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Cooperative Communication Mechanisms Applied to Wireless Sensor Network*

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Abstract. The purpose of this paper is to present ongoing PhD work that investigates both the cooperative diversity and techniques of network coding needed to improve communication reliability in wireless sensor networks. In this context, we propose a relay selection technique. It aims to select the smallest number of relay nodes under certain constraints. One of the main innovations is that this approach is formulated as an optimisation problem. In addition, we analyse the best approach for solving the proposed optimisation problem. The assessment results highlight that the proposed technique significantly improves the communication reliability of the network in comparison with the state-of-the-art techniques for selection of relay nodes. Network coding techniques will be tackled in the second stage of development of this research.

Keywords: Wireless Sensor Network, Industry 4.0, Relay Selection.

1 Introduction

Industry 4.0 is a recent concept that is transforming physical objects into intelligent virtual objects and can promote better control in all industries. One of the technologies that supports the Industry 4.0 paradigm involves wireless sensor networks (WSNs). WSN nodes link the physical world with the digital, thus integrating machines, humans and/or environments with the cyber-physical world [1].

However, WSNs are subject to restrictions on their reliability when exchanging messages between network nodes. The quality of communication provided by the link layer depends on the channel condition and inter-node distance, which vary with the environment in which the WSNs are deployed [2]. In this context, this ongoing PhD work investigates new solutions for improving the reliability of WSNs using cooperative diversity and network coding techniques.

When cooperative diversity techniques are used, the relay nodes transmit both their own data and the data previously stored from other nodes. Relay selection is a critical step that may affect the quality of transmission, and it is important to find the most appropriate relay selection criteria for the operation of the network [3].

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In addition, network coding techniques can be used to allow relay nodes to perform retransmissions. In this technique, intermediary nodes acting as relays retransmit stored messages according to specific mathematical coding techniques. The use of these techniques can increase the effective transmission rate of the network and the overall communication reliability [3].

This study aims to address the communication limitations of WSNs by treating the selection of relay nodes in a holistic way, combining both cooperative diversity techniques and the use of network coding algorithms to enhance the communication reliability of WSN networks. The fundamental issue addressed here can be summarised in the form of the following research question:

“Is it possible to increase the reliability of WSN communication by proposing a relay selection technique that considers a set of relevant criteria for the operation of the network, combined with a network coding technique for message retransmissions?”

For this question, the research hypothesis is that, considering the appropriate criteria for the selection, only nodes with optimal characteristics will be relays. This will increase the reliability of the network without generating excessive energy consumption. In addition, the use of a network coding technique in the retransmissions will allow encoding several messages in a single packet, with a size t , which is equal to the size of a single message before encoding.

This paper is organised as follows. In Section 2, we present the contributions to life improvement; Section 3 discusses some relevant research works on the selection of relay nodes in WSNs; Section 4 describes the primary contributions of this ongoing PhD research and explains the proposed relay selection technique. Section 5 contains a discussion of the simulation results, and finally, conclusions and future work are presented in Section 6.

2 Contribution to Life Improvement

This work aims to improve the reliability of communications in WSNs, one of the technologies enabling the dissemination of the Internet of Things (IoT) and Industry 4.0 paradigms. This research positively impacts several applications, and consequently makes a contribution to improving daily life in several areas, for example healthcare, smart cities, smart agriculture, Industry 4.0 and the sustainable use of terrestrial ecosystems.

In the healthcare domain, IoT devices can be used to monitor a patient’s health status, regardless of his or her location. A monitoring system is often used to oversee a patient’s vital parameters, such as blood pressure, heart rate and body temperature. This monitoring system permits the patient greater mobility due to the fact that it is a wireless technology [4].

In smart cities, WSNs can be used in several applications that combine advanced sensors with information and communication technologies to help in efficiently managing the assets of the city and to promote sustainable development. These applications include home automation, city security services, parking optimisation, road traffic management, environmental monitoring, and energy management [5].

The use of IoT applications in agriculture helps to minimise challenges such as extreme weather conditions and climatic changes. These applications have helped farmers to monitor temperature, humidity and water levels in real-time, making the irrigation process more efficient, increasing food's production.

Industry 4.0 impacts the way in which products are manufactured, and allows a higher level of operational effectiveness, productivity and better working conditions to be achieved. To improve productivity, many products may have an electronic identification throughout the product life cycle, thus enabling the collection of data on the use of this product. This makes it possible to understand the patterns of consumption and to improve products to meet the requirements of users [6].

Finally, IoT sensors can be used to monitor terrestrial ecosystems in many applications, for example monitoring animal behaviour and the movements of animal species in a natural environment with minimal human interference. Analysis of monitored data allows us, for example, to find new ways of managing the populations under study, to determine the impact of human development on them, or to understand whether there are enough individuals of a species in a given area to ensure survival. Another application is the forest monitoring, which permits the efficient detection of forest fires and the avoidance of major catastrophes [7].

WSNs are increasingly present in people's everyday lives, facilitating the development of daily activities and improving the quality of life.

3 Related Work

In the literature, there are many works about relay selection techniques. However, most of them do not give importance to the criteria used to select the relay nodes. We can classify the state-of-the-art relay selection techniques into five categories, considering the criteria used for relay selection, i.e. those based on quality of link [8–12], quality of link and energy [13–16], quality of link and neighbourhood [17, 18], quality of link and data rate [19, 20], and random relay selection [21].

Table 1 summarises the works cited here, and compares them to each other with respect to the following set of classifiers: the category used to select the relays, whether or not the reason for choosing the parameters used to select the relay nodes is specified, and whether or not the use of additional message is required.

From Table 1, we can observe several similarities between these works. For instance, most of these studies consider only the quality of link criterion, which may generate an incorrect relay selection [22]. The main reason for this is that hardware metrics are based on a sample of only the first eight symbols of a successfully received message, and do not consider lost messages. Therefore, this can provide an inaccurate estimate of the quality of the link.

Another characteristic is that additional message exchanges are necessary to make the selection in most state-of-the-art techniques. However, when WSNs are used, these messages may generate a significant overhead in the network.

Finally, all of these works mention only the criteria used to select the relay nodes, without performing any analysis of their real impact. It is worth mentioning that factors such as the different combinations of relay selection criteria, the way in which

they are modelled and the parameters they use directly impact on the relay selection performance.

To minimize some of the disadvantages observed in this analysis, the relay selection technique proposed in this paper considers the parameters that are relevant for network operation as criteria for the relay selection. In addition, it does not require the exchange of any additional messages.

Table 1. Characteristics of the state-of-the-art relay selection techniques.

State-of-the-Art	Classification Categories	Analysis of the Used Criterion	Additional Messages
Liu et al. [8]	Quality of Link		
Senanayake et al. [10]	Quality of Link		
Zhu et al. [12]	Quality of Link		✓
Marchenko et al. [9]	Quality of Link		✓
Valle et al. [11]	Quality of Link		
Etezadi et al. [18]	Quality of Link and Neighborhood		✓
Alkhayyat, Gazi and Sadkhan [17]	Quality of Link and Neighborhood		✓
Brante et al. [14]	Quality of Link and Energy		
Ahmed, Razzaque and Hong [13]	Quality of Link and Energy		✓
Pham and Kim [16]	Quality of Link and Energy		✓
Cheikh, Simpson and Sun [15]	Quality of Link and Energy		✓
Gokturk and Gurbuz [19]	Quality of Link and Data Rate		
Ouyang et al. [20]	Quality of Link and Data Rate		
Willing and Uhlemann [21]	Random Relay Selection		✓
Proposed Technique	Multi Parameters	✓	

Source: Adapted from [23].

4 Research Contributions

This work aims to investigate new solutions for improving the reliability of WSNs using cooperative diversity and network coding techniques. In the initial phase of this PhD research, it was proposed a relay selection technique (PRST) [23]. This formed the first step of the present research and is almost finished. The second stage of the research, relating to network coding, is currently in progress, together with the development of the proposed technique using a real WSN prototype.

4.1 Proposed Relay Selection Technique

The proposed relay selection was formulated as an optimisation problem, considering a benefit function with the following selection criteria: (a) the number of neighbours of the candidate node; (b) the remaining battery energy; (c) the quality of the link between the candidate node and its neighbour nodes; and (d) the historical success rate of recent node transmissions. The mentioned criteria were selected because they have a great impact on the adequate operation of the network. In addition, this paper considers an adaptive relay selection in which the interval between each relay selection occurs dynamically based on the success rate of the network.

The system model considers a network organised in a star topology. It is also assumed that relay nodes will be used as intermediate nodes to establish communication between the nodes without a direct communication with the coordinator node. A slotted communication approach is used in which the medium access is based on a TDMA (Time Division Multiple Access) scheme. The IEEE 802.15.4 communication standard is used for the PHY (physical) and MAC (medium access control) layers of the network. It operates in time-slot mode and with beacon-enabled. The PRST assumes that specific configuration information is exchanged between the coordinator and the nodes in each beacon interval, i.e. the coordinator sends configuration commands piggybacked with the beacon frame, and the nodes send configuration information along with the sensed data. When the relay nodes have been selected, communication takes place through two stages: transmission and retransmission. In the transmission stage, each node makes one transmission; the relay nodes will stand by, listening to and storing all messages received together with the identification (ID) of the sending node. If the node is not a relay, after its transmission step, it will enter sleep mode.

In the retransmission stage, each relay node will retransmit one message to the coordinator node, containing all the IDs of the received messages. In a table, the coordinator stores all messages received. Whenever the coordinator receives a retransmission message, it verifies if all the messages in this retransmission are in the table. If they are, it counts this retransmission as a duplicate; otherwise, it adds the messages to the table. After retransmission, the relay enters sleep mode.

In order to find the minimum number of relay nodes, while ensuring that each node has a reachable relay, an optimisation problem was formulated. Due to space limitations, the details are omitted in this paper. For further details, the reader is referred to [23].

5 Discussion and Results

The relay selection technique proposed in this work was evaluated by simulation experiments. The network simulation tool called OMNeT++ was used along with the Castalia framework. A total of 5 simulation scenarios were defined, varying the number of nodes. The scenarios were defined to have 20, 40, 60, 80 and 100 nodes. In each scenario, an extra node was configured as a coordinating node. Nodes were randomly deployed over a 50x50m² area, with the PAN coordinator placed in the center of the area. Castalia supports some propagation channel models to be used in the simulation, and the free space was used to be simple and efficient. Each simulation was executed for 450 s, which corresponds to the time needed for the coordinator to send up to 50 beacons. In each simulation experiment, the topology was dynamically generated, as proposed in [23].

In the first assessment, the proposed relay selection technique (PRST) was analysed and contrasted with other techniques. This paper describes the comparison with three techniques considered as the state-of-the-art: opportunistic [11], random around the coordinator (RAC) [18], and completely random (CR) relay selection [21].

Figure 1 (a) illustrates the correlation between the total of cooperation messages sent by each node. This correlation allows us, for example, to verify how many cooperation sent by each node are necessary to obtain a minimum success rate. PRST achieved the best results. In all situations, their success rate reached values above 95%, and it also showed the smallest number of cooperation messages. This behavior was obtained thanks to the proposed optimization technique, which selects a smaller number of relay nodes. Of the state-of-the-art techniques, the opportunistic scheme achieved the best results for the success rate. However, it was one of the worst techniques analysed when considering the metric that assesses the number of cooperation messages sent by each node. The CR scheme achieved the worst results for both metrics.

Figure 1 (b) shows the correlation between the energy consumption and the percentage of redundant retransmitted messages. This correlation illustrates that when the network contained numerous redundant retransmitted messages, some unnecessary relay nodes were selected and, consequently, more energy was expended by these nodes. The PRST technique achieved the best results, with the lowest energy consumption and the smallest number of unnecessary retransmitted messages, showing that an adequate number of relay nodes was selected. The other analysed techniques performed a large number of unnecessary retransmission messages, meaning that they required a higher energy consumption.

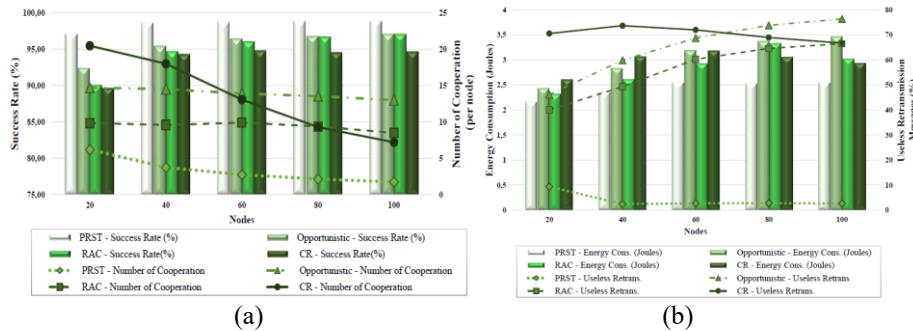


Fig. 1. Correlation between (a) success rate and number of cooperation messages per node; and (b) energy consumption and percentage of useless retransmission messages.

In the second assessment, we evaluated the performance and solution quality of three different algorithms, a greedy algorithm [24], a genetic algorithm [25] and branch and bound algorithm (B&B) [26], which are suitable for solving the optimisation problem of the PRST technique. The B&B algorithm was used in the first stage of this assessment (Figure 1 (a) and (b)).

These three algorithms were coded in the C++ language, and were tested on the same computer using a Ubuntu 18.04 operating system, with an Intel® Xeon® E3-1240 v2 (3.40 GHz) CPU and 16 GB memory. The execution time for each algorithm represents the simulation time required to perform the relay selection. This metric allows us to evaluate whether the algorithm is a viable solution for use in a real-time WSN. In the system model used by the proposed relay selection technique [23], the

coordinator node must use only a 15.36 ms time slot to select the relay nodes and to send the beacon.

The genetic algorithm needs a longer time (63 ms) than the greedy algorithm (0.7 ms) in order to achieve a similar success rate (98,54% for the genetic algorithm and 98,74% for the greedy algorithm). The B&B algorithm performs the relay selection in 12 ms and achieves a success rate of 98.9%. The greedy and genetic algorithms showed many redundant retransmissions (14 % for the greedy algorithm and 15% for the genetic algorithm). The B&B presented 9% of the redundant retransmissions. In this way, the greedy algorithm can be considered a viable solution to this problem, based on characteristics such as extremely low execution time and a success rate that was very similar to that of the B&B algorithm. The B&B algorithm was the approach that showed the best results for all metrics, and this can be considered the best solution.

6 Conclusion and Future Work

Relay selection is an essential step in guaranteeing adequate cooperative communication. The primary research of this doctoral work is on techniques for the best selection of retransmission nodes. These techniques are being designed to have low overhead and without consuming energy from the nodes unnecessarily.

In future work, we intend to merge cooperative diversity techniques with a network coding technique. The basis of this idea is an improvement in the communication success rate of the WSN nodes. We also expect to implement the proposed technique in a real WSN prototype, running some real-world applications in a variety of scenarios.

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