Efficient Receive Diversity in Distributed Sensor Networks using Selective Sample Forwarding

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***Abstract*—We study the potential of exploiting receive diversity in a distributed Wireless Sensor Network (WSN). In contrast to other approaches, we fully rely on diversity combining on signal level by introducing selective sample forwarding to a centralized receiver. That way, we use the WSN as a distributed antenna array and still take the rather limited data rates between the sensor nodes into consideration. In particular, we consider a distributed ground network in the wild to track bats in their natural habitat. The bats are equipped with a sensor node of only 2 g, which limits the energy budget available for communication. The main challenges to be addressed are the limited bandwidth between nodes and the need for accurate time synchronization to combine signal copies constructively at a central node. We study the performance based on a GNU Radio implementation both in simulations as well as in lab experiments. Our results clearly indicate a substantial performance gain while keeping the data rate in the distributed sensor network in a feasible range.**

I. Introduction

One of the most promising application domains of Wireless Sensor Networks (WSNs) is wildlife monitoring [1], [2]. Following the early ZebraNet application [3], more recent studies turned towards monitoring rats [4] and, most recently, to birds in the Encounternet project [5]. In the scope of our BATS project, we target an even more challenging species: mouse-eared bats (*Myotis myotis*). We equip these bats with a sensor node (here referred to as a mobile node) to study their social and foraging behavior [6]. The mobile sensor node may weigh only 2 g because of the limited size and weight of target species. Whenever a mobile node comes into contact with another mobile node, the contact information is stored and transmitted to a ground network that is deployed in hunting areas of bats. The ground network is composed of distributed single antenna nodes, which are also used to track the bats' trajectories in this area. These ground nodes do not have strict energy limitations and are connected to a central node via a wireless multi-hop network. Bats equipped with mobile nodes sporadically appear in a communication range of the ground network. When in range, the ground network triggers the wake-up receiver of the mobile node, causing it to transmit all saved information to the ground network.

In this application domain, the communication channel is greatly affected by several factors such as multipath fading and shadowing. Hence, we exploit the distributed nature of the ground network and use diversity combining to improve the Packet Delivery Ratio (PDR) [7]. Similar ideas are used in macro-diversity [8], where architectural requirements and communication protocols are different from the BATS project. Macro-diversity is usually recommended at soft-bit level rather than signal level because of bandwidth constraints between the distributed receivers [9]. Such conventional diversity combining uses multiple antennas mounted on a single receiver. Hence, no synchronization of the receivers is required.

In our preliminary work [10], we studied the general concepts of diversity and went one step further and proposed a framework that exploits signal level receive diversity in a distributed network by forwarding only selected 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. However, this poses several research challenges such as tight synchronization in the ground network, forwarding of data through a limited bandwidth link from ground nodes to a central node, and continuous phase and frequency offset tracking for coherent combining. This paper extends this work to address all issues arising from practical diversity combining at distributed receivers including synchronization and phase correction. We discuss the efficient node placement and adapt parameters like transmit power to maximize diversity gain. Taking a different perspective, our study shows how receive diversity allows to reduce the transmit power of the mobile nodes while maintaining the same level of reliability, thus, increasing the lifetime of the mobile node [11].

In order to demonstrate the effectiveness and efficiency of our approach, we implemented multiple diversity combining techniques in the GNU Radio Software Defined 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 compared the performance of single receivers that decode the signal separately to a full diversity system combining received samples from multiple ground nodes. Our results clearly show the advantages of signal level diversity combining in a distributed environment with only a marginal trade-off in system complexity.

Our main contributions can be summarized as follows:

- We make use of a sensor network as a distributed antenna system for applying receive diversity algorithms.
- We propose a novel technique for selecting relevant signal samples to be forwarded to a central receiver.

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- Our system provides substantial gain in the overall packet delivery rate while keeping the data rate in the ground network at an acceptable rate.
- We implemented the system both in simulation and an SDR-based experimental setup.

II. Related Work

A. Diversity Combining

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) [12]. Of all these, MRC is considered the best combining technique. SD, in turn, provides a lower diversity gain, but also introduces less complexity. A detailed comparison of these techniques when using multiple antennas at a receiver is presented in [13]. By combining SD and EGC, a hybrid diversity technique is also proposed, in which the performance is close to MRC with only incremental complexity [14].

Some practical applications offer insufficient spacing between antennas due to their limited size and, hence, give rise to correlated fading among different diversity branches. Therefore, the asymptotic error performance in correlated fading scenarios is analyzed in [15]. The results are further extended for a complex fading such as Nakagami [16]. Later, the impact of interference on the outage probability of diversity combining is analyzed in [17]. 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 [8]. As a drawback, this also requires more complex 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 [8], [9]. 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 [18]. However, the diversity gain still reduces because of the conversion of signal into soft values [7]. Moreover, symbol-error-rate for MRC in macro-diversity is analyzed in [19], but there is still a need of 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 [20]. This approach shows that the idea of cooperative diversity suits well within the scope of WSNs, albeit it also comes with practical limitations [21].

In recent years, diversity combining is used to enhance the physical layer performance of Body Area Networks (BANs) [22], [23]. Furthermore, diversity combining also helped in improving the performance of animal monitoring through WSNs [24]. 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 work focuses on the practical aspects within the application of ultra-low power WSNs.

Apart from the diversity combining strategy, also the position of receivers is important to maximize performance and to optimize the coverage area [8]. Cooperative diversity helps reducing the number of nodes that are required to cover a specific region [25]. However, the factors affecting the coverage areas are not discussed in the literature. In this work, we present a detailed description of these coverage areas along with practical considerations with regard to diversity combining in distributed systems.

B. Protocol Basics

A detailed description of our protocol and rationale for the design decisions was provided in prior works [26]. In a nutshell, each mobile node stores contact information with other nodes when not in communication range of a ground network. The ground network is composed of nodes with an inter-distance of 30 m, which is required for accurate localization [27]. Since the mobile nodes have limited energy capacity, a wake-up receiver is employed on the node. The wake-up sequence helps distinguishing between mobile–mobile and mobile–ground connections. Whenever in range of a ground node, the mobile node is supposed to transmit all stored contact information. The data transfer is initiated when the wake-up receiver of the mobile node is triggered by a signal from ground nodes. To avoid collisions from multiple bats in range, the channel is accessed with a Time Division Multiple Access (TDMA) scheme, orchestrated by the ground nodes. The TDMA scheme allows a mobile node to select a fixed-length time slot of 10 ms within a super-slot of 100 ms, supporting up to 10 bats. A mobile node sends its information with a maximum transmit power of 10 dBm by using a short burst signal of 12 B. If possible, the node tries decreasing the transmit power, to increase lifetime of the node [11]. These short packets are transmitted with a data rate of 200 kbit/s at a carrier frequency of 868 MHz.

III. Distributed Signal Level Diversity

When applying diversity combining to increase reception quality, several research challenges arise:

- Efficient forwarding of received information to a central node through a limited bandwidth link.
- Tight synchronization of ground nodes to align the start of all signal copies received at different nodes.
- Precise phase and frequency offset tracking to combine signals from different nodes constructively.
- Optimal placement of ground nodes or, alternatively, minimal transmit power for reliable communication.

Table I
SPECTRUM OF POSSIBLE APPROACHES TO BALANCE THE TRADE-OFF BETWEEN DIVERSITY GAIN AND DATA RATE IN THE GROUND NETWORK.

Diversity Level	Single Node (Mbit/s)	20 Nodes (Mbit/s)	Possible Gain
Signal	64.00	1280.00	Highest
Signal (packets)	**3.07**	**61.44**	**High**
Soft-Bit Values	0.31	6.14	Medium
Hard Decision Bits	0.20	4.00	Very low

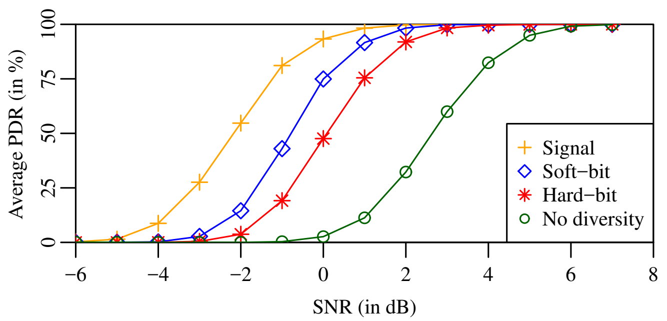


Figure 1. Simulated average PDR at different SNRs for a three-branch diversity system (AWGN channel).

A. Diversity Gain vs. Data Rate

We can distinguish a number of different options for diversity combining, each with its own advantages and drawbacks. Table I summarizes the performance and bandwidth required in the ground network when applying diversity at different levels. The receiver operates with a sample rate of five samples per symbol (relevant for signal level). A simple solution is to do all processing at ground nodes and forward only *hard bits* to a central node. Applying diversity combining at bit level minimizes traffic in the ground network and does not require co-phasing of diversity branches. However, the achievable diversity gain is also much lower as information is lost when converting to bits. In previous works [7], we studied the performance gain of diversity combining at *soft-bit* level. While this already improved reception quality, it is still not ideal as also soft-bits cannot exploit the full diversity gain. For diversity combining at a *signal level*, the complete sample stream needs to be forwarded to the central system. This would result in a data stream of 64 Mbit/s from just a single ground node. Considering a network with 20 ground nodes, this would lead to a maximum data rate of 1280 Mbit/s when all TDMA slots are used. While having complete information at signal level provides the best possible improvements, i.e., offers the maximum diversity gain, the high bandwidth demand often renders the approach unfeasible in practice.

Figure 1 compares the performance of applying diversity combining schemes at different levels of the BATS transceiver designed in [7]. Since diversity combining at *hard bits* is typically used in systems with more than two diversity branches, the PDR is simulated for a three-branch diversity system. The system uses branches with equal gain and power, and the performance is evaluated using an AWGN channel.

In the figure, *signal* corresponds to the classical EGC [12]

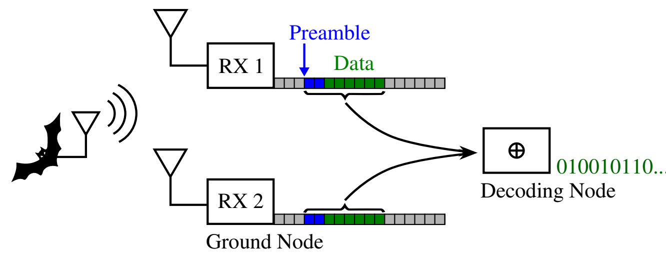


Figure 2. Overview of the BATS scenario. The transmissions from the mobile node are received by multiple SDR-based ground nodes that forward only selected signal samples to a central node for more robust decoding of the combined signal.

and yields the best performance. Its PDR improvement directly relates to the simple addition of signal powers from different branches, i.e., two branches provide an improvement of about 3 dB. Similarly, a three-branch system improves the PDR up to 4.77 dB in comparison to the *no diversity*. *Soft-bit* shows the performance achieved by combining signal copies after the conversion of signal into soft values. It is similar to Soft Equal Gain Combining (SEGC) described in [7]. The performance loss in comparison to *signal* is due to the downsampling of signals before applying diversity combining. In *hard-bit* diversity system, signals from all branches are converted into hard bits and the final decision is taken by a majority combiner same as the Post-Detection Combining (PDC) [28]. In such a case, the PDR reflects the probability that more than half of the branches recover the signal bits correctly.

B. Selective Signal Sample Forwarding

To overcome these bandwidth demands while maintaining a maximum diversity gain, we propose a novel approach that is outlined in Figure 2. The core idea is that each receiver performs signal detection locally by using a known training sequence, i.e., a preamble, and forwards signal samples equivalent to the maximum packet length only if a packet was detected. Even with the highest possible packet rate of 100 packets per second, this allows to reduce the required bandwidth by a factor of about 20 (cf. Table I). In such a system, a ground network with 20 nodes results in a maximum data rate of 61.44 Mbit/s, which is less than the data rate of a single node that forwards the complete signal stream. Diversity combining at signal level using only a subset of the samples is an attractive solution since it saves bandwidth in the ground network and maintains a high diversity gain.

If there are fewer receivers taking part in diversity combining, no tight synchronization is required as all receivers forward the packet copies as soon as they are detected. The central processor receives all copies of the same signal without any interference from the other transmissions as the protocol allows transmission of only one packet every 10 ms at maximum. In the case of diversity combining with many nodes, the network might get overloaded and require some time to process all information. Hence, tighter synchronization (equivalent to the packet length, i.e., 480 µs, which is further relaxed due to one transmission per sub-slot, i.e., 10 ms) is required for an accurate signal reception timing information at each receiver. In order to synchronize all ground nodes to the central node, we make use of the Network Time Protocol (NTP) [29]. NTP synchronizes neighboring nodes up to a few milliseconds and guarantees for accurate synchronization within a half time slot. In each slot, packet detection is done using a preamble. Once a slot is finished, the central node combines the data from all ground nodes within that slot.

Phase and frequency offsets of all signals are calculated using a preamble and compensated to combine signals constructively. The geographical position of ground nodes is crucial for the overall diversity gain. Hence, it is important to study the areas around nodes where diversity is maximized. These areas are characterized in terms of probability of detection or reception of a packet by a ground node. We discuss these areas and their effect on diversity gain in more detail in the application performance section.

IV. Diversity Gain

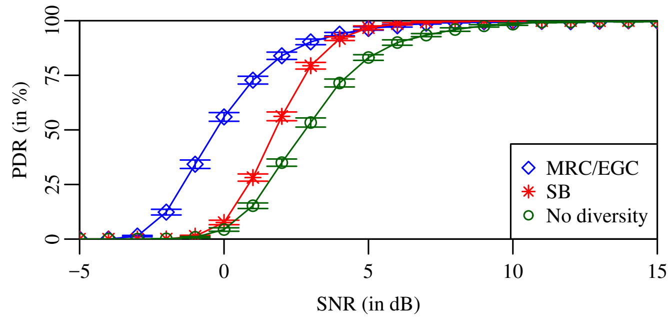
To compare the diversity gain of different diversity techniques with distributed receivers, we implemented a transceiver in the GNU Radio real-time signal processing framework. Simulations over an AWGN channel and over-the-air measurements using Ettus USRPs were performed to determine the baseline performance of these techniques.

A. GNU Radio Implementation

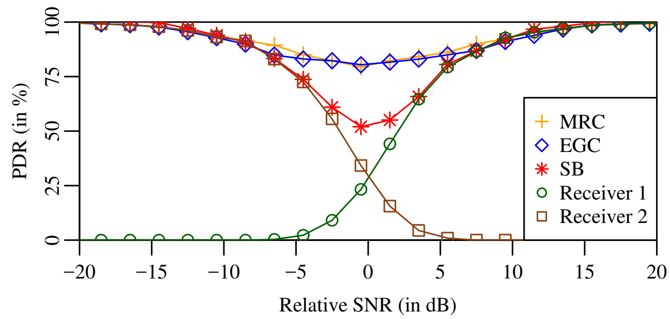
We implemented a complete transceiver for packet-based communication that sends a Differential Binary Phase-Shift Keying (DBPSK) modulated packet of 12 Byte periodically every 100 ms with a data rate of 200 kbit/s (cf. the original BATS protocol architecture [6]). The packet is composed of a preamble and start-of-frame delimiter, 1 B each. 8 B are used for data while the remaining 2 B are reserved for a Cyclic Redundancy Check (CRC). This translates into a packet length of 480 µs, which is compliant with the BATS protocol.

In the receiver, the first step is to detect packets by correlating the signal with the known preamble. In the case of detection, signal parameters such as SNR are estimated. Furthermore, phase and frequency offsets are calculated using the preamble and compensated for constructive combination of the diversity branches. Every 10 ms, i.e., the time for one transmission in our TDMA scheme, the part of the detected sample stream equivalent to the packet duration is forwarded. Signal copies from all receivers that detected the packet are combined coherently before differential decoding. Before weighing the diversity branches, we normalize them to a common noise level. We then apply weights, which we set to unity or proportional to the overall received SNR to realize EGC and MRC, respectively. Finally, we recover bits by using the Mueller and Müller clock recovery algorithm [30] and use CRC to check whether decoding was successful.

To compare these diversity techniques, we use our original network as the baseline, i.e., we check if the signal was received by any ground node on its own (here referred to as a Successful Branch (SB)). With SB, all signal processing is done locally and, in the case of successful reception, only the application data has to be forwarded to the central node.



(a) Equal SNR diversity branches



(b) Unequal SNR diversity branches

Figure 3. Simulated PDR for a two-branch diversity system (AWGN channel).

B. Simulations

We first simulated the performance of different diversity techniques in terms of PDR over an AWGN channel. Noise generated in each branch is independent, but identically distributed. Figure 3a shows the comparison of these techniques for a two-branch diversity system with 95 % confidence intervals plotted over different SNRs. All simulations were repeated 30 times. The “no diversity” case reflects the performance of a system that uses only a single branch for reception. Since the channel in these experiments does not include fading, the average SNR in both branches remains the same. In that case, the optimal combining strategy is simply adding the branches, which is why MRC and EGC yield a comparable performance. Furthermore, we use only those packets for diversity combining that are detected successfully. This lowers the potential advantage of MRC in comparison to EGC, because packets with low SNR are already dropped. Lowering the correlation threshold increases the diversity gain of MRC, but also leads to an increased false-positive rate.

Using SB is the simplest approach. It succeeds if any of the branches recovers the signal. In Figure 3a, we can see that already SB provides a performance gain of about 0.8 dB in comparison to no diversity. Applying diversity combining on signals further improves the performance up to more than 2 dB when compared with SB. With that, the overall diversity gain becomes about 3 dB than the no diversity case. Such an improvement in performance matches the theoretical results presented in [12] and, thus, validates our implementation.

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

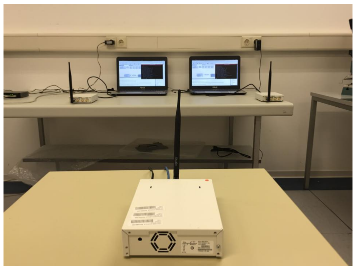
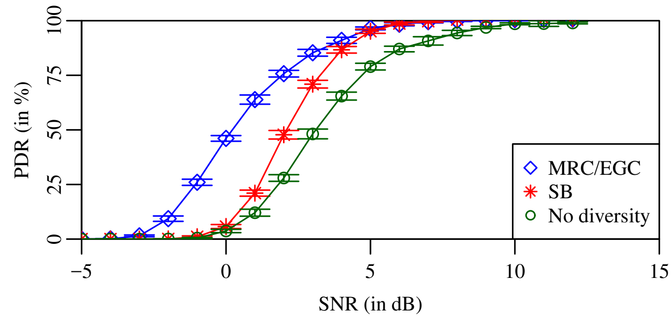
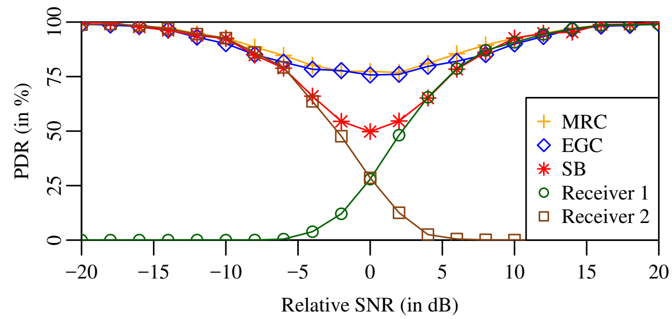


Figure 4. Lab setup for experimental study of diversity combining techniques with selective sample forwarding.



(a) Equal SNR diversity branches



(b) Unequal SNR diversity branches

Figure 5. Experimental PDR for a two-branch diversity system.

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 3b. We did not plot the confidence intervals, which are about the same size as in Figure 3a.

As expected, 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, EGC performs well and the PDR stays above 75 % for all SNRs. MRC performs only marginally better than EGC, especially when the SNR difference between diversity branches is high.

C. Measurements

To perform over-the-air measurements in a lab (similar to an office environment), we used three Ettus N210 and B210 USRP devices as shown in Figure 4. There were no obstructions between transmitter and receivers for good Line-of-Sight (LOS) communication. The measurements were performed in a static setup without any intervention, therefore, the multipath effects that arise in an indoor environment did not change throughout the measurements. In a real deployment, the noise levels of each branch would have to be normalized to achieve the maximum diversity gain. In our experiments, we manually adjusted the gains of the receiver USRPs to a common level (by selecting appropriate gain values in the software) and placed them so that they experienced the same average SNR. Finally, the devices are connected to laptop computers that orchestrated the measurements. Measurements are performed for a two-branch diversity system. Time synchronization in the network is done by configuring all laptops with NTP. To compare all considered diversity techniques under exactly the same conditions, we record the raw samples and post-process them with the various receive algorithms.

Results from these measurements are plotted for different SNRs in Figure 5a. Since USRPs are not calibrated to measure absolute powers, we shift the measurement curves to match the simulation results. It can be seen that the measurement results of all diversity schemes match perfectly with the simulations.

In an indoor environment, the SNR is not only determined by noise and the distance between transmitter and receiver; also the multipath environment might have an huge impact. Hence, it is difficult to capture measurement data for all relative SNRs between branches (like we did in simulations, cf. Figure 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 and the results are plotted in Figure 5b. Again, confidence levels are not shown for 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. EGC 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.

V. Application Performance

A. Receiver Coverage Areas

When planning a real deployment in the woods, the density of the ground nodes is an important factor. Figure 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,

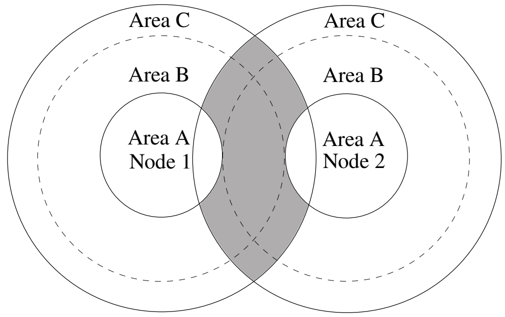


Figure 6. Schematic coverage areas around ground nodes with region where diversity gain is observed.

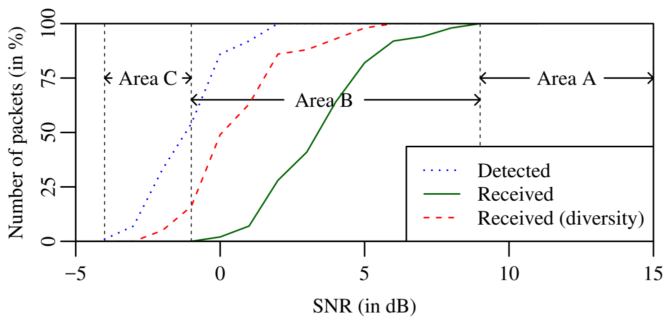


Figure 7. Packet reception rate for the different regions.

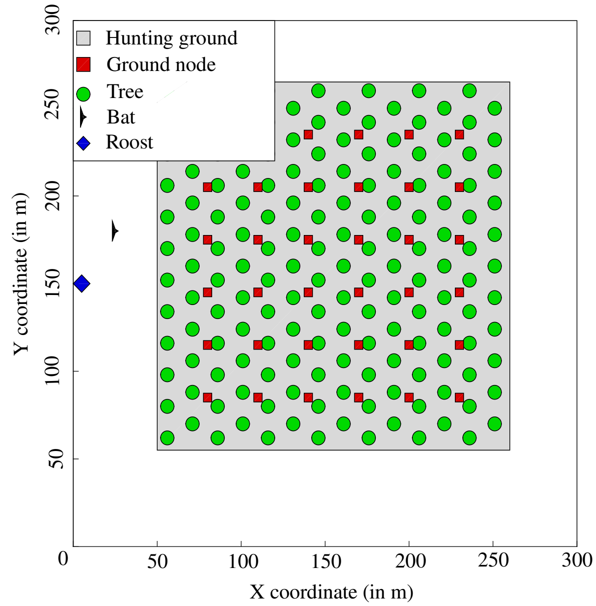


Figure 8. Overview of the scenario simulated in MATLAB.

as all packets are already received by the first node. Area B represents a region where a nodes' 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 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 initial measurements in a lab environment. The number of packets detected and received are calculated from an experiment by using a single receiver and are plotted for relative values of SNRs in Figure 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.

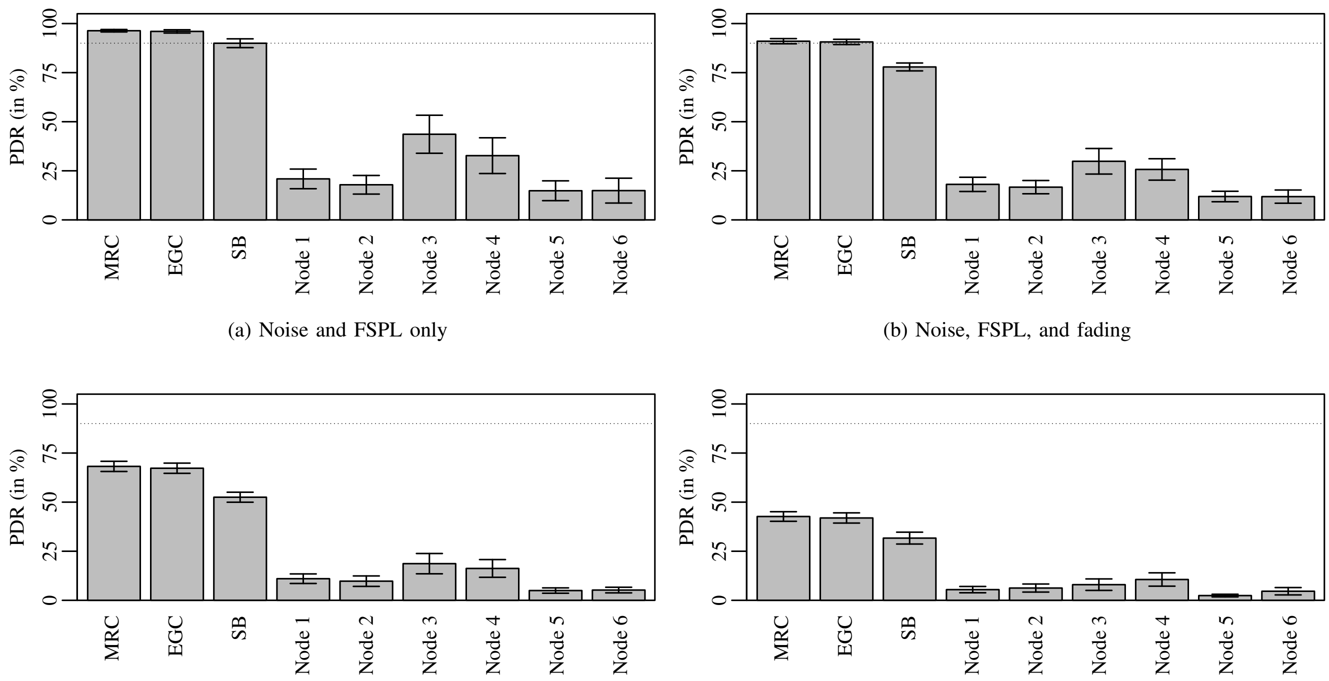
It can be seen, in area C, up to 50 % of the packets are successfully detected at a single receiver. Still, none of them are correctly received by that particular receiver. Through combining diversity branch of another similar receiver, a few of the detected packets can be received. In area B, diversity 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. This experiment is performed in a controlled lab environment where fading and other channel conditions remain 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.

B. 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 8) having 36 nodes. A bat starts its movement in the roost and flies towards the



(a) Noise and FSPL only

(b) Noise, FSPL, and fading

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

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

Figure 9. Packet delivery ratio by considering different channel effects in a small-scale scenario (six ground nodes) with a transmit power of −50 dBm.

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 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 [31]. Experiments 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 mobile 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 LOS are counted every 100 ms, i.e., every TDMA super-slot. At the end of each run, we calculate FSPL based on the distance measures, introduce shadowing for every single tree with a uniform distribution between 0 dB–5 dB [31], 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) [32] calculated for maximum speed of bats (i.e., 50 km/h) [33]. This also supports our earlier experimental observations, therefore, attenuation is calculated once per every packet during the transmissions.

C. *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 3a, it is clear that for higher SNRs, i.e., for PDRs over 90 %, the performance gain of MRC or EGC over SD is less in comparison to lower SNRs. Hence, if the required PDR is low, a huge improvement is experienced by using MRC or EGC [10]. 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 EGC is employed in presence of simple channel models (i.e., noise and FSPL). Thus, the results are easily comparable when fading and shadowing are introduced. The selected transmit power is slightly higher than the one (i.e., −52 dBm) used in [10], which achieves a PDR of only around 86 % in similar conditions. 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 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, size and shape of the coverage areas around receivers remain constant and, hence, easily provide maximum possible diversity gain. Under these channel conditions, none of the ground nodes achieves an average PDR of more than

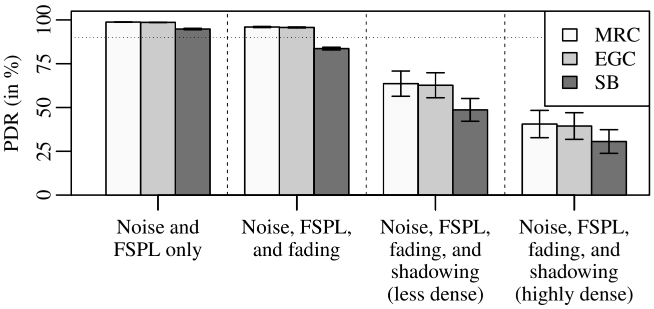


Figure 10. Packet delivery ratio by considering different channel effects in the large-scale scenario (36 ground nodes) with a transmit power of −50 dBm.

45 % alone. By considering SB, a PDR of 90 % is achieved. EGC provides an huge improvement over SB and reaches to an overall PDR of 96 %. MRC improves the performance only incrementally in comparison to EGC, however, it is still 0.4 % and 6.4 % better than EGC and SD, respectively.

These experiments were repeated using exactly the same simulation parameters, but in addition using Rayleigh fading. As shown in Figure 9b, fading does not remain constant and, hence, affects the areas around ground nodes, decreasing the overall system gain. Still, diversity combining improves the performance with a huge margin in comparison to SB. Under these channel conditions, the PDRs of all ground nodes now remain less than 30 %. Using MRC, the system achieves a performance of about 91 %. This is about 0.4 % and 13.1 % better than EGC and SB, 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 9c and Figure 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 0.9 % and 0.7 % over EGC in less dense and highly dense shadowing environments, respectively. Similarly, in comparison to SB, MRC has an improvement of 15.7 % and 11 %.

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, resulting PDR by applying considered diversity combining techniques with different channel effects are shown in Figure 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 SNR estimation is easy to implement, MRC is the perfect solution for maximum diversity gain. In some systems where SNR estimation is not that straight forward, EGC might be the better alternative. The marginal performance loss is a trade-off with system 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. A future experimental study with outdoor measurements will, therefore, provide further insights into diversity combining in final application deployments.

Table II
AVERAGE PACKET DELIVERY RATIO BY CONSIDERING A SET OF TRANSMIT POWERS WITHIN THE LARGE-SCALE SCENARIO (36 GROUND NODES).

Channel (noise plus)	**Transmit power** (dBm)	**PDR** (%) **MRC**	**EGC**	**SB**
FSPL	−50	98.8	98.6	94.8
	−47	99.9	99.9	98.9
	−44	100.0	100.0	100.0
	−41	100.0	100.0	100.0
FSPL and fading	−50	96.0	95.7	83.6
	−47	99.5	99.5	96.6
	−44	100.0	100.0	99.5
	−41	100.0	100.0	99.8
FSPL, fading, and shadowing (less dense)	−50	63.6	62.7	48.6
	−47	84.3	83.5	71.9
	−44	95.1	94.8	88.2
	−41	98.9	98.8	96.3
FSPL, fading, and shadowing (highly dense)	−50	40.6	39.4	30.6
	−47	64.9	63.8	51.4
	−44	84.2	83.6	72.9
	−41	94.6	94.2	88.2

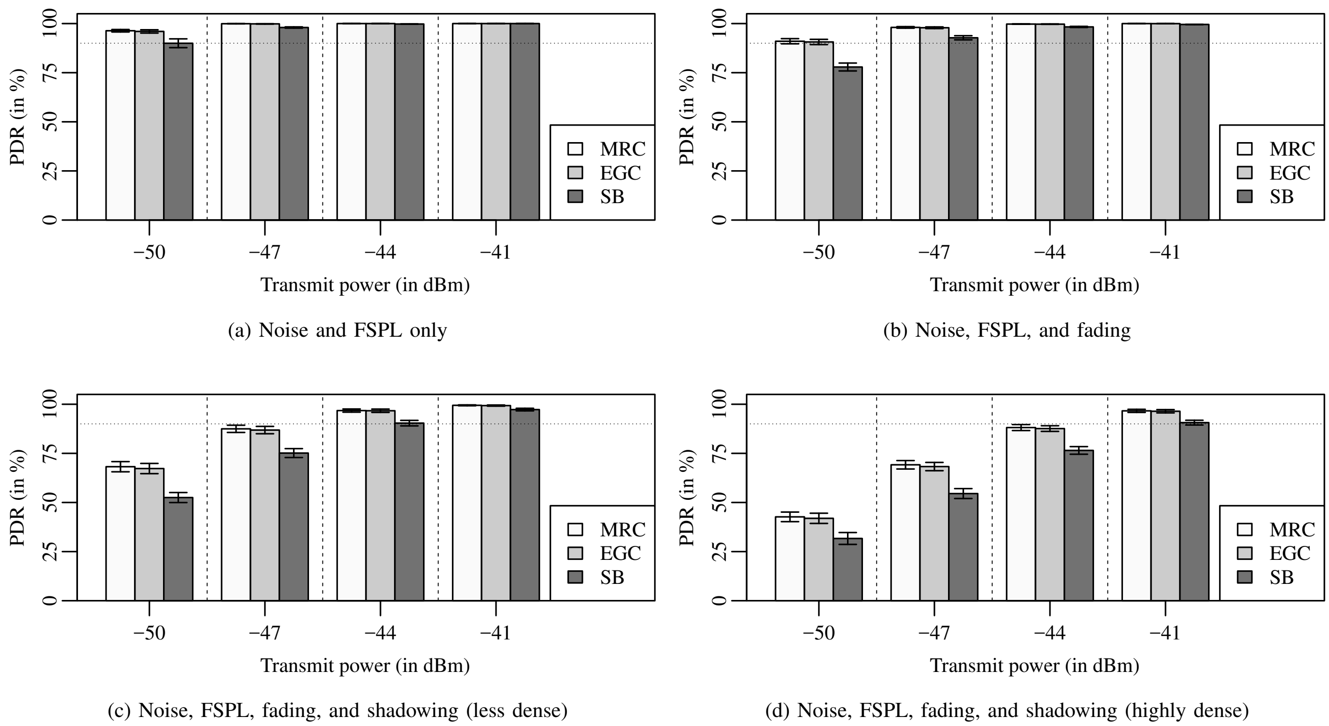
D. Transmit Power

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 mobile 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 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 plotted by repeating the experiments 30 times.

In Figure 11c and Figure 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, relatively MRC performs marginally better than EGC and provides significant improvement in comparison to SB.

A transmit power of −41 dBm reaches an average PDR of more than 90 % even in the most challenging environment.



(a) Noise and FSPL only

(b) Noise, FSPL, and fading

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

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

Figure 11. Packet delivery ratio by considering a set of transmit powers within the small scenario (six ground nodes).

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 mobile sensor node, which is currently around two weeks [26]. These plots also show the aspect discussed earlier: the higher the PDR, the lower the benefit of MRC or EGC over SB. Within one plot, the more MRC and EGC 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 II. Again, the average PDR achieved is same as observed for the small-scale scenario and, hence, shows the potential of diversity combining also on a large-scale scenario.

VI. Conclusion

In this work, we address the research challenges involved in implementing practical receive diversity for a distributed sensor network. We target wildlife monitoring as an application and propose the use of diversity combining for improved reception quality without the need to adapt the original protocol. In particular, we propose 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 forward those parts of the sample stream that actually contain the packet. We evaluated our solution using both realistic channel simulations and over-the-air experiments. With realistic channel models of noise, FSPL, fading, and shadowing, the system still provides an improvement of more than 10 % compared to the original network. 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. Future work will focus on first experiments in the wild to assess the performance in a real hunting ground of bats.

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References

[1] F. Dressler, *Self-Organization in Sensor and Actor Networks*. John Wiley & Sons, Dec. 2007.

[2] A.-J. Garcia-Sanchez, F. Garcia-Sanchez, F. Losilla, P. Kulakowski, J. Garcia-Haro, A. Rodriguez, J.-V. Lopez-Bao, and F. Palomares, "Wireless Sensor Network Deployment for Monitoring Wildlife Passages," *Sensors*, vol. 10, no. 8, pp. 7236–7262, 2010.

[3] P. Juang, H. Oki, Y. Wang, M. Martonosi, L.-S. Peh, and D. Rubenstein, "Energy-Efficient Computing for Wildlife Tracking: Design Tradeoffs and Early Experiences with ZebraNet," *ACM SIGOPS Operating Systems Review*, vol. 36, no. 5, pp. 96–107, Dec. 2002.

[4] J. A. B. Link, G. Fabritius, M. H. Alizai, and K. Wehrle, "BurrowView - seeing the world through the eyes of rats," in *8th IEEE International Conference on Pervasive Computing and Communications (PERCOM 2010), 2nd IEEE International Workshop on Information Quality and Quality of Service for Pervasive Computing (IQ2S 2010)*. Mannheim, Germany: IEEE, Mar. 2010, pp. 56–61.

[5] C. Rutz, Z. T. Burns, R. James, S. M. Ismar, J. Burt, B. Otis, J. Bowen, and J. J. S. Clair, "Automated mapping of social networks in wild birds," *Current Biology*, vol. 22, no. 17, pp. R669–R671, 2012.

[6] F. Dressler, S. Ripperger, M. Hierold, T. Nowak, C. Eibel, B. Cassens, F. Mayer, K. Meyer-Wegener, and A. Koelpin, "From Radio Telemetry to Ultra-Low-Power Sensor Networks: Tracking Bats in the Wild," *IEEE Communications Magazine*, vol. 54, no. 1, pp. 129–135, Jan. 2016.

[7] 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.

[8] Y. Tang and M. C. Valenti, "Coded transmit macrodiversity: block space-time codes over distributed antennas," in *53rd IEEE Vehicular Technology Conference (VTC2001-Spring)*. Rhodes, Greece: IEEE, May 2001, pp. 1435–1438.

[9] Y. Wang and G. Noubir, "Distributed Cooperation and Diversity for Hybrid Wireless Networks," *IEEE Transactions on Mobile Computing*, vol. 12, no. 3, pp. 596–608, Mar. 2013.

[10] 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.

[11] I. Dietrich and F. Dressler, "On the Lifetime of Wireless Sensor Networks," *ACM Transactions on Sensor Networks*, vol. 5, no. 1, pp. 1–39, Feb. 2009.

[12] D. Brennan, "Linear Diversity Combining Techniques," *Proceedings of the IRE*, vol. 47, no. 6, pp. 1075–1102, Jun. 1959.

[13] T. Eng, N. Kong, and L. B. Milstein, "Comparison of diversity combining techniques for Rayleigh-fading channels," *IEEE Transactions on Communications*, vol. 44, no. 9, pp. 1117–1129, Sep. 1996.

[14] B. Chun, "A Hybrid Selection/Equal-Gain Combining over Correlated Nakagami-m Fading Channels," *IEEE Communications Letters*, vol. 11, no. 2, pp. 161–163, Feb. 2007.

[15] S. Liu, J. Cheng, and N. C. Beaulieu, "Asymptotic error analysis of diversity schemes on arbitrarily correlated rayleigh channels," *IEEE Transactions on Communications*, vol. 58, no. 5, pp. 1351–1355, 2010.

[16] N. C. Beaulieu and A. M. Rabiei, "Linear Diversity Combining on Nakagami-0.5 Fading Channels," *IEEE Transactions on Communications*, vol. 59, no. 10, pp. 2742–2752, Oct. 2011.

[17] A. Chopra and B. L. Evans, "Outage Probability for Diversity Combining in Interference-Limited Channels," *IEEE Transactions on Wireless Communications*, vol. 12, no. 2, pp. 550–560, Feb. 2013.

[18] A. B. Sediq and H. Yanikomeroglu, "Diversity Combining of Signals with Different Modulation Levels in Cooperative Relay Networks," in *68th IEEE Vehicular Technology Conference (VTC2008-Fall)*. Calgary, Canada: IEEE, Sep. 2008, pp. 1–5.

[19] D. A. Basnayaka, P. J. Smith, and P. A. Martin, "The Effect of Macrodiversity on the Performance of Maximal Ratio Combining in Flat Rayleigh Fading," *IEEE Transactions on Communications*, vol. 61, no. 4, pp. 1384–1392, Apr. 2013.

[20] J. Laneman, D. Tse, and G. Wornell, "Cooperative Diversity in Wireless Networks: Efficient Protocols and Outage Behavior," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[21] M. C. Valenti and N. Correal, "Exploiting macrodiversity in dense multihop networks and relay channels," in *IEEE Wireless Communications and Networking Conference (WCNC 2003)*, vol. 3. New Orleans, LA: IEEE, Mar. 2003, pp. 1877–1882.

[22] G. A. Conway, S. L. Cotton, and W. G. Scanlon, "An Antennas and Propagation Approach to Improving Physical Layer Performance in Wireless Body Area Networks," *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 1, pp. 27–36, Jan. 2009.

[23] L. Vallozzi, P. V. Torre, C. Hertleer, H. Rogier, M. Moeneclaey, and J. Verhaevert, "Wireless Communication for Firefighters Using Dual-Polarized Textile Antennas Integrated in Their Garment," *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 4, pp. 1357–1368, Apr. 2010.

[24] K. Sasloglou, I. A. Glover, K.-H. Kwong, and I. Andonovic, "Wireless sensor network for animal monitoring using both antenna and base-station diversity," in *11th IEEE Singapore International Conference on Communication Systems (ICCS 2008)*. Guangzhou, China: IEEE, Nov. 2008, pp. 27–33.

[25] M. Herlich and H. Karl, "Reducing Power Consumption of Mobile Access Networks with Cooperation," in *2nd International Conference on Energy-Efficient Computing and Networking (e-Energy '11)*. New York, NY: ACM, May 2011, pp. 77–86.

[26] F. Dressler, B. Bloessl, M. Hierold, C.-Y. Hsieh, T. Nowak, R. Weigel, and A. Koelpin, "Protocol Design for Ultra-Low Power Wake-Up Systems for Tracking Bats in the Wild," in *IEEE International Conference on Communications (ICC 2015)*. London, UK: IEEE, Jun. 2015, pp. 6345–6350.

[27] F. Dressler, M. Mutschlechner, B. Li, R. Kapitza, S. Ripperger, C. Eibel, B. Herzog, T. Hönig, and W. Schröder-Preikschat, "Monitoring Bats in the Wild: On Using Erasure Codes for Energy-Efficient Wireless Sensor Networks," *ACM Transactions on Sensor Networks*, vol. 12, no. 1, 2016.

[28] C. Tepedelenlioglu and P. Gao, "On diversity reception over fading channels with impulsive noise," *IEEE Transactions on Vehicular Technology*, vol. 54, no. 6, pp. 2037–2047, Nov. 2005.

[29] D. L. Mills, "Internet Tme Synchronization: the Network Time Protocol," *IEEE/ACM Transactions on Networking (TON)*, vol. 39, no. 10, pp. 1482–1493, Oct. 1991.

[30] K. Mueller and M. Müller, "Timing Recovery in Digital Synchronous Data Receivers," *IEEE Transactions on Communications*, vol. 24, no. 5, pp. 516–531, May 1976.

[31] 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.

[32] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Prentice Hall, 2009.

[33] R. Arlettaz, "Feeding behaviour and foraging strategy of free-living mouse-eared bats, Myotis myotis and Myotis blythii," *Animal Behaviour*, vol. 51, no. 1, pp. 1–11, 1996.

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