Preamble-Less Diversity Combining: Improved Energy-Efficiency in Sensor Networks

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***Abstract*—Recent advances in the field of sensor networks helped miniaturizing nodes and, thus, enabling novel application domains for, e.g., remote monitoring or more generally the Internet of Things (IoT). One of the most critical issues in this context is the limited energy capacity of a sensor node, and its implication on communication reliability. Recently, we have investigated the use of diversity combining in a distributed sensor network to improve both the communication reliability and the energy footprint of mobile sensors transmitting to stationary receiver nodes. In this work, we go one step further and integrate the idea of preamble-less communication proposed by mSync with diversity combining to gain the added advantage of both. The elimination of preambles allows to further minimize the transmission energy. We implemented the proposed integrated model in GNU Radio and evaluated its performance both in simulations as well as lab experiments. Our results demonstrate that applying diversity combining together with mSync not only reduces the energy required for transmission but also improves the communication performance in terms of Packet Delivery Ratio (PDR), especially at higher Signal-to-Noise Ratio (SNR).**

I. Introduction

Wireless Sensor Networks (WSNs) have become a practical tool over the last two decades supporting many applications such as remote monitoring, medical devices, and many others [1], [2]. Recent advances in technology helped miniaturizing the sensor nodes to target even more challenging applications [3]. As a result, the energy budget available is now very limited. Thus, on one hand, it is important to incorporate wireless communications solutions which offer improved performance and reliability, and on the other hand, energy-efficient operations are required to increase the lifetime of ultra-low power nodes.

The available literature presents many simple solutions such as a space diversity [4] to increase the robustness of wireless communications. The concept of receive diversity combining was initially developed for systems which use multiple antennas at a receiver to receive uncorrelated copies of the same signal. The receiver then selects the best among multiple received signal copies or adds them all constructively for an increased signal strength. In many sensor networks, copies of the transmitted data are also received at several nodes due to their distributed nature. Therefore, these nodes may act as a distributed antenna array to offer receive diversity and, hence, can improve the signal reception [5]. While applying diversity combining techniques, the preamble plays a significant role. It is not only used for the detection of signal in different receiving branches but also for frequency and timing offsets recovery and correction, so that coherent and constructive combination of signals is possible.

Since the communication in WSNs is usually packet-based, selecting an optimal packet-size is considered as one of the successful strategies for an energy-efficient operation [6]. To further minimize the energy consumption, packet-size can also be jointly optimized with transmit power control [7]. Recently, the concept of preamble-less data communication mSync has been proposed [8]. The mSync does not require a preamble (i.e., training sequence) and uses the packet itself in a unique fashion to re-identify the beginning of packets. The elimination of preamble not only lowers the energy requirements at the transmitter but also reduces the utilization of wireless channel. However, using mSync results in more processing overhead at the receiver due to buffering, thus, suiting it well for the applications where only transmitters have limited energy.

In this paper, we combine both concepts: diversity combining and preamble-less communication. For short burst transmissions in WSNs, the preamble introduces a significant overhead. Eliminating the preamble certainly reduces the packet-length and, hence, minimizes the energy required for transmissions. Combining preamble-less communication with receive diversity would not only lower the energy requirements at the transmitter, but also improves the overall network reliability. To the best of our knowledge, diversity combining in the literature is only possible after successful signal detections in multiple diversity branches through a unique training sequence (or preamble). Therefore, in this work, we investigate in detail the effect of omitting preamble on diversity application. Additionally, we compare its performance with normal (preamble based) packet format and discuss the achieved performance.

Our main contributions can be summarized as follows:

- We propose a novel system model that successfully combines preamble-less communication with receive diversity in a distributed antenna system.
- We developed the proposed model in GNU Radio, and performed extensive set of simulations and lab experiments to show the achievable performance gain.
- We present the possible energy conservation and, finally, investigate the application performance under realistic channel conditions.

II. Related Work

Receive diversity is considered as one of the most powerful techniques to increase the robustness of system against fading without the need of increase in transmit power. In some practical applications such as a WSN, it is not possible to mount multiple antennas at a single node due to its limited size, however, multiple nodes can act as a distributed antenna array [5]. Performing diversity combining with such a distributed antenna array makes the system less prone to shadowing and interference [9]. Commonly employed receive diversity techniques include Selection Diversity (SD), Maximum Ratio Combining (MRC), and Equal Gain Combining (EGC) [4]. At any time instant, SD selects the branch with highest Signal-to-Noise Ratio (SNR). Being the most simple solution, it certainly increases the system performance, nevertheless, it does not achieve best diversity gain. MRC and EGC achieve much higher gain, however, the involved complexity is also increased as all branches need phase alignment for constructive combination of signals before addition. A detailed theoretical analysis of these diversity combining techniques is provided in [10], [11]. Since the literature is rich of basic mathematical analysis involved in diversity combining, our focus here is on practical implementation of these approaches.

In a distributed multi-antenna system, it is difficult to forward data from all nodes to a single processing unit due to limited data rate of the network links. Therefore, selecting the branch with successfully decoded signal (i.e., performing Successful Branch (SB)) [12] or doing diversity on soft-bit values is preferred [13]. Also, since nodes in WSNs have limited processing capability, they may not be able to perform such operations locally but can act as relays to a stronger node [14]. The technique proposed in [12] forwards only the signal samples that achieve full diversity gain without increasing the local processing or overloading the network.

To increase the lifetime of ultra-low power nodes, a simple principle is to completely switch them off when not communicating. This idea has been explored in-depth using smart duty-cycling [15], wake-up receiver [16], and, most recently, combinations thereof [17], [18]. Another option for an energy-efficient communication is to optimize packet-sizes and the use of Forward Error Correction (FEC) [6]. Even though FEC introduces additional overhead, it is found that using it improves overall energy efficiency. Recently, the concept of mSync [8] has been proposed, which uses a novel physical layer packet format avoiding the usual preamble sequence.

In this work, we go one step further and combine mSync with selective signal sample forwarding based receive diversity. The combination of both concepts not only leads to energy-efficient communication but also improves the overall communication performance in distributed sensor networks.

III. Integrating Diversity Combining with mSync

In WSNs, the communication is usually packet-based and the packet structure on the physical layer normally includes a preamble, a Start of Frame Delimiter (SFD), the actual data, and a Cyclic Redundancy Check (CRC). The preamble is a repeating sequence used to detect a signal at the receiver and to estimate symbol timing, sampling clock offset, and frequency offset. With these estimated parameters, the receiver clock is synchronized with the transmitter to coherently decode the received data. SFD is also similar to the preamble in structure, however, its last bit normally breaks the flow of repeating sequence to identify the start of actual data, assuming that the clocks are already synchronized. In contrast, mSync eliminates the preamble from the packet structure, which certainly reduces the overall packet-length, however, this breaks state of the art receive diversity schemes. So, its implication on signal detection and coherent combination is still an open question.

A. *mSync*

With no preamble sequence in the packet structure, mSync uses the SFD in a unique fashion to estimate clock parameters. In brief, the mSync transmitter sends packets in flipped bit-order, starting from CRC and ending with SFD. The receiver continuously performs correlation of the incoming data with flipped SFD and keeps storing the samples in a buffer equivalent to the packet size. In case of positive detection, the stored samples are then appended at the end of the received packet in reversed (now correct) order. Thus, the clock module first receives the flipped data with back to back SFDs serving as a longer training sequence and then the data in correct order. From the flipped data, the clock module initiates coarse timing recovery and then further refines it through concatenated SFDs. The receiver structure after clock recovery remains unchanged as the flipped data is discarded by the decoder.

B. *Distributed Diversity Combining*

In most conventional diversity systems, all of the participating antennas are mounted on a single device, so, the diversity algorithm can directly be applied to the received samples. However, in a distributed network, the receiving nodes have bandwidth-limited connections to a (central) decoding node. Thus, forwarding all signal samples from every node to the central decoder is prohibitive, which makes diversity combining a challenging task. In order to avoid network overloading, only relevant samples of the detected packets are to be forwarded to the central node as proposed in [12]. Once all detected copies of the transmitted packet reach the central node, diversity combining is performed.

C. *Novel Integrated Preamble-Less Diversity Combining*

Our novel concept integrating mSync and receive diversity is depicted in Figure 1. In essence, the transmitter structure of mSync [8] is kept and the receiver is extended with the diversity combining denoted as the addition. In case of signal detection at multiple antennas, the adder coherently combines these signal copies before appending the buffered packet in correct order. These detections are an important part of a diversity system due to the fact that higher gain is only achieved by combining the signal copies which are detected but not recovered at a single antenna.

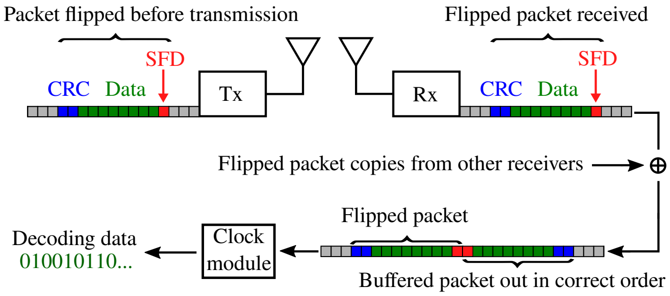

Figure 1. Combining mSync and receive diversity.

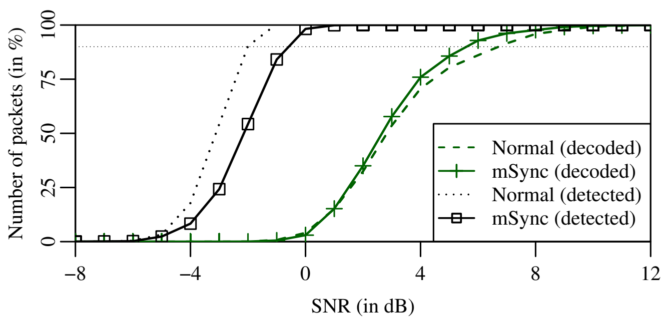

Figure 2. Packets detected vs. correctly decoded over an AWGN channel.

Since, mSync eliminates the preamble and detection is performed with SFD only, first, we need to assess its packets detection rate. To test this performance, we use the BATS transceiver described in [8] and simulate the detections as well as reception quality over different SNR values in an Additive White Gaussian Noise (AWGN) channel. In brief, we periodically transmit a Differential Binary Phase-Shift Keying (DBPSK) modulated packet of 12 B that contains 1 B each for preamble and SFD, 2 B of CRC, and remaining 8 B for the actual data. This translates into 8.3 % of preamble for the total packet length. Further details of the implementation are provided in Section IV. First, we simulate the performance with normal packet structure and then with mSync based flipped packet format without preamble. The results demonstrating the number of successfully detected and correctly decoded packets with each packeting format are plotted in Figure 2.

As can be seen, packets can be detected at an SNR that is 4 dB less than that required for correct decoding of the packets. This is a promising result which motivates the use of receive diversity to constructively combine the samples of detected packets from all nodes to further improve their quality. Furthermore, we are interested to see the effect of performing phase alignment for constructive combining of signals in mSync packet format through SFD only.

Looking from a different perspective and considering the performance plot of correctly decoded packets, we can confirm the findings in [8] that there is no performance drop, however, there are significant energy savings. Also, it is interesting to note that at higher SNR values, mSync performs better than the normal packet structure. This is because of the additional coarsely grained tuning of clock parameters from flipped data

Table I
DATA RATES IN THE NETWORK WITH NORMAL AND MSYNC BASED PACKET FORMATS.

Samples Forwarding	**Single Node** (Mbit/s)	**20 Nodes** (Mbit/s)	**Data Rate** (%)
All samples	64.00	1280.00	100.00
Selected samples (normal)	3.07	61.44	4.80
Selected samples (mSync)	**2.82**	**56.32**	**4.40**

before the start of actual packet and is further discussed in Section V.

Moreover, as already outlined in [12], considering the BATS application, forwarding all signal samples is prohibitive (64 Mbit/s for just a single node). Reducing this to the relevant signal samples, drops the required link capacity to 3.07 Mbit/s per node or about 61.44 Mbit/s for a total of 20 network nodes (i.e., for a packet size of 12 B). When integrating mSync and eliminating 1 B of preamble, this further drops to 2.83 Mbit/s per node or about 56.32 Mbit/s for a total of 20 network nodes. A summary of calculated data rates from the receiving nodes to the central node with and without selected signal samples forwarding is listed in Table I.

IV. IMPLEMENTATION DETAILS

For the use-case of our proposed method, we have followed the specifications provided for custom ultra-low power transceiver design in the BATS project [19]. In this project, we equip bats with very light weight sensor nodes weighing less than 2 g, and help biologists to track and monitor bats in their natural habitat. These nodes record the bats' encounters whenever they are in the range of each other, and upon their visit to a hunting area, transmit this information to a ground network. The ground network is deployed in hunting areas of bats and composed of static single antenna nodes (referred to as ground nodes). These ground nodes do not have any strict energy limitations and their primary purpose is to gather all information that is stored on the bat node. The resulting communication channel is greatly affected by several factors such as Free Space Path Loss (FSPL) and fading. For this reason, we use the ground network as a distributed antenna array for reception and apply our proposed concept.

We implemented both the transmitter and the receiver in GNU Radio for assessing the performance of the preambleless receive diversity system. We chose GNU Radio as a platform because of its wide-spread use as a real-time signal processing framework and the ability to do rapid prototyping, also in combination with Software Defined Radios (SDRs).

The validation of both approaches, with and without diversity, is done in two stages. We first performed simulations in an AWGN channel that provides the baseline performance. Then, we performed over-the-air measurements in a lab environment to observe the practical implications of mSync packet structure on diversity gain. For the normal packet, the implementation details of both transmitter and diversity receivers have already been discussed in [12]. Thus, in the next subsections, we focus only on the implementation details of mSync with receive diversity.

A. Transmitter Design

For the transmitter implementation, we have followed the BATS protocol [17], which uses DBPSK modulation with a data rate of 200 kbit/s, i.e., a packet duration of 480 µs. With mSync, preamble is not required anymore, thus, reducing the packet duration to 440 µs, which contributes towards the ultra-low power communication requirement of the bat node.

In our transmitter implementation, the encoder first generates flipped (or mirrored) packets of 11 B, and then modulates them using DBPSK. Afterwards, the modulated output is interpolated and sent either using an AWGN channel in simulation mode or via SDRs for over-the-air experiments. Additionally, for wireless transmissions, we used a carrier frequency of 868 MHz and interpolated each bit by a factor of 5, thus, leading to a channel bandwidth of 1 MHz.

B. Receiver Design

The design of our ground nodes is rather flexible in-terms of energy, complexity, and size. This design flexibility of ground nodes is the main reason for employing receive diversity with mSync, which not only improves the system reliability but reduces the transmit power requirements as well.

At our receiver, the packets are detected by correlating the received samples with the flipped SFD. In the case of successful detection, the phase offset is estimated from the available 1 B of SFD and compensated for constructive diversity combining. After phase compensation, the stored packet samples are flipped and appended at the end (as shown in Figure 1). With such a packet structure, the clock recovery module first performs coarse timing recovery through the flipped payload, and then does fine recovery using two back to back SFDs. For clock recovery, we have used the GNU Radio's built-in *Mueller and Müller* block which implements a two taps feedback system that estimates the sampling clock and frequency offsets [20]. Further details of this algorithm and its impact on mSync have been discussed in [8]. Finally, the receiver performs demodulation, decoding, and a CRC check to ensure successful decoding.

We implemented two diversity techniques, namely SB and EGC. Theoretically, MRC leads to the highest diversity gain, however, we leave it for future work due to the involvement of perfect channel estimation from training data. In SB, each receiver decodes the received data, hence, the signal is successfully decoded if any of the receiver decodes it correctly. In EGC, data from all branches is combined after co-phasing, thus, the receiving branches are highly dependent on each other, and if one branch contains just noise or a distorted packet, it affects the overall performance of EGC.

V. Performance Comparison and Discussions

In the following, we report first on the physical layer communication performance, and then, discuss energy efficiency and application performance issues.

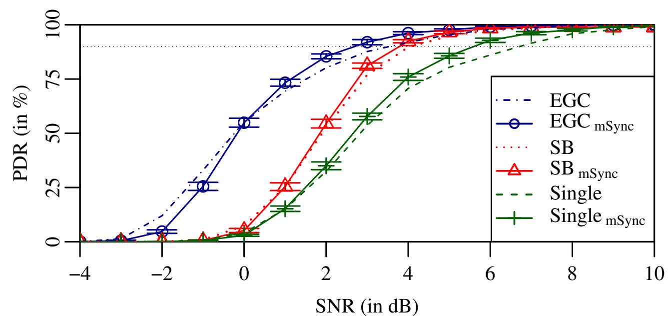

Figure 3. Simulated performance of mSync and normal approach with diversity combining over an AWGN channel.

A. Simulations

To analyze the performance in simulations, we used an AWGN channel. For a fair comparison, both mSync and normal packets are transmitted using the exact same channel conditions. The receiver design for simulations is relatively simple as there are no hardware nonlinearities, wireless channel impairments, and frequency and phase offsets to consider. It thus provides a baseline performance.

Figure 3 shows the Packet Delivery Ratio (PDR) performance of mSync and normal packet structure over an AWGN channel at different SNR values (labeled as "single" in the legends). The graph also plots the results for SB and EGC to show the achieved diversity gain with two receivers. We repeated the simulation 30 times for each SNR level to obtain a PDR with 95 % confidence intervals. A PDR threshold of 90 % is marked with a horizontal dotted line.

It can be seen that without diversity combining, the performance of mSync is roughly the same as a normal packet reception at low SNR, however, at higher SNR, mSync provides overall better PDR. The slightly improved performance is because of the additional coarse tuning of the clock acquired through the flipped data samples, prior to fine timing recovery via two back to back SFDs.

When applying diversity combining with two receivers, SB provides an average improvement of 0.8 dB for both approaches in relation to the single receiver performance. Employing EGC, however, improves the system performance by 3 dB for normal packet structure. These results match the theoretical diversity gain and are in line with the results reported in [12]. In the case of mSync with EGC, a diversity gain of 3 dB is observed at high SNRs only (for a PDR of 50 % and higher). At low SNRs, the diversity gain drops down to 2.2 dB in the worst case. This is because at low SNR values there is a high chance that the limited training data which is used for the phase estimation is corrupted and, thus, the signal copies from different diversity branches are not added constructively. Nevertheless, this performance loss is compensated at higher SNR, where SFD alone provides a good phase estimate and the overall achieved PDR becomes even better than EGC with normal packet structure. These results for an AWGN channel clearly demonstrate the advantages of using mSync, when combined with receive diversity.

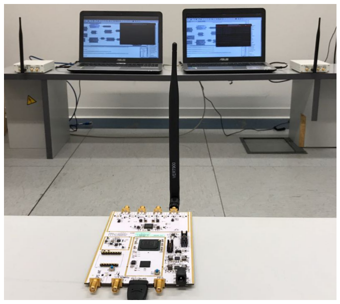

Figure 4. Lab setup used for the experimental study.

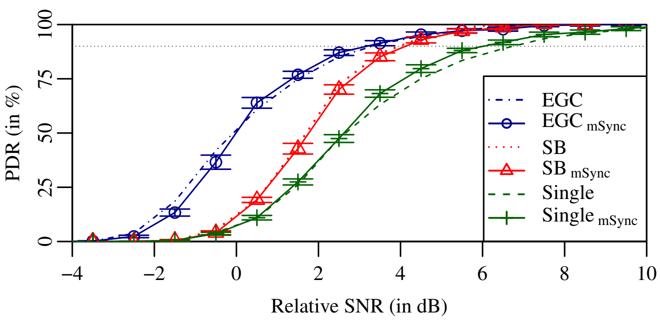

Figure 5. Experimental performance of mSync and normal approach with diversity combining in a lab environment.

B. Experiments

To perform over-the-air measurements for a two-branch diversity system in a lab environment, we used three Universal Software Radio Peripherals (USRPs) B210 / N210. To maintain the same noise floor for both receivers, the gain of each receiver is fixed and their placement is done such that both receivers experience approximately similar SNR. Each USRP is connected to a laptop computer, which first records the measurement data (i.e., selective samples corresponding to the detected packets) and, afterwards, post-processing is done to generate performance results. The experimental setup with one transmitter and two receivers is shown in Figure 4.

To evaluate the practical performance, we used the exact same implementation as in simulations and replace AWGN with real wireless channel in a lab environment. The obtained PDR at different SNRs from both approaches along with diversity combining techniques is plotted in Figure 5. The measurements were repeated 30 times to plot the 95 % confidence intervals. The USRP devices used in the experiments are not calibrated to measure absolute power levels. For this reason, in order to make the experimental results comparable to the simulations, we shifted all the measurement curves by a constant SNR offset.

It can be seen that the performance of mSync, both with and without diversity, is slightly degraded compared to what we have seen in simulations. The reason for this performance degradation is the receiver lock-time, which sometimes distorts the first few samples of the received packet. Unlike normal packet structure, which starts with a preamble, mSync has flipped CRC samples at the beginning. Thus, losing these samples due to occasional imperfect locking results in packet loss, which degrades the overall mSync performance. Nevertheless, the performance of mSync is still better or equivalent compared to the normal packet structure at the desired PDR of 90 %. These experimental results further support the applicability of diversity combining in conjunction with mSync approach, despite the fact that mSync only contains an SFD for detection, phase estimation, and timing recovery.

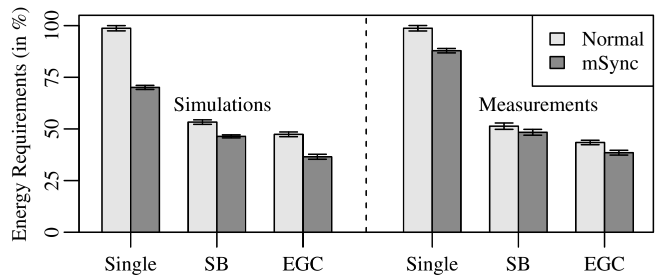

Figure 6. Relative energy requirements at the transmitter to achieve an average PDR of 90 %.

C. Energy Efficiency

Considering our application scenario, mSync approach decreases the packet-length by a byte, which reduces the energy requirement at the transmitter by 8.3 %. When diversity combining techniques are applied together with mSync, these energy requirements are further reduced. Based on our presented simulation and experimental results, a visualization of achievable energy savings for a strict 90 % PDR with 95 % confidence intervals is shown in Figure 6.

The normal approach without diversity combining requires the most energy to achieve a PDR of 90 %, therefore, it is considered as a reference, i.e., 100 % energy usage. The energy savings of mSync are slightly lower in measurements compared to simulations. This is intuitive because we already reported that the performance of mSync is slightly degraded in our measurements. As a result, to retain the desired PDR level, increase in energy bars is certain and can be seen in the plot. In any case, the energy savings using mSync are clearly larger compared to the normal receiver system using a preamble. For instance, to achieve a PDR of 90 % in measurements, the energy required with combined mSync and EGC diversity is only 39 % of what is needed in the case of normal approach with no diversity.

These energy savings are obtained when diversity combining is employed with just two receivers. If there are more receivers available in the ground network, then diversity application with mSync can further lower the power requirements.

D. Application Performance

In order to gain more insight of our system's performance in realistic channel conditions, we used our bat movement model [12], which computes realistic channel values. The implemented two-dimensional bat mobility model comprises of a $120\,\mathrm{m} \times 120\,\mathrm{m}$ hunting ground with six nodes. In the model, a bat flies from its roost towards the hunting ground,

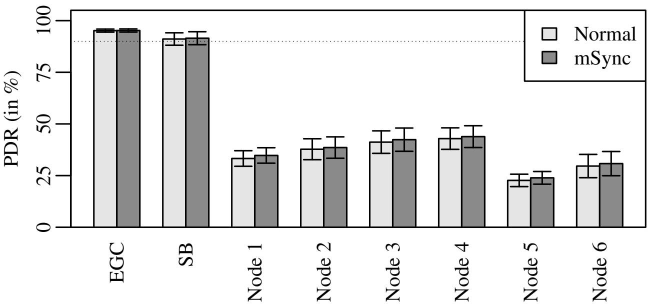

Figure 7. Performance analysis in the application scenario using a realistic channel model.

preys, and then returns back to its roost. As soon as the bat enters in the communication range of the ground nodes, its distance from all nodes is calculated. For every 100 ms, channel impairments such as FSPL, flat Rayleigh fading, and noise is computed. Additionally, shadowing is introduced for every single tree that lies in between the bat and any ground node.

First, we simulated the flights of bats using the discussed bat mobility model in MATLAB and then the obtained channel is imported into our GNU Radio implementation to analyze the application performance. Based on these channel values, simulation results for a fixed transmit power level are obtained.

Figure 7 shows the average PDR achieved with each ground node individually as well as from implemented diversity combining techniques. It can be noted that mSync outperforms normal packet approach by 1 %–4 % in all cases. Also, the advantage of applying receive diversity in this distributed scenario is quite evident. When the maximum PDR with a single ground node is about 40 %, the receive diversity provides a PDR of more than 90 %. These results certainly suggest that mSync with diversity application not only provides better performance in-terms of PDR but also reduces the energy requirement considerably.

VI. Conclusion

In this work, we combined the concept of preamble-less communication with receive diversity for ultra low-power WSNs. We implemented the proposed model in GNU Radio and performed simulations as well as experiments using SDRs to evaluate its performance. Our results clearly demonstrate that the proposed model optimizes energy-consumption at the transmitter and, at the same time, improves the reception rate. For an application scenario with six receiving nodes and realistic channel conditions, a performance improvement of 1 %–4 % is observed along with substantial energy savings in comparison to the conventional system. Our future work is focused on accurate channel estimates through preamble-less packets to apply more complex diversity techniques such as MRC.

Acknowledgements

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