A Practical Implementation of a Cooperative Antenna Array for Wireless Sensor Networks

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Abstract. Energy consumption is a key issue to be handled in Wireless Sensor Networks, especially considering low-end sensor nodes, i.e. sensor with severe energy resources limitations. When sensor nodes have their energy resources depleted, they stop working which can compromise the whole network functioning, thus its lifetime. As communication is the most energy-consumption task, enhancements in communication that diminish the amount of messages lost and the need for retransmissions are very important to preserve energy resources and extend the network lifetime. Considering the impact of the energy preservation and the opportunity to exploit it in terms of communication, this paper discusses the practical implementation of a cooperative MIMO scheme based on virtual antenna array using sensor nodes in order to enhance data communication in wireless sensor networks. The conducted experiments present evidence of the feasibility of the proposed approach highlighting performance aspects.

Keywords: Wireless sensor networks · Cooperative antenna array · Cooperative multiple input multiple output · Energy efficiency

1 Introduction

The use of wireless sensor networks (WSN) is considered a key enabling feature to a number of emerging applications in many areas, from precision agriculture to military and defense systems [1]. Despite the number of applications that can benefit of the usage of WSN, their energy resource limitation is a practical issue in their employment, which still hinders their massive usage. Wireless sensor nodes are usually tiny resource constrained platforms, driven by batteries with limited energy budget. In most of cases, they are deployed in places difficult to be accessed, such as large areas mixed with all kind of hazards or even inside building structures. This particularity in the WSN deployment makes impracticable the replacement of their energy resources. To overcome this problem, a smart energy resource management must take place.

Studies demonstrate that the most energy consuming task in wireless sensor nodes is communication [2]. Thus, efficient communication mechanisms are highly

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desirable to reduce the sensor nodes energy depletion and consequently, enlarge the whole network lifetime. Observing this aspect, a number of proposals try to address the problem with alternative routing protocols [3], energy aware broadcast [4], energy aware MAC protocols [5] and Multiple Input Multiple Output (MIMO) based systems [6]. Among these approaches, the three first are extensively explored in several different ways to optimize respectively the network and data link layers. The last one is a promising technology that tries to complement the energy saving effort in the upper layer addressing the problem in the physical layer.

Conventional MIMO techniques explore antenna arrays installed in a single node, as how it is used in WIFI access-points and routers. Due to the resource scarcity of the wireless sensor nodes, the same strategy used in WIFI equipment is not feasible. However, WSN are inherently cooperative distributed systems. Observing this aspect, an opportunity can be explored, which is the composition of a virtual MIMO system, or a cooperative MIMO system. In this alternative the antenna array is formed by the antennas of different nodes, which cooperate to compose this virtual antenna array [6]. Despite the promising advantage of this approach, there are technical issues that might hinder its feasibility, which is mainly related to the synchronization of the sender nodes, as discussed in [7]. Observing these practical issues, the goal of this project is present the results of a feasibility test of a cooperative MIMO approach application to WSN by the evaluation of a practical implementation.

The remaining text is structured as follows: Section 2 presents a brief discussion about cooperative MIMO and its usage in WSN. Section 3 provides an overview about the synchronization problem. Section 4 describes the framework for the feasibility tests, while Section 5 reports and discusses the acquired results. Section 6 concludes the paper providing directions for future work.

2 Cooperative MIMO and Its Usage in WSN

Wireless sensor networks are cooperative by nature. Observing this aspect, a cooperative MIMO approach can be implemented in order to minimize the energy consumption due to communication. As opposed to traditional MIMO systems, in which a set of antenna is present at the transmitter and at the receiver nodes, the cooperative MIMO utilizes a virtual MIMO scheme. In this virtual MIMO scheme, the multiple antennas involved are present at different nodes. This avoids the increased hardware complexity, which is especially important due to the limitations of the hardware platform of the sensor nodes. The additional complexity is transferred to the communication protocol.

Figure 1 presents an example in which two clusters of sensors establish a communication as a MIMO system. Notice that in this text the term “cluster” refers to groups of cooperating nodes in a cooperative MIMO arrangement, it is not the same meaning as used in hierarchical WSN. The figure also presents another possible situation in which a cluster of sensors establish communication with a single sensor similar to a single input multiple output/ multiple input single output (SIMO/MISO) system. Using this approach, if two sensors near to each other cooperate to transmit information, and two sensors on a far cluster cooperate to receive data, the efficiency is effectively doubled, as two symbols can be transmitted over the same time slot [8].

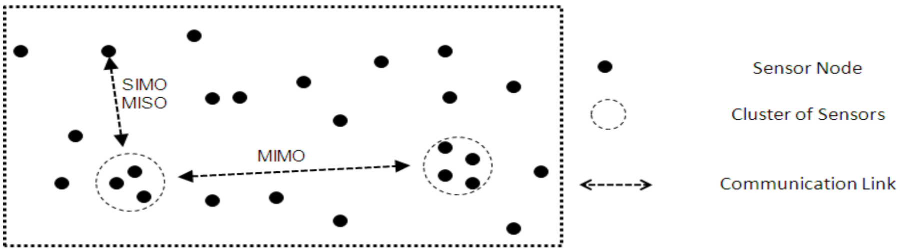


Fig. 1. Cooperative MIMO Applied to WSN: communication between clusters of sensors nodes and SIMO/MISO communication between a cluster an individual sensor.

Figure 2 presents the steps involved in a cooperative MIMO communication.

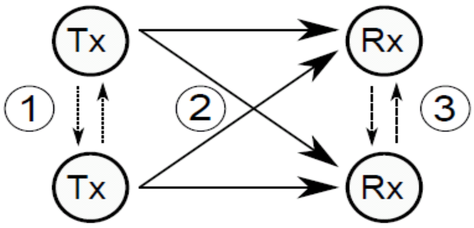


Fig. 2. Cooperative MIMO Transmission Steps.

In the 2 by 2 MIMO system example presented in Figure 1 the numbers represent the steps that are described as follows: (1) The transmit sensors exchange the information that needs to be transmitted; (2) Both sensors transmit different symbols at the same time slot; (3) The receive sensors exchange the received information so that the original symbol sequence can be obtained. If the data is destined to only one sensor of the receiving cluster this exchange becomes uni directional. Another option is to exchange only a portion of the received information so that every sensor is responsible for part of the decoding, alleviating the computational burden of a single node.

3 The Synchronization Problem in Cooperative MIMO Communications

The synchronization problem is widely studied in the WSN research area, with a number of different solutions proposed in the literature [9]. Some of these solutions rely on GPS synchronization, which despite the great accuracy (with variations being kept as small as 200 ns), has the severe drawback of the energy consumption overhead and the problem of WSN dependence to the GPS system. Other approaches proposed broadcast synchronization schemes, which are capable to achieve 1 µs accuracy, which is a good result, but not sufficient considering, for instance, conventional sensor networks operating at a 256 kbps rate and using BPSK modulation. Taking these networks as example, as they have the symbol duration of approximately 4 µs, 1 µs represents an error of 25%. This example makes clear the point in searching for other means of synchronization.

A synchronization method that can address the problem is to over sample a received tonal wave and compare it to a reference wave kept internally. This can be done by using a sliding matched filter to digitally find the delay, in samples, resulting in maximum correlation with the received wave. Assuming the networks are initially synchronized with a maximum error of 1 µs the range of comparison is reduced. The work reported in [7] proposes such a method, consisting in scheduling a tonal transmission between a pair or tonal broadcast to a group of nodes, the sampling on the receiving nodes will start at the scheduled time, and the clock error can be compensated.

In order to avoid problems created by sampling with a difference of more than a period of the tonal wave, the time length of the tonal transmission needs to be known to the receiving nodes. With this information, if a signal with less than the expected length is received, the receiver can compensate by starting sampling earlier or later, adjusting its internal clock accordingly. This mechanism is shown in Figure 3, in which sampling synchronization error *d* can be compensated by applying the sliding correlator. For a complete discussion about this method, interested readers are referred to [7].

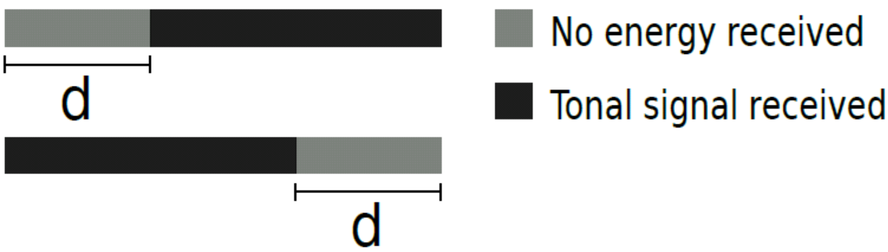


Fig. 3. Cooperative MIMO Transmission Steps.

4 Feasibility Test Framework

As introduced in Sections 2 and 3, despite the usefulness of the cooperative MIMO approach in WSN, there are practical implementation issues that have to be addressed in order to effectively apply cooperative MIMO. Motivated by these issues, the following feasibility test framework was designed.

The framework is composed of two sensor nodes, whose description is kit freescale MC1322x Sensor Node, instrumented with a developed firmware to control the communications tests and a software-programmable radio transceiver equipment from Texas Instruments (USRP 2932).

The developed firmware was generated by the *Beekit* based on the firmware *Connectivity Test* provided by Freescale. It basically controls the transmission and reception of synchronization messages. Its block diagram is depicted in Figure 4.

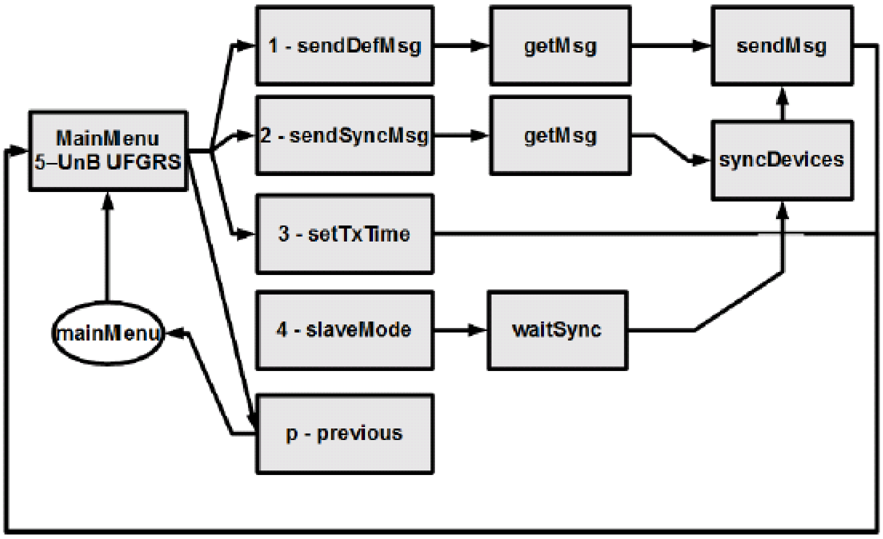
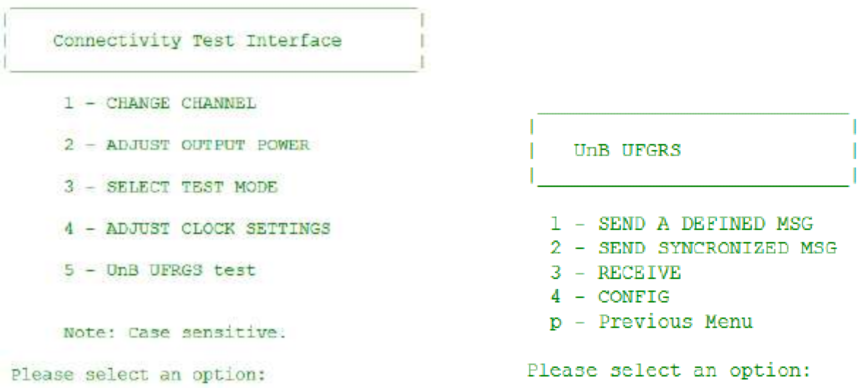


Fig. 4. Block Diagram of the Developed Firmware.

The UART serial interface of the sensor nodes was used for data input and output. To handle this interface, it is necessary to use a serial communication software, as the HyperTerminal, which was the one used in this work. An option labeled *UnB UFRGS* was introduced in the start menu of the *Connectivity Test* firmware (Figure 5a) to access the sub-menu with functionalities developed to perform the planned feasibility tests (Figure 5b).



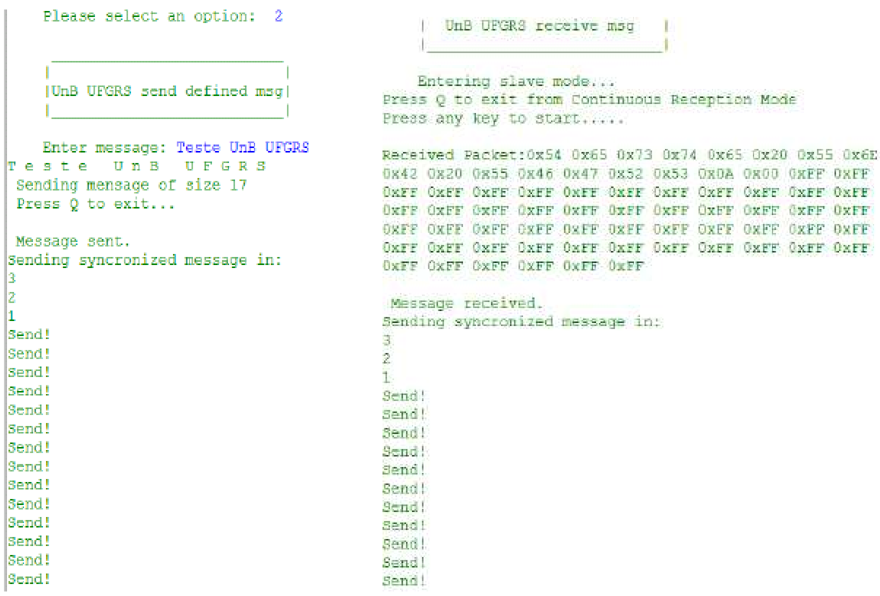
(a) (b)

Fig. 5. Menu: (a) Connectivity Test Firmware start menu. (b) UnB UFRGS Feasibility Test Submenu.

Accessing the UnB UFRGS submenu, there are options for sending messages entered by the user (1), for sending synchronized messages (2), for setting transmission or reception of synchronous messages (3), and a configuration option that will be implemented in the future according to specific tests setups (4).

Option 1 sends a user defined message, while option 2 sends a message to a slave sensor and waits a pre-established time for retransmission. Option 3 waits for a message from a master sensor. Once a message is received, the slave waits a pre-established time to resend the message so that the message is sent simultaneously by the slave and the master. Figure 6 presents this procedure from the master (Figure 6a) and the slave (Figure 6b) perspectives.

To receive the signal sent by the sensor nodes, a software defined radio using USRP 2932 was used. Figure 7 presents the deployed framework setup.



(a) (b)

Fig. 6. Synchronous message transmission: (a) Master. (b) Slave

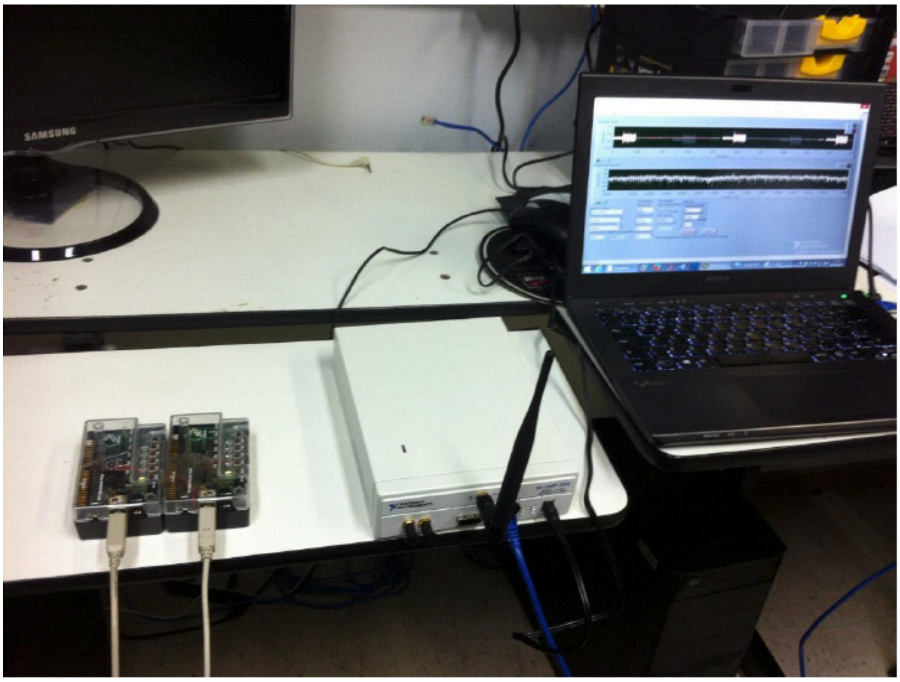


Fig. 7. Deployed Test Framework Setup

5 Experimental Results

Using the USRP 2932, a constructive interference between signals from the two sensor nodes was generated to increase the communication range using a cooperative MIMO virtual array.

The performed tests used the channel 21 of the IEEE 802.15.4 standard with central frequency of 2455 MHz, which is located between the channels 9 and 10 of the IEEE 802.11 standard (WIFI) due to the fact that this was the choice that receives less interference in the place where the tests were performed. Figures 8 to 10 show the received signals.

In Figure 8, observe the signal transmitted by one single radio in time and frequency without perceptible interferences. The signal amplitude is approximately 0.0005 V according to the display Amplitude [V] vs Time [s]. The time interval between two pulses is approximately 0.01 s, while the pulse width is approximately 0.0033 s.

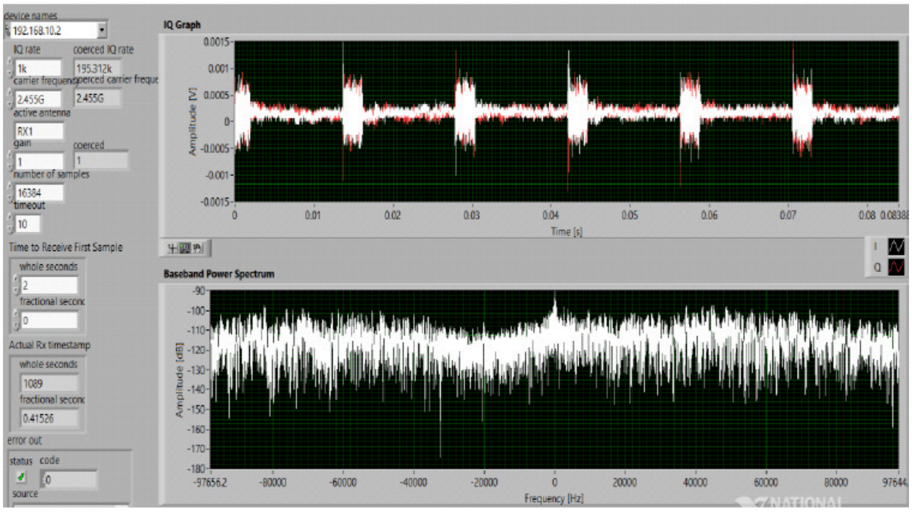


Fig. 8. Results acquired by the Spectrum Analyzer during the transmission of a single sensor

In Figure 9 the results of the radios of the two sensor nodes performing an unsynchronized transmission are shown. Note that the pulses from each radio are received in different time intervals. The time interval between two pulses is ranging around 0.005 s.

Figure 10 show the constructive interference of the signals from the two sensor nodes, which are almost completely overlapped. Note the increased signal power due to this overlap.

Performing these feasibility tests, we show the gain obtained due to the synchronization by means of a software implementation. Note that when the transmissions of the two sensors were synchronized, the amplitude of the signal approximately doubles. Moreover, during the experiments, it was possible to notice that there is sufficient channel diversity to assure the MIMO transmission, at least for the tested case of two sensor transmitting at the same time.

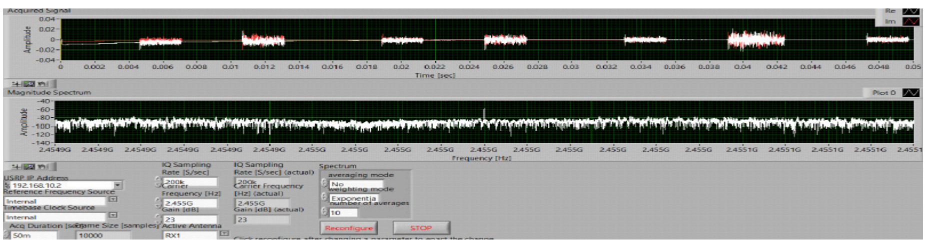


Fig. 9. Results acquired by the Spectrum Analyzer for non-synchronized sensors

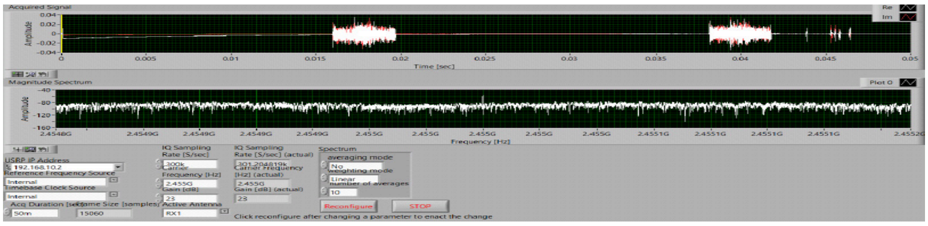


Fig. 10. Results acquired by the Spectrum Analyzer when the sensors are synchronized.

6 Conclusions and Future Work

Radio transmissions are responsible for the highest amount of consumed power in wireless sensor networks. This work provided a practical experiment for testing a promising approach for saving power on data transmissions, the cooperative MIMO. To take full advantage of cooperative MIMO in WSNs, synchronization is the key aspect to provide increased data rates or transmission range. In this work a firmware was created to check the feasibility of cooperative MIMO by only adapting the higher layers of communication. The tests showed that it is possible to merge packets and increase transmission power. However, achieving complete and precise synchronization is still challenging.

The next step in this type of experiment is to access the waveform directly from the physical layer. Once the physical layer is accessed, the first task it to synchronize carriers. Once that is done, WSNs can take full advantage of the increased performance and efficiency provided by cooperative MIMO. These techniques can then be explored in order to save power in wireless sensor networks.

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