Selective Signal Sample Forwarding for Receive Diversity in Energy-Constrained Sensor Networks

Muhammad Nabeel, Bastian Bloessl and Falko Dressler
Heinz Nixdorf Institute and Dept. of Computer Science, University of Paderborn, Germany
{nabeel,bloessl,dressler}@ccs-labs.org

***Abstract*—Receive diversity increases the reliability and robustness of ultra-low power Wireless Sensor Networks (WSNs) by using spatially separated antennas without modifying the physical layer. 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 that limits the energy budget available for communication. In this work, we exploit the distributed nature of the ground network to employ diversity combining, i.e., we use the ground nodes as a geographically distributed multi-antenna array. However, this causes several research challenges given the limited bandwidth between nodes and the need for accurate synchronization to combine signal copies constructively at a central node. Sending all signal samples from all ground nodes to the central node is prohibitive due to the required data rates in the network. As a novel concept, we propose a system that only forwards selected signal samples belonging to a packet with high probability. We study the performance in simulations as well as in a testbed using a Software Defined Radio (SDR) prototype implementation. Our results clearly indicate a substantial performance gain while keeping the data rate in the ground network in a feasible range.**

I. Introduction

Wireless Sensor Networks (WSNs) are playing a vital role in wildlife monitoring [1], [2]. In the BATS[1] project, we target mouse-eared bats (*Myotis myotis*) and equip them with a sensor node (here referred to as a mobile node) to study their social and foraging behavior [3]. 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, contact information is stored and needs to be transmitted to a ground network 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, i.e., triggered by a wake-up receiver, the mobile nodes are supposed to transmit all saved information to the ground network.

The communication channel is greatly affected due to several factors such as multipath fading and shadowing. Hence, we exploit the distributed nature of ground network and propose the use of diversity combining for enhanced Packet Delivery Ratio (PDR). However, this poses several research challenges such as required synchronization in the ground network, forwarding data with limited bandwidth link from ground nodes to a central node, and the need for continuous phase and frequency offsets tracking for coherent combining. Most of these challenges do not arise in conventional diversity combining, which uses multiple antennas mounted on a single receiver. Similar ideas are used in macro-diversity [4], 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 [5]. However, this reduces the overall diversity gain since information is lost when converting the signal into soft values before applying diversity combining.

In this work, we go one step further and propose 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. We also address all issues arising from practical diversity combining at distributed receivers including synchronization and phase correction. We implemented multiple diversity combining techniques in the GNU Radio Software Defined Radio (SDR) platform and also compared the performance of the distributed diversity system to decoding at each receiver separately. We are able to show a substantially increased diversity gain coming with only a marginal trade-off in system complexity. To study application performance, we implemented a bat mobility model in MATLAB and conducted simulations of a complete deployment. In these simulations, we consider channel effects like Free Space Path Loss (FSPL) and fading to evaluate our system in a realistic environment.

Our main contributions can be summarized as follows:

- We present a solution to use a distributed sensor network as a distributed antenna system for applying receive diversity algorithms in a wildlife monitoring scenario.
- We propose a novel technique for selecting relevant parts of the signal sample stream to be forwarded to a central entity applying diversity algorithms at signal level.
- We implemented the system both in simulation and a SDR-based lab setup to investigate the overall performance gain of our solution.
- We present first results indicating a substantial gain in the overall packet delivery rate while keeping the data rate in the ground network at an acceptable rate.

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

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) [6]. Of all these, MRC is considered to be the best combining technique, while SD provides least diversity gain with reduced complexity. A detailed comparison of these techniques when using multiple antennas at a receiver is presented in [7]. By combining SD and EGC, a hybrid diversity technique is also proposed in which the performance is close to MRC with only incremental complexity [8]. If the 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 [4], [5]. 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.

The idea of applying diversity at distributed receivers, e.g., in cellular networks, is well studied in the literature [4], [5]. 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 [9]. However, the diversity gain still reduces because of the conversion of signal into soft values [10]. Moreover, symbol-error-rate for MRC in macro-diversity is analyzed in [11], but there is still a need of practical considerations.

The position of receivers is important to maximize performance and to optimize the coverage area [4]. 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

Conceptually, our protocol works like this [12]: Each mobile node stores contact information with other nodes when not in radio communication range of a ground network. 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 required to transmit all stored contact information. An uplink communication begins when this wake-up receiver is woken up by a continuously transmitted signal from ground nodes. The ground nodes use a Time Division Multiple Access (TDMA) scheme to avoid collisions from multiple bats in range. 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 transmission power of 10 dBm by using a short burst signal of 12 B. 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 from all ground nodes 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 signal from different nodes constructively.
- Optimal placement of ground nodes to achieve maximum diversity gain.

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 of a receiver that operates with a sample rate of five samples per symbol (relevant for signal level). An easy 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 work [10], 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.

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 1. 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

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

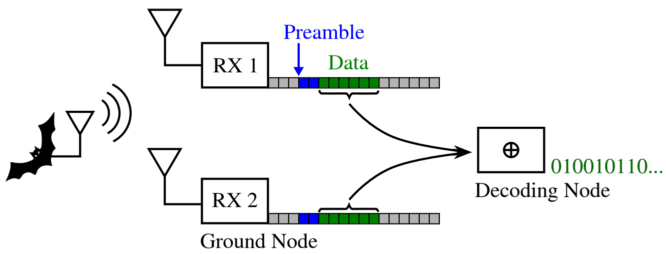

Figure 1. Overview of the BATS scenario. The transmissions from the mobile node are received by multiple SDR-based ground nodes that forward only selected signal samples to a central node for more robust decoding of the combined signal.

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.

Tight synchronization of the receivers within one packet duration (i.e., 480 µs) is required to combine the received signals. However, this condition is relaxed as the protocol allows transmission of only one packet every 10 ms at maximum. In order to synchronize all ground nodes to the central node, we make use of the Network Time Protocol (NTP) [13]. 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 received 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 achieved by different diversity techniques in distributed receivers, we implemented a transceiver in the GNU Radio real-time signal processing framework. Simulations over an Additive White Gaussian Noise (AWGN) channel and over-the-air measurements were performed for a 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. 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 and is compliant with the BATS protocol.

In the receiver, the first step is to detect packets by correlating the signal with a known preamble. In case of detection, signal parameters such as signal-to-noise ratio (SNR) are estimated. Furthermore, phase and frequency offset 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. We recover bits by using Mueller and Müller clock recovery algorithm [14]. Before weighing the diversity branches, we normalize them to a common noise level. We then apply a gain, which we set to unity or to the square root of received SNR to realize EGC and MRC, respectively. Finally, the CRC is used 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 case of successful reception, only the application data has to be forwarded to the central node.

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 2 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 the same 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 2, 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 [6] and, thus, validates our implementation.

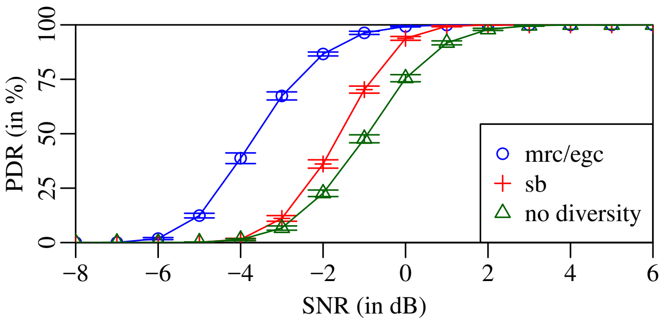

Figure 2. Simulated PDR for a two-branch diversity system (AWGN channel).

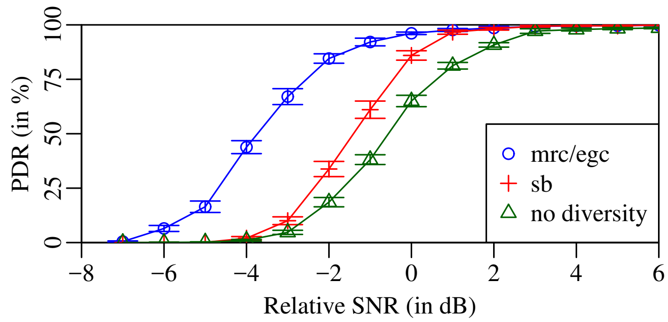

Figure 4. Experimental PDR for a two-branch diversity system.

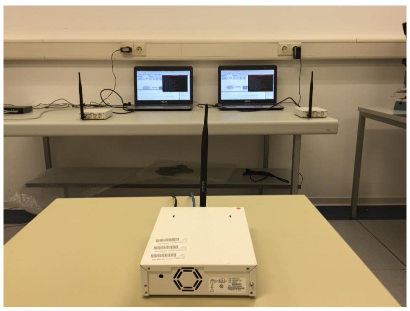

Figure 3. Lab setup for experimental study of diversity combining techniques with selective sample forwarding.

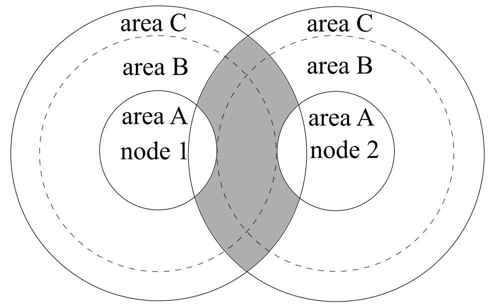

Figure 5. Schematic coverage areas around ground nodes with region where diversity gain is observed.

C. Measurements

To perform over-the-air measurements, we used three Ettus N210 and B210 USRP devices as shown in Figure 3. In practice, the noise levels of each branch are normalized for maximum diversity gain. In our experiments, we manually adjusted the gains of the USRPs to a common level 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 same conditions, we record the raw sample data. The recorded data is then post-processed with the various receive algorithms.

Results from these measurements are plotted for different SNRs in Figure 4. 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 reflect same performance obtained from simulations and the curves perfectly match for all the considered techniques.

These results show the baseline performance of the different techniques in a simplified scenario. EGC provides the improvement of about 3 dB 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 diversity 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.

V. Application Performance

A. Receiver Coverage Areas

When planning a real deployment in the woods, the density of the ground nodes is an important parameter. Figure 5 depicts a simplified model of the coverage areas of a node. Area A shows a region around node where the probability of detecting and receiving is essentially 100 %. If another node is placed within that region, it provides no advantage of diversity gain as all packets are already received by a single node. Area B represents a region where the probability of receiving packets for a single node is between 0 %–100 %. If the overlap of these regions is maximized, the diversity gain is maximized. The outer most area C is defined by an area in which there is no probability for a single node to successfully receive any packet, however, some of the packets can still be detected and made useful with 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, however, there would be a higher chance of false positives. If ones 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 envi-

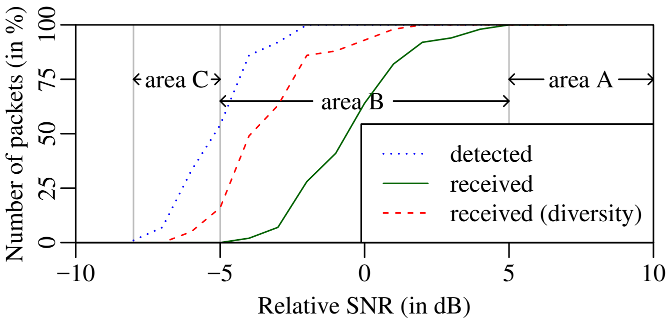

Figure 6. Packet reception rate for the different regions.

ronment. 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 6. The regions that are observed around a receiver are highlighted. Moreover, diversity combining is performed by including another receiver to explain the idea. In case of diversity, increasing SNR directly corresponds to increase in overlapping of coverage areas between receivers.

It can be seen, in area C, up to 50 % of the packets are successfully detected at a single receiver, however, none of them is correctly received by using the same single receiver. By using another receiver with the same characteristics, a few of the detected packets can be received through diversity combining. In area B, diversity combining provides a great improvement in successful reception when a single receiver has already some probability, i.e., between 0 %–100 % to receive a packet. Area A is useless for diversity combining as a single receiver already receives all of the packets successfully without performing any diversity.

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. This experiment is performed in a controlled lab environment where fading and other channel parameters 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 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 a two-dimensional bat mobility model as discussed in [15], we simulate a complete ground network. The simulation scenario has a total size of $200\,\mathrm{m} \times 200\,\mathrm{m}$, including a $120\,\mathrm{m} \times 120\,\mathrm{m}$ hunting ground (cf. Figure 7). The hunting

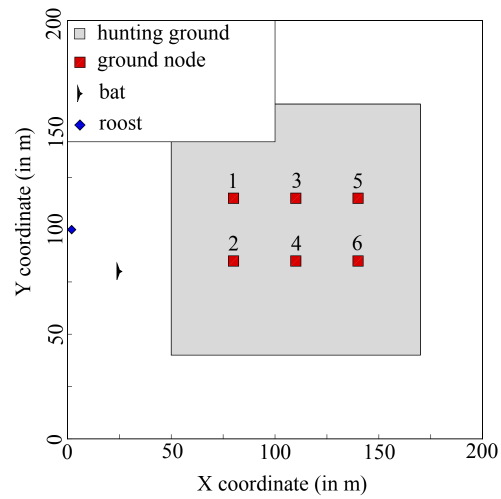

Figure 7. Overview of the scenario simulated in MATLAB.

ground is composed of six nodes, forming a grid with inter-distance of 30 m. A bat 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 [15]. 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 every 100 ms, i.e., every TDMA super-slot. At the end of each run, we calculate FSPL based on the distance measures and apply flat Rayleigh fading. These channel values are then imported into our GNU Radio implementation, where we attenuate the signal accordingly.

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 transmission power to maximize the overlap of area B when considering noise and FSPL only. The PDR for different diversity techniques with confidence intervals obtained by repeating the whole experiments 30 times are shown in Figure 8. The PDRs are calculated for all involved ground nodes separately as well as for the different diversity combining techniques.

By considering channel parameters such as noise along with FSPL only, size and shape of the coverage areas around receivers remain constant and, hence, provide maximum possible diversity gain. None of the ground nodes achieves an average PDR of more than 30 % alone with these channel parameters. By considering the simplest approach SB, the overall PDR reaches up to a 64.4 %. When using EGC, a huge improvement is experienced. In that case, diversity increases the performance as much as up to 86.3 %. MRC improves the performance only incremental in comparison to EGC, i.e., 0.3 %, however, is 22.2 % better than SB.

These experiments were repeated using exactly same simulation parameters, but adding Rayleigh fading. The results are plotted in Figure 9. Fading does not remain constant and, hence, affects the areas around ground nodes. This

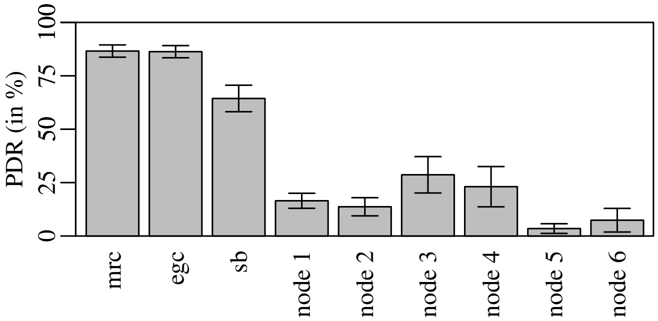

Figure 8. Packet delivery ratio by considering noise and FSPL only.

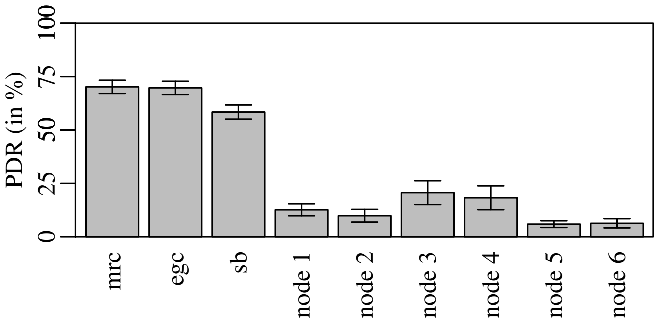

Figure 9. Packet delivery ratio by considering noise, FSPL, and fading.

decreases the system performance, however, using diversity combining still improves the performance with a huge margin in comparison to SB. With these channel parameters, the PDR of all ground nodes remain less than 20 %, while using MRC the system achieves a performance of about 70 %. This is about 0.5 % and 12 % better than EGC and SB, respectively.

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. In a real scenario, there will be some additional factors such as shadowing affecting channel quality and, thus, the interested areas around ground nodes. A future experimental study with outdoor measurements will, therefore, provide further insights into diversity combining in final application deployments.

VI. Conclusion

In this paper, we address the research challenges involved in 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 for performing 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 parameters such as noise, FSPL, and fading, the system still provides an improvement of 12 % compared to the original network. Furthermore, we have developed a model that helps to dimension distributed diversity systems by selecting optimal receiver positions to maximize the diversity gain. Future work will focus on first experiments in the wild to assess the performance in a real hunting ground of bats.

Acknowledgements

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