Experimental Evaluation of Receive Diversity Techniques in Distributed Sensor Networks

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Abstract

We study the need and practical performance of receive diversity techniques (both on soft-bits as well as signal samples) using selective signal sample forwarding in a distributed sensor network. Receive diversity techniques have been studied in the literature in-depth and such algorithms are massively deployed in, for example, cellular networks, where usually antennas are simply connected to a single receiver. In previous work, we transferred these ideas to ultra low-power sensor networking applications in which a ground network forms a distributed antenna array. In particular, we are developing wildlife monitoring application to study the foraging behavior of bats in their natural habitat – here, the mobile nodes are heavily energy constrained. We use receive diversity in the ground network to overcome limitations of the quite unpredictable radio channel in a forest environment. In this paper, we go one step further. We first provide a unified framework for studying receive diversity techniques in both simulation and field testing. Secondly, we show results from an extensive set of outdoor measurements complementing analytical findings as well as data from simulations and lab experiments.

Key words: Wireless sensor networks, diversity techniques, reliable communication, energy efficiency

1. Introduction

In the last decade, sensor networking gained considerable attention due to its efficient operation and self-organizing behavior [1, 13]. Wireless Sensor Networks (WSNs) were initially used in military applications, however, they soon became popular in other fields such as healthcare, environmental monitoring, smart home, and many others. One of the most popular application domains of WSNs is wildlife monitoring [11]. After a successful monitoring of animals on a large scale [21], the focus turned towards smaller mammals [23] and birds [38]. Such new applications now require further minimization of the sensor node size, hence, researchers are making efforts to cope with these challenges [20].

WSNs can be of different types and are characterized depending upon their application requirements, underlying network architecture, and the properties of involve sensor nodes (such as processing capability and available energy budget). In this work, we target specific heterogeneous sensor networks which involve three types of sensor nodes, i.e., mobile (energy- and size-constrained), stationary (less strict energy limitations), and sink (no energy restrictions). Examples of such heterogeneous networks include industrial automation, Radio Frequency Identification (RFID) systems, etc. In particular, our main focus is the BATS project [16]. In this project, we help biologists in studying the foraging behavior and habitat of an even more challenging species: mouse-eared bats (*Myotis myotis*). Due to the very limited weight and size of the target species, the sensor hardware is restricted to at most 2 g including the battery (referred to as a mobile node). The mobile node continuously exchanges and stores meeting information between individuals. To collect this stored information, we use a distributed sensor network in the bats' hunting areas (referred to as a ground network) as shown in Figure 1. The ground network is composed of stationary single antenna sensor nodes, which have less strict energy limitations and are connected to a sink via resource-constrained (data rate) wireless connections. Whenever, a mobile node visits a hunting ground, which happens on an irregular basis, its wake-up transceiver is triggered by a signal periodically broadcast by the ground network. After waking up, the mobile node transmits down all of the stored contact information (see [14] for more details). The primary purpose of this ground network is to collect this stored information. However, a transmission from a mobile node faces challenging channel conditions due to an unpredictable behavior of a flying bat characterized by a high speed and abruptly changing direction and altitude in a forest environment. Since the ground network already consists of distributed sensors, they can be used as a distributed antenna array to apply receive diversity techniques for improved communication reliability.

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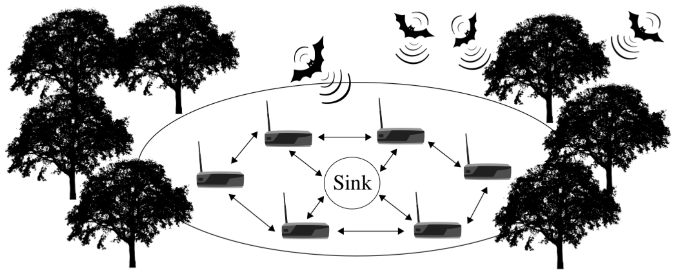


Figure 1: BATS scenario: A network of ground stations receives and processes bat encounter data transmitted by very small senders mounted to the bats.

Since more than half a century, diversity combining is considered as one of the most promising techniques to increase the robustness of wireless communication systems [7]. It is often realized by employing multiple antennas at the transmitter (referred to as a transmit diversity) or receiver (referred to as a receive diversity). With a same radiated power, transmit diversity often performs poorer than the receive diversity [2]. Therefore, it is not efficient to employ transmit diversity on our transmitter (i.e., mobile node) as it is energy-constrained. Moreover, as the mobile node is also size-constrained, it does not allow to mount multiple antennas on the transmitting side. Hence, using distributed sensors of the ground network as a distributed antenna array to realize receive diversity is an optimal solution in such a case. In receive diversity, uncorrelated copies of the transmitted signal are received at several antennas, which are then aligned, co-phased, and added constructively. This helps in improving the received signal strength without the need of increase in transmit power. In most cases, the signal-to-noise ratio (SNR) of the resultant signal is higher than the SNR of any individual copy received [18].

Again, the concept of receive diversity was initially proposed for systems that employ multiple antennas at a single receiver but, later, extended to systems with distributed receivers, e.g., cellular networks [28]. By using distributed receivers as a distributed antenna array to employ receive diversity not only overcomes fading but also makes the system more robust against interference and shadowing [36]. However, this increased robustness comes at the expense of additional hardware and extra processing required at each receiver. Furthermore, this also gives rise to several research challenges such as the passing of information in the network through links that offer only limited data rate [43].

Using the BATS ground network as a distributed antenna array to realize receive diversity is different compared to other solutions due to the difference in architecture and communication protocol used (e.g., only the transmitting node has very limited energy budget and due to its high mobility in a forest environment, the transmission faces adverse channel conditions). Since ground sensor nodes are placed in a forest environment, it is also important to note that these ground nodes do not have strict size limitations. Therefore, it is possible to implement basic signal processing modules on the ground nodes and attach batteries to them for the required time of operation (which is currently limited to two weeks due to the energy limitations of a mobile node). Moreover, the BATS protocol for communication between mobile node and ground network is discussed in [14], whereas communication within the ground network relies on standard Wi-Fi.

In our earlier work [30], we proposed to use the ground network as a distributed antenna array and studied the performance of simple soft-bit diversity combining. We noted that converting the signal into soft-bits comparatively reduces the amount of data that needs to be forwarded in the network, however, the absolute data rates required were still very high. Moreover, combining soft-bits with equal gains (i.e., Soft Equal Gain Combining (SEGC)) does not achieve the highest diversity gain and is highly prone to gain imbalance between receivers. Later, we addressed these issues and proposed the concept of selective signal sample forwarding [31]. With that, all receivers in a distributed system detect signal locally and forward I/Q (In-phase and Quadrature components of complex) signal samples equivalent to the known packet-length only for diversity combining. Since the selective sample forwarding approach does not involve complex signal processing and requires ground nodes to simply detect, slice, and forward fixed number of signal samples, it is possible to realize this approach on the ground nodes. We investigated the performance of combining selective signal samples (i.e., Maximum Ratio Combining (MRC)/Equal Gain Combining (EGC)) in simulations and limited lab environment. We reported that using the proposed concept reduces the required data rates dramatically without losing any diversity gain. These results are further verified by additional simulations with realistic channel effects in [32]. Finally, we also studied data forwarding between different ground nodes and sink at a network level using Wi-Fi links, and proposed solutions to efficiently collect data for the purpose of diversity combining [34].

In this work, we go one step further and develop selective signal sample forwarding system for soft-bit combining with weighted gains (i.e., Soft Maximum Ratio Combining (SMRC)) along with MRC. Additionally, we also incorporate well-known Selection Diversity (SD) in the same system to compare their performances. Furthermore, we perform not only simulations and lab measurements to validate our implementation but also carry out an extensive set of experiments in the wild to study the practical application performance. To the best of our knowledge, this is the first work which compares diversity combining when performed at signal level (i.e., received I/Q signal samples) and soft-bits (i.e., single sample corresponds to a bit) in an unified framework with practical experiments.

Our core contributions can be summarized as follows:

- We present several receive diversity techniques for distributed sensor systems using selective signal sample forwarding approach and study them in an unified framework (Section 3).

- We develop the complete system in a Software Defined Radio (SDR) platform and validate our implementation through simulations and lab measurements (Sections 4 and 5).
- We perform an extensive set of real-world experiments to investigate the performance of all considered diversity techniques in realistic environments (Section 6).

2. Related Work

The most commonly used receive diversity techniques include SD, EGC, and MRC [7, 18]. SD being simplest of all, selects the receive branch with the highest SNR. It achieves better performance than not using diversity at all, however, the diversity gain is not fully achieved as it discards signal copies received at other branches. EGC takes the advantage of all branches and combines all signal copies after co-phasing for an improved diversity gain. Even though EGC provides better performance than SD in most cases, in worst case scenarios, it faces problems due to the addition of corrupted copies to the original signal. In order to avoid this, MRC sets a weight of each branch according to its received SNR before combining to achieve full diversity gain. However, this comes at the expense of increased processing required to estimate the channel in each branch and implementation complexity. The literature is rich of theoretical and analytical analyses of all these diversity techniques under different fading models and channel conditions [10, 24, 6, 9]. Implementation issues in actual systems were discussed in [45].

In some systems, it is not possible to mount multiple antennas at a single receiver due to its limited size or weight. However, if the network is distributed, cooperative diversity can be exploited by using relaying schemes in which several network nodes act as relays to a stronger node [22]. Here, in contrast to relay networks, we focus on systems in which all distributed nodes act as receivers in the network. These receivers can be used as a distributed antenna array to apply receive diversity for an improved reception along with a better coverage [26]. Such a concept of distributed diversity was first introduced in a practical application within the scope of cellular networks [28, 19]. Regardless of optical fiber connections between base stations, it still does not allow to pass all signal information from all base stations in the network due to limited data rate links. Hence, a possible diversity solution in this scenario is to switch every time to a diversity branch that decodes the signal correctly as, for example, done in Successful Branch (SB). In order to realize complex diversity combining techniques, data is usually processed locally and only soft-bit information is passed in the network. Therefore, diversity combining is applied on soft-bits rather than the signal samples [28, 44]. Soft-bit diversity uses the same combining techniques as the conventional diversity, however, the performance gain achieved is lower in comparison due to the loss of signal properties while converting the signal into bits [40]. Moreover, in the past, error performance of distributed diversity techniques has been studied numerically, analytically, or empirically through simulations [41, 5, 36, 3].

Applying the same concepts in distributed sensor networks give rise to new practical research challenges due to the limited energy available and even stricter data rate offered between nodes [43]. Earlier works in the sensor networking domain that target combining multiple copies of the same signal to improve reception quality involve Hybrid Automatic Repeat Request (HARQ) systems [17]. They focus on fusion of retransmitted signal with the previous transmissions rather than combining the signal copies received at different distributed nodes. Apart from that, analytical performance of combining decisions in sensor networks in presence of rayleigh fading channel has been explored in [35]. A nice work that discusses distributed diversity combining in WSNs is [39], which presents preliminary results for only SD with no insights or comparisons of different diversity combining techniques. Recently, authors in [12] showed that it is possible to apply diversity combining in practical Low-Power Wide Area Networks (LPWANs). Moreover, low-cost receivers can collaboratively decode wideband signals which are impossible to decode by a single receiver individually due to its limited processing capability [8]. In this paper, we cover the missing literature gap and compare conventional diversity techniques with the combining at soft-bits in an unified framework with practical experiments.

In our earlier works, we proposed to use the distributed ground network as a distributed antenna array and applied diversity combining without overloading the network [32, 34, 33]. We studied the performance of considered diversity techniques in simulations and through a limited indoor measurement setup. Now, we go one step ahead and study the practical performance of improved diversity techniques in an unified framework and we also conducted, for the first time, an extensive set of real-world experiments. Since this work mainly focuses on practical experiments of different diversity techniques in specific distributed sensor networks, it is also important to highlight that realizing diversity combining at a network level involves several other challenges, e.g., avoiding collision from multiple transmitters, efficient node placement, and efficient data collection to perform diversity combining successfully at a single point in a network. Since these issues are beyond the scope of this work and we have discussed these issues in detail in our previous works, we do not address them here.

3. Receive Diversity in Distributed Sensor Networks

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

When diversity combining is employed at a single receiver, detected I/Q signal samples from different antennas are co-phased and summed before converting the signal into soft-bits and final decoding. If these antennas belong to spatially separated receivers, the data needs to be aggregated for diversity operation. In the BATS project, all nodes in the ground network are wirelessly connected to each other and to a sink node in an ad hoc fashion as depicted in Figure 1. As stated earlier, we aim to use these single antenna ground nodes as a distributed antenna array to realize receive diversity. A simple solution in this case is to forward data from all network nodes to one processing unit for the combination of signal copies constructively and, finally, signal decoding at a single point. However, these links between the nodes offer only limited data rates. Therefore, in this section, we present several possibilities of applying diversity techniques in a distributed sensor network and discuss the system design according to the requirements in the BATS project.

3.1. Signal Detection and Forwarding

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

Since the bat node uses short packets (that also include a preamble) for transmission [14], detection of signal at any ground node can be performed locally at each receiver by correlating received data with the preamble. In the case of detection, we propose to forward only selected signal samples (starting from the preamble to the known packet-length, i.e., about 480 µs of samples) rather than the whole raw sample stream to avoid overloading the network [31]. Considering a maximum reception rate of 100 Hz, this lowers the required data rate by a factor of 20 in the ground network in comparison to forwarding all raw samples. If all detections are successfully performed, there will be no loss in performance as all useful I/Q signal samples still take part in the diversity process. The disadvantage of this approach is that a slightly higher processing is required at the local ground nodes to detect and cut the useful signal samples before forwarding.

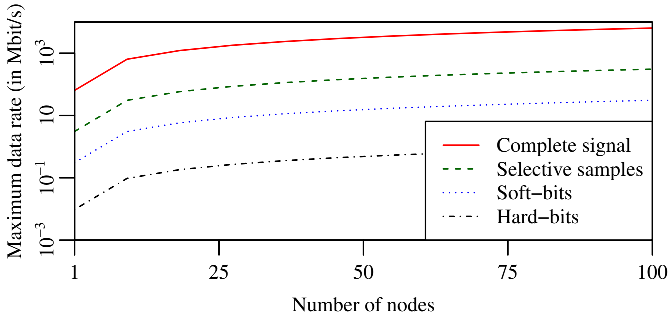


Figure 2: Maximum data rate for various approaches of transmitting signal samples in the ground network.

Forwarding Data as	1 Node (Mbit/s)	50 Nodes (Mbit/s)	Diversity Gain
Complete signal	64	3200	Highest
Signal samples	3.07	153.6	Highest
Soft-Bits	0.31	15.36	Medium
Hard-Bits	0.01	0.48	Very low

Table 1: Possible diversity gain with maximum data rate for various approaches of transmitting signal samples in the ground network (signal corresponds to 5 samples/bit).

Another option to further reduce data rate in the ground network is to forward only soft-bit information. Converting the I/Q signal samples into soft-bits minimizes the data-rate from one node to only 0.31 Mbit/s. This reduction in the data rate comes at the expense of even higher processing required at the local nodes to convert the detected packets into soft-bits and forward them equivalent to the packet-length. In the same context, another approach is to decode the signal completely at ground nodes and forward hard-decision bits to the sink further limiting the data rate to 0.01 Mbit/s. The required data rates for different possible approaches with various numbers of nodes in the ground network are depicted in Figure 2. These results are also summarized for a total of 50 network nodes in Table 1.

3.2. Diversity Combining

In literature, diversity combining is usually applied on I/Q signal samples received at different diversity branches (i.e., antennas or nodes). Synchronization and phase correction is required in all participating diversity branches to combine received I/Q samples constructively. Combining is performed sample by sample before the conversion of signal into bits or symbols. Once all received samples are successfully combined, signal processing is performed to obtain the final signal. In soft-bit combining, received I/Q samples are first processed and converted into soft-bits (i.e., one float value per bit) before combining. One advantage of combining soft-bits is that phase correction is not required (e.g., in the case of Differential Binary Phase-

Shift Keying (DBPSK)), however, synchronization between branches is still needed. Similarly, diversity combining can also be applied on hard-bits after all the signal processing is performed. Since there are several options to reduce the data rate in the ground network, i.e., by forwarding signal samples, soft-bits, or hard-bits, we investigate the performance of diversity combining when applied on these different stages of the signal.

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

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

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

To apply diversity combining on hard-bits, one simple approach is to take the final decision for each bit by a majority combiner as in Post-Detection Combining (PDC) [42]. Along with performing timing recovery in each branch individually, converting the information into hard-bits loses most of the signal properties and, hence, all branches contribute equally for diversity combining. Therefore, the performance gain achieved with hard-bits is even poorer than soft-bit diversity combining. Apart from the performance, applying diversity at bits also requires more processing at the nodes themselves affecting the lifetime of distributed sensor nodes. Table 1 summarizes these concepts and their performances along with the data rate requirements in the network.

Furthermore, in order to compare the performances of applying diversity combining on signal samples (i.e., MRC) and soft-bits (i.e., SMRC), we also implement SD and SB. We do not consider EGC, which is relatively simpler to implement compared to MRC due to its reduced performance in practical environments. In SD, a branch with the highest SNR is selected and signals from rest of the branches are discarded. In presence of Rayleigh fading, the resultant signal power p for n diversity branches is given by [7]

$$p = \sum_{i=1}^{n} 1/i \ . \tag{2}$$

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

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

$$\rho = 1 - \prod_{i=1}^{n} (1 - \rho_i) \ . \tag{3}$$

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

4. Implementation Details

In order to compare the performance of various diversity techniques in an extensive set of experiments, we realized both the transmitter and receiver in GNU Radio. GNU Radio is an Open Source real-time signal processing platform to implement the software part of an SDR. To introduce a realistic channel, we used a mobility model specifically developed for Bats in Matlab. These channel values are then imported into our GNU Radio model to apply various diversity techniques when running in simulation mode.

4.1. GNU Radio

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

On the receiver side, the incoming data is continuously correlated with the training sequence (i.e., preamble) for signal detection. In the case of detection, SNR and phase (including the starting phase and its variation during the signal duration due to the imperfect hardware clock) are estimated using the preamble and compensated for constructive combining. The detected packets are then forwarded to the clock recovery module to compensate frequency and timing offsets. This is done by the GNU Radio built-in *Mueller and Müller* clock recovery module [27]. This algorithm uses a feedback system to estimate the sampling instants of the received signal and adjusts them accordingly. Finally, the obtained signal is differentially decoded and successful reception is confirmed by checking the CRC.

To apply most diversity techniques on received selective samples, the I/Q samples from all receivers are weighted and added before the clock recovery module. Soft-bit combining is performed after most of the signal is processed and each sample corresponds to a single bit, just before taking the hard-bit decisions. In the following, we will analyze the performance of MRC, SMRC, SB, and SD in our application domain. As mentioned previously, we do not consider EGC as it performs comparatively poorer than MRC especially in distributed systems when the gain imbalance between branches is really high.

4.2. MATLAB

To introduce realistic channel effects, we use our mobility model developed in MATLAB to simulate bats over a hunting area that has a total size of 120 m × 120 m and consists of 36 ground nodes. The ground nodes are placed with an inter-distance of 30 m for accurate localization [15, 16]. We consider a forest scenario with trees each having a radius of 2.5 m and spaced from 20–24 m throughout the hunting ground. It is important to note that this developed shadowing model is based on our earlier experiments [29]. In a real deployment scenario, the network size and number of nodes will vary depending upon the total area available and the density of trees in that area. The affect of different environments on receive diversity combining is discussed in detail in [32]. In brief, increase in density of trees lowers the diversity gain achieved due to the change in area between neighboring nodes where diversity combining is observed.

Here, in this simulation setup, a single bat flies from its roost towards the hunting ground, hunts there, and comes back to the roost. Details of the simulation model and bats movement patterns are provided in [15, 32]. In short, whenever a bat reaches the hunting ground, its distance from all ground nodes and the numbers of trees that lie in between are calculated every 100 ms (i.e., time duration to transmit a packet by a single bat). For every packet received at any ground node, Free Space Path Loss (FSPL) is calculated based on the distance measured, flat Rayleigh fading is applied, and shadowing is introduced for every single tree. The attenuation is calculated only once per packet due to the much smaller packet length (i.e., 0.48 ms) [14] than the coherence time (i.e., 10 ms) [37] for the maximum speed of bats (i.e., 50 km/h) [4]. These channel values are then imported to our GNU Radio implementation for simulation-based experiments.

5. Model Validation

In order to validate our implementation, we investigated the Packet Delivery Ratio (PDR) for various diversity techniques in simulations and then compared it to the lab measurement results.

5.1. Simulations

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

Figure 3 plots the PDR over different SNR values for a two-branch diversity system for an AWGN channel. The curves reflect the performance of all considered diversity

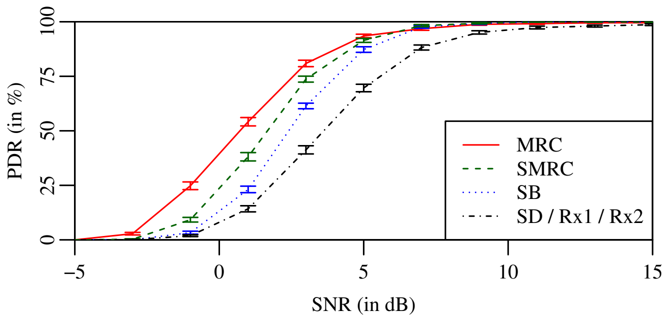


Figure 3: Simulated packet delivery ratio for a two-branch diversity system over an AWGN channel.

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

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

Similarly, SMRC shows a significant performance improvement in comparison to the no diversity case, however, it is about 0.8 dB on average worse than the combining at signal level. As already stated, this happened due to the loss of signal properties while down-converting the signal into bits. SB performs much better than SD as there is a high probability that even when the average SNR is same in both receivers, only one of them decodes the signal successfully. It is also interesting to note that SD is not performing better than any individual diversity branch with this particular configuration due to the long-term same average SNR across both receivers.

Since, in field measurements, it is very difficult to place receivers in a way that they all experience similar SNR, we performed additional simulations to investigate the diversity gain when the received SNR is different across receivers. Figure 4 shows the performance of various diversity techniques to achieve a PDR of 50 % when there is a SNR imbalance of up to 3 dB in a two branch diversity system. In the figure, diversity gain refers to the improvement over branch that experiences better channel quality. As the branch with highest received SNR has same performance as SD, we show the diversity gain for MRC, SMRC, or SB

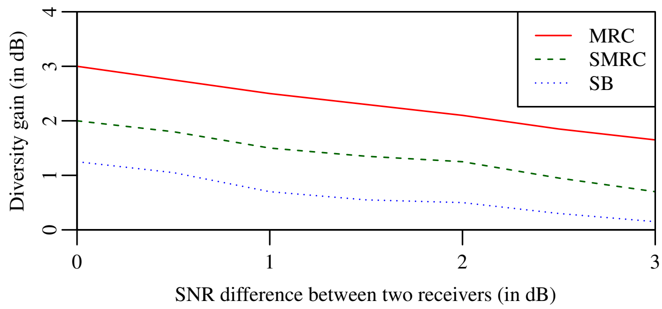


Figure 4: Simulated performance for a two-branch diversity system with SNR imbalance over an AWGN channel.

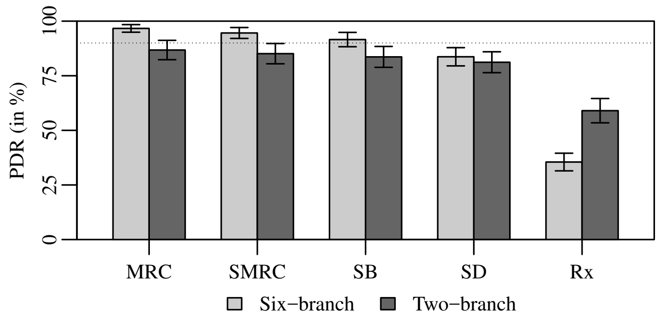


Figure 5: Simulated packet delivery ratio for the BATS scenario under realistic channel effects with a ground network of 36 nodes (and selecting best six (or two) among them to realize six-branch (or two-branch) diversity system).

only. It can be observed that SNR imbalance of 3 dB in a two-branch system affects the diversity performance up to more than 1 dB in all cases.

To further analyze the effect of a complex channel on the various diversity techniques, the transmitted signal is modified based on the values imported from MATLAB before adding AWGN. This way, for every transmitted packet, channel values for all receiving nodes in the ground network are imported. We realize receive diversity in the BATS scenario with a maximum of six receivers (among 36 receivers which experience the best channel conditions) and use a transmit power of −43 dBm for an energy-efficient operation [32]. We select these six receivers (referred to as diversity branches here) among 36 receivers based on their received SNR by using the algorithm provided in [34]. Running GNU Radio in simulation mode, we determined the PDR for the various diversity techniques. The results are shown in Figure 5. The 95 % confidence intervals are obtained by repeating the experiments with a new seed for bat mobility 30 times. A PDR of 90 % is also highlighted with a horizontal dotted line. The performance of two-branch diversity system (by selecting two receivers that experience the best channel conditions) is also investigated to compare it later with outdoor measurement results.

It can be noticed that there is a clear performance difference between the two-branch and the six-branch diversity systems. Also, the relative difference in PDR between various diversity techniques in the six-branch system is more prominent than the two-branch system. In all cases, MRC provides the highest performance as expected. SMRC performs marginally inferior than MRC, however, the achieved PDR is still higher than the SB and SD. It is also interesting to note that for the six-branch diversity system, there is a clear performance gain of SB over SD. However, this is not the case in the two-branch diversity system when both considered receivers do not have same average SNR. The reduced performance of SB is the result of imperfect channel estimation caused due to the very short length of training data (i.e., preamble). In the figure, Rx highlights the mean average PDR of all individual participating receivers. The individual PDR for the best six receivers is also shown in Figure 6. It also explains why the mean average PDR of Rx for a two-branch diversity system is better than six-branch system. As higher the number of receivers with relatively bad performances are added, lower is the mean average PDR of all these receivers. These results clearly indicate the potential of using distributed receivers as a distributed antenna array for an improved reception and the baseline performance of considered diversity techniques.

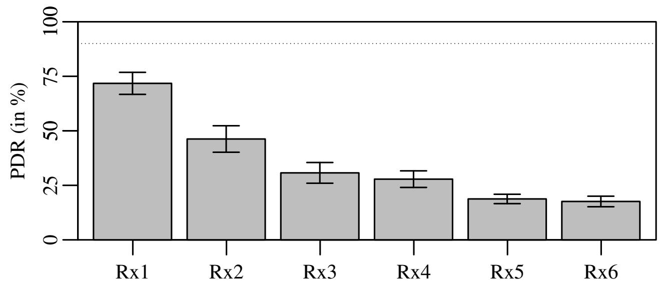


Figure 6: Simulated packet delivery ratio for the best six ground nodes in the BATS scenario under realistic channel effects.

5.2. Lab Measurements

In order to perform over-the-air experiments in a lab environment, we used Ettus B210 Universal Software Radio Peripherals (USRPs) as shown in Figure 8a. The lab is similar to an office environment and the experiments were performed without any human intervention to provide nearly static channel conditions. Hence, the multipath effects that arise in an indoor environment remain constant throughout the experiments. We used the exactly same implementation of the transmitter and receiver as in the simulations for a fair performance comparison. However, here we synchronize all receivers additionally by using Network Time Protocol (NTP) [25] which provides synchronization up to a level of ms and also helps in identifying signal copies (received at different receivers) that belong to the same signal. The transmissions are initiated by the transmitter USRP and are received by two receiver ones, all connected to laptop computers. Receiver gain values are set in the software to have on average equal noise power

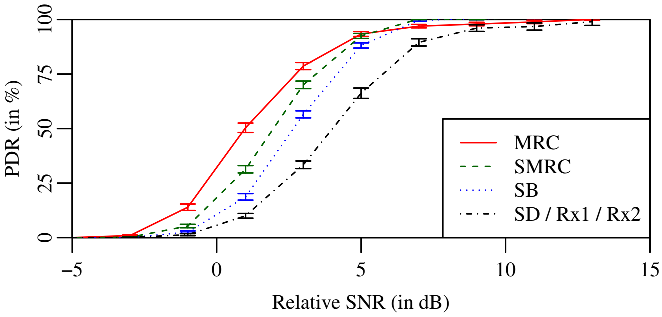


Figure 7: Experimental packet delivery ratio for a two-branch diversity system in a lab environment.

across receivers and they are placed carefully in a way that they experience roughly equal SNR. To observe PDR over different SNR values, the transmit gain is changed accordingly in the software. In case of detection, selective samples that belong to the detected signal are forwarded to a third laptop computer that is connected via wireless links for the realization of different diversity techniques. In order to compare all diversity techniques under exactly same channel conditions, we stored and post-processed the selective signal samples.

Figure 7 shows the resulting PDR for the various diversity techniques. Since the USRPs are not perfectly calibrated, we added a constant shift in all curves to compare them with simulation results over same SNR values. It can be seen that all considered diversity techniques provide the same performance what we have noted earlier. The PDR curves from the measurement data perfectly match the simulations over an AWGN channel. From these results, we conclude that our implementation model can be used for the real-world experiments to investigate various distributed diversity techniques.

6. Outdoor Field Measurements

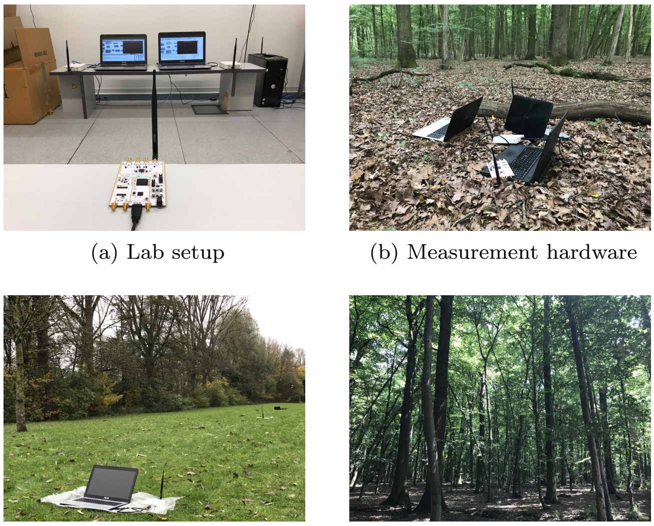
To analyze the performance of different diversity techniques in an outdoor environment, we performed an extensive set of experiments for a two-branch diversity system. In the following, we report about the most relevant findings.

6.1. Measurement Setup

We used the same hardware as in the lab environment; now outdoors (cf. Figure 8b). For experiments, we selected two types of areas:

Line-of-Sight area: To ensure a good testing environment, it is situated away from the main population. The ground is completely covered with grass and has trees only in the surroundings as shown in Figure 8c. Since there are no obstructions in between, it offers good LOS communication between transmitter and receivers.

Foliage area: The foliage area is full of tall trees that are spaced with a distance of about 3 m and the ground is a mixture of soil, grass, and low-level branches as illustrated



(a) Lab setup

(b) Measurement hardware

(c) LOS area

(d) Foliage area

Figure 8: Hardware setup and measurement sites.

in Figure 8d. It is very similar to the hunting area of bats in their natural forest environment.

We first performed static measurements in both of these areas by keeping the positions of transmitter and receivers static in order to compare their performance with the indoor experiments. The transmitter is then moved during a mobile measurement (to reflect a moving bat and) to get further insights. A detailed top view of outdoor measurements setup is shown in Figure 9.

In order to perform static measurements in both of the environments (i.e., LOS and foliage), the receiver USRPs (i.e., Rx1 and Rx2) are kept at a distance of 30 m to represent a ground network of two nodes (across position B in Figure 9). The transmitter USRP (representing a bat) is then fixed at a position B between the receivers. Received signal samples are recorded at both the receivers for different transmit gain values. The recorded data is then post-processed to apply the considered diversity techniques.

The experiments were then repeated by moving the transmitter USRP on a walking speed, i.e., 5 km/h, on a straight line between position A and C to represent mobile measurements. Finally, we performed experiments at higher speeds (up to 25 km/h) corresponding to a flying bat in order to realize the affect of transmitter speed on the PDR.

6.2. Results in the Static Case

The PDR results from the static (distance) experiments are shown in Figures 10a and 10b for the LOS and forest scenarios, respectively. As mentioned before, in the given setup of outdoor experiments, it is very difficult to ensure exactly the same SNR for both receivers even with the same software and hardware settings. This is due to the presence of numerous uneven multipath components from the ground and trees (in the case of foliage area). Therefore, the PDR curves shown for Rx1 and Rx2 are not the same. The relative difference observed between two receivers for

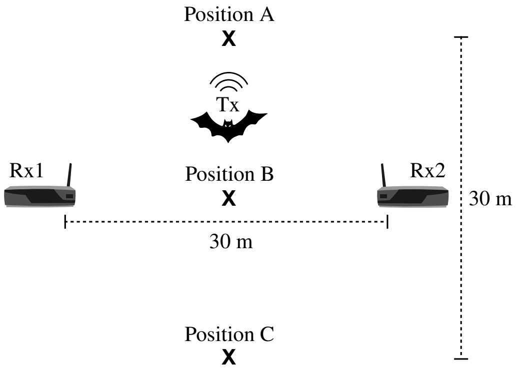
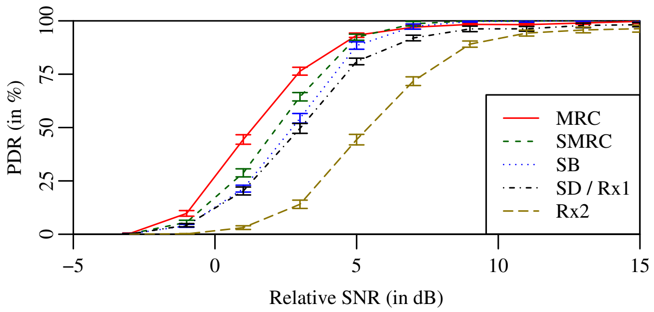
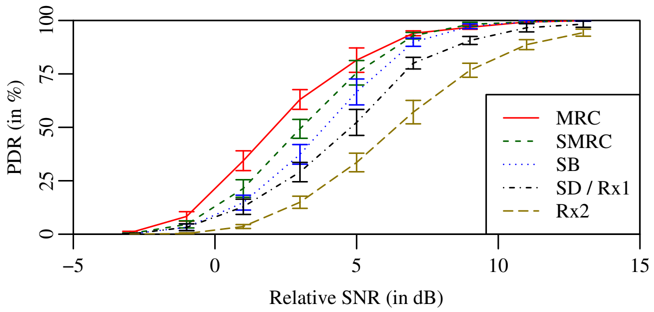


Figure 9: Outdoor measurement setup.



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



(b) Measurements in the foliage area

Figure 10: Experimental packet delivery ratio for a two-branch diversity system with a statically placed transmitter in the outdoor environments.

static experiments is about 2.5 dB and 1.8 dB in LOS and forest scenario, respectively.

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

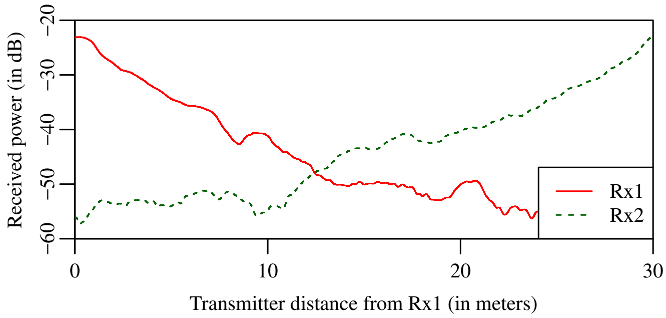


Figure 11: Relative received power while moving the transmitter from one receiver to the other in the foliage area.

6.3. Results in the Mobile Case

The more interesting results, of course, are those in the mobile case. We first measure the relative received power across both receivers while moving the transmitter from one receiver towards the other at a walking speed in the foliage area. The resultant received powers for both receivers are plotted in Figure 11.

As expected, it can be noted that with the aforementioned setup, received power of one receiver gradually decreases while the other increases. The variation in the received power for a single receiver is as much as 25 dB when the receivers are placed with an inter-distance of 30 m. Since, the ground network is dense with receiver nodes, there is a high probability that with a mobile node transmitting, a decreasing received power at one receiver will eventually lead to an increased received power at some other receiver. Therefore, combining the signal copies from several receivers will keep the overall received power on average same in the resultant signal.

To evaluate the performance of various diversity techniques with a mobile transmitter, we use the setup described earlier. With that, at every transmitter position,

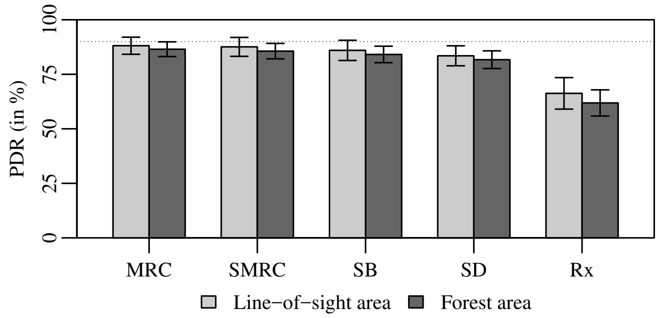


Figure 12: Experimental packet delivery ratio for a two-branch diversity system with a mobile transmitter (at a walking speed) in the outdoor environments.

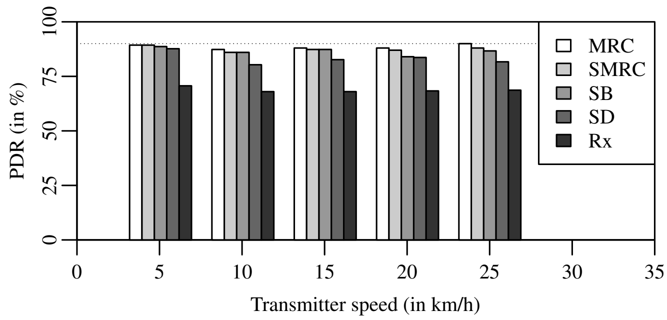


Figure 13: Experimental packet delivery ratio for a two-branch diversity system with various speeds of a mobile transmitter in the foliage area.

its distance from both receivers remains the same and, therefore, both receivers contribute for signal combining roughly the same. Since it is not easily possible to measure the absolute transmit power, we select the transmit gain in such a way that both receivers achieve an average PDR of more than 50 %. Furthermore, we select the same value for the transmit gain when performing LOS experiments and in the foliage area for a fair comparison.

The results of the various diversity techniques are shown in Figure 12. We note that the qualitative performance of all diversity techniques is similar to what we have seen in Section 5.1 for a two branch diversity system. The PDRs for LOS are marginally better than those for the foliage area due to the absence of shadowing from trees. Since the maximum distance between the transmitter and a receiver cannot be more than 30 m in the given setup, very few trees lie in between. Therefore, the PDR achieved in the foliage area is only marginally worse. These experiments also support the argument that the obstruction because of trees at smaller distances only affects the average received power and not the PDR [29].

Finally, to analyze the PDR at higher speeds corresponding to a flying bat, we increase the distance between position A and C from 30 m to 75 m (for freely fast movement). We now also mount the transmitter on an e-bike to achieve higher speeds (up to a 25 km/h). Resultant PDR with various speeds of a transmitter in the foliage area is depicted in Figure 13. It is interesting to note that the benefit of diversity combining still retains and there is no major impact of speed on the resultant PDR in our scenario. Moreover, it is also worth mentioning that these experiments are performed only with a two-branch diversity system and the advantage is still evident. In the final Bats deployment, diversity techniques will be applied with several receivers to achieve higher diversity gain. Furthermore, it is also concluded that SD and SB are not optimal in this scenario because of the low diversity gain and the requirement of more processing, respectively. Also, using MRC is superior to SMRC without the need of very high data rate in the network with simple selective signal sample forwarding.

7. Conclusions

In this work, we evaluated the performance of various receive diversity techniques using selective signal forwarding approach for practical use in the wild to find an optimal solution for reliable communication in our Bats scenario. We implemented all considered diversity techniques based on signal samples as well as on soft-bits in GNU Radio to compare them in an unified framework. We also discussed the possibility of using distributed sensor nodes as a distributed antenna array to efficiently apply receive diversity. Based on that framework, we performed simulations, over-the-air lab experiments, and, most importantly, real-world field experiments in Line-of-Sight (LOS) and foliage scenarios to compare the performance of the considered diversity techniques. We concluded to use Maximum Ratio Combining (MRC) with selective signal sample forwarding for the best performance without overloading the network. This also leads to low-processing at the network nodes, which eventually will increase the overall lifetime of the network.

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