Low-Complexity Soft-Bit Diversity Combining for Ultra-Low Power Wildlife Monitoring

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***Abstract*—Diversity combining is a popular technique to increase the robustness of wireless communications. Multiple independent paths are needed for successful combining to recover a signal; which is particularly helpful in fading scenarios. Typically, this is achieved using multiple, sufficiently spaced apart antennas at a single receiver. We consider a Wireless Sensor Network (WSN) to monitor bats in the wild by equipping them with sensor nodes weighing only 2 g and, therefore, having very tight energy budgets. A distributed ground network is used to receive the signals from bats at multiple nodes. We propose to exploit the distributed nature of these receivers to cooperatively decode the received signal. This scenario poses a number of research challenges related to the necessary synchronization of the receivers as well as the very limited energy budget at the nodes. To optimize link utilization in the ground network, we study the performance of low-complexity soft-bit diversity and unequal gain combining for robust packet-based communication. To assess the performance of diversity combining strategies, we conduct simulations and measurements using MATLAB as well as a Software Defined Radio (SDR)-based prototype. Finally, our application-specific diversity techniques are adapted to provide a more general solution.**

I. Introduction

Wireless Sensor Networks (WSNs) are widely used for wildlife monitoring to study individuals over long period of time without any human interruption [1], [2]. In the BATS[1] project, we are developing a WSN to support biologists studying foraging behavior and social interactions of bats (mouse-eared bats, *Myotis myotis*) [3]. A sensor node (here referred to as a mobile node) of only 2 g is used for monitoring the target species because of their restricted body weight. The nodes continuously exchange contact information with other mobile nodes. For tracking and for uploading contact information, a ground network is used, composed of multiple stationary ground nodes (here referred to as base nodes) deployed in the hunting areas of the bats. If a mobile node is in communication range of at least one of these base nodes, which happens on an irregular basis, it is supposed to upload stored information.

The ground network is deployed in a foliage environment where the system faces adverse multipath fading and shadowing effects. The continuous motion of mobile nodes during transmission makes the channel also highly time varying. Thus, the Packet Delivery Ratio (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 mobile nodes. In previous work, we investigated the use of Forward Error Correction (FEC) using fountain codes [4] to improve the communication reliability, which is still not at a sufficiently high level. Novel solutions are needed to overcome these limitations.

Space/antenna diversity is one of the most effective techniques, which makes use of spatially separated antennas to combat fading in challenging wireless environments [5], [6]. A conventional diversity receiver aligns the phases of all signals and combines them before converting into bits, which, however, is more complex due to the necessary phase alignment. Hence, combining signals at a signal level requires more processing power. Performing diversity on bits greatly reduces the system complexity [7]. Signals received on different branches are processed separately and diversity is applied when they are already converted into bits. Such a diversity does not require any phase alignment and is usually implemented for Differential Phase-Shift Keying (DPSK) with differential detection. Diversity on bits can be performed by computing hard bits at each branch and then taking a decision by majority combining [8]. However, this solution is not optimum because of losing soft information, therefore, diversity is observed before computing hard bits by combining signals at a soft-bit level from different branches. In most cases, the performance of diversity combining at bits is slightly worse than the conventional diversity combining [7], [8]. Furthermore, when applying any type of diversity, it is frequently assumed that all branches provide equal noise power [5]. However, the use of automatic-gain-control (AGC) breaks this assumption and can degrade the performance [9], [10].

This work exploits 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 base nodes as distributed single antenna receivers. We thus envision to use the ground network as a distributed antenna array on physically separated receivers. This certainly creates new challenges such as the necessary synchronization of all base nodes. This idea is similar to a macroscopic diversity that is used for different applications where the architectural requirements, communication protocol, and packet structure is different compared to the BATS project (e.g., diversity techniques in cellular networks for minimizing shadowing effects [11]).

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

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In this paper, we study low-complexity soft-bit diversity techniques and the effect of unequal gain branches in the wildlife monitoring scenario. As all data needs to be transmitted to a central node for diversity combining, this also reduces the load in the network. Transmitting signal rather than bit samples would be prohibitive in the wireless ground network due to link limitations. We investigate the performance using both a MATLAB simulation model and a Software Defined Radio (SDR) prototype.

Our main contributions can be summarized as follows:

- We investigate different low-complexity soft-bit diversity techniques for their applicability in our low-power communication scenario.
- We implemented all studied diversity combining techniques in an SDR prototype along with a MATLAB simulation model for bat mobility.
- We particularly study the effect of unequal gain receivers for packet-based communication.
- We evaluate the resulting performance in terms of PDR through simulations and lab measurements.

II. Related Work

The idea of using space diversity by aligning the phases and combining all signals received on different branches has been well studied in the literature [5], [6]. The most widely used diversity techniques are Selection Diversity (SD), Equal Gain Combining (EGC), and Maximum Ratio Combining (MRC). There also exists hybrid diversity techniques in which SD and EGC are combined; the resulting performance is better and the complexity is only marginally increased [12], [13].

SD is considered to be the most simple one of all these techniques: the branch with highest signal-to-noise ratio (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 unity or according to their individual SNR, respectively. Using MRC, inaccurate SNR estimation degrades diversity performance. 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.

Diversity at bit level uses the same combining techniques as used by the conventional diversity but requires less processing overhead. Soft-Bit Maximum Ratio Combining (SBMRC) performs 2 dB better than SD without any bandwidth loss or extra channel information [7]. It has also been shown that in presence of impulsive noise, diversity at bits outperforms [8]. Recently, Priority Maximum-Ratio Combining (PMRC) and Post Soft-Demodulation Combining (PSDC) techniques have been proposed for distributed diversity in cellular wireless networks [14]. Again, equal noise power receivers have been considered.

Performing diversity at bit level might suit well when using distributed diversity without AGC. However, since the implementation of AGC is needed to cover dynamic range of the input signal at the receiver, gains differ between branches. For two-branch conventional diversity systems, a gain imbalance of 10 dB degrades the overall performance up to about 3 dB when using MRC and EGC, and degrades much faster in case of SD [9]. For postdetection SD, the degradation is 1.5 dB with gain imbalance of 3 dB in presence of Additive White Gaussian Noise (AWGN) [10]. In our scenario, limitations of the system ask for simple dedicated diversity techniques, which also mitigate the effect of these unequal branch gains.

III. System Model

A. BATS Diversity Technique

In practice, channel estimation is one of the most difficult tasks of the receiver. Imperfect estimation of the channel degrades the overall diversity gain. Unlike MRC, EGC does not rely on estimation of fading amplitudes and is less complex to implement. However, the system performance is still affected due to gain imbalances between different diversity branches. In some cases, a branch with high noise power adds more noise to the resulting signal reducing the overall SNR. Therefore, there is a need of a diversity technique, which cope with gain imbalances between different branches without introducing too high complexity. When using soft-bit diversity, the signal is at a bit level and, hence, it is easy to take a bit decision. This property helps checking whether the received signal can be recovered from a diversity branch before combining. Such a technique improves the diversity gain by increasing the complexity only marginally. We discuss this technique in more detail in the following.

In each diversity branch, the received data is correlated against a known sequence (such as a preamble) for detecting the signal. In case of detection, the incoming data is normalized and fed into a clock recovery algorithm to calculate a soft-bit value. The clock recovery algorithm produces one soft value per symbol. Finally, a bit decision is applied after differential phase detection for decoding purposes. A Cyclic Redundancy Check (CRC) is used to check whether decoding was successful or not. If the received data is correctly decoded, hard decision bits are forwarded to a main unit (here referred to as the central node). Otherwise, soft-bit information is forwarded.

The central node receives data from all diversity branches and processes them for final decisions. If correctly decoded data (hard-bits) is received from any of the branches, the rest of the signals are simply discarded. In case of unsuccessful decoding from all branches, they are all combined with equal gain at a soft-bit level. Finally, the CRC is used to check if combining recovered the signal successfully.

Checking for a Successful Branch (SB) that already decoded the signal is more reliable than SD as it does not rely on SNR. Combining SB with Soft Equal Gain Combining (SEGC) performs better than SEGC alone because combining is only done when all of the branches fail to recover received signal. Since combining is done with equal gains, the performance is improved by increasing only marginal complexity. It is shown later that this low-complexity combined diversity technique retains the advantage of SB as well as of SEGC and outperforms both even when there is a gain imbalance.

B. Network Architecture and Synchronization

The ground network is deployed in hunting areas of the bats. It consists of multiple base nodes distributed throughout the hunting ground. These base nodes have a distance of approximately 30 m between each other and are connected to a central node via a wireless link. The complete protocol for uplink communication from mobile nodes to the ground network is described in [15]. A Wake-Up Receiver (WuRx) is employed on the mobile nodes to coordinate with the ground network for communication. The base nodes in the ground network have no strict energy limitations and periodically transmit a wake-up signal. Whenever a mobile node enters in the communication range of a ground network, the WuRx is woken up by those signals and the uplink communication is initiated. Moreover, the ground network is responsible for timing control during communication and uses Time Division Multiple Access (TDMA) scheme to support multiple mobile nodes without collision. In this TDMA scheme, a mobile node selects a fixed-length time slot after it is woken up. Then it transmits a short burst signal in the selected slot of 10 ms within a super-slot of 100 ms, i.e., supporting up to 10 bats within radio communication range. A mobile node transmits with a data rate of 200 kbit/s and has a transmission power of only 10 dBm. At a carrier frequency of 868 MHz this results in a maximum distance of 50 m.

Strict time synchronization is required between base nodes in order to successfully apply the proposed BATS diversity technique. For this purpose, we propose the use of the Network Time Protocol (NTP). NTP synchronizes all base nodes up to a level of a few milliseconds.

If a signal is detected at a base node, it is processed and converted into a baseband. Data equivalent to the packet length is forwarded to a central node after the end of each time slot. As the time slots are roughly synchronized, the central node receives data from all distributed base node receivers that detected the signal in the respective slot. The central node then synchronizes all the packets to apply diversity combining.

IV. Experimental Details

We implemented the BATS diversity technique in a GNU Radio SDR prototype. Simulations and measurements are performed to evaluate the performance of a two-branch diversity system. To realize real channel impairments, we further realized a realistic bat mobility model in MATLAB. This simulation model includes a ground network with multiple base nodes. For realistic signal propagation models, we used the MATLAB results and imported these in GNU Radio when running in simulation mode in order to evaluate the overall application performance.

A. MATLAB Simulation

We use a simple two-dimensional bat mobility model as described in [4] to generate realistic channel values. We always simulated a single bat to avoid collisions. The total size of simulation area is 200 m×200 m. It consists of a 120 m×120 m hunting ground. Six base nodes are present in the hunting ground with inter-node distances of at least 30 m. Trees are present throughout the hunting ground spaced from 3 m–5 m. The scenario is shown in Figure 1. For clarity, the dimensions are not exactly scaled in the figure.

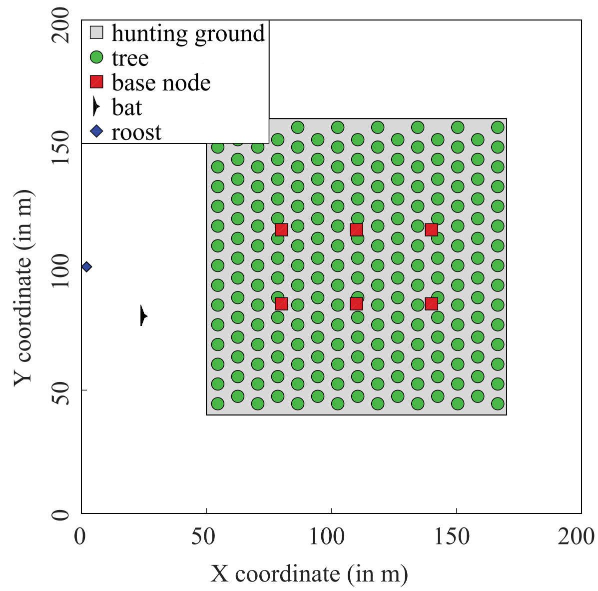


Figure 1. Overview of the simulated BATS scenario.

Table I
Bat mobility pattern.

Movement Pattern	Speed	Until
Towards hunting ground	30 km/h–50 km/h	reaching hunting ground
Search of prey	15 km/h–35 km/h	capturing a prey
Prey capturing	0 km/h	0.5 s–1 s
Prey consumption	15 km/h	10 s–20 s
Resting	0 km/h	1 s
Return to roost	30 km/h–50 km/h	roost is reached

For each simulation, the bat starts its movement in the simulation from a same roost. At first, the bat moves towards the hunting ground within a defined speed. Upon reaching there, it slow downs in search for a prey and stops for capturing a prey. To consume the prey, bat follows a circular path with a radius of 2 m–4 m. After consuming, it finally goes back to the roost. All mobility model parameters are detailed in Table I.

The mobile node transmits a packet every 100 ms when in the hunting ground, i.e., after receiving the wake-up signal. We use a channel model incorporating receiver noise and Free Space Path Loss (FSPL) only. Noise is generated as thermal noise calibrated to the receiver noise figure of the USRP B210 hardware platform. FSPL is realized by calculating the distance between mobile node and each base node at the time of transmission. There can be other effects such as fading and shadowing from trees, however, we do not consider them for the ease in this work.[2] Finally, the channel values are imported to GNU Radio model for further processing.

[2]Please note that we have exact shadowing measurements from our previous work but tried to keep the model as simple as possible to better understand the effects of diversity combining in this paper.

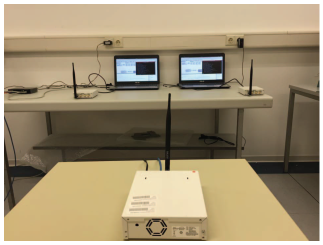


Figure 2. Lab measurement setup consisting of three Ettus USRP devices.

B. GNU Radio SDR Implementation

We have implemented a two-branch diversity system that involves packet-based communication in GNU Radio. The system consists of a transmitter and two receiver links. Transmitter periodically sends a packet every 100 ms within its time slot. The packet is of 12 B including 1 B of preamble and 1 B of start of frame delimiter. Each packet contains 8 B of data and a 2 B CRC. The data is Differential Binary Phase-Shift Keying (DBPSK) modulated and transmitted at a rate of 200 kbit/s. Such a packet translates into 480 µs and complies with the BATS protocol for uplink communication [15].

Each branch from the transmitter to a receiver is modeled as an AWGN channel. Noise in each branch is independent and uncorrelated from the other. We further extended the system to a six-branch diversity additionally with channel attenuation values imported from MATLAB. For unequal gain experiments, a constant is multiplied to scale the received signal and noise power at each receiver. After receiving a signal, each branch detects the packet by using a start of frame delimiter and downsamples it. The performance of soft-bit diversity system greatly depends upon the receiver implementation. We use the Mueller and Muller clock recovery algorithm [16] to recover bits before differential detection. If a packet is detected, it is differentially decoded and forwarded. At the end of every 10 ms time slot (i.e., the TDMA window per mobile node), the receiver applies a diversity technique.

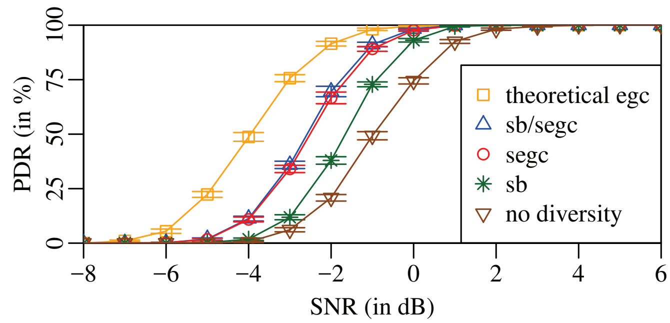
C. Experimental Setup

Real over-the-air measurements were performed in a controlled lab environment using our SDR implementation. We used three Ettus B210 and N210 USRP devices connected to laptop computers as shown in Figure 2 to perform the measurements. The gain settings of the devices were calibrated to provide desired average noise powers. The locations of the devices were chosen to achieve the required relative SNR. Measurements were conducted for the two-branch diversity system. All the laptops were configured with NTP for time synchronization. We recorded soft-bit data from both receiver laptops along with the time stamps. This data is then processed offline to apply a variety of diversity combining techniques.

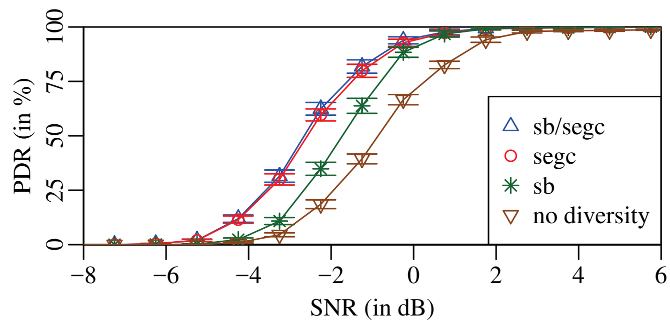
V. Results and Discussion

A. Equal Gain

In a first set of experiments, we have simulated different diversity techniques and compared the performance in terms of PDR for a two-branch diversity system. We did not consider MRC due to its computational complexity. Also, EGC performs only marginal inferior to MRC and is simple to implement in practical systems.



(a) Simulations over an AWGN channel

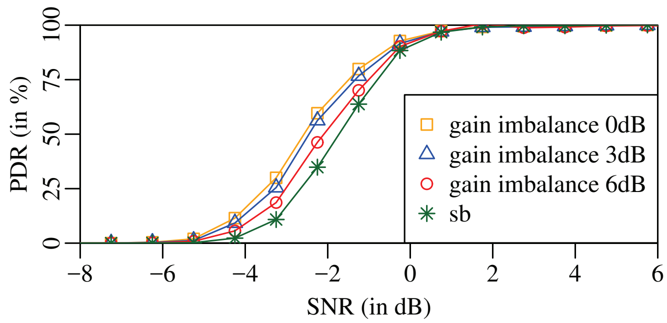


(b) Experiments in a lab environment

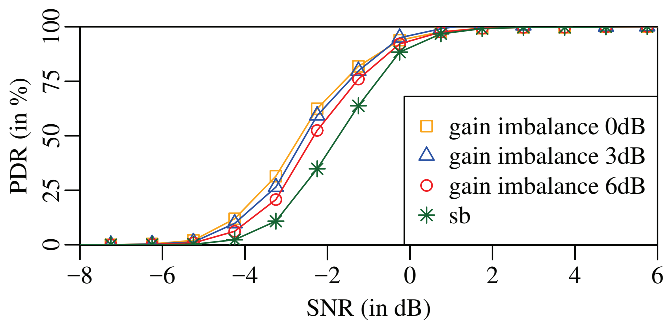
Figure 3. Packet delivery ratio for a two-branch diversity system with equal gains.

Figure 3a shows the comparison with 95 % confidence intervals for different SNRs in presence of an AWGN channel. Noise in each branch is independent and uncorrelated from the other, however, the average noise power is the same. Average SNR across both branches is also the same, hence, the "no diversity" case reflects the performance of each receiver itself. The performance of these diversity techniques is also compared with a theoretical EGC. The theoretical EGC is obtained by shifting the curve of no diversity by 3 dB. It also represents the maximum diversity gain which can be achieved by conventional EGC without any combining losses [5]. All relevant steps for practical use were applied including preamble detection in each diversity branch and synchronization of packets for combining at the main receiver.

With our implementation, SEGC performs about 0.8 dB better than SB and 1.6 dB better in comparison to when using no diversity at all. The performance benefit of SEGC over SB becomes less pronounced for very high SNRs because the signal quality is already good enough to recover the packets without combining. When comparing with combined diversity of SEGC and SD, SEGC is only about 0.1 dB worse. Since both branches have equal noise power and same average SNR, SEGC recovers most of the packets and SB does not contribute much for the combined approach in such a case. The performance of SEGC is about 1.4 dB worse than theoretical EGC.



(a) SEGC only



(b) SEGC and SB combined

Figure 4. Effects of unequal gains for a two-branch diversity system.

It can be stated that performing diversity combining at soft-bit level performs worse than conventional diversity on signal level with a trade-off in system complexity. Moreover, using SEGC seems to be an obvious solution in comparison to SB for low SNRs. The combined use of SEGC and SB outperforms under all conditions with just an incremental processing overhead for a two-branch diversity system.

To compare these simulation results with a real hardware, over-the-air measurements are done using the same implementation in a controlled lab environment. Figure 3b plots the PDRs for different SNRs from these measurements. The USRP devices are calibrated to provide desired average SNR and noise powers across both receivers. The absolute power values cannot be perfectly measured, hence, the measurement curves are shifted to match the simulation results. It can be seen, the measurement results perfectly match with the simulations (cf. Figure 3a) and yield same performance for all the considered diversity techniques.

B. Unequal Gain

To study the effect of unequal gains, both simulations as well as over-the-air measurements were repeated. Unequal gains do not effect the SNR at a single receiver but only relative noise powers between receivers, and the overall diversity gain after combining. Therefore, SB can be used as a reference performance to compare with SEGC and the combined diversity approach.

Figure 4a shows the effect of unequal gains between receivers for a two-branch diversity system when using SEGC. The performance results are only plotted from measurements

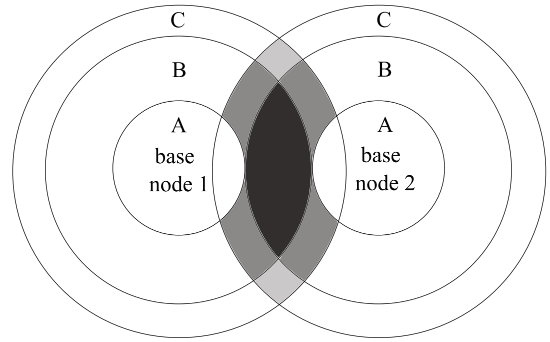


Figure 5. Schematic coverage areas between the base nodes.

data (simulations yield same results). Confidence levels are also not shown for clarity and are similarly small as in Figure 3b. Because of the short packet lengths, we have analyzed the performance by varying AGC for a gain imbalance of up to 6 dB between receivers. Here, gain imbalance corresponds to unequal noise powers between different diversity branches or receivers. As stated earlier, without any gain imbalance, SEGC performs about 0.8 dB better than SB. However, with an AGC and the gain changing within a signal duration, it becomes hard to normalize the noise power. When the noise power is increased up to 3 dB in one of the branches, the performance becomes 0.18 dB worse in comparison to balanced noise case. Gain imbalance of 6 dB further degrades the performance and the overall SNR gain becomes only 0.33 dB over SB and up to 0.5 dB worse than balanced noise receivers.

We then evaluated the performance of combined diversity approach when using SEGC and SB together for different gain imbalances. The results are shown in Figure 4b. Combined diversity approach is influenced less and degrades much slower for a gain imbalance than SEGC. When compared with balanced noise branches, gain imbalance of 3 dB and 6 dB degrade the performances up to 0.12 dB and 0.36 dB, respectively. It can be concluded that our combined BATS diversity technique makes the system more robust to high gain imbalances, i.e., unequal noise powers.

C. Application Performance

In the realistic scenario, we can differentiate three coverage areas between the base nodes defined by the probability of receiving a packet shown in Figure 5. The probability for a base node to receive a packet in its inner most coverage area denoted by A is essentially 100 %. The central coverage area B corresponds to an area around base node where the probability of receiving a packet with some constant transmit power decreases, i.e., stays between 0 %–100 %. In the outer most coverage area C, the probability for a single base node to receive any packet is zero, however, signal can be still detected in this area and be used for diversity combining.

The benefit of diversity combining can mainly be observed in the overlapping coverage areas of neighboring base nodes where probability for a single node to receive a packet is less than 100 %. The size and shape of these coverage areas greatly

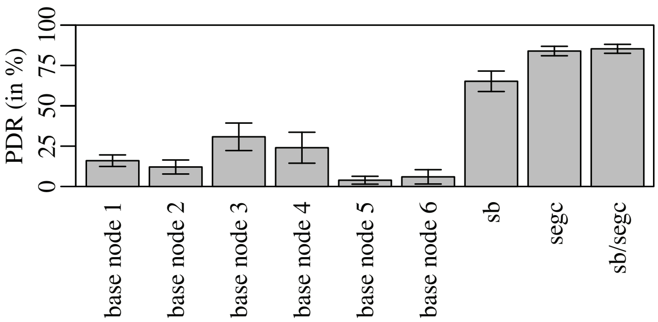


Figure 6. Packet delivery ratio for a realistic application scenario.

depends upon the channel parameters. Parameters that does not remain constant such as fading and shadowing make these areas non-deterministic. Hence, we conducted simulations by considering channel parameters such as noise and FSPL only with a constant transmit power to study this phenomenon.

To compare the performance of all diversity techniques for the specific BATS application, we simulated the behavior and mobility of a bat in MATLAB. The base nodes are placed in a way that the overlapping area between neighboring nodes where diversity combining can be realized is maximum with some constant transmit power. The channel values for each transmitted packet from all runs are then imported into our GNU Radio model and PDR is calculated for all base nodes. The average noise powers in all base nodes is considered the same for these experiments.

Figure 6 plots the PDRs for each base node separately as well as for the different diversity techniques. The 95 % confidence intervals are obtained by repeating the experiments 30 times. With these channel values, none of the base nodes reach to an average PDR of more than 30 %. By using the combined BATS diversity technique, the system achieves a PDR of about 85.3 %. This reflects an improvement of 1.4 % and 20 % compared to using SEGC and SB, respectively.

Using the simple low-complexity combined BATS diversity technique provides a great improvement in PDR. We also see that even in this simplistic setup with only six base nodes, the positions of the base node play crucial role. One aim is to maximize the overlapping of outer coverage areas of neighboring base nodes. In practice, these areas will be greatly affected by other non-deterministic channel parameters.

VI. Conclusion

In this work, we studied the performance of different soft-bit diversity combining techniques in a wild life monitoring application. The unique feature of this application is the need for low-complexity solutions as well as its distributed nature. By considering the collaborative use of multiple base nodes as a distributed receiver, we can perform diversity combining to improve the overall application performance and, thus, to reduce the energy consumption of the system. For this, we need to provide sufficient time synchronization between the base nodes (below the length of one time slot). In the paper, we studied several standard diversity solutions and propose the combination of SEGC and SB for best results. Our performance evaluation clearly shows that this BATS diversity technique outperforms other low-complexity solutions. We were able to achieve a performance gain of more than 20 % in a semi-realistic setup. In future work, we plan several outdoor measurements to deepen our understanding of these effects.

Acknowledgements

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