Turning Sensor Networks into Distributed Antenna Arrays for Improved Communication Performance

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***Abstract*—We study the potentials of using sensor networks as a distributed antenna array for improved packet reception performance. In many sensor network applications, nodes can be distinguished according to their roles. Backbone (or ground) nodes establish a core network used to deliver data to a (possibly central) sink, whereas mobile nodes transmit sensor readings to this backbone. In the case of errors, the transmitted information is either lost or must be repeated. Considering very energy constrained nodes, such retransmission is often prohibitive. Making use of the spatial distribution of such a ground network, macrodiversity can be exploited. By combining received signal samples from multiple ground stations, the chance for successful decoding can be substantially improved. Using a specific wildlife monitoring application, we demonstrate the advantages of this concept. To the best of our knowledge, the first work to make use of a sensor network as a distributed antenna array, which offers many possibilities in upcoming Internet of Things (IoT) applications.**

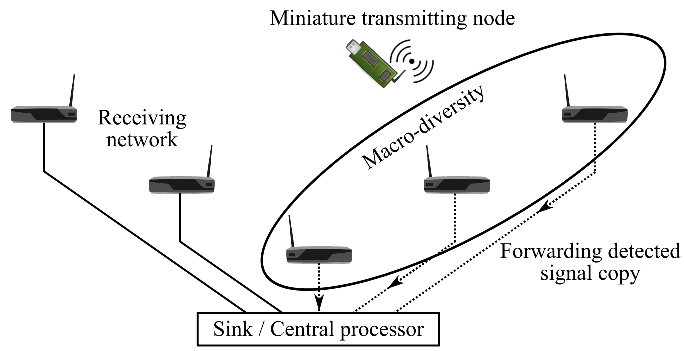

Figure 1. Multiple receiving ground nodes are detecting the same signal from a mobile sender and forward it to a sink for further processing, for example, for an improved reception through macrodiversity.

I. Introduction

Today's application domains of Wireless Sensor Networks (WSNs) go well beyond environmental monitoring and smart home applications; particularly wildlife monitoring has become a major field. Recent advancements in technology focus on further minimizing the sensor node size with all essential functionalities at hand [1]. One of the most critical issue is still energy consumption; due to size or weight constraints, also energy harvesting is often prohibitive for mobile nodes [2].

Conceptually, the network topology and data processing follows the scheme presented in Figure 1. The mobile node collects the required information (e.g., encounters, physiological data, location information) and transmits it to a ground network that consists of several receiving nodes connected to a sink. The ground nodes are typically less energy restricted and often interconnected by wired or wireless communication networks supporting higher data rates. The reduced size of the transmitting node, however, results in a tight energy budget and, hence, poses numerous research challenges. One crucial task is to reliably pass information from one or many miniature nodes to a receiving network [3, 4]. As these transmitting nodes are mobile, the reliability is affected even more due to a time-varying channel. Apart from WSNs, modern technologies such as Internet of Things (IoT), industrial automation, medical implants, and many others which involve same kind of architecture also come across the same issue. To cope with this issue, a possible solution is to incorporate the idea of diversity combining in the receiver network.

In wireless communications, space diversity is considered as an inexpensive and simple solution to increase the robustness of a system [5, 6]. Multiple antennas connected to a single receiver are used to receive multiple copies of the same signal and, eventually, to constructively combine them to improve the reception quality in presence of multipath environments. If the antennas are distant at a level of wavelength and the channels are uncorrelated, the technique is referred to as a microdiversity. However, if the distance between antennas is much larger and they are mounted at different receivers, to additionally combat shadowing, then it is called a macrodiversity technique. With macrodiversity, we can also expect higher throughput along with an extended network coverage in a continuously changing environment.

Macrodiversity is quite popular in cellular communication systems where connections to all base stations are usually through optical fiber [7]. Realizing macrodiversity with coherent base stations helps against inter-cell interference. In the literature, realizing macrodiversity is mature enough when it comes to widely distributed networks, however, its applicability in practical WSNs to achieve full benefits is still in infancy. The main experimental problems arise due to the difference in network size, network topology, propagation environment, and induced fading. Bandwidth limitation and mobility of nodes in a WSN impose further challenges in designing a stable algorithm. Therefore, to achieve maximum gain, it is important to realize macrodiversity efficiently in a network which involves finite capacity and finite latency links.

In this article, we discuss receive diversity (macrodiversity at the receiving side) for a packet-based communication without overloading or increasing data rate requirement in a distributed sensor network. We make use of multiple ground nodes in a network to establish a distributed antenna array. The main aim is to highlight limitations, technical challenges involved, and lessons learned from practical experiments while achieving maximum diversity gain. The findings are not only

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limited and helpful for sensor networks but can also be useful for other modern technologies that use similar network architectures for their many applications.

Our main contributions can be summarized as follows:

- We summarize and highlight the challenges involved when incorporating macrodiversity for improved reception in distributed sensor networks and present preliminary solutions (Section II).
- We develop a small network for basic performance analysis of proposed solutions and report our results from practical experiments (Section III).
- Finally, we briefly present the future extension and potential possibility of incorporating macrodiversity in other advanced low-power applications (Section IV).

II. Receive Diversity in Distributed Sensor Networks: Challenges and Solutions

In this section, we highlight all steps that are required to perform diversity combining efficiently in distributed networks.

A. Signal Decoding

1) Challenge: In widely distributed networks, macrodiversity is usually observed with cooperation by using a relay node between transmitter and receiver or allowing multiple nodes in a network to coordinate with each other in order to enhance system performance. The receivers thus cooperatively decode information from the transmitter and relay by applying different diversity combining techniques [8].

Cooperation of nodes within a network to achieve diversity gain and improve decoding is known as a node cooperative method [7]. In a node cooperative method, participating nodes form a distributed antenna array. Thus, diversity combining and decoding is done either jointly at a central entity or in a more decentralized way by processing the information locally in adjacent nodes. A fully centralized cooperation achieves maximum theoretical gain by applying diversity combining at a central node before decoding.

2) Solution: Cooperation without the involvement of a central entity can in general be more reliable as network is not susceptible to node failures. In cellular networks, such a decentralized cooperation is realized by forming fixed size clusters, each made up of multiple base stations [9]. Whenever a data reception is detected at any of the base stations, it is passed to other base stations within the cluster; this way, diversity combining and decoding is performed at one of the involved nodes.

The achieved diversity gain in cooperative networks greatly depends upon channel conditions and the underlying network topology. In the case of mobile transmitting nodes, the channel conditions are time varying and, hence, introduce extra challenges when applying receive diversity through cooperation. Fixed size clustering is of no benefit anymore as there is a high probability that the copies of transmitted data will be received at base stations in different clusters. Hence, there is a need of cooperation between clusters as well which introduces additional information overhead to exchange in the network. To tackle this challenge effectively, one solution is a dynamic clustering in which the size and structure of cluster is changed based upon received channel quality at different base stations [10]. Hence, at any time instant, the dynamic cluster includes only those nodes for cooperative decoding which detect the transmitted signal successfully.

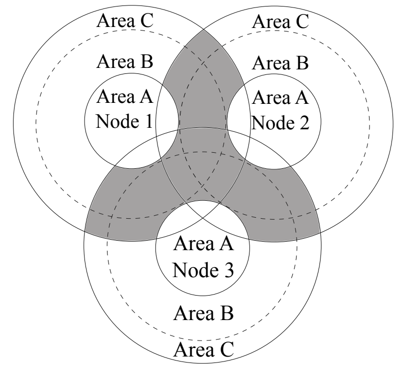

Figure 2. Schematic coverage areas around receivers with a shaded region where diversity gain is observed.

B. Efficient Node Placement

1) Challenge: The geographical position of nodes in a distributed network plays a vital role in achieving maximum diversity gain and improving overall coverage [11]. If nodes are placed too close to each other, diversity combining is of no use as there is a high probability of receiving data successfully by a single node in that region. In case of very distant nodes, neighboring nodes do not contribute at all to enhance signal strength and applying diversity does not improve the system performance. It has been learned from cellular networking that boundary between the cells is exactly the region where a mobile station is expected to suffer the most degradation in a received signal [9]. Therefore, nodes are preferred to be placed at the coverage area border of another node to increase the overall diversity gain. However, in order to further improve the performance, it is important to highlight the area between nodes where diversity gain achieved is maximum.

2) Solution: Every receiving node is usually surrounded by three types of areas based on the probability of detecting and receiving a signal successfully as shown in Figure 2 [12]. The shape and size of these areas depend upon different factors such as receiver sensitivity and channel losses due to obstacles. In inner most area A, all transmitted signals are detected and decoded successfully by a single node while in the outer most area C, the probability of any successful decoding is close to zero, even though a few signals can still be detected. The middle area B is an area where detecting and decoding a signal successfully stays between $0\,\%$ and $100\,\%$. For maximum diversity gain, the nodes are placed in a way that overlapping of external two areas between neighboring nodes is maximum. Overlapping of inner most areas is not helpful in improving reliability as a single node can successfully decode all signals without any combining already. Similarly, if nodes are placed far apart with no overlapping in any of these areas, no diversity gain is achieved.

C. Synchronization

1) Challenge: Synchronization between receiving nodes is an important requirement for constructive signal combining to achieve maximum diversity gain. If a system suffers from synchronization issues, the signals are not perfectly aligned and diversity combining cannot be performed efficiently. In a typical wireless system, different types of synchronizations (e.g., carrier, symbol, frame) are required between the transmitter and receiver for a successful recovery of transmitted data [13]. Microdiversity systems do not need additional synchronization as all receiving signals derive their clock frequency from a single oscillator. However, in macrodiversity, tight synchronization between distributed nodes (or branches) is required. For example, there is a continuous requirement of sharing Channel State Information (CSI) in cellular communications to coordinate in their signaling strategies in addition to user scheduling in time and frequency. In many other systems, carrier synchronization is usually achieved by sharing some information between nodes such as using common beacon signals or communicated phase offset signals. Sufficient synchronization is achieved through GPS (up to a level of ns) or Network Time Protocol (NTP) (up to a level of ms).

2) Solution: If the communication is packet based and there is a predefined guard interval between transmissions, an effective method to achieve sufficient synchronization between nodes is to use a training data [12]. In such a case, all receiving nodes detect the start of signal (and hence synchronize the start of signal copies in different branches) and process the training data within a guard interval to attain other synchronizations. This approach is similar to non-cooperative random access schemes in which the received samples are correlated with the training sequence for detection and later used for the refinement of packet timing at the physical layer.

D. Signal Detection and Channel Estimation

1) Challenge: To constructively combine signal copies received at distributed nodes, it is essential to first detect a signal copy at each receiving node individually and then estimate the channel for accurate phase correction. One option to realize this is by transmitting a pilot signal along with the data. However, such an approach consumes additional energy especially at the transmitter and, hence, makes it difficult to use in energy-constrained networks.

2) Solution: Most of the modern distributed networks involve packet-based communication in which the packet structure on physical layer normally involves a preamble, a Start of Frame Delimiter (SFD), the actual data, and a Cyclic Redundancy Check (CRC). The preamble is a known training sequence that is continuously correlated with the incoming signal at a receiver for the detection of the desired signal. These preamble training symbols can also be used to estimate the channel. The receiver can thus synchronize with the transmitter by calculating frequency offset, sampling clock offset, and symbol timing. The SFD is comparatively shorter than the preamble in length and is usually used to indicate the start of actual data by breaking the flow of training sequence.

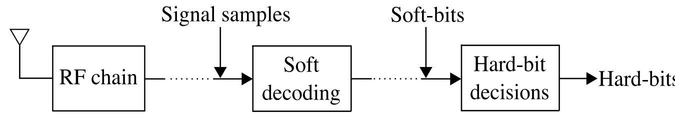

Figure 3. A generalized wireless communications receiver.

Finally, the CRC is used to check whether the reception is successful.

While applying receive diversity in distributed systems, different nodes confirm the detection of signal by using the preamble and, thus, take part in the combining process. The same preamble is used to estimate and correct the phase of received signal copy and to align it with other receptions so that coherent and constructive combination of signals is possible. The obtained channel estimate, e.g., received signal strength, can also be used to select the weight of respective signal copy before combining. Once the combining has been performed successfully, the decoding process can be started.

E. Data Rate Requirement

1) Challenge: In macrodiversity systems, since all branches correspond to spatially separated receivers, high capacity links are required between nodes to reliably pass information. In this regard, a major constraint in distributed networks are network links that offer only limited data rate. Legacy cellular networks tackle this problem by performing diversity at hard decision bits or selecting a signal with highest strength. These methods reduce the network load but at the expense of low diversity gain.

2) Solution: Here, we discuss the possibility of performing diversity combining at different stages of a receiver and their relative performance in a distributed network [12]. A generalized wireless communications receiver with different levels of a signal is depicted in Figure 3. After receiving complex signal samples, the signal is first processed and then downconverted into soft-bits (i.e., one float value per bit). These soft values are then mapped to nearest decision points to obtain hard-bits and for final decoding. In the following, we highlight the advantages and disadvantages of applying diversity combining at these different levels. Also the comparison of diversity gain and required data rate for these various approaches of transmitting information in the network for a specific application example (BATS protocol, cf. Section III) are summarized in Table I.

a) Complex signal sample: A conventional method to perform receive diversity is combining copies of all I/Q signal samples from different antennas or nodes at signal level. It is more popular in microdiversity systems where signal copies from different antennas are combined to improve received signal strength. Phase estimation and correction is required in all branches before applying diversity for coherent combining of signals. Signal level diversity achieves maximum possible gain, i.e., two independent signal copies increase the system performance as much as $3\,\mathrm{dB}$. However, it is unrealistic in practical distributed networks due to the forwarding of all signal samples from multiple nodes.

Table I
POSSIBLE DIVERSITY GAIN WITH MAXIMUM DATA RATE FOR VARIOUS APPROACHES OF TRANSMITTING SIGNAL SAMPLES IN THE GROUND NETWORK (SIGNAL CORRESPONDS TO 5 SAMPLES/BIT).

Forwarding data as	**Single node** (Mbit/s)	**32 nodes** (Mbit/s)	**Diversity gain**
Complete signal samples	64	2048	Highest
Soft-Bits	0.31	9.83	Medium
Hard-Bits	0.01	0.31	Very low
Selected signal samples	3.07	98.3	Highest

b) Soft-bit values: To overcome this issue, a simple solution is to process the signal locally and to forward only soft decision bits in the network. Soft-bit level combining still retains the advantage of some diversity gain, however, the performance is worse compared to signal level diversity due to the tradeoff with low data rate requirements.

c) Hard decision bits: In some very high data rate applications, the network does not support even soft-bit forwarding. To realize cooperation within these limitations, each node performs most of the processing locally and forwards hard decision bits in the network. Participating nodes in such a scenario can also be viewed as relays performing decode-and-forward to a central processor. Though it generates minimal load in the network, diversity gain achieved is also the least.

d) Selected signal samples: As stated earlier, most transmissions in a packet-based communication involve a preamble. Hence, it also provides an opportunity to detect the transmitted signal at distributed nodes and forward only those received I/Q samples in the network that correspond to the relevant signal. Therefore, the amount of data that needs to be forwarded in the network reduces drastically which can be further minimized by switching between different signal levels. Using such a selective signal sample forwarding approach does not lose any diversity gain; however, the processing load at the network nodes is marginally increased due to the detection of signal locally before forwarding [12].

F. Diversity Combining Techniques

1) Challenge: Diversity combining has been the focus of researchers since many decades and is still popular in new technologies due to its simplicity and very high gain [5]. In the literature, several diversity techniques have been proposed. Selection Diversity (SD) selects a branch with highest signal strength and is considered as the least complex diversity combining technique. It does not achieve full diversity gain as signals from other branches are dropped and do not contribute to the final signal. Other popular diversity combining techniques include Equal Gain Combining (EGC) and Maximal Ratio Combining (MRC). In EGC, signal copies from all branches are summed up with equal gains after phase alignment, while in MRC each branch is weighted according to its individual signal-to-noise ratio (SNR) before addition. Using EGC is usually not an optimum choice except when the channel estimation is impossible because the diversity gain is affected if any of the branches involve a corrupt signal copy. In contrast to that, MRC provides the highest diversity gain, however, the implementation complexity is higher and erroneous estimation of channel heavily affects its performance. Most of these diversity techniques are usually applied at the signal level and, hence, cannot be realized directly in distributed networks due to excess data rate requirements.

2) Solution: To reduce the data rate requirements without compromising on the diversity gain, selected signal sample forwarding approach is used. With that, complex diversity techniques such as MRC and EGC can still be successfully realized in distributed networks. The same diversity techniques can also be applied at soft decision bits but with a drawback of relatively lower diversity gain as mentioned previously. If combining is performed at hard-bits, a majority combiner is used to take a decision for each bit such as in Multiply Detected Macrodiversity (MDM).

III. DIVERSITY COMBINING IN DISTRIBUTED WSNS: MONITORING BATS IN THE WILD

In this section, we target an application scenario, namely monitoring bats in the wild, to apply all solutions discussed in the previous section to achieve maximum diversity gain.

A. Application Domain

We mainly focus on a wildlife monitoring application within the scope of the BATS project [2]. In this project, we are helping biologists in investigating the foraging behavior of bats in their natural habitat. In brief, we are equipping bats with a $2\,\mathrm{g}$ sensor node that continuously records contact information between individuals. To extract this information that is saved on the miniature chip, we use stationary single antenna sensor nodes which are present throughout the hunting areas of bats and form a distributed ground network. This ground network is also responsible for tracking the trajectories of a flying bat when in range. Transmissions from miniature bat nodes in such a forest environment are highly affected due to bad channel conditions. However, due to the distributed nature of the ground network, there is a high probability that the signal transmitted will be received by more than one ground node. Therefore, using multiple ground nodes as a distributed antenna array to realize receive diversity for enhancing received signal quality seems to be quite promising.

Given the available energy budget, all communications use only short time slots of $480\,\mu\mathrm{s}$. To comply with this time limit and other present constraints, packets have a size of $12\,\mathrm{B}$ containing $8\,\mathrm{B}$ of payload, and $2\,\mathrm{B}$ each for training data and CRC. A bat node sends Differential Binary Phase Shift Keying (DBPSK) modulated packets at $868\,\mathrm{MHz}$ with a data rate of $200\,\mathrm{kbit/s}$. For accurate localization during flight maneuvers, neighboring ground nodes are placed $30\,\mathrm{m}$ far apart [4].

To detect signals transmitted by the bat node, all ground nodes continuously correlate the incoming samples with the known data. If a bat transmits over the ground network, the signal is detected and channel is estimated through the training data at the local nodes. This estimation is then used for symbol synchronization (and also for frame synchronization at later stages) before slicing the packet and forwarding it to apply diversity combining at a central processor [12]. Once a packet

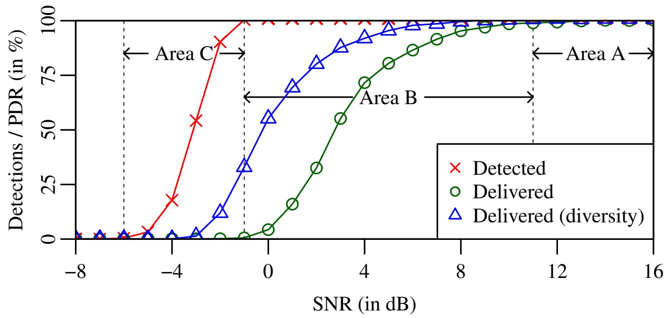

Figure 4. Regions around a receiver and the performance of a two-branch diversity system.

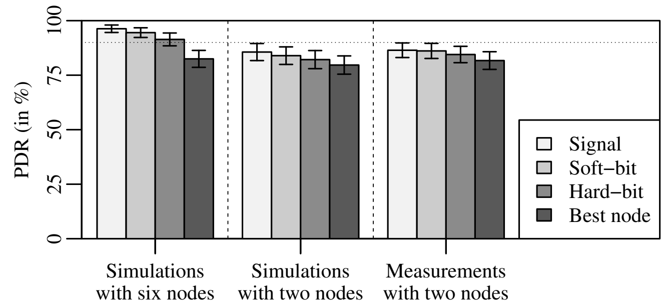

Figure 5. Packet delivery rate in simulations with realistic channel values and in outdoor field measurements.

is combined and decoded at the central processor, the success of decoding is checked by the CRC.

Slicing the signal and forwarding samples equivalent to known packet-length greatly reduce the maximum data rate required in network as not all nodes have to send all data to the central processor. The forwarding data can be soft-bits or I/Q signal samples. In case of soft-bits, more processing is performed locally which lowers the data that needs to be forwarded, however, full diversity gain is not achieved. Selective signal sample forwarding not only reduces data rate requirements in comparison to a complete data forwarding but also provides a possibility of achieving full diversity gain [12].

B. Application Performance

We developed both the BATS transmitter and ground node receiver in GNU Radio, which is an open source software defined radio platform. First, to analyze the regions discussed in Section II-B, we simulated transmissions over independent and identically distributed Additive White Gaussian Noise (AWGN) channels for a single transmitter and two receivers (i.e., two diversity branches). We then used the same implementation and performed over-the-air experiments in an office environment by using three Universal Software Radio Peripherals (USRPs) (one as a transmitter and two as receivers) to investigate the performance. The resultant Packet Delivery Rate (PDR) and detections over different SNR values with and without diversity along with the highlighted regions is plotted in Figure 4. We also plot the number of packets detected by a single receiver. Due to space restrictions, we only show results for simulations only; our measurements yield exact same curves. It can be noticed that in area C, packets are detected, however, single receiver fails to receive any of the packets successfully. With diversity combining, some of the detected packets can even be successfully decoded. In area B, the single receiver recovers some packets but the performance is lower in comparison to diversity combining with two receivers. Area A is the region where all packets are successfully received even without employing any diversity. It is also interesting to note that simply combining signal samples from two receivers with equal gains provide a performance gain of roughly $3\,\mathrm{dB}$ and, hence, validate our implementation.

Further, to analyze the performance in our application scenario, we implemented a bats movement model in MATLAB and simulated a bat over a ground network with six nodes (details can be found in [12]). Every transmission from the bat is thus attenuated by Free Space Path Loss (FSPL), fading, and shadowing. It is important to note that the considered species of bats fly with a maximum speed of $50\,\mathrm{km/h}$, which results in a coherence time of about $10\,\mathrm{ms}$. Since the coherence time is much greater than the duration of a single transmission (i.e., $0.48\,\mathrm{ms}$) in our case, the attenuation is applied only once per transmission. The obtained channel values are then imported to our GNU Radio implementation, where we simulated the transmissions along with AWGN and applied EGC at different levels of the receiver. We focused on EGC due to its low implementation complexity and used a transmit power in a range such that the results are easily comparable with field measurements. The resultant PDR by employing diversity combining with all six receivers as well as with only two best receivers is shown in Figure 5. The horizontal dotted line denotes a desired PDR of $90\,\%$. We repeat the experiments 30 times to obtain the error bars indicating $95\,\%$ confidence intervals.

Diversity combining with all six nodes achieve a PDR of $96\,\%$, $94\,\%$, and $91\,\%$ when applied at signal, soft-bits, and hard-bits, respectively. Best node provides a performance of about $82\,\%$ that is $9\,\%$ less in comparison to hard-bits. When using only two receivers to perform diversity combining, the comparative advantage is now less pronounced due to the lesser number of nodes involved. The achieved PDR now reaches up to $86\,\%$, $84\,\%$, and $82\,\%$, respectively. The hard-bit combining does not provide high advantage over best node in this case (i.e., only $3\,\%$) due to the least even number of receivers involved. Nevertheless, the advantage of performing diversity combining at a signal level over all other approaches is clear.

Finally, we went into a forest environment and performed field measurements with two receivers that are $30\,\mathrm{m}$ apart and transmitter moving at a human walking speed between the two receivers throughout measurements. The results are also plotted in Figure 5. Here, applying diversity combining achieves a PDR of $87\,\%$, $86\,\%$, $84\,\%$, and $81\,\%$ when applied at signal, soft-bits, hard-bits, and best node respectively. Qualitatively, they yield same performance as simulations and, hence, also support our approach as a whole.

Even though the advantage of employing diversity combining is clear, it is important to mention that it also has some drawbacks due to the computational complexity involved and the latencies introduced in the network [14]. Detecting the transmitted signal at each network node and slicing the relevant signal samples increase the processing overhead. This overhead is further increased if the receiving nodes perform additional computations to convert the signal into soft-bits and, finally, into hard decision values. Since nodes in our ground network do not have strict energy limitations and the mobile node transmits only once per Time Division Multiple Access (TDMA) slot, we successfully realize receive diversity in our scenario.

IV. Conclusion and Future Research Directions

Many modern technologies such as industrial automation, health care applications, and the Internet of Things (IoT) involve a heterogeneous network architecture in which data is transmitted in form of short packets from very low-power devices to a backbone network. The information is often lost due to infinite multipath effects in the environment. The backbone (or receiving) network usually do not face strict resource limitations and, hence, employing diversity combining to combat multipath fading and obstacle shadowing turns out to be an excellent solution. In this article, we have targeted receive diversity in such networks to enhance the quality of their operated signal without any modification in the low-power transmitting node. We have described limitations and challenges while employing receive diversity in distributed networks and provided solutions to tackle these challenges. We have also applied our solutions in an application scenario and reported the results from practical experiments. Nevertheless, it has been proved that diversity combining can be applied in distributed networks which significantly improves the communication process.

Acknowledgments

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