the signal into soft-bits and final decoding. If these antennas belong to spatially separated receivers, the data needs to be aggregated for diversity operation. In the BATS project, all nodes in the ground network are wirelessly connected to each other and to a sink node in an ad hoc fashion. As stated earlier, we aim to use these single antenna ground nodes as a distributed antenna array to realize receive diversity. A simple solution in this case is to forward data from all network nodes to one processing unit for the combination of signal copies constructively and, finally, signal decoding at a single point. However, these links between the nodes offer only limited data rates. Therefore, in this section, we present several possibilities of applying diversity techniques in a distributed sensor network and discuss the system design according to the requirements in the BATS project.

4.3.1 Signal Detection and Forwarding

As mentioned previously, the simplest approach for data collection at a sink is to forward all raw data samples from all receiving nodes at all times. This also minimizes the processing load of local network nodes. However, it is not a realistic solution as ground network will be overloaded with data in no time. For instance, if the transmissions from a bat node are oversampled with a factor of 5, using 4 Byte floats for the real and imaginary parts of the received complex samples lead to a data rate of 64 MBit/s just from a single ground node. With several nodes in the network, data rate increases dramatically and makes it impossible to handle. Therefore, there is a need of solutions that reduce data rate in the ground network without any major loss of information.

Since the bat node uses short packets (that also include a preamble) for transmission [24], detection of signal at any ground node can be performed locally at each receiver by correlating received data with the preamble. In the case of detection, we propose to forward only selected signal samples (starting from the preamble to the known packet-length, i.e., about 480 µs of samples) rather than the whole raw sample stream to avoid overloading the network as shown in Figure 4.1. Considering a maximum reception rate of 100 Hz, this lowers the required data rate by a factor of 20 in the ground network in comparison to forwarding all raw samples. If all detections are successfully performed, there will be no loss in performance as all useful complex signal samples still take part in the diversity process. The disadvantage

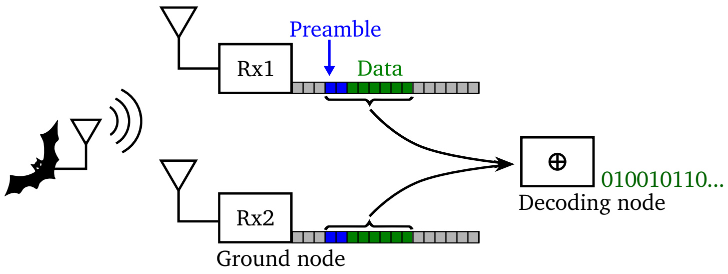


Figure 4.1 – Overview of the selective signal sample forwarding approach. The transmissions from the bat node are received by multiple SDR-based ground nodes that forward only selected signal samples to a central node for more robust decoding of the combined signal. (Reproduced from [34], © 2018 IEEE.)

of this approach is that a slightly higher processing is required at the local ground nodes to detect and cut the useful signal samples before forwarding.

Another option to further reduce data rate in the ground network is to forward only soft-bit information. Converting the complex signal samples into soft-bits minimizes the data-rate from one node to only 0.31 MBit/s. This reduction in the data rate comes at the expense of even higher processing required at the local nodes to convert the detected packets into soft-bits and forward them equivalent to the packet-length. In the same context, another approach is to decode the signal completely at ground nodes and forward hard-decision bits to the sink further limiting the data rate to 0.01 MBit/s. The required data rates for different possible approaches with various numbers of nodes in the ground network are depicted in Figure 4.2. These results are also summarized for a total of 64 network nodes in Table 4.1.

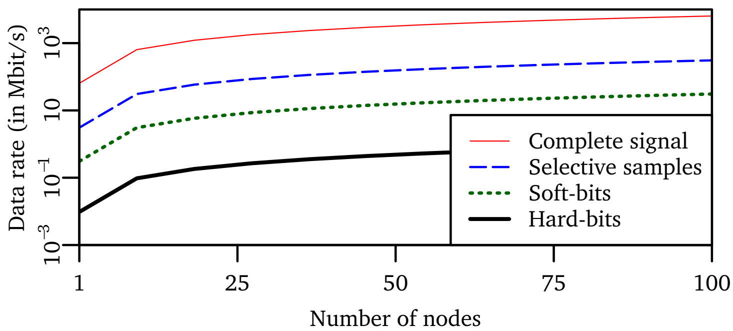


Figure 4.2 – Maximum data rate required with various approaches for forwarding signal samples in the ground network.

Forwarding Data as	Single Node (Mbit/s)	64 Nodes (Mbit/s)	Diversity Gain
Complete signal	64	4096	Highest
Signal samples	3.07	196.6	High
Soft-Bits	0.31	19.66	Medium
Hard-Bits	0.01	0.61	Very low

Table 4.1 – Possible diversity gain and maximum data rate with various approaches for forwarding signal samples in the ground network (signal corresponds to 5 samples/bit).

4.3.2 Diversity Combining

Since there are several options to reduce the data rate in the ground network, i.e., by forwarding signal samples, soft-bits, or hard-bits, we investigate the performance of diversity combining when applied on these different stages of the signal.

When diversity combining is applied on complex signal samples, in the best case (i.e., traditional MRC), resultant signal power ratio p is obtained as

$$p = \sum_{i=1}^{n} p_i \ , \tag{4.1}$$

where, p_i is the power in i^{th} receiving branch and n represents the total number of diversity branches. As the resulting signal exhibits relatively higher power, the timing recovery performs better than if performed on individual branches separately on lower power signals. In the case of soft-bits, each branch involves its own timing recovery leading to relatively poorer soft-bit estimate. Hence, combining soft-bits does not achieve the highest diversity gain. The loss in performance totally depends upon the receiver structure and timing recovery algorithm used.

To apply diversity combining on hard-bits, one simple approach is to take the final decision for each bit by a majority combiner as in Post-Detection Combining (PDC) [47]. Along with performing timing recovery in each branch individually, converting the information into hard-bits loses most of the signal properties and, hence, all branches contribute equally for diversity combining. Therefore, the performance gain achieved with hard-bits is even poorer than soft-bit diversity combining. Apart from the performance, applying diversity at bits also requires more processing at the nodes themselves affecting the lifetime of distributed sensor nodes. Table 4.1 summarizes these concepts and their performances along with the data rate requirements in the network.

Furthermore, in order to compare the performances of applying diversity combining on signal samples (i.e., MRC) and soft-bits (i.e., Soft Maximum Ratio Combining (SMRC)), we also implement SD and Successful Branch (SB). We do not consider

EGC (or Soft Equal Gain Combining (SEGC)), which is relatively simpler to implement compared to MRC (or SMRC) due to its reduced performance in practical environments. Similarly, for the same reason, we also do not consider diversity at hard-bits as well. In SD, a branch with the highest SNR is selected and signals from rest of the branches are discarded. In presence of Rayleigh fading, the resultant signal power ratio p for n diversity branches is given by [44]

$$p = \sum_{i=1}^{n} 1/i \; . \tag{4.2}$$

It is interesting to note that adding the i^{th} branch in a SD system contributes only $1/i$ in the resultant power ratio, hence, diminishing the diversity advantage.

Considering SB, all receivers decode the signal completely on their own and forward hard-bit data to sink only if the reception is successful. If ρ_i is the probability of success for the i^{th} diversity branch, then the success probability ρ of an SB system with n diversity branches is calculated as

$$\rho = 1 - \prod_{i=1}^{n} (1 - \rho_i) \; . \tag{4.3}$$

SB performs better than SD as it does not rely on any particular metric such as SNR. It is also preferable in distributed systems as there is no coordination needed between diversity branches for the selection of any particular branch. However, using SB is more power hungry as all nodes decode the complete data locally.

4.4 Model Implementation and Validation

In order to compare the performance of various diversity techniques in an extensive set of experiments, we realized both transmitter and receiver in GNU Radio. Furthermore, simulations over an Additive White Gaussian Noise (AWGN) channel and over-the-air measurements using Ettus USRPs were performed to validate our implementation and to determine the baseline performance.

4.4.1 GNU Radio Implementation

We implemented the transceiver in GNU Radio framework. The transmitter transmits a 12 Byte Differential Binary Phase-Shift Keying (DBPSK) modulated packet periodically every 100 ms. The packet structure contains a preamble and a start-of-frame delimiter of 1 Byte each, 8 Byte of data, and 2 Byte of CRC. The data is transmitted at a carrier frequency of 868 MHz with a rate of 200 kbit/s that translates into 480 µs packets.

On the receiver side, the incoming data is continuously correlated with the training sequence (i.e., preamble) for signal detection. In the case of detection, SNR and phase are estimated using the preamble and compensated for constructive combining. The detected packets are then forwarded to the clock recovery module to compensate frequency and timing offsets. This is done by the GNU Radio built-in *Mueller and Müller* clock recovery module [89]. This algorithm uses a feedback system to estimate the sampling instants of the received signal and adjusts them accordingly. Finally, the obtained signal is differentially decoded and successful reception is confirmed by checking the CRC.

To apply diversity combining on received selective samples (i.e., MRC here), the complex signal samples from all receivers are weighted and added before the clock recovery module. Soft-bit combining (i.e., SMRC here) is performed after most of the signal is processed and each sample corresponds to a single bit, just before taking the hard-bit decisions. In the following, we will analyze the performance of MRC, SMRC, SB, and SD in our application domain.

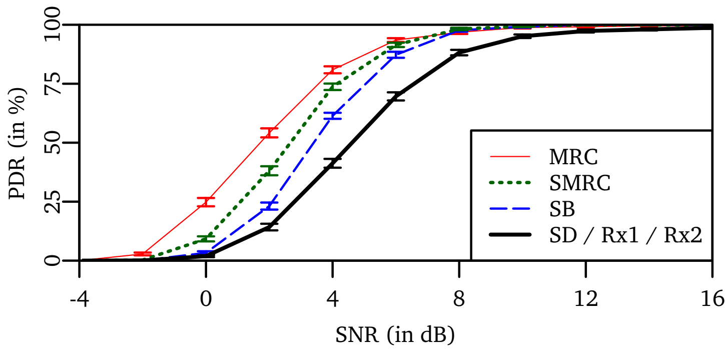
4.4.2 Simulations

For a baseline performance of various diversity techniques, first, we used our GNU Radio model and performed simulations over an AWGN channel for a two-branch diversity system. To offer the best case scenario, noise between both branches is kept uncorrelated, independent, and identically distributed.

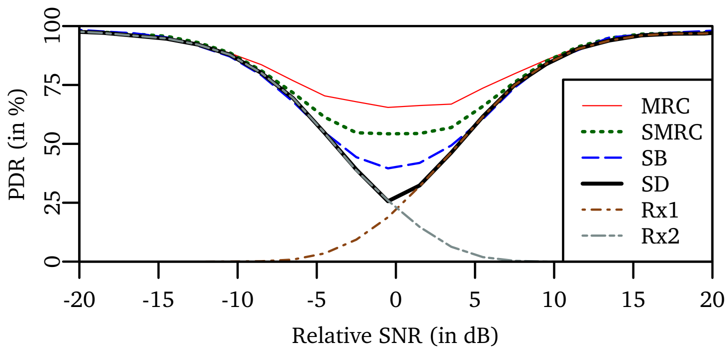
Figure 4.3a plots the PDR over different SNR values for a two-branch diversity system for an AWGN channel. The curves reflect the performance of all considered diversity combining techniques with 95 % confidence intervals. On average, both receiving branches (i.e., Rx1 and Rx2) individually face similar channel conditions, hence, their performance is overlapped. MRC represents the combining at signal level, while, SMRC at soft-bit level. SD shows the performance of a system in which the branch is chosen based on the instant SNR value for each packet and the signal copy from other branch is discarded. SB is computationally more complex than SD because both branches decode the signal completely regardless of the SNR values.

It can be seen that applying MRC leads to the best performance and provides a gain of about 3 dB in comparison to not using diversity at all. This matches the theoretical upper bound when two equal power signals are added constructively. It is also important to highlight that EGC would also perform exactly the same as MRC in this case. This is due to the equal SNR branches that leads to the weighted gain of both branches equal and, hence, results in similar performance for both MRC and EGC.

Similarly, SMRC shows a significant performance improvement in comparison to the no diversity case, however, it is about 0.8 dB on average worse than the



(a) Equal SNR diversity branches



(b) Unequal SNR diversity branches

Figure 4.3 – Simulated packet delivery rate for a two-branch diversity system over an AWGN channel.

combining at signal level. As already stated, this happened due to the loss of signal properties while down-converting the signal into bits. SB performs much better than SD as there is a high probability that even when the average SNR is same in both receivers, only one of them decodes the signal successfully. It is also interesting to note that SD is not performing better than any individual diversity branch with this particular configuration due to the long-term same average SNR across both receivers.

In the case of a mobile transmitter, it is unlikely that all diversity branches of a distributed receiver exhibit the same SNR. If the mobile transmitter is moving from one receiver to another, the SNR in one diversity branch decreases with time while other increases. We develop such a simulation setup with a two-branch diversity system and the results are shown in Figure 4.3b. We did not plot the confidence intervals, which are about the same size as in Figure 4.3a.

As expected, the performance of SD always overlaps with the best diversity branch. SB performs better than the performance of any individual diversity branch, however, it is interesting to see that SB provides much better PDR when both branches have the same SNR. This is because the probability is very high that packets that are successfully received at one diversity branch are not completely the same as the ones received at the other branch. Even in such an unbalanced case, SMRC performs well and the PDR stays above 55 % for all SNRs. MRC overall performs even better than SMRC.

For further insights into the unequal SNR diversity branches, we performed additional simulations. Figure 4.4 shows the performance of various diversity techniques to achieve a PDR of 50 % when there is a SNR imbalance of up to 3 dB in a two branch diversity system. In the figure, diversity gain refers to the improvement over branch that experiences better channel quality. As the branch with highest received SNR has same performance as SD, we show the diversity gain for MRC, SMRC, or SB only. It can be observed that SNR imbalance of 3 dB in a two-branch system affects the diversity performance up to more than 1 dB in all cases.

4.4.3 Lab Measurements

In order to perform over-the-air experiments in a lab environment, we used Ettus B210 USRPs. The lab is similar to an office environment and the experiments were performed without any human intervention to provide nearly static channel conditions. Hence, the multi-path effects that arise in an indoor environment remain constant throughout the experiments. We used the exactly same implementation of the transmitter and receiver as in the simulations for a fair performance comparison. The transmissions are initiated by the transmitter USRP and are received by two receivers, all connected to laptop computers. Receiver gain values are set in the software to have on average equal noise floors and they are placed carefully in a way that they experience roughly equal SNR. To observe PDR over different SNR values, the transmit gain is changed accordingly in the software. In case of detection,

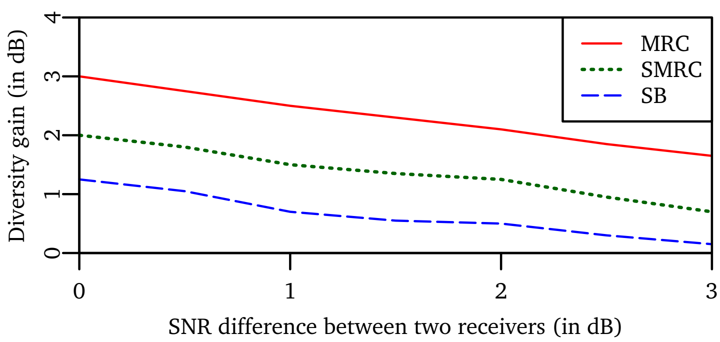
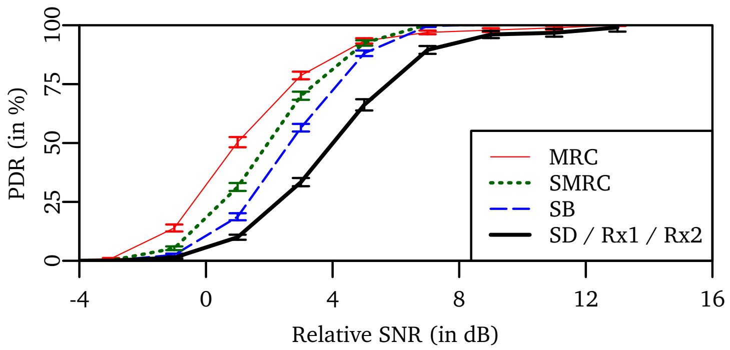


Figure 4.4 – Simulated performance for a two-branch diversity system with SNR imbalance over an AWGN channel.

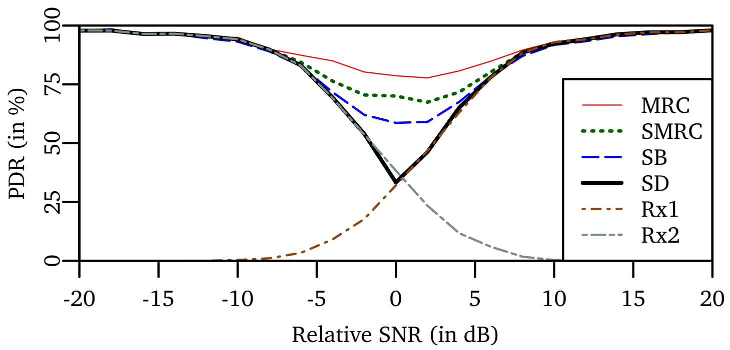
the received raw packets are stored and post-processed to compare all diversity techniques under exactly same channel conditions.

Figure 4.5a shows the resulting PDR for the various diversity techniques. Since the USRPs are not perfectly calibrated, we added a constant shift in all curves to compare them with simulation results over same SNR values. It can be seen that all considered diversity techniques provide the same performance what we have noted earlier. The PDR curves from the measurement data perfectly match the simulations over an AWGN channel.

In an indoor environment, the SNR is not only determined by noise and the distance between transmitter and receiver; also the multi-path environment can have a huge impact. Hence, it is difficult to capture measurement data for all relative SNRs between branches (like we did in simulations, cf. Figure 4.3b). Therefore, we recorded raw data at each receiving branch for multiple SNRs in the lab environment by varying the relative transmit power (i.e., by changing the transmit gain in the software). The recorded data is then post-processed and mapped to the simulations results for each diversity branch. Finally, various receive algorithms are applied



(a) Equal SNR diversity branches



(b) Unequal SNR diversity branches

Figure 4.5 – Experimental packet delivery rate for a two-branch diversity system in a lab environment.

and the results are plotted in Figure 4.5b. Again, confidence levels are not shown for the sake of clarity. We can see that also these measurement results match the simulations, as they yield perfectly the same curves for all the considered diversity techniques.

These results describe the baseline performance of the different techniques in a simplified scenario. MRC provides an improvement of about 3 dB in the best case for a two-branch diversity system, even when forwarding selective signal samples only. Hence, it is clear that using the proposed approach, we can achieve the same diversity gain as a conventional scheme, while we keep the data rate much lower in the network. This comes with a marginal increase in system complexity through signal processing for phase detection and frequency offset correction at local receivers. From these results, we conclude that our implementation model can be used for the application and real-world experiments to investigate various distributed diversity techniques.

4.5 Application Performance

4.5.1 Receiver Coverage Areas

When planning a real deployment in the woods, the density of the ground nodes is an important factor. Figure 4.6 depicts a simplified model of the coverage areas of a node. Area A is a region around the node where the probability of detection and reception is essentially 100 %. If another node is placed within that region, it provides no advantage, i.e., diversity gain, as all packets are already received by the first node. Area B represents a region where a node probability to receive a packet is between 0 %–100 %. If the overlap of these regions is maximized, the diversity gain is maximized. The outermost area C is defined as the area in which the probability

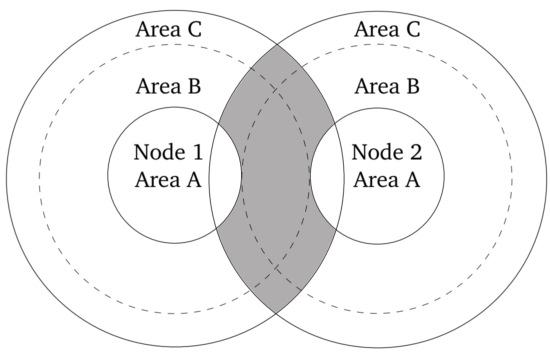


Figure 4.6 – Schematic coverage areas around ground nodes with region where diversity gain is observed. (Reproduced from [34], © 2018 IEEE.)

for a single node to successfully receive a packet is zero. However, some of the packets can still be detected and contribute to the decoding process through diversity combining. The size of area C mainly depends on the correlation threshold used for packet detection. Lowering the threshold increases the size and, hence, provides more advantage for diversity combining, but increases the chance of false-positives. If the aim is to maximize diversity gain, the ground nodes are placed in a way that overlapping of areas between nodes where the probability of successfully receiving a packet for single node is between 0 %–100 % is maximized. The shape and size of these areas depend upon transmit power and receiver noise, and are affected by channel effects such as fading and shadowing.

To determine the boundaries of the regions around a receiver, we performed additional simulations. The number of packets detected and received are calculated by using a single receiver and are plotted for different values of SNRs in Figure 4.7. The regions that are observed around a receiver are highlighted. Moreover, another receiver with the same characteristics is introduced to analyze the diversity gain with two branches.

It can be seen, in area C, almost all of the packets are successfully detected at a single receiver. Still, none of them are correctly received by that particular receiver. Through combining diversity branch of another similar receiver, a few of the detected packets can be received. In area B, diversity combining provides a great improvement in successful reception when a single receiver has already a non-zero probability to receive a packet. Area A is not interesting as already a single receiver can decode the packet.

Using this model, we can see why the position of the receivers is a key factor that has to be considered when implementing diversity combining techniques in a distributed network. One should either find optimal node position or, if the network is already deployed, adapt the transmit power to maximize diversity gain. During

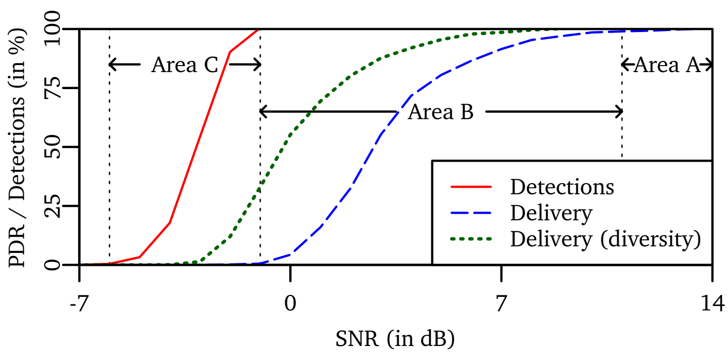


Figure 4.7 – Packet detection and reception rate for the different regions. (Reproduced from [34], © 2018 IEEE.)

this simulation, fading and other channel conditions are kept constant over time. In an outdoor environment, these regions are affected by continuous variations of the channel, which makes actual node placement more complicated. Still, we believe that our model with the different zones of a receiver proves useful for dimensioning the network or adapting reliable transmit power during the planning phase.

4.5.2 MATLAB Implementation

Using a mobility model that was specifically developed to model bats in their hunting grounds, we implement the BATS scenario in MATLAB to calculate realistic channel values. These values are then imported into our GNU Radio implementation, where we simulate the actual physical layer transmission to analyze application specific performance of different diversity combining techniques.

Using our two-dimensional bat mobility model, discussed in [27], we simulate a complete ground network. Two simulation scenarios are created: *Small* – A total area of 200 m × 200 m, including a 120 m × 120 m hunting ground that is composed of six nodes, forming a grid with inter-distance of 30 m. *Large* – An area of 300 m × 300 m with a hunting ground of 210 m × 210 m (cf. Figure 4.8) having 36 nodes. A bat

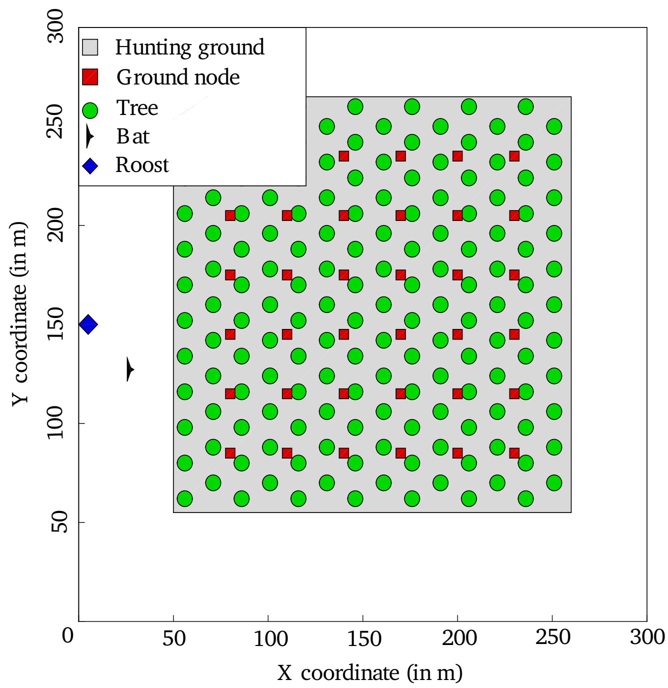


Figure 4.8 – Overview of the scenario simulated in MATLAB. (Reproduced from [34], © 2018 IEEE.)

starts its movement in the roost and flies towards the hunting ground to capture prey and return to the roost. Details of these mobility patterns are explained in [27]. To model shadowing, trees each having a radius of 2.5 m are introduced throughout the hunting ground. Two types of tree distributions are considered: *Less dense* – Trees spaced from 20 m–24 m. *Highly dense* – Trees spaced from 15 m–18 m (cf. Figure 4.8). These models certainly need to be carefully calibrated using real-world measurements. The used shadowing model has been developed based on our earlier experiments performed in a foliage environment (cf. Section 3.5.3). Experiments also revealed that, even with the maximum speed of a bat, all transmitted packets are attenuated equally throughout the whole packet transmission due to their short length. Therefore, it is possible to estimate the channel only during the beginning of the packet using the preamble. Similarly, speed of a bat does not influence overall PDR at any particular distance. Using these observations, when a bat node is in the hunting ground, i.e., in radio communication range of the ground network, the distance of the bat from all ground nodes is calculated and number of trees that lie in between the Line-of-Sight (LOS) are counted every 100 ms, i.e., every Time Division Multiple Access (TDMA) super-slot. At the end of each run, we calculate Free Space Path Loss (FSPL) based on the distance measures, introduce shadowing for every single tree with a uniform distribution between 0 dB–5 dB, and apply flat Rayleigh fading. These channel values are then imported into our GNU Radio implementation, where we attenuate the signal accordingly. It is interesting to note that the packet length used in BATS (i.e., 0.48 ms) is much smaller than the coherence time (i.e., 10.5 ms) [40] calculated for maximum speed of bats (i.e., 50 km/h) [90]. This also supports our earlier experimental observations, therefore, attenuation is calculated once per every packet during the transmissions.

4.5.3 Performance

To assess the application performance, we use our model of the different receiver regions to maximize the diversity gain. That means, we adjust the transmit power to maximize the overlap of area B in presence of noise and FSPL only. From Figure 4.3a, it is clear that for higher SNRs, i.e., for PDRs over 90 %, the performance gain of MRC or SMRC over SB is less in comparison to lower SNRs. Hence, if the required PDR is low, a huge improvement is experienced by using MRC or SMRC. To show the comparative advantage of diversity combining in different channel conditions, we performed an extensive set of experiments and, finally, decided to select a transmit power of −50 dBm. With that, the system achieves a PDR of more than 90 % when MRC or SMRC is employed in presence of simple channel models (i.e., noise and FSPL). The PDR for different diversity techniques in the case of a small-scale scenario, i.e., ground network of six nodes with confidence intervals obtained by repeating the whole experiments 30 times, is shown in Figure 4.9. The PDRs are calculated for all involved ground nodes separately as well as for the different diversity combining techniques. An expected PDR of 90 % is highlighted by a dotted line.

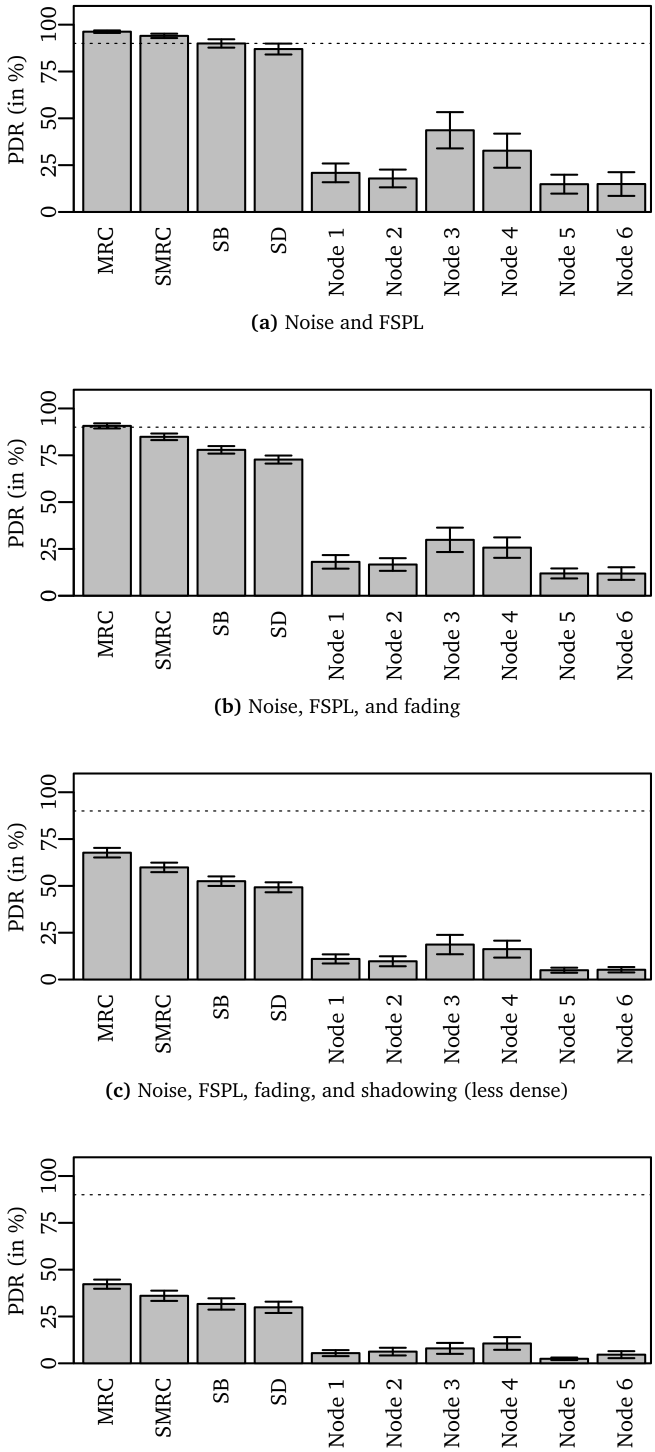
By considering channel impairments such as noise along with FSPL only, none of the ground nodes achieves an average PDR of more than 45 % alone. With SD and SB, PDRs of 87 % and 90 % are achieved, respectively. SMRC provides an huge improvement over SD and reaches to an overall PDR of 94 %. MRC improves the performance only incrementally in comparison to SMRC, however, it is still 2.3 % better than SMRC.

These experiments were repeated using exactly the same simulation parameters, but in addition using Rayleigh fading. As shown in Figure 4.9b, fading does not remain constant and, hence, affects the areas around ground nodes, thus decreasing the overall system gain. Still, diversity combining improves the performance with a huge margin in comparison to no diversity. Under these channel conditions, the PDRs of all ground nodes now remain less than 30 %. Using MRC, the system achieves a performance of about 90.7 %. This is about 5.8 %, 12.8 %, and 18 % better than SMRC, SB, and SD, respectively.

To also consider shadowing through trees, the experiments are repeated with both tree distributions, i.e., less dense and highly dense. The resulting PDRs are plotted in Figure 4.9c and Figure 4.9d. The overall PDR reduces drastically due to the addition of shadowing effect while keeping the transmit power constant. However, the advantage of diversity combining is still significant. Applying MRC improves the PDR about 7.8 % and 6.2 % over SMRC in less dense and highly dense shadowing environments, respectively. Similarly, in comparison to SB, MRC has an improvement of 15.2 % and 10.5 %, while over SD, the improvement is 18.5 % and 12.3 %.

To generalize overall performance, all of the simulations are repeated for the large-scale scenario that contains 36 ground nodes. To make a fair comparison, for every packet transmitted, only the six nodes that are closest to the bat take part in the diversity combining process. Since investigating individual node reception (for all 36 nodes) is not of interest in such a case, therefore, the resulting PDR with considered diversity combining techniques under different channel conditions are shown in Figure 4.10. The results reflect on average the same relative performance as for the small-scale scenario with a limited number of nodes. The larger confidence intervals in the shadowing environment can be well explained by the random movement of the bat in a larger area. These results prove that the advantage of diversity gain is retained even on the large-scale without any performance loss.

Hence, we conclude that if selective signal samples are forwarded, MRC is the perfect solution for maximum diversity gain. In some systems where forwarding complex signal samples is not that straight forward, SMRC might be the better



(a) Noise and FSPL

(b) Noise, FSPL, and fading

(c) Noise, FSPL, fading, and shadowing (less dense)

(d) Noise, FSPL, fading, and shadowing (highly dense)

Figure 4.9 – Packet delivery rate by considering different channel effects in a small-scale scenario (six ground nodes) with a transmit power of −50 dBm.

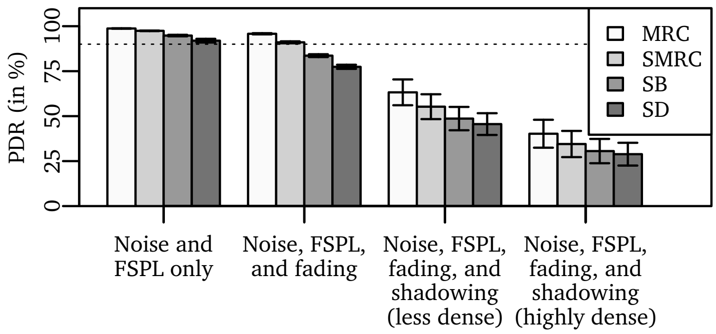


Figure 4.10 – Packet delivery rate by considering different channel effects in the large-scale scenario (36 ground nodes) with a transmit power of −50 dBm.

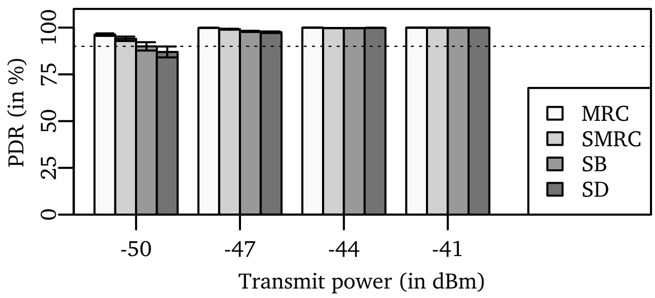
alternative. The marginal performance loss is a trade-off with the required data rate and receiver complexity. Moreover, it can be noted that by incorporating diversity in the BATS scenario, we can achieve a huge performance improvement without the need to redesign the complete architecture. An experimental study with outdoor measurements will, therefore, provide further insights into diversity combining in final application deployments.

4.5.4 Transmit Power

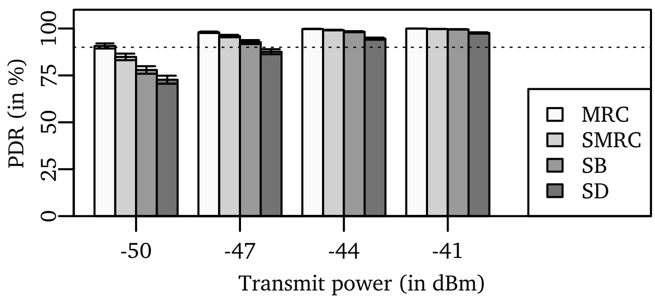
As mentioned earlier, a spacing of 30 m is required between ground nodes to allow accurate localization of the bat. Hence, the inter-node distance cannot be changed. Still, other parameters can be adopted for maximization of area B and, hence, maximum diversity gain. For this purpose, the transmit power of the bat node is studied and varied over multiple intervals while keeping the inter-node distance 30 m. As noted in the previous section, a transmit power of −50 dBm is required to achieve an expected PDR of more than 90 % in the presence of noise and FSPL. However, when additional channel effects are introduced, there is a huge decline in PDR.

To determine the minimum transmit power that is required for a reliable communication (a PDR over 90 %), we conduct simulations, considering various channel conditions. The results for the small-scale scenario are depicted as bar plots in Figure 4.11. Considering that a run corresponds to one hunting session of a bat, each individual bar shows the average PDR of all runs for a particular configuration. The 95 % confidence intervals are obtained by repeating the experiments 30 times.

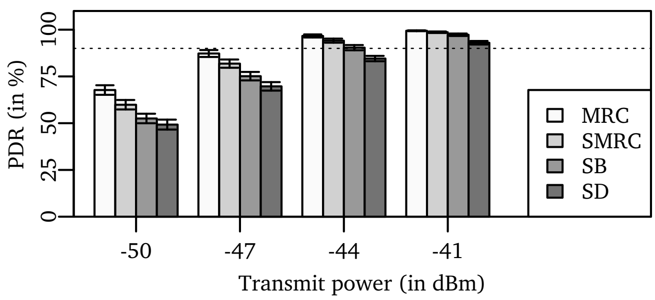
In Figure 4.11c and Figure 4.11d, we can see that the size of confidence intervals is increased. This can be well explained due to the addition of more channel effects. Furthermore, we notice that for all set of experiments, MRC performs marginally



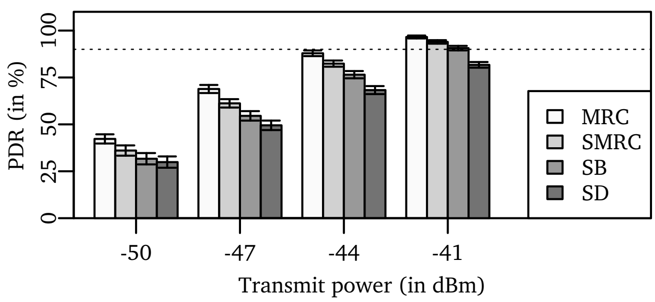
(a) Noise and FSPL



(b) Noise, FSPL, and fading



(c) Noise, FSPL, fading, and shadowing (less dense)



(d) Noise, FSPL, fading, and shadowing (highly dense)

Figure 4.11 – Packet delivery rate by considering a set of transmit powers within the small scenario (six ground nodes).

Table 4.2 – Average packet delivery rate by considering a set of transmit powers within the large-scale scenario (36 ground nodes).

Channel (noise plus)	**Transmit power** (dBm)	**PDR** (%) MRC	SMRC	SB	SD
FSPL	−50	98.7	97.4	94.8	92.0
	−47	100.0	99.7	98.9	98.6
	−44	100.0	100.0	100.0	100.0
	−41	100.0	100.0	100.0	100.0
FSPL and fading	−50	95.8	91.0	83.6	77.4
	−47	99.5	98.6	96.6	90.6
	−44	100.0	99.8	99.5	96.0
	−41	100.0	99.9	99.8	98.1
FSPL, fading, and shadowing (less dense)	−50	63.2	55.3	48.6	45.6
	−47	84.1	78.2	71.9	65.3
	−44	95.0	92.1	88.2	80.4
	−41	98.8	97.8	96.3	89.3
FSPL, fading, and shadowing (highly dense)	−50	40.2	34.5	30.6	28.9
	−47	64.5	57.5	51.4	46.2
	−44	83.9	78.6	72.9	63.9
	−41	94.5	91.6	88.2	76.9

better than SMRC and provides significant improvement in comparison to SB and SD.

A transmit power of −41 dBm reaches an average PDR of more than 90 % even in the most challenging environment. Adopting this value and reducing the transmit power from 10 dBm to −41 dBm for an inter-node distance of 30 m in the ground network would considerably increase the lifetime of a bat node, which is currently around two weeks [24]. These plots also show the aspect discussed earlier: the higher the PDR, the lower the benefit of MRC or SMRC over SB. Within one plot, the more MRC and SMRC approach a PDR of 100 %, their diversity gain over SB becomes less pronounced.

To compare those results with the large-scale scenario, all simulations are repeated and the results are summarized in Table 4.2. Again, the average PDR achieved is same as observed for the small-scale scenario and, hence, shows the potential of diversity combining on a large-scale scenario as well.

4.6 Outdoor Field Measurements

4.6.1 Measurement Setup

To analyze the performance of different diversity techniques in an outdoor environment, we performed an extensive set of experiments for a two-branch diversity system. We used the same hardware as in the lab environment; now for outdoor measurements. For experiments, we selected two types of areas:

Line-of-Sight area: To ensure a good testing environment, it is situated away from the main population. The ground is completely covered with grass and has trees only in the surroundings. Since there are no obstructions in between, it offers good LOS communication between transmitter and receivers.

Foliage area: The foliage area is full of tall trees that are spaced with a distance of about 3 m and the ground is a mixture of soil, grass, and low-level branches. It is very similar to the hunting area of bats in their natural forest environment.

We first performed static measurements in both of these areas by keeping the positions of transmitter and both receivers static in order to compare their performance with the indoor experiments. The transmitter is then moved during a mobile measurement (to reflect a moving bat and) to get further insights. A detailed top view of outdoor measurements setup is shown in Figure 4.12.

In order to perform static measurements in both of the environments (i.e., LOS and foliage), the receiver USRPs (i.e., Rx1 and Rx2) are kept at a distance of 30 m to represent a ground network of two nodes (positions A and C in Figure 4.12). The transmitter USRP (representing a bat) is then fixed at a position B between the receivers. Received signal samples are recorded at both the receivers for different transmit gain values. The recorded data is then post-processed to apply the considered diversity techniques.

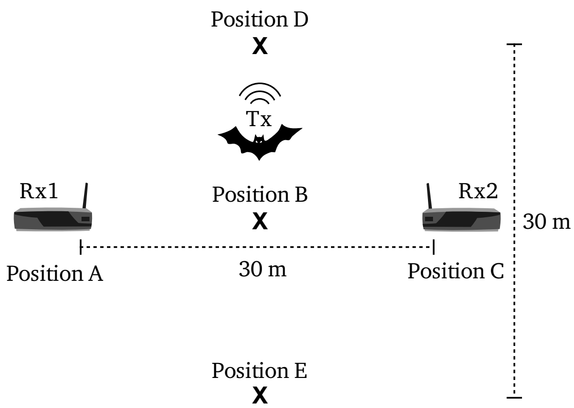
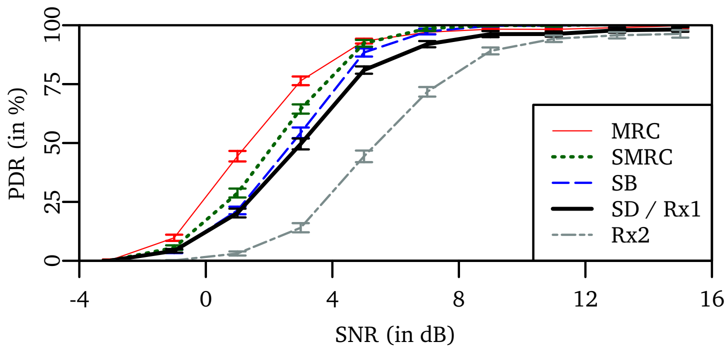


Figure 4.12 – Outdoor measurement setup.

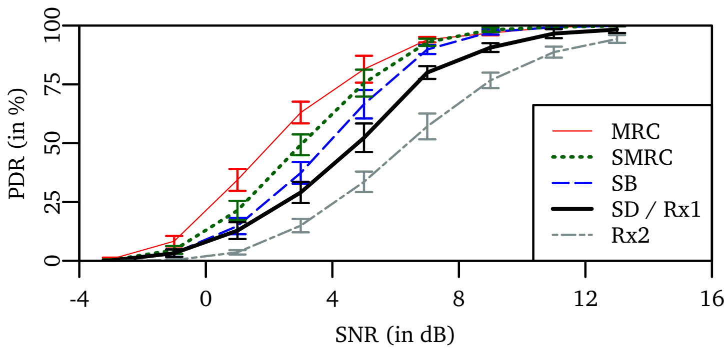
For mobile experiments, the transmitter USRP was moved on a walking speed, i.e., 5 km/h, in a straight line between position D and E representing the mobile measurement points. It is also worth mentioning that we do not perform experiments at higher speeds corresponding to a flying bat. Previously, we confirmed that the PDR is not substantially affected by the speed in the range of normal bat hunting maneuvers (cf. Section 3.5.3).

4.6.2 Results in the Static Case

The PDR results from the static (distance) experiments are shown in Figures 4.13a and 4.13b for the LOS and forest scenarios, respectively. As mentioned before, in the given setup of outdoor experiments, it is very difficult to ensure exactly the same SNR for both receivers even with the same software and hardware settings. This is due to the presence of numerous uneven multi-path components from the ground and trees (in the case of foliage area). Therefore, the PDR curves obtained with individual receivers, i.e., Rx1 and Rx2, are not the same. The relative difference



(a) Measurements in the line-of-sight area



(b) Measurements in the foliage area

Figure 4.13 – Experimental packet delivery rate for a two-branch diversity system with a statically placed transmitter in the outdoor environments.

observed between two receivers for static experiments is about 2.5 dB and 1.8 dB in LOS and forest scenario, respectively.

Since Rx1 experiences better channel quality among the two receivers, its performance is overlapped with SD. Even with such a case of SNR imbalance, SB performs marginally better than the SD for an average PDR of 50 %, i.e., 0.3 dB and 0.8 dB in the LOS and forest scenario, respectively. The MRC and SMRC still provide relatively increased performance gain than the rest of diversity techniques. However, their absolute improvement is much lower than what we have seen in the simulations and lab measurements. This can be well explained by the non-overlapping performance of involved receivers. In LOS setup, SMRC achieves 0.95 dB while MRC provides 1.7 dB improvement over the respective SD. Due to less pronounced SNR imbalance between branches in forest scenario, the improvement over respective SD increases to 1.6 dB and 2.5 dB for SMRC and MRC, respectively. These experimental results differ up to a maximum of 0.3 dB in comparison to what we have observed in AWGN simulations earlier. This slight variation in results is due to the effects of outdoor wireless channel and non-linearities of analog frontend. Also, the size of confidence intervals for the same number of runs in the foliage area is larger than the LOS area because of the non-uniform distribution of trees present between transmitter and receivers. Furthermore, it is also interesting to note that the slope of all PDR curves in the LOS area is similar to the ones observed in the indoor experiments. However, in the foliage area, the slope of PDR curves is less steep. This means that to achieve a target PDR, a higher SNR is required which was expected due to the additional involvement of shadowing effect. Even though these experiments are performed with only two receivers, the advantage of using diversity techniques in the outdoor environments is evident.

4.6.3 Results in the Mobile Case

The more interesting results, of course, are those in the mobile case. We first measure the relative received power across both receivers while moving the transmitter from one receiver towards the other at a walking speed in the foliage area. The resultant received powers for both receivers are plotted in Figure 4.14.

As expected, it can be noted that with the aforementioned setup, received power of one receiver gradually decreases while the other increases. The variation in the received power for a single receiver is as much as 35 dB when the receivers are placed with an inter-distance of 30 m. Since, the ground network is dense with receiver nodes, there is a high probability that with a mobile bat node transmitting, a decreasing received power at one receiver will eventually lead to an increased received power at some other receiver. Therefore, combining the signal copies

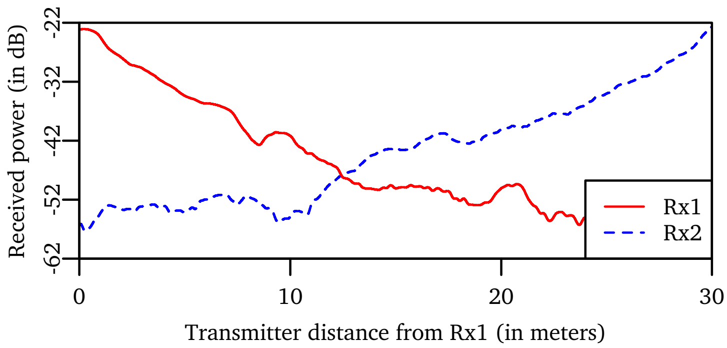


Figure 4.14 – Relative received power while moving the transmitter from one receiver to the other in the foliage area.

from several receivers will keep the overall received power on average same in the resultant signal.

To evaluate the performance of various diversity techniques with a mobile transmitter, we use the setup described earlier. With that, at every transmitter position, its distance from both receivers remains the same and, therefore, both receivers contribute for signal combining roughly the same. Since it is not easily possible to measure the absolute transmit power, we select the transmit gain in such a way that both receivers achieve an average PDR of more than 50 %. Furthermore, we select the same value for the transmit gain when performing LOS experiments and in the foliage area for a fair comparison.

The results of the various diversity techniques are shown in Figure 4.15. We note that the qualitative performance of all diversity techniques is similar to what we have seen earlier (cf. Section 4.5.3). The PDRs for LOS are marginally better than those for the foliage area due to the absence of shadowing from trees. Since the maximum distance between the transmitter and a receiver cannot be more than

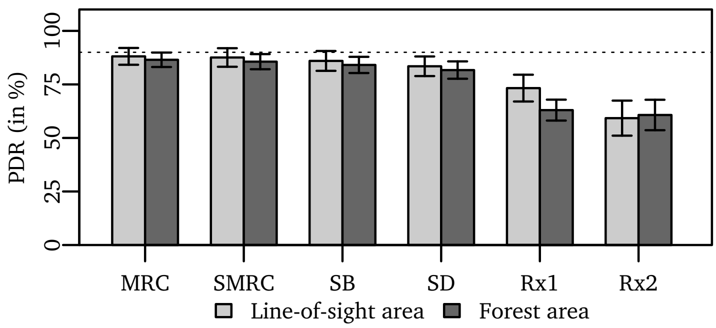


Figure 4.15 – Experimental packet delivery rate for a two-branch diversity system with a mobile transmitter in the outdoor environments.

30 m in the given setup, very few trees lie in between. Therefore, the PDR achieved in the foliage area is only marginally worse. These experiments also support the argument that the obstruction because of trees at smaller distances only affects the average received power and not the PDR. Moreover, it is also worth mentioning that these experiments are performed only with a two-branch diversity system and the advantage is still evident. In the final BATS deployment, diversity techniques will be applied with several receivers to achieve higher diversity gain. Furthermore, it is also concluded that SD and SB are not optimal in this scenario because of their low diversity gain and the requirement of more processing, respectively. Also, MRC is superior to SMRC without the need of very high data rate in the network with simple selective signal sample forwarding.

4.7 Conclusion

In this chapter, we addressed the research challenges involved in implementing practical receive diversity for a distributed sensor network. In particular, we proposed a novel approach to perform diversity combining at signal level, but without the need for sending the full sample stream to a central entity – which would be prohibitive due to the very high data rate. Instead, we selectively forwarded those parts of the sample stream that actually contain the packet. Furthermore, we have developed a model that helps to dimension distributed diversity systems by selecting optimal receiver positions or by minimizing the transmit power while maintaining reliable communication. Based on that framework, we performed simulations, over-the-air lab experiments, and, most importantly, real-world field experiments in LOS and foliage scenarios to compare the performance of the considered diversity techniques. We concluded to use MRC with selective signal sample forwarding for the best performance without overloading the network.

Chapter 5

Data Collection Algorithms

In the previous chapter, we have shown that a system that only forwards selected signal samples to a (central) sink for applying diversity combining keeps the data rate in the ground network at an acceptable rate and still achieves full diversity gain. However, since ground nodes in the BATS project do not have strict energy limitations, diversity combining can be also applied locally at ground nodes. Collection of data at one of the ground nodes and employing diversity combining locally without the involvement of a central entity reduce the redundant information in the network. Hence, less network nodes are involved in forwarding the same data resulting in energy-efficient solution and that also without overloading the network.

In this chapter, we propose a tree-based algorithm that helps reducing the data transfers in the ground network. Ground nodes try applying diversity techniques early whenever they receive signal samples from multiple receivers. We compare the proposed algorithm with a cluster-based algorithm and the naïve centralized solution. In extensive simulations, we show that the tree- and cluster-based algorithms substantially outperform the naïve centralized solution.

This chapter is based on the following publication:

- M. Nabeel, V. K. Singh, and F. Dressler, "Efficient Data Gathering for Decentralized Diversity Combining in Heterogeneous Sensor Networks," in *IEEE Wireless Communications and Networking Conference (WCNC 2019)*, Marrakech, Morocco: IEEE, Apr. 2019, © 2019 IEEE.

  In this conference publication, my contribution was to propose a variant of tree algorithm for applying diversity combining locally at ground nodes. I performed an extensive set of simulations to investigate its performance and to compare it with a variant of cluster algorithm and the naïve centralized solution.

5.1 Motivation

To employ diversity combining for an improved reception, the most naïve solution is to forward the detected data from different ground nodes to the (central) sink without decoding. The sink then combines the data copies detected at different nodes constructively. However, forwarding multiple data copies from different ground nodes at the same time might not be feasible due to redundant information in the ground network. To cope with this challenge, data aggregation algorithms have been proposed [30]. However, the focus is usually a stationary homogeneous sensor network in which all nodes have similar size and energy limitations or a heterogeneous network where nodes with different capabilities are uniformly distributed. In contrast to the literature, our network is a heterogeneous sensor network which consists of three different types of nodes, i.e., bat, ground, and sink. To pass data reliably and efficiently from bat node to the sink, we propose a variant of tree algorithm, and explore the idea of diversity combining for the reduction of data rate requirement in the ground network. We then compare its performance with an already proposed cluster-based algorithm and the naïve centralized solution.

Our main contributions of this chapter can be summarized as follows:

- We propose a variant of tree algorithm for applying diversity combining locally at ground nodes.
- We develop the whole system model in a simulation environment to investigate its performance.
- We present results from an extensive simulation study, which clearly demonstrate that the proposed variant of tree algorithm and the presented cluster-based algorithm not only reduce the data rate required in the ground network but also improve the network lifetime due to less number of transmissions involved.

5.2 Preliminaries

Data gathering or aggregation in sensor networks have been a research focus for many years [30]. Data aggregation not only reduces redundant information but also increases the lifetime of sensor nodes. As a result, the amount of data sent through the network also reduces. Commonly used data aggregation algorithms are classified as cluster-based and tree-based. In cluster-based algorithms [91], [92], clusters are formed within the network and a Cluster Head (CH) is elected in each cluster by a variety of methods. The CH gathers data from its Cluster Members (CMs) and performs data aggregation locally before forwarding the data towards the sink either directly or using intermediate network nodes. In tree-based algorithms [93], [94], a spanning tree rooted at the sink is constructed in which the data trickles down from the leaves towards the root. It means that the data aggregation is performed within the network at intermediate nodes while forwarding the data towards the sink. Tree algorithms are energy-efficient and require only local information about the network topology. To further improve the energy-efficiency in Wireless Sensor Networks (WSNs), hybrid cluster-tree based algorithms also exist [95].

If the transmitting sensor node is highly mobile, data aggregation algorithms can be still successfully applied [96]. However, most of these algorithms target homogeneous sensor networks in which all nodes have similar capabilities and energy limitations. Therefore, to optimize performance of heterogeneous sensor networks, several other algorithms have been proposed such as in [97]. Nevertheless, these works consider that nodes with different capabilities are uniformly distributed within the same area and, hence, use powerful nodes to perform higher processing functions improving the lifetime of energy-constrained sensors. Moreover, the main concern of most algorithms is the energy-efficiency of sensor nodes due to their limited capability and available energy.

Here, we consider a heterogeneous sensor network in which the architecture deployed and protocol used are different. Only the transmitting sensor node is very energy-constrained due to which the transmit power is very low. Furthermore, the data that is transmitted to the ground nodes is crucial because the loss of reception can lead to a loss of data forever. In Chapter 4, we proposed to forward detected signal samples that with high probability belong to the same packet from all ground nodes to a central sink for centralized diversity combining. With the proposed technique, the data that needs to be passed in the network reduces dramatically, however, it is still not realistic due to the forwarding of all data to one centralized unit through capacity limited network links.

In this chapter, we focus on reducing the huge cost (in terms of channel utilization, energy consumption, time delay, and required data rate) of forwarding the received information to the central sink through the ground network. For that, we develop a variant of tree algorithm in which diversity combining is applied already early at the ground nodes before forwarding the combined data to the sink.

5.3 Data Gathering Algorithms

In this section, we present the naïve centralized, the cluster-based, and the proposed tree-based algorithms. A conceptual overview is shown in Figure 5.1. It is important to note that we assume routing in our ground network is performed by any ad hoc routing protocol, forming a multi-hop network towards the sink. The centralized approach (cf. Algorithm 5.1) is straight forward and passes all detected signal samples to the sink for employing diversity combining at a single point.

5.3.1 Cluster Algorithm

In the cluster approach (cf. Algorithm 5.2), ground nodes that detect the transmitted data from the bat node form a cluster. The involved nodes select and start a *cBackoff* timer based on the received Signal to Noise Ratio (SNR) to decide if they want to become a CH. The ground node with the smallest *cBackoff* starts the process, broadcasts a CH selection message, and starts its *slaveBackoff* timer. CMs receiving the CH broadcast forward their signal copy to the CH and cancel *cBackoff*. Finally, on the expiry of *slaveBackoff*, the CH applies diversity combining locally before forwarding the decoded data to the sink as a single data message. In the algorithm, SNR_{max} and

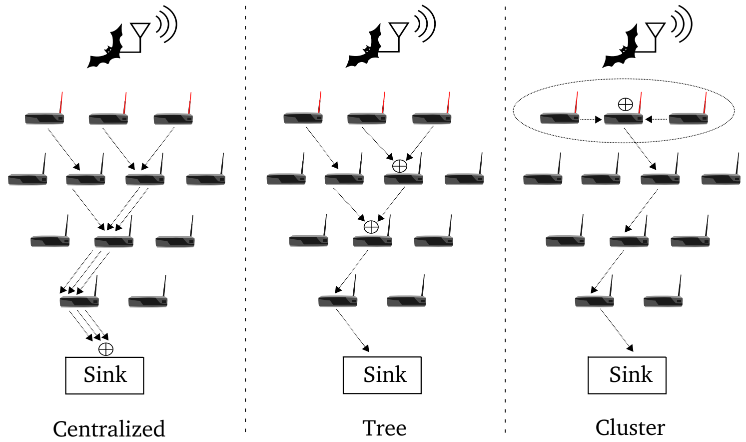


Figure 5.1 – Mobile bat transmitter and distributed ground nodes that detect the transmitted signal. The addition function shows where diversity combining is employed. Arrows indicate necessary transmissions. (Reproduced from [35], © 2019 IEEE.)

SNR_{min} represent configurable SNR thresholds, *cBackoff* is the CH selection backoff time, and *slaveBackoff* is the waiting time at the CH for receiving samples before forwarding the combined signal to the sink.

5.3.2 Tree Algorithm

In the proposed tree approach (cf. Algorithm 5.3), all nodes in the ground network form a collection tree towards the sink. If signals from a mobile node are received in the ground network, the involved ground nodes decode the received signals, and if successful, the decoded signals are forwarded towards the sink without any delay. In the case of unsuccessful decoding, the *tBackoff* timer of the node is computed

Require: event ∈ {signal from bat node, signal from ground node}
Ensure: received signal is forwarded to sink

switch (event)
case signal from bat node**:**
case signal from ground node**:**
  if `currentNode` is `sink` **then**
    employ diversity combining with the signal copies received and, afterwards, decode
  else
    forward the received signal to sink
  end if
end switch

Algorithm 5.1 – `Centralized`. (Reproduced from [35], © 2019 IEEE.)

Require: event ∈ {signal from bat node, signal from ground node, *cBackoff* expired, *slaveBackoff* expired}
Ensure: received signal is forwarded to sink
switch (event)
case signal from bat node**:**
  if received SNR > SNR_{max} **then**
    cBackoff ← 0.0
  else
    map received SNR on the scale of SNR_{diff} (calculated from SNR_{max} - SNR_{min})
    cBackoff ← wait time from the scale
  end if
  start *cBackoff*
case *cBackoff* expired**:**
  broadcast CH selection and start *slaveBackoff*
case signal from ground node**:**
  if `currentNode` is `sink` **then**
    employ diversity combining with the signal copies received and, afterwards, decode
  else if CH selection broadcast **then**
    forward received signal copy to CH
    cancel *cBackoff*
  else
    forward the signal to sink
  end if
case *slaveBackoff* expired**:**
  employ diversity combining with the signal copies received, decode, and forward the result to sink
end switch

Algorithm 5.2 – `Cluster`. (Reproduced from [35], © 2019 IEEE.)

as the product of its *level* and *baseBackoff*. Once the *tBackoff* expires, the received signal is forwarded towards the sink.

The *level* represents the ground node position relative to the sink in the network topology. The value of *level* is lower at farther nodes (integer value starting from zero) and it increments by one for every *level* when we move towards the sink. Moreover, multiple nodes in the ground network can have the same *level*. Whereas, the *baseBackoff* is a predefined time (same for all ground nodes) and its value also depends upon the underlying network topology. With such a calculation of *tBackoff*, nodes farthest from sink receiving the bat node signal forward it earlier in the network than the nodes that are nearer to the sink. Hence, there is a high probability of employing diversity combining early in the network.

On reception of signal from neighboring ground nodes, *tBackoff* of a node is equivalent to *baseBackoff*, or zero if the signal is already decoded. If any ground node encounters multiple copies of the detected data before its *tBackoff* is expired,

```
Require: event ∈ {signal from bat node, signal from ground node, tBackoff expired}
Ensure: received signal is forwarded to sink
switch (event)
case signal from bat node:
  tBackoff ← level ∗ baseBackoff
  start tBackoff
case signal from ground node:
  if currentNode is sink then
    employ diversity combining with the signal copies received, if still not decoded
  else if signal already decoded then
    tBackoff ← 0.0
    start tBackoff
  else
    tBackoff ← baseBackoff
    start tBackoff
  end if
case tBackoff expired:
  if received more than one copy of the same signal then
    employ diversity combining
  end if
  forward the signal to sink
end switch
```

Algorithm 5.3 – `Tree`. (Reproduced from [35], © 2019 IEEE.)

it employs diversity combining before forwarding the received data, hence, resulting in a reduced output stream. Also, once the required number of data samples to successfully decode the signal are combined, the resultant data is forwarded to the sink without further delays.

5.4 Evaluation

5.4.1 Application Scenario

To evaluate the performance of the proposed algorithms in the BATS project, we implement a two-dimensional bat mobility model as discussed in [27] in an area of 1000 m × 1000 m including a hunting area of 300 m × 300 m in the center. The ground network is placed in the hunting area with a total of 121 nodes in form of a grid with an inter-distance of 30 m as shown in Figure 5.2. We divide the ground network into three regions, i.e., far, middle, and near, based on their distances from the sink for a more detailed study. We also assume that nodes in the network are synchronized up to a level of ms using Network Time Protocol (NTP) [98]. A bat always starts its movement from top left corner of the simulated ground network based on the adopted Levy flight mobility model and transmits every 100 ms with a power of −47 dBm using a packet size of 12 Byte that also contains a 2 Byte of training data (preamble) for channel estimation. The bat node transmits with a data rate of 200 kBit/s according to the BATS protocol described in [24]. For communication within ground network, nodes rely on standard Wi-Fi. To simulate the wireless channel, we include Free Space Path Loss (FSPL) based on the distance measures and linear fading loss of 0.25 dB/m.

5.4.2 Implementation and Calibration

We implemented all three algorithms, whereby the centralized algorithm is rather straight forward and passing of information from the ground nodes to the centralized sink is based on static routing.

For the cluster algorithm, the first important task is to choose a CH. Whenever a bat signal is detected by the ground network, the involved nodes use the SNR to decide if they want to become a CH. We then calculate two points around a ground node, i.e., max-point and min-point as shown in Figure 5.3. At any time instant, a bat can be within a max-point of only one ground node, hence, leading to a SNR at that node greater than SNR_{max} and easily declaring this node as a CH. Here, SNR_{max} (in dB) is calculated as

$$SNR_{max} = (P_{\text{tx}} - L_{\text{FadingMax}} - L_{\text{FreeSpaceMax}}) - P_{\text{noise}}, \tag{5.1}$$

where P_{tx} and P_{noise} are the transmit and noise powers, respectively, whereas L represents the different loss terms. Similarly, if the SNR is less than SNR_{max} but greater than SNR_{min}, where SNR_{min} (in dB) is calculated as

$$SNR_{min} = (P_{\text{tx}} - L_{\text{FadingMin}} - L_{\text{FreeSpaceMin}}) - P_{\text{noise}}, \tag{5.2}$$

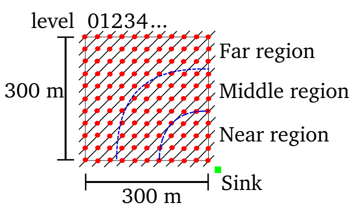


Figure 5.2 – Overview of the simulated ground network with 121 nodes placed in a grid highlighting three considered regions. (Reproduced from [35], © 2019 IEEE.)

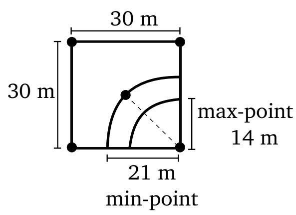


Figure 5.3 – Schematic of a sub-grid with four ground nodes with an inter-distance of 30 m to show the min-point and max-point. (Reproduced from [35], © 2019 IEEE.)

the respective ground node can be a contender for a possible CH because of sharing the same area with neighboring ground nodes. For the final selection of a CH among the contender nodes, we calculate $SNR_{diff} = SNR_{max} - SNR_{min}$ and then divide it into equal parts discretizing using the distance in meter between the two mentioned points. Every contender node finds *cBackoff* (in ms) by mapping its received SNR on the scale of SNR_{diff} as depicted in Figure 5.4. The contender node then broadcasts a CH announcement when its *cBackoff* expires and if it has not received another announcement. Once a CH is broadcast, nodes receiving the broadcast join the cluster to become CMs and forward their signal copies to the CH. The CH waits for *slaveBackoff* time to receive the responses of its CMs before it finally employs diversity combining and forwards the resulting signal as a single message towards the sink. We set the *slaveBackoff* time to 10 ms in our implementation as the ground network can receive at most once per that time interval according to the BATS protocol [24].

For the proposed tree algorithm, we define a *level* in the ground network based on its topology shown as the diagonal lines in Figure 5.2. The order of *level* increases when we move towards the sink. Obviously, *baseBackoff* is a critical value. If too small, ground nodes will forward their received signal before copies from nodes at a lower level arrive; if too large, the end-to-end time delay will increase. We thus empirically identified a good backoff time for our scenario. In particular, we recorded the average number of transmissions within the ground network for routing the received signal copies completely to the sink. The results are shown in Figure 5.5. As can be seen, the number of transmissions in the network stop reducing further after 6 ms and the standard deviation stabilizes, hence, making it an optimal *baseBackoff* for this topology.

Before discussing the performance of these algorithms, we performed additional simulation experiments to study the possible gain of diversity combining for different numbers of received signal samples. In our previous work [31], [34], we studied the expected PDR for different SNRs both in simulation as well as in experiments. Therefore, in this work, we consider different bat positions in the simulated area and calculate the received SNR at different ground nodes for every transmission. We then apply Maximum Ratio Combining (MRC) (i.e., the weighted sum of all signal copies) and plot the resulting PDR. Figure 5.6 shows the PDR achieved with different number of nodes involved. As an example, we highlight a PDR of 90 % by a horizontal dotted line. With five ground nodes (i.e., five diversity branches), the

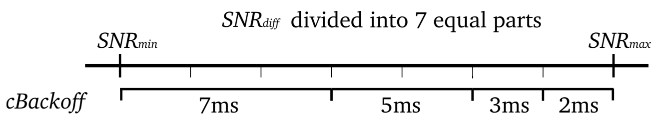


Figure 5.4 – Mapping of received SNR on the scale of SNR_{diff} to find the *cBackoff*. (Reproduced from [35], © 2019 IEEE.)

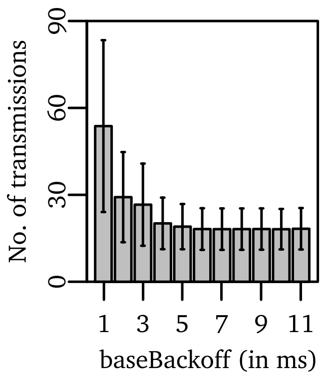


Figure 5.5 – Average number of transmission to find optimal *baseBackoff* for the tree algorithm. (Reproduced from [35], © 2019 IEEE.)

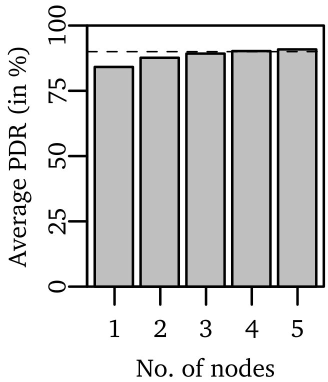


Figure 5.6 – Achieved PDR with different number of ground nodes or diversity branches. (Reproduced from [35], © 2019 IEEE.)

achieved PDR reaches 91 % in comparison to a single node that achieves a PDR of only about 84 % without any diversity combining. In the following, we focus on the overall application layer performance of the different collection algorithms.

5.4.3 Results and Discussion

To compare different considered algorithms, first, we analyze the end-to-end time delay, i.e., the time it takes from transmission by the bat node to reception at the sink. Figure 5.7 shows the mean end-to-end time delay of the considered algorithms when combining at least two, three, or four signal copies. The error bars show the standard deviation; for better interpretation, the horizontal line highlights a delay of 100 ms.

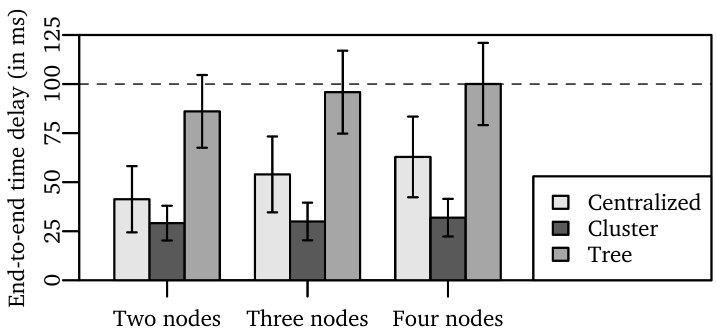
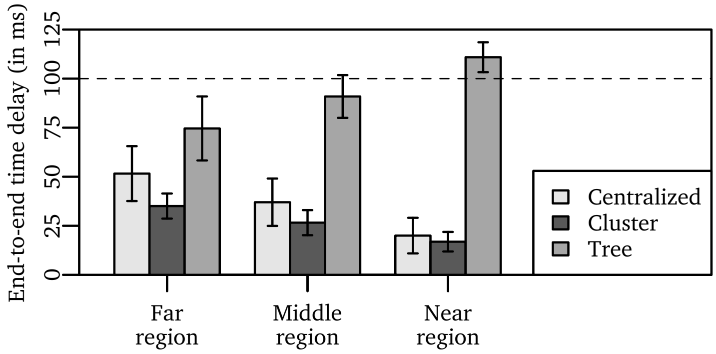
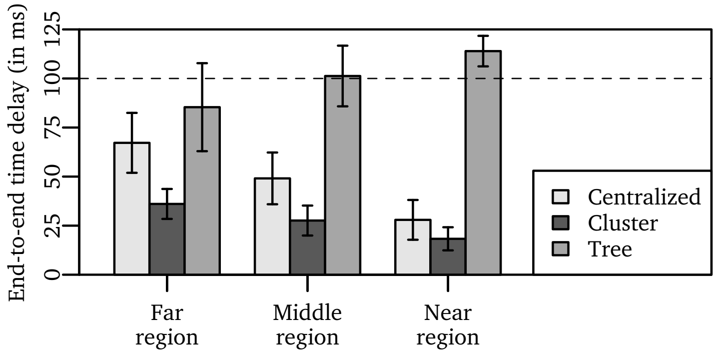


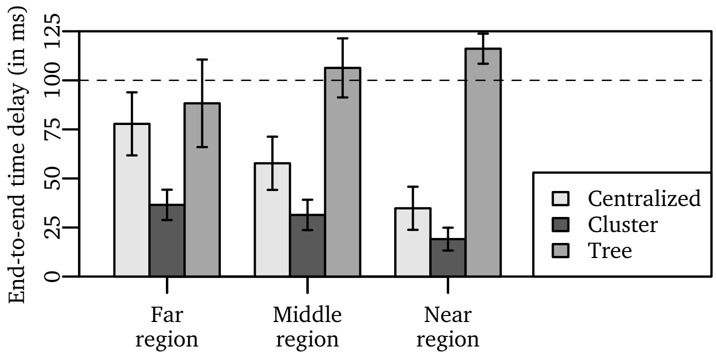
Figure 5.7 – Average end-to-end time delay for the different algorithms to combine at least two, three, or four signal copies. (Reproduced from [35], © 2019 IEEE.)



(a) Combining at least two signal copies of bat transmissions



(b) Combining at least three signal copies of bat transmissions



(c) Combining at least four signal copies of bat transmissions

Figure 5.8 – Average end-to-end time delay for the different algorithms to combine different number of signal copies in the considered regions. (Reproduced from [35], © 2019 IEEE.)

For the centralized algorithm, combining more signal copies leads to increased time delays due to the additional waiting time required for more transmissions to reach to the sink. It is interesting to see that the mean end-to-end delay for the cluster algorithm always stays around 30 ms. The overhead of collecting more signal copies is marginal because, once a cluster is formed, it takes a negligible amount of time to get data from an additional ground node. The tree algorithm, on average, takes more time compared to other algorithms as it involves overhead due to the backoff at every ground node.

Since the plot shows average time delays for bat transmissions over the whole network area, we further study the protocol behavior in the mentioned regions (cf. Figure 5.2) in Figure 5.8. We can see that the more a bat transmission happens near the sink, the less is the end-to-end time delay for the cluster and the centralized algorithm. However, for the tree algorithm, an opposite effect can be seen. This is due to the *level*-based backoff calculation. A transmission far from the sink provides a high chance for early signal combination and, hence, forwarding the resultant signal with a small delay. However, in the case of a bat transmission near to the sink, every node has to wait for a longer backoff due to the higher *level* order involved, resulting in longer end-to-end delays. For example, in such a scenario, the end-to-end delay for the tree-based algorithm is more than 100 ms, regardless of the number of signal copies combined.

Secondly, we investigate the number of nodes involved as a metric for the energy load distribution. Figure 5.9 shows the total number of ground nodes that participate either in processing or forwarding the received bat signal for all algorithms. The error bars depict the standard deviation of the mean values. The tree and centralized algorithms show a similar performance and involve between 8 and 21 ground nodes, depending on the region. Such a similar performance trend is due to the fact that a signal from a ground node is forwarded to the sink through exact same route based

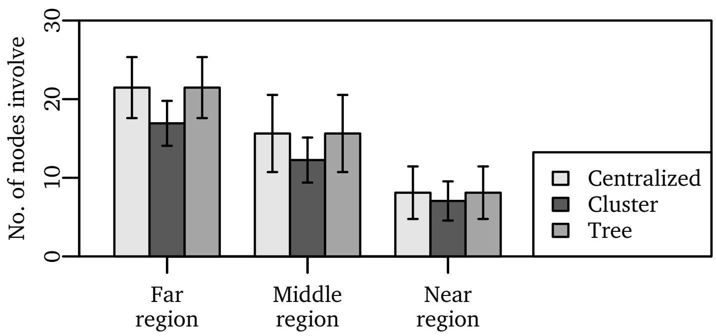


Figure 5.9 – Total number of ground nodes involved for the different algorithms to forward the signal successfully to the sink. (Reproduced from [35], © 2019 IEEE.)

on the implemented static routing, regardless of whether it is combined with other signal copies or not. Nevertheless, the cluster algorithm performs slightly better and uses only between 5 and 18 nodes because it does not consider static routing for data aggregation within the cluster.

Next, we compare the number of transmissions in the ground network for each considered algorithm. The results are shown in Figure 5.10. Even though the tree algorithm involves the same number of nodes as the centralized algorithm and end-to-end time delay is much higher than the other two algorithms, the total number of transmissions is very low. The performance of tree is marginally better than the cluster algorithm in near region because cluster involves additional transmissions for forming the cluster. These additional transmission are negligible in comparison to the higher number of network transmissions in other regions. The tree and cluster algorithms involve about three times less transmissions compared to the naïve centralized one.

Finally, we consider the channel utilization of ground nodes in all three regions for bat transmissions over the whole network area and plot an eCDF in Figure 5.11.

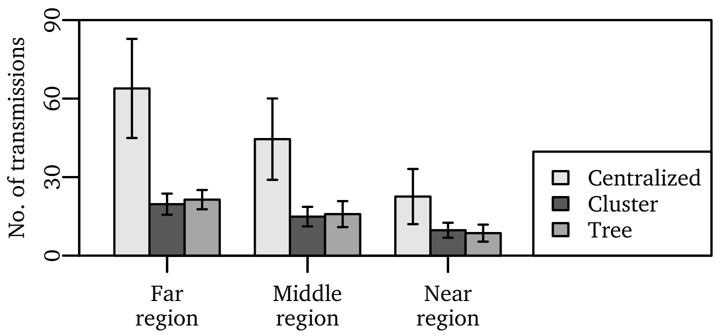


Figure 5.10 – Total number of transmissions in the ground network for the different algorithms to forward the signal successfully to the sink. (Reproduced from [35], © 2019 IEEE.)

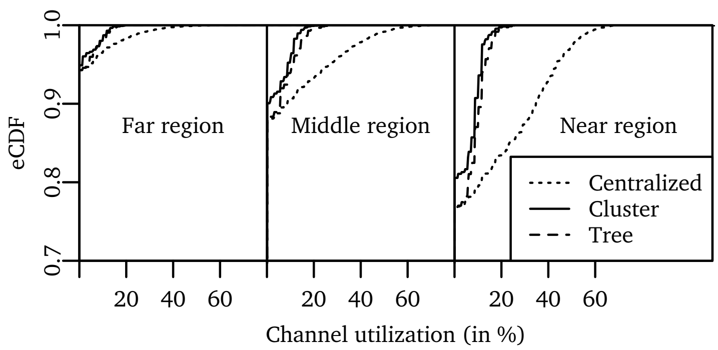


Figure 5.11 – Channel utilization of ground nodes in different regions. (Reproduced from [35], © 2019 IEEE.)

It can be seen that the channel utilization of the cluster algorithm is always better or equivalent to the tree algorithm but much better compared to the centralized algorithm in all cases. This can be well explained by the fact that once a cluster combines all signal copies, the resulting signal is usually routed on a single path towards the sink. However, for the centralized algorithm, many of the nodes are involved in forwarding multiple signal copies through different routes in the network resulting in the worst channel utilization. In the tree algorithm, the signal is routed in the same way as in the centralized algorithm, but since the number of transmissions involved are much lesser, the channel utilization is highly improved in comparison to the centralized algorithm. Furthermore, it is interesting to note that the ground nodes near to the sink are involved in processing or forwarding the received signal copy for every bat transmission in the network. Therefore, channel utilization for nodes in the near region is comparatively worse than the nodes in other regions for all the considered algorithms.

5.5 Conclusion

In this chapter, we proposed and developed a tree-based solution to collect received signal samples and, instead of sending those to a central sink node, applying diversity combining early in the collection process. The main objective was to reduce the load in the sensor network. Using the BATS application as a realistic example, we calibrated the protocol accordingly to study the performance gain in an extensive set of simulations. Our results show that even though the tree algorithm is energy-efficient and reduces the network load, its performance is the worst when looking at the end-to-end delay. In contrast, the cluster algorithm is a better alternative as it not only provides improved energy-efficiency due to reduced number of transmissions in the network but also provides better channel utilization.

Chapter 6

Conclusion

Since the last two decades, sensor networking has supported a wide range of applications, including, but not limited to, healthcare, smart environment, military, logistics, and wildlife monitoring. Researchers are now targeting applications in which the energy and size limitations of a sensor node are extremely higher, which, as a result, give rise to new research challenges. Our investigations in this PhD thesis focused on sensor nodes which are mobile as well as highly size- and energy-constrained. Our main objective was to improve the communication performance between sensors without increasing the energy-consumption at the mobile sensor.

We considered a specific wildlife application scenario in which we equipped bats with a sensor node of 2 g. This bat node continuously recorded contact information between individuals, and upon its visit to a hunting area, transmitted this information to a ground network. The ground network was deployed in hunting areas of bats and was composed of static single antenna nodes which did not have any strict energy limitations. The primary purpose of the ground network was to track a flying bat over the hunting ground and gather all information that was stored on the bat node.

First, to realize energy-efficient communication, we used Binary Offset Carrier (BOC) modulation alongside with Binary Phase-Shift Keying (BPSK) in order to perform data communication and ranging simultaneously at a single carrier and, hence, minimized the energy consumption at the bat node. BOC modulation has been widely studied and used in Global Navigation Satellite Systems (GNSSs). However, its implication in ultra-low power sensor systems required thorough investigation due to the difference in system architectures and communication protocols used. In contrast to GNSSs, we used short burst BOC signals to comply with the limited battery of the bat node and performed transmissions at a much higher data rate. We developed the whole transceiver model in a Software Defined Radio (SDR)-based platform and performed an extensive set of real-world experiments to investigate its feasibility. Our results clearly demonstrated that the developed BOC transceiver is fully compliant with the used protocol. Moreover, it can be successfully used for energy-efficient communication in ultra-low power sensor networks with a performance trade-off of only 0.5 dB in comparison to traditional BPSK.

Second, we explored the possibility of using ground network as a distributed antenna array to employ diversity combining for improved communication performance. We also explored a new concept of selective sample forwarding to avoid overloading the ground network. We built upon our SDR-based implementation and realized diversity combining at complex signal samples as well as at soft-bits. We then compared different diversity techniques by means of simulations, lab measurements, and outdoor experiments. Our results show that using Maximum Ratio Combining (MRC) with selective signal sample forwarding reduced the data rate required in the ground network by 20 times and still achieved full diversity gain.

Finally, to reduce the huge cost (in terms of time delay, energy consumption, required data rate, channel utilization, etc.) of forwarding the received information to the central sink through the ground network, we examined the feasibility of applying diversity combining locally at ground nodes rather than at the centralized sink. For that, we proposed a variant of tree algorithm, and compared its performance with the most naïve approach of realizing diversity at a centralized sink. Our results from an extensive set of simulations revealed that the proposed variant of the tree algorithm comparatively provided better channel utilization and required less number of transmissions in the network.

In summary, this thesis applied complex signal theory concepts in ultra-low power sensor networks to improve the performance in terms of energy-efficiency and communication reliability. Our system exploited packet-based communication using a packet size of 12 Byte only. Since this packet length was much lesser than the coherence time of the channel, training data in the start of the packet was enough to estimate the channel. We did not investigate longer packet lengths. Hence, it will be an important direction for the future work to consider longer packet lengths and then study the necessary changes required in the packet structure to obtain better channel estimates throughout the packet duration. Moreover, we noticed that incorporating diversity combining in distributed sensor networks improved the reception quality, however, achieving full diversity gain in practical experiments was nearly impossible. This was due to the geometry of areas around nodes where diversity combining was observed. In future, It will be interesting to study these areas in more detail and investigate their impact on diversity gain of micro-diversity systems as well. Furthermore, we have conducted mobile experiments with an e-bike and, with that, not only the moving speed was limited but also it was difficult to move with high speeds in a forest environment. A good alternative for future experiments is to use the drone technology which requires minimal manpower and it is also easy to use in an area like a forest. Finally, as this thesis investigated different ideas with not only simulations but with practical experiments in the fields, we believe that the lessons learned from these experiments are extremely helpful in designing next generation systems.

List of Abbreviations

ADC	Analog-to-Digital Converter
AF	Amplify-and-Forward
AGC	automatic-gain-control
AOA	Angle Of Arrival
ARQ	Automatic Repeat-Request
AWGN	Additive White Gaussian Noise
BAN	Body Area Network
BER	bit-error-rate
BOC	Binary Offset Carrier
BPSK	Binary Phase-Shift Keying
CH	Cluster Head
CM	Cluster Member
CRC	Cyclic Redundancy Check
DAC	Digital-to-Analog Converter
DBPSK	Differential Binary Phase-Shift Keying
DF	Decode-and-Forward
DPSK	Differential Phase-Shift Keying
ECC	Error Correcting Code
EGC	Equal Gain Combining
FEC	Forward Error Correction
FPGA	Field-Programmable Gate Array
FSPL	Free Space Path Loss
GNSS	Global Navigation Satellite System
GPP	General Purpose Processor
GPS	Global Positioning System
HARQ	Hybrid Automatic Repeat Request
HEAP	Powered by Ambient Energy Harvesting
IoT	Internet of Things
ISI	intersymbol intereference
LEACH	Low-Energy Adaptive Clustering Hierarchy

LOS	Line-of-Sight
MDM	Multiply-Detected Macro-diversity
MRC	Maximum Ratio Combining
NIC	National Intelligence Council
NLOS	Non Line-of-Sight
NTP	Network Time Protocol
OOT	Out-of-Tree
PC	Personal Computer
PDC	Post-Detection Combining
PDF	Probability Density Function
PDR	Packet Delivery Rate
PEGASIS	Power-Efficient Gathering in Sensor Information Systems
PMRC	Priority Maximum-Ratio Combining
PSD	Power Spectral Density
PSDC	Post Soft-Demodulation Combining
RF	Radio Frequency
RFID	Radio Frequency IDentification
RSS	Received Signal Strength
SB	Successful Branch
SD	Selection Diversity
SDR	Software Defined Radio
SEGC	Soft Equal Gain Combining
SEP	Stable Election Protocol
SMRC	Soft Maximum Ratio Combining
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access
TDOA	Time Difference Of Arrival
TOA	Time Of Arrival
USRP	Universal Software Radio Peripheral
WSN	Wireless Sensor Network
WuRx	Wake-Up Receiver

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