Experimental Assessment of Using Network Coding and Cooperative Diversity Techniques in IEEE 802.15.4 Wireless Sensor Networks

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***Abstract*—The use of wireless sensor networks (WSN) to support critical monitoring applications is becoming a relevant topic of interest. These networks allow a highly flexible approach to data monitoring and, consequently, a major breakthrough for several application domains, from industrial control applications to large building domotics and health care applications. One of the major impairments of using wireless networks to support critical monitoring applications is the electromagnetic noise, which may increase the packet loss ratio to unacceptable values. In this paper, we assess different techniques of cooperative communication and network coding that can be useful to mitigate the aforementioned problem. These techniques may be implemented in WSN nodes in conformance with the IEEE 802.15.4 standard, to reduce the impact of electromagnetic interferences upon the packet loss ratio. In this paper, we report an experimental assessment of the network coding and cooperative diversity techniques, where the network is subjected to a controlled electromagnetic interference inside of an anechoic chamber. The experimental results show that, by using these techniques, it is possible to increase the success rate of communication in typical electromagnetic noisy environments.**

***Index Terms*—IEEE 802.15.4, network coding, reliability**

I. Introduction

Wireless sensor networks (WSN) are being increasingly used to support critical monitoring applications. Among the available standards, it can be emphasized the IEEE 802.15.4, which proposes the use of ISM (Industrial, Scientific and Medical) frequencies in the PHY layer and slots for real-time communication in the MAC sublayer. Nevertheless, the use of slotted communication does not guarantee by itself the timely delivery of messages, specially when the communication environment is highly susceptible to noise. This misbehaviour may be a direct consequence of existing obstacles and/or from the interference of equipment or other networks sharing the same ISM frequencies.

Within this context, techniques such as Cooperative Diversity and Network Coding are potentially promising to support communication in noisy environments [1], [2]. In this paper, we perform an experimental assessment of some of these techniques in IEEE 802.15.4 networks, in the context of slotted communication. These experiments were conducted in an anechoic chamber, considering a controlled electromagnetic interference (EMI) environment. The implemented experimental setup allows a meticulous analysis of the network behavior with different PER (Packet Error Rate) values. The experimental results showed that the use of network coding and cooperative diversity techniques enables a significant improvement of the message delivery, even in harsh communication environments with PER above 30%.

This paper is organized as follows: Section II briefly presents the concepts of cooperative diversity and network coding techniques, and discusses some related works. In Section III, the proposed communication approach is described. In sections IV and V the experimental assessment results are discussed. The conclusions are summarized in Section VI.

II. Background

A. Cooperative diversity techniques

The use of cooperative diversity techniques aims to increase the reliability of networks [1]. The basic principle is to select specific nodes that listen the transmissions from other nodes and act as relayers retransmitting the information. The performance improvement is mainly due to the transmission and reception of messages through multiple paths, at different instants of time. In summary, cooperative diversity combines the properties of spatial diversity and temporal diversity to increase the communication reliability.

A critical issue when using these techniques is how to quantify the number of relay nodes and how to define the set of relay nodes. Clearly, selecting all nodes of the network as relay nodes is not an effective approach, since these nodes have to stay awake all the time and therefore will consume more energy.

B. Network coding techniques in WSN

Message streams that are independently produced and consumed in the network do not need to be kept separate in

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their transport, as it is possible to match multiple messages into a single message and, after, on arrival of that message, to extract the independent information from the different message streams. One way to combine this information is called Network Coding [3].

The coding may be binary, using a simple XOR operation between two messages, as illustrated in Figure 1, with use of relay nodes. This figure illustrates the time slots required for the exchange of two messages between nodes A and C using relay node B.

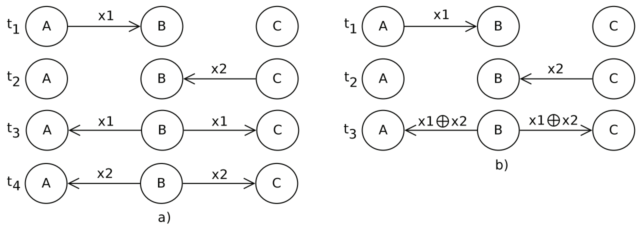

Figure 1. Network Coding in wireless environment.

In Figure 1a) is presented a traditional transaction and in Figure 1b) a transaction using network coding with the binary field $\mathbb{F}_{2^1}$. In this example, node B makes an XOR operation with messages $x1$ and $x2$ and broadcasts the new encoded message to both nodes [2]. Each node, upon receiving the encoded message and in possession of the original message, will be able to extract the missed message by applying an XOR operation between them.

For more complex networks with a larger number of nodes, network coding techniques that use a field $\mathbb{F}_{2^1}$ are not able to encode a large set of messages. In this case, one of the solutions adopted in the literature is linear network coding (LNC) [4], [5], which assumes that all messages can be considered vectors of elements of a finite field $\mathbb{F}_q$ ($m_i = [m_{i1} \ldots m_{in_c}], m_{ij} \in \mathbb{F}_q$) and all operations $+, -, \times$ and $\div$ for encoding and decoding messages should be performed in this field. For simplicity, the field $\mathbb{F}_q$ should be the lowest possible. In this experimental assessment we adopt a field $\mathbb{F}_{2^8}$ which allows encryption of up to 256 messages, guaranteeing a linearly independent system.

C. Related work

In [6] was proposed techniques to increase reliability in dense WSN, by reducing the network congestion. The use of different retransmission techniques within the context of WSNs was discussed in [7]. More specifically, and considering LNC techniques, in [5] was proposed a retransmission mechanism based on LNC and cooperative diversity that increases the success rate of the transmission of messages in noisy communication environments. As the scope was slotted communication, the adopted mechanism was TDMA-based. In [8] it was also used a TDMA-based approach in links subject to losses, with relay nodes assisting other nodes in order to minimize deadline misses, and focusing on when and how the transmission slots are used. In this paper, the used LNC approach is similar to these two techniques [5], [8]. That is, the purpose is to select *how many* and *which* nodes can be used in cooperation to increase the success rate in delivering messages. Additionally, we extend the assessment presented in [5], by performing an experimental assessment with the injection of controlled EMI noise in an anechoic chamber.

The focus of the work presented in [9] is also increasing reliability and, simultaneously, meeting the messages deadlines. The selection of the best relays is based on their spatial positioning. Differently, in this paper we have a dynamic selection of the best relays based on signal strength of received messages.

In [10] was proposed the use of network coding in messages sent in reserved slots (Guaranteed Time Slot – GTS) of IEEE 802.15.4 networks, improving the energy efficiency of the network.

III. Proposed Communication Approach

In this work, it is assumed a star topology with a set of nodes periodically sensing the environment and sending messages to the coordinator. Each message sent by a node has more than one opportunity to reach the coordinator: the message itself (*1st chance*) and within some coded message transmitted by a relay node and decoded by the coordinator (*2nd chance*).

As it can be seen in Algorithm 1, the coordinator selects the set of new relays in two steps. In a first step, it determines of the number of relays that will be used in the network (line 2). This value is calculated based on the value of PER, which reflects the network error rate. In a second step, the coordinator selects which will be the relay nodes. This selection (line 3) is made based on the nodes with the best average values of RSSI (Received Signal Strength Indication). The coordinator includes the information about the set of relay nodes in the payload of beacon messages (line 4).

```
1  for ever do
2      Coordinator determines the number of relays based on the PER,
3      Determines the set of relays based on the RSSI of each node and
4      Transmits these information into the beacon payload
5      foreach node in the network do
6          Receives the beacon information
7          Waits its reserved slot and transmits its message
8      end
9      foreach relay node in the network do
10         Overhears the messages from neighbours, encodes them,
11         Waits its reserved slot and transmits the coded message
12     end
13     Coordinator receives messages from nodes and from relay nodes,
14     Solves the linear system,
15     Estimates the network PER and the values of node's RSSI
16 end
```

Algorithm 1: Overview of transmission algorithm.

Relay nodes overhear messages from the neighborhood and are able to transmit messages in two distinct opportunities. The first transmission occurs within its reserved slot (line 7). The second transmission occurs in a slot reserved for coded messages, where the message of the relay and all the overheard messages are encoded into a single message through a linear combination technique, and retransmitted in that slot (lines 10 and 11).

The coordinator, that sent the beacon message, receives all the messages from both nodes and relays (line 13). It decodes the messages solving a linear system (line 14) and estimates the network PER by accounting for the number of messages that could not be correctly received in the 1st chance (line 15). For further details about the proposed mechanism, please refer to [5].

IV. Experimental setup

An anechoic chamber was used to perform an experimental assessment of the proposed approach (Figure 2). The chamber is equipped with an antenna for EMI generation that was used to irradiate EMI noise over the communication environment. Figure 2 depicts the adopted configuration, where it is possible to see the antenna (A) and a WSN on a table (B) inside the anechoic chamber (C), according to the diagram in Figure 3.

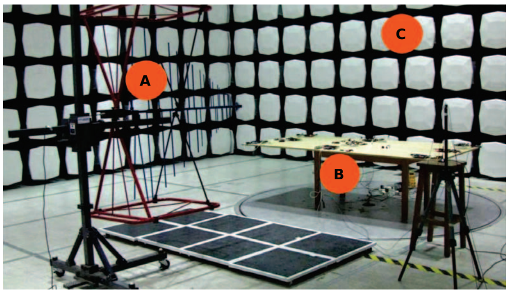

Figure 2. Anechoic chamber.

The WSN nodes were exposed to the irradiated EMI. Specifically, AM/FM noise being irradiated with a carrier frequency of 2.425 GHz (channel 15 of 802.15.4), AM modulation: 80%, AM modulated carrier frequency: 20 kHz, signal bandwidth: 40 kHz and power generator from -20 dBm to -10 dBm.

For the experimental assessment were used 10 WSN nodes with processor ATmega256RFR2 and a radio compatible with the IEEE 802.15.4 standard. The network was configured as a star with the beacon mode, being node 1 the PAN coordinator. This node is responsible for transmitting the beacon and synchronizing the network.

The parameters of IEEE 802.15.4 were $BO = 8$ and $SO = 6$, resulting in a beacon interval (periodicity) of $BI = 3.93s$. The CAP (Contention Access Period) was divided in slots used by the nodes 2 to 10. These nodes periodically monitor the environment and send their data to the coordinator. Messages sent by the nodes have a frame size of 80 bytes, with a payload of 64 bytes. The objective of this paper is to assess the cooperative diversity and network coding techniques, therefore the acknowledgement mechanism of IEEE 802.15.4 has been turned off.

As can be seen in Figure 3, nodes were arranged in two perpendicular rows with 7.0 m x 5.0 m. The numbers next to the nodes are the RSSI values, which were estimated by the coordinator, indicating the quality of the radio signal to the respective node. Nodes 2 and 3 were placed at the extremity of one of the rows, next to the coordinator. Nodes 4 and 5 were placed at a distance of less than 3m to the coordinator and, the same way as nodes 2 and 3, they achieve high RSSI values.

The EMI antenna was installed about halfway down the L formed by the two rows of nodes. This directional antenna is responsible for generating electromagnetic interference and, therefore, is responsible for hindering the communication among the nodes and coordinator, especially from the nodes 6 to 10.

Nodes 6 and 8 have a power amplifier (PA) in their radio module. Because of this, despite the EMI, these nodes achieved a good RSSI value, unlike nodes 7, 9 and 10, that were not able to send messages directly to the coordinator in the first attempt (Table I). The purpose of using these nodes with PA has been to introduce in the environment some nodes with good signal quality and to verify if the proposed approach based on network coding and cooperation among nodes is able to select them as relays.

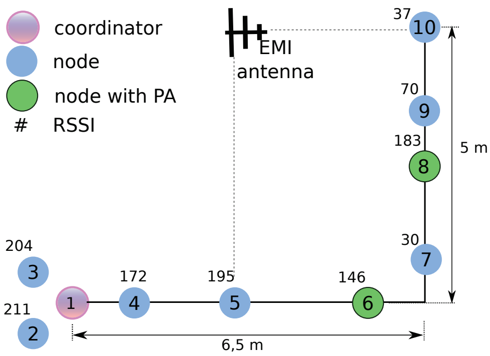

Figure 3. Monitored area setup.

V. Experimental assessment

A. Analysis of the achieved success rate

As can be seen in Table I, nodes with higher RSSI values have more chance of success in their first transmission attempt. Nodes 2, 3, 4 and 5 that are closer to the coordinator and nodes 6 and 8 with PA, get values close to 100% success in their first transmission attempt.

Table I
Comparison between RSSI and success rates of each node.

Node	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RSSI	211	204	172	195	146	30	183	70	37
Success in the 1st chance	100%	98.1%	91.8%	95.7%	84.4%	0%	99.5%	0%	0%
Goodput	100%	100%	100%	97.6%	84.7%	33.3%	100%	96.1%	91.3%

The goodput value shown in Table I refers to the overall success rate resulting from the 1st and 2nd chance. The success in 2nd chance for receiving messages from nodes 7, 9 and 10 is due exclusively to the use of cooperation and network coding techniques. Without the proposed mechanism, these nodes would not transmit any messages because their RSSI values measured on the coordinator were very low. Note that nodes 9 and 10 achieve more than 90% of success rate due solely to the proposed mechanism. Node 7 was quite affected by the EMI and had difficulty of sending messages even to its neighbors, achieving a goodput of just 33.3%.

B. Analysis of success rate and number of relays over time

Figure 4 shows the behavior over time of the proposed approach, during about 200 beacon intervals.

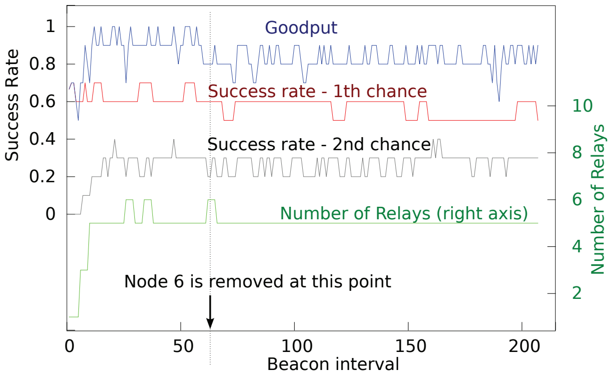

Figure 4. Success rate and number of relays.

The average success rate in the 1st chance approached just 60%. By using network coding and cooperative diversity techniques, it was possible to recover almost 3/4 of the undelivered messages (2nd chance), and therefore the average goodput approached 90%. By means of this double mechanism, the goodput ranged from 80% to 90%.

In order to verify the ability of the algorithm to adjust itself to the environment conditions, node 6 – that was equipped with PA and was constantly being chosen as a relay – was removed from the network at a given point of time. At that moment there was a decrease in the overall system goodput.

Results illustrated in Figure 4 show that, on average, 5 nodes were selected as relays over time. As long as node 6 was operating, nodes 2, 3, 4, 5, 6 and 8 alternated as relays. When node 6 was removed, only nodes 2, 3, 4, 5 and 8 play this role of relay, because nodes 7, 9 and 10 were not selected as relays due to its low RSSI values. After the removal of node 6, the network has a slight decrease in goodput, even sustaining high values (about 80%). This reduction was due to the inexistence of new nodes with good RSSI values to be selected as relays.

Nodes 2 and 3 achieved good RSSI values because they were placed next to the coordinator. However, due to their positions behind the coordinator, in general these nodes were useless as relays, since messages received by these nodes probably were also directly received by the coordinator. These results indicate that the selection of relays based only on the RSSI values may be inadequate.

C. Analysis of goodput with high PER values

Data obtained in the anechoic chamber was analyzed in relation to different PER values. The aim was to experimentally verify the behavior of the proposed approach in the presence of extreme PER values. This is an important experiment, as usually simulation results are not trustworthy for extreme values. Thus, PER values over 30% were also analyzed.

Table II summarizes the achieved goodput results. The proposed LNC mechanism can keep the goodput (total success rate) at high values (close to 75%) even in the presence of PER of up to 60%. Only as from values of PER above 70%, the network behaviour begins to degrade.

Table II
COMPARISON BETWEEN PER AND GOODPUT.

PER	40%	50%	60%	70%
Goodput	76%	73%	74%	50%

VI. CONCLUSION

The use of powerful nodes with power amplifiers (PA), placed in strategic points of the network, makes possible to set up more reliable communication networks with good cost-benefit relation. However, it is important to note that, even if all nodes had PA, this does not guarantee a clean direct sight between every node and the coordinator, due to obstacles, EMI etc. In this sense, the use of cooperative diversity and network coding techniques arises as promising solution. Within these techniques, the use of appropriate mechanisms to select the set of relay nodes is of paramount importance.

Through an extensive experimental assessment in an anechoic chamber with controlled electromagnetic interference, the work referred in this paper concluded that, even in very noisy environments (PER above 30%), it is possible to keep a success rate acceptable for critical monitoring environments employing network coding and cooperative diversity techniques. Concerning the status of this ongoing project, we are analysing the impact of using LNC techniques upon the network performance, namely its timing behavior.

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