Experimental Evaluation of Multiple Retransmission Schemes in IEEE 802.15.4 Wireless Sensor Networks

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Abstract

One of the motivations for use of wireless sensor networks (WSNs) in industrial environments is related to the reduced deployment and maintenance costs, when compared to the use of wired networks for connecting single I/O points. Nevertheless, a well-known problem for the use of wireless communication in industrial environments is related to the unreliable nature of the communication medium. Therefore, the search for communication reliability in WSNs is a relevant topic of research for the scientific community. In this paper we propose an innovative message retransmission scheme, based on network coding techniques, to increase the reliability of message exchanges in industrial environments. The proposed technique: `NetCod`*, that improve the probability of message deliver by allowing the message retransmission whenever a loss occurs is experimentally compared with state of the art techniques:* `BlockACK`*,* `Redundant TDMA` *and* `Master/Slave`*. A comparative experimental assessment of these four techniques was performed using MicaZ motes. Metrics such as: message loss, message transmission delay and power consumption were used to comparatively assess the behavior of these retransmission techniques.*

1 Introduction

Traditionally, data communication within manufacturing applications is supported by wired networks. However, the disadvantage of using wired networks is related to higher deployment and maintenance costs, and therefore it is difficult to promote its massive penetration in industry. Structured cabling can cost up to $ 300.00 per meter in the case of traditional industrial applications, and up to U.S. $ 6,000.00 per meter [1] in the case of intrinsic safety areas. Wireless systems can lead to the elimination of tens of thousands of meters of wiring, with the consequent reduction in deployment and maintenance costs. Another advantage of using wireless networks is related to their inherent flexibility when dealing with mobile equipments.

Wireless Sensor Networks (WSN) are networks composed of low-cost battery-powered nodes that use the wireless medium to exchange messages. Basically, WSN nodes are composed of a power source, a sensing unit, a processing unit and a radio module. The sensors can monitor a wide variety of physical phenomena such as pressure, temperature, humidity, soil composition, vehicular movement, ultrasound, infrared radiation, vibration, noise, light, presence or absence of certain objects, mechanical stress levels, etc. [2, 3].

On the other hand, industrial communications are characterized by their real-time requirements, typically associated with control applications, where real-time control data must be periodically transferred between sensors, controllers and actuators according to strict transfer deadlines. An important problem in industrial environments is the interferences caused by mobile obstacles or by the electromagnetic noise due to motors, frequency inverters etc. Likewise, other wireless communication systems operating in the same frequency band may become an important interference factor in WSNs [4, 5].

Many open WSN standards are being proposed to meet the demands of industrial communication, among which stands out: WirelessHART [6], ISA 100.11a [7] and the draft IEEE 802.15.4e [8]. As the industrial environment is normally subject to high levels of electromagnetic noise, there is the need to provide adequate and efficient mechanisms for message retransmissions. Therefore, these WSN standards implement a set of mechanisms intended to increase the reliability of message transmissions.

On the other hand, network coding (NC) is a well-known communication mechanism that may be used to increase the performance of packet transmission. This mechanism implements a coding technique to group separate packets within a single message, and then, at the reception side, the extraction of the original packets is done using the related decoding technique. In this paper we

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propose the use of NC in WSNs, to increase the message transmission reliability, while diminishing the used resources.

There are already some relevant works in the literature about the use of NC techniques and mechanisms for message retransmission [9–11]. However, there is the need to compare different NC techniques within the specific context of WSNs, as there is the need to assess the inherent trade-offs among reliability, real-time and power consumption constraints.

The two main contributions of this paper are: *i)* the proposal of new NC techniques adequate for increasing the reliability of messages retransmission in WSNs and *ii)* an experimental evaluation of four message retransmission schemes, implemented upon a IEEE 802.15.4 WSN network: `BlockACK`, `Redundant TDMA`, `Master/Slave` and the proposed `NetCod` technique. All these message retransmission schemes may be easily adapted to any of the previously referred standards. Within the context of this work, the aforementioned schemes were implemented in a IEEE 802.15.4 network composed of MicaZ[1] nodes running OpenZB[2], where the WSN coordinator has the sink role in a star topology. Several experiments were performed to evaluate the performance of each message retransmission scheme. The considered metrics include: message loss, transmission delay and power consumption.

This paper is structured as follows. Section 2 presents some of the most relevant background concepts. Section 3 presents relevant state-of-the-art works related to message retransmission and NC. An innovative proposal for the application of NC techniques to WSNs is presented in section 4. Section 5 describes some implementation details, and finally the experimental assessment results are presented in Section 6. Section 7 concludes the paper.

2 Background

2.1 IEEE 802.15.4

IEEE 802.15.4 [12] is a communication standard that defines a protocol for the interconnection of devices via radio communication in a personal area network (WPAN). The standard defines CSMA-CA as a mechanism for the medium access and supports star topology, peer-to-peer and cluster tree. The medium access is based on containment. However, using an optional superframe structure, time slots can be allocated by a PAN coordinator for devices with data subject to time constraints. Using this superframe structure, the medium access is done without using the CSMA-CA mechanism.

The MAC sublayer supports two operating modes: with and without beacon. In the beacon mode, beacons are periodically generated by the PAN coordinator, in order to synchronize and identify the PAN. In this mode, a structure called the superframe is created. This structure is defined by Beacon Order (BO) and Superframe Order (SO). An example of this type of structure can be seen in Fig. 1. Its format is defined by the coordinator and is divided in two parts: active and inactive.

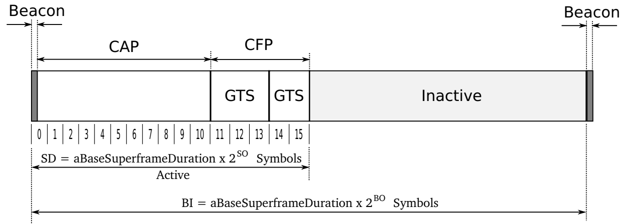

Figure 1. Superframe of IEEE 802.15.4.

The active part can be further divided in two parts: CAP (Contention Access Period) and CFP (Contention-Free Period) that altogether have 16 equal compartments (slots). The latest CFP slots, from zero to a maximum of seven, compose the GTS (Guaranteed Time Slots).

During the CAP, a device that wants to communicate must use a slotted CSMA-CA scheme when competing for the media access with other devices. The duration of a frame must not exceed the duration of the slot; therefore, we can have, at most, 15 frames being sent during a CAP.

2.2 Diversity

Diversity in wireless networks, also referred as channel diversity [13] or link diversity is related to the phenomenon in which transmissions through different channels, different frequency range or different time periods, has different reception characteristics, or suffer different attenuations and/or losses. A diversity scheme seeks to minimize the effects of such phenomena, aiming to obtaining better transmission quality [14].

Temporal Diversity – Samples at different transmission time intervals may have significant variations in the level of mitigation, even if the transmitter and receiver are stationary. In an extreme situation, such variations can be observed within a single transmission. To fight against this phenomenon, identical messages can be transmitted at different instants of time, providing greater robustness to the system.

Spatial Diversity – Between a transmitter and a receiver there might be multiple paths to propagate the signal (with or without a line of sight). The composition of these propagation paths depends on the exact positions of the transmitter, receiver and all obstacles. A small change in the relative position of these elements may vary significantly the quality of the channel. Using spatial diversity means that multiple transmitters are being used to transmit together the same message.

2.3 Network Coding

In [15], the authors introduced the concept of NC applied to message processing at the network layer. At this layer, a simple observation is that intermediate nodes may not only relay independent incoming streams, but can also process and combine them together. For example, at

[1]http://www.xbow.com
[2]thttp://www.open-zb.net

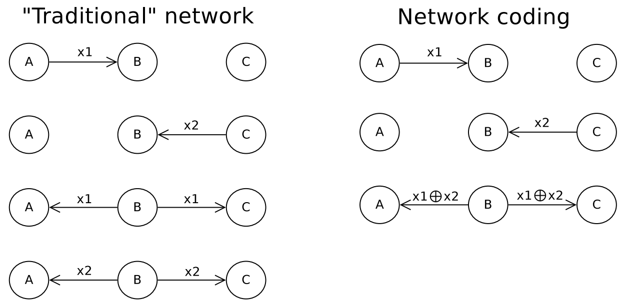

Figure 2. Example of Network Coding.

the network layer, intermediate nodes can make additions to independent binary bit streams. In other words, data flows that are independently produced and consumed at the transport layer must not necessarily be kept separate at the network layer. There are ways to combine them and, later, to extract independent information. This paradigm shifts the way how the network layer manages, operates and understand the organization of the network as well as brings a profound impact on several areas such as: reliable delivery, resource sharing, efficient flow control, network monitoring and security [16].

One example of application for NC occurs in wireless networks [16], where the medium is highly broadcast. The NC can be used to provide benefits in terms of battery life, bandwidth and lower delays. Consider the following example. A wireless ad-hoc network, where devices A and C want to exchange binary data $x1$ and $x2$ using device B as a relay. Assume that the time is slotted, and that only one device can transmit or receive a message during each time slot. Fig. 2 (left) shows the traditional sequence of message exchanges. One may observe that it takes four time slots to perform the entire operation. In Fig. 2 (right) it is illustrate an example of message exchanges using a NC scheme, where device B makes a XOR operation (codification) between the two incoming messages and then transmits the encoded message. The receiving device, knowing its original information, is able to decode the unknown part of the message. The decoding is done again by applying the XOR operation between the received message and the known message.

3 Related Work

A framework for reliable communication in WSN, that is able to support the transfer of real-time data using retransmissions is proposed in [9]. The proposed solution enables one or more retransmissions of messages reported as corrupted, without compromising the ordinary message deadlines. The main idea is to reserve part of the transmission time for a given number of retransmissions, which are made using a piggyback approach or through a dedicated channel for real-time acknowledgements. It is assumed that the medium is full-duplex, in the sense that packet and acknowledgements are transmitted in a simultaneous way. If an acknowledgement is not received after a predefined time interval, the packet should be retransmitted in a specific time that is specifically reserved for this purpose. This proposal [9] is similar to the `BlockACK` schema implemented in this paper, with the difference that the acknowledgement (ACK), or negative acknowledgement (NACK), group is sent using a single frame (as allowed by the star topology).

In [10], it is proposed a mechanism for automatic data retransmission, that assumes a two-phase cooperation protocol. In the first phase, the source transmits a signal and the destination sends back an ACK or a NACK to indicate success or not. Due to the broadcast nature of the wireless medium, intermediate nodes can overhear this signal. If the destination sends back an ACK, all intermediate nodes just idle. On the other hand, if the destination sends back a NACK, and some intermediate nodes were able to correctly receive the packet, they will forward the packet to the destination. Another alternative approach adequate for large distances is to use a multistage protocol, where an intermediate node that correctly received the packet becomes responsible for retransmitting the message to another intermediate node, until it reaches its destination. The purpose of using intermediate nodes is to save energy. The authors conclude that in some scenarios (for distances greater than 20 m), the cooperative approach is the best choice.

A window-less block acknowledgement scheme that guarantees continuous packet forwarding irrespective of the underlying link unreliability is proposed by [17]. The proposal is based on a bursty convergecast scheme. The sender node organizes its packet queue as linked lists. The most recent packets, with smaller retransmissions number, receive higher priorities, and are first transmitted in the network. Only when the node is without new packets, it begins to retransmit packets that were unconfirmed. The confirmation of reception is made using a block acknowledgement, which confirms the reception of a group of messages. As the message occupies a place in a buffer, whenever a confirmation is received, the respective buffer is cleared. In order to avoid the system overload, the number of retransmissions is upper-bounded.

These two proposals [10, 17] are intrinsically related to multi-hop networks. In what concerns a star topology, implementing a cooperation scheme would also be desirable. Whenever a node has difficulties to reach the coordinator, the other nodes may cooperate among them to retransmit messages. This is the type of cooperation that is adopted in the proposed `NetCod` scheme.

There are also some relevant works that deal with the reliability issues at the MAC sub-level. For example, in [18] it is proposed an energy-aware MAC with low latency that was developed and optimized for data collection in WSNs with tree topology. Its retransmission mechanisms are based on implicit NACKs, where a node automatically retransmits a packet whenever it has not received any ACK after a certain time. This proposal is not mutually exclusive with the proposed `NetCod` scheme;

both can be combined to improve its robustness.

In [11], it is proposed a polling approach that is similar to the implemented `Master/Slave` scheme, with the following difference: in the original scheme, it is proposed a theoretically unlimited number of retransmissions, where the bound is just the deadline of the message. Another difference remains on the use of the Earliest Deadline First (EDF) scheduling approach for scheduling real-time messages. In the work presented in this paper, it was assumed the support of periodic traffic, where each node has a fixed slot for transmission. Therefore, there is no need for the implementation of any dynamic scheduling scheme.

Other polling approaches are proposed in [19]: Queued Retransmissions (QR) and Adaptive QR (AQR). For QR the controller makes a series of rounds searching for data. In the first round it requests data to all nodes; in the following rounds it only requests data from nodes that have not yet succeeded. This has two effects: greater temporal diversity and the number of retransmission attempts can be increased when compared with ARQ (Automatic Repeat reQuest), as in QR a successful node gives his time in favor of the group. The difference between the QR and AQR is that the latter maintains a long-term history of success about each node, which is similar to the proposed `NetCod`.

In [20], it is proposed COPE, a new routing architecture that greatly increases the throughput in wireless networks that have devices grouped in a mesh topology. The challenge of COPE was to extend the idea of NC for duplex flows, ie, the mutual exchange of data between two nodes with the collaboration of some intermediate node. This purpose was achieved by exploring the broadcast nature of the wireless medium, enabling the nodes to listen to all transmissions and storing packets that were listened during a short period of time. As a result, a relay can do a XOR operation upon two packages, to deliver two different neighbors in a single transmission, when he knows that the two neighbors heard at least one of those packets. A similar approach is proposed in the `NetCod` scheme but, in our work, only some nodes are intended to be listening and cooperating among them during all time.

SenseCode is a protocol for sensor networks [21], which allows the introduction of a configurable amount of redundant information in the network. SenseCode uses NC to enable a new form of communication through multiple paths, where each node disseminates information on all available paths without having the need to find or maintain these routes. In addition, it uses decentralized and simple algorithms that do not exceed the reduced processing power and memory of WSN nodes. The proposal is to use NC to balance efficiency with reliability. Redundant information was introduced in the network to preserve the likelihood of message recovery. In SenseCode, nodes build and maintain a referral tree to sink. However, each node propagates not only its own message and his sons, but a small portion of what they have heard from their neighbors. More specifically, each node propagates a linear combination of its message, the packets received from their children and a small portion of packets heard from their neighbors, essentially making the NC. The NC can achieve higher reliability in a energy efficient way.

In [22], it is proposed a retransmission scheme based on time diversity and NC. The receiver sends immediately a NACK if it does not correctly received the packet or if the deadline expired. However, the source does not immediately retransmit the lost packet when it receives a NACK. Instead, the source maintains a list of lost packets and the corresponding recipients who had lost their packets. During the relay operation, the source form a new packet for the encoding (XOR) of a maximal set of lost packets from different receivers before retransmitting the encoded packet; then all the receivers can decode their message of interest, and then return to the transmission phase. Therefore, instead of retransmitting individual packets for each receiver, it is retransmitted a set for multiple destinations simultaneously.

In [23], it is used NC in the context of real-time and traffic regulations on IEEE 802.15.4 networks. The published results show that NC together with denial of service (space in a buffer) techniques can significantly increase the number of on-time received packets, under different traffic loads and for different timeliness requirements. Its applicability was assessed by simulation in a two-hop IEEE 802.15.4 network in beaconless mode.

Given these and other published research works, there is the interest to propose the use of a NC approach to provide greater robustness during the CAP period of IEEE 802.15.4 in beacon mode. Therefore, we propose the `NetCod` retransmission scheme.

4 NetCod

The use of NC may represent a gain in the communication performance; however, such gain is obtained at the cost of a higher computational load, given the need for on-line coding and decoding of messages. These coding/decoding procedures involve linear combination of messages (arithmetic operations with coefficients and messages) that aims assembling linearly independent systems, to obtain success in decoding messages. All these type of operations require a certain amount of processing power and memory, which are not always available in WSN nodes. Within this context, we propose an opportunistic usage of NC techniques, ie, as the medium noise level increases, it will increase the need for message retransmission and the need for NC, since only retransmitted messages are coded.

The main idea of the `NetCod` approach is illustrated in Fig. 3. Firstly (left side), the set of sensor nodes forward their messages to the coordinator. The coordinator evaluates the current level of message losses, determines how many and which nodes should cooperate among them, and forwards to these nodes a cooperate call message. The

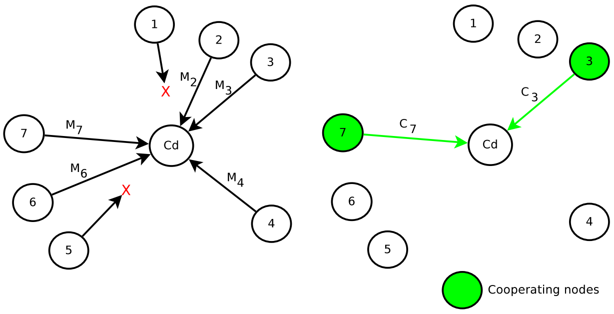

Figure 3. Network Coding: the main idea.

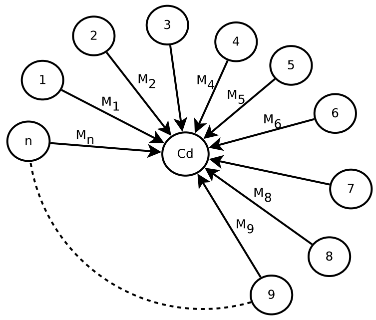

Figure 4. System model.

nodes that were selected for cooperation, encode all the messages heard during the transmission of ordinary messages and forward also these encoded messages to the coordinator. The coordinator having received both ordinary and coded messages, will decode the missing messages.

The most relevant details of the NetCod proposal are described below. The messages that implement the cooperation between the nodes have the following format:

$$C_i = [c_{i1}M_1 \oplus c_{i2}M_2 \oplus \ldots \oplus c_{iv}M_v]$$

where:
• C_i is the coding message of node i;
• c_{iv} is the random coefficient of node i to neighbor v, obtained as proposed in [24];
• M_v is the message heard from neighbor v.

The decision about the number of cooperating nodes is calculated by an exponentially weighted average, such as the one used Jacobson's algorithm for TCP, that considers the estimated losses ($EstLoss$) and the standard deviation ($DevLoss$):

$$NCoop = \lceil 2EstLoss + DevLoss \rceil$$

where:
• $EstLoss = (1 - \alpha)EstLoss + \alpha SamLoss$, being $SamLoss$ the current sample of losses
• $DevLoss = (1-\beta)DevLoss + \beta|SamLoss - EstLoss|$
• $\alpha = \beta = 0.2$, being 0.2 the a value that was adjusted to obtain the desired performance. ie, most weight is put on the topicality.

The election of the set of cooperating nodes considers nodes that have a good record of message transmission (low noise and no obstacles until the coordinator) and are aware of some of the bad transmitters. It is given by the weighted equation:

$$CN_i = \frac{WN_i + N_i + [1 - (\sum_{j=1}^{v} SR_j)/v]}{3}$$

where:
• index i refers to all each node of the network, $1 \leq i \leq n$, and v refers to on the neighbors of the node i;
• WN_i is the weight of the node i, which represent the association of the following rates: success rate in recent transmissions (SR), link quality (LQI) and battery voltage (BV), where $WN = \frac{SR+LQI+BV}{3}$ for $SR = (1 - \alpha)SR + \alpha SampleSR$;
• N_i reflects how many neighbors a node i has, which is the number of nodes within the range of its radio;
• the third term of the formula considers the neighborhood with nodes that had limited success rate in recent transmissions, ie, nodes that had more neighbors with low success rates will be elected.

For the example represented in Fig. 3, the coordinator elects nodes 3 and 7, they heard theirs neighbors and codify messages like that: $C_3 = c_{31}M_1 \oplus c_{32}M_2 \oplus c_{33}M_3 \oplus c_{34}M_4$ and $C_7 = c_{71}M_1 \oplus c_{72}M_5 \oplus c_{73}M_6 \oplus c_{74}M_7$. With these messages and with M_2, M_3, M_4, M_6 and M_7 the coordinator is able to decode all the messages.

5 Practical Implementation of Retransmission Schemes

5.1 System Model

The work presented in this paper considers an IEEE 802.15.4 cluster of sensor nodes within the coverage area of a single node, called the coordinator. The organization of networks in star topology has several advantages in terms of latency, synchronization and easy organization when compared to mesh topologies or tree groups and, therefore, is one of the most suitable for industrial use.

It is assumed that the coordinator will be the responsible for the initialization, synchronization and network maintenance. Each node i of the star, Fig. 4, periodically collects a sensed variable and forwards its value to the coordinator using a message M_i. The coordinator collects all the information and takes the appropriate action.

5.2 Retransmissions Schema

The four techniques that will be experimentally evaluated are: the proposed NetCod scheme, and three adaptations of state of the art mechanisms: BlockACK, Master/Slave and Redundant TDMA. All these techniques are designed to enable a second chance to retransmit data from sensors nodes to the coordinator. All use a slotted time approach, where time is divided into

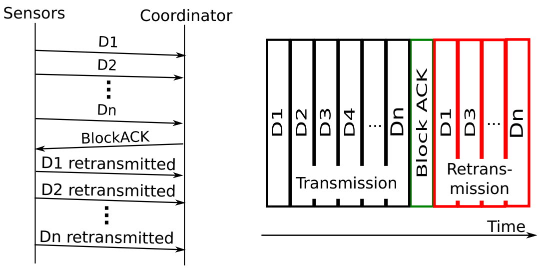

Figure 5. BlockACK.

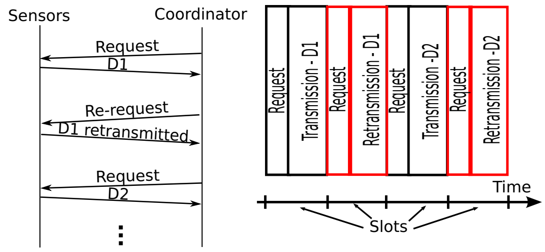

Figure 6. Master/Slave.

equal slices. Each slice can be used by only one node, avoiding message collisions in the medium access.

The target of application for these techniques is the usage of WSNs in industrial environments, where the exchange of information between sensors, controllers and actuators must be carried out in well-defined time intervals, requiring loss-tolerant mechanisms to improve the communication robustness.

Figures 5, 6, 7 and 8 illustrates a timeline of the message exchanges, the medium occupation and the slots used for sending or resending (second chance) messages.

The `BlockACK` technique, Fig. 5, uses a TDMA approach with a single confirmation message and a second chance for transmission. Briefly, the TDMA frame length is split, and each node has its own slot to send data to the coordinator. The `BlockACK` frame is a message broadcast by the coordinator, which contains one bit per node in the data field. If this bit is zero (NACK), it means that the coordinator has not received, or received with errors, the message of the respective node; otherwise, if it is one, it means that the message was correctly received. The second chance will be used for forwarding messages from nodes that received a NACK. Each node, upon receipt of `BlockACK` and based on its position in the cycle, knows in which slot it will be allowed to retransmit. If there are no lost messages, the frame will contain one slot per node, plus one. In the worst case, if the coordinator did not receive any message, the period of Second Chance is equal to the TDMA cycle, and therefore the frame will double the number of slots, plus one.

The use of a `BlockACK` scheme can be advantageous for a network. First, when compared to the individual ACK sending, it results in a smaller energy consumption and medium occupation. Using the `BlockACK`, an entire set of individual ACKs will be replaced by a single message. Furthermore, the use of `BlockACK` provides greater temporal diversity, since it will sparse in time push messages, acknowledgement and resent data, which can be of interest in industrial environments. On the other hand, the use of `BlockACK` increases the average delay jitter.

In the `Master/Slave` (polling) scheme (Fig. 6), the coordinator makes explicit data requests to the nodes. Upon request, the node sends a message containing their data. If the coordinator does not receive the message, the coordinator may immediately request a retransmission. It should be noted that this approach might be interesting for typical industrial applications, such as NCS (*Networked Control System*), where messages should be periodic, and delays may result in degradation of the control efficiency [25]. Our implementation of this technique has virtually no temporal diversity, nor spatial diversity.

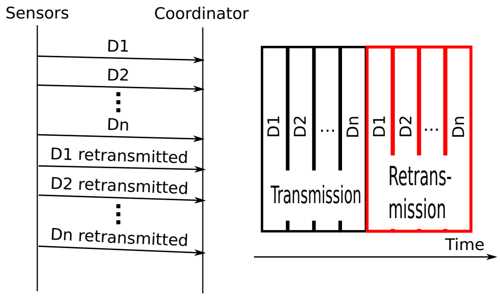

Figure 7. Redundant TDMA.

In the `Redundant TDMA` scheme (Fig. 7), the frame is divided in two equal TDMA sets, where each node has two slots, one in each TDMA block. Therefore, a node sends each message twice (temporal diversity). Once in the first TDMA block and a copy in the second TDMA block. There is no confirmation of message reception; if at least one of the messages is received, the communication was successfully completed. This scheme is implemented to serve as a reference, like in [21].

In Fig. 8, it is represented a timeline of the message exchanges, the medium occupation and the used slots for the `NetCod` scheme, which is similar to the timeline of `BlockACK` scheme. The frame `BloCop` contains the list of cooperating nodes. When there is the need to change the set of cooperating nodes, the `BloCop` frame has its data field duplicated, transmitting both the list of current cooperating nodes and futures ones. Nodes that were elected must remain active during the transmission period, store all incoming messages, encode and, in the period of cooperation, transmit them.

Considering the fact that a message generated and transmitted by a node, is listened by another node and, if coded, is then again retransmitted, one can consider that this scheme implements both temporal and spatial diversity techniques.

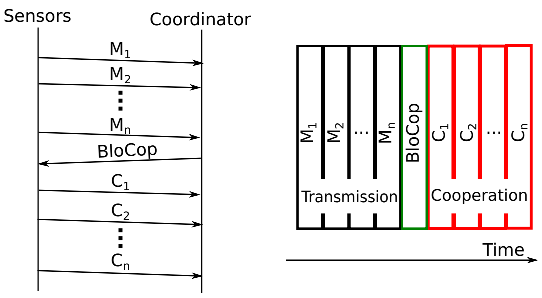

Figure 8. NetCod.

6 Experimental Evaluation

The above described retransmission schemes were implemented during the CFP, using a set of MicaZ nodes running the OpenZB micro-kernel. The OpenZB implements the protocol stack specified by the IEEE 802.15.4, and it is developed in nesC[3] on the TinyOS[4] operating system. For network monitoring, we used a packet capture tool of Microchip Technology Inc., named Zena[5].

For comparison purposes, the time scale was considered to be discrete and measured in number of slots. The same time slot and macro-cycle sizes were considered for the four retransmission schemes. One macro-cycle was set to be long enough to contain all messages in one poll: transmission and retransmission from sensor nodes and messages from coordinator (when applicable), therefore there is no need for the use of a scheduling algorithm. Note that for `Master/Slave` technique, within a time slot there are both a request message from the coordinator and a reply message from the sensor node.

All frames are 17 bytes in length, including 9 bytes for header and tail (2 for frame control, 1 for sequence number, 4 for address and 2 for frame check sequence) and 8 bytes for payload. The coordinator node can send different messages to control the network, which depends on the technique being assessed. The duration of each slot was set to 20 ms for all retransmission schemes. Continuously, the nodes generate data simulating the act of gathering information from the environment, process information, store it into a buffer and send it in first and second chance (when available).

A logical star topology was used, consisting of 9 nodes, one being the coordinator node. In the experiments, there was no intention to test topology variation, nor any changes in size of the network. The target was to assess the performance of each retransmission scheme and to directly compare them with each other and with a baseline TDMA (TDMA is used in several industrial networking standards, such as the WirelessHART). Nodes are randomly arranged, with the maximum distance between them of about 1 m. For all the experiments, messages were collected during about 10 minutes. This time allows a total of about 5159 slots, not considering specific compartments of the IEEE 802.15.4 protocol. This amount of data characterizes a relevant statistical sample, which guarantees a confidence interval of 95% for the results.

One sensor node was powered by a DC power supply, in order to accurately measure its power consumption. The current was measured by a current monitor[6] that converts current to voltage and enables the acquisition using a NI USB-6008[7] device.

Based on the manufacturer's data-sheet, it is possible to make some considerations about the power consumption of MicaZ nodes. A node in idle state consumes a current of 20 μA; in the receive mode consumes 19.7 mA; and in the sending mode consumes 11, 14 or 17.4 mA, depending on signal strength, which varies according to distance to destination. The operating voltage is 3 V, therefore the power consumption is between 6 μW to 59.1 mW.

During the experiments, the nodes were deployed near each other to minimize external interferences in the radio signal. Before starting each experiment, a set of small tests were performed to verify if there was any interferences that would lead to the loss of messages, fact that never occurred.

To impose a realistic packet error rate (PER), we adopted the Gilbert-Elliot model presented in [26], which has been demonstrated to provide a fair approximation of fading in industrial environments [27]. This model uses a Markov chain with two states: `Good` and `Bad`, with sojourn times T_G and T_B, respectively. Each state is associated with a constant bit error rate (BER), e_G in `Good` state, e_B in the `Bad` state and $e_G \ll e_B$. In each state it is assumed that errors occur independently of the other state and, for simplicity, some studies consider $e_G = 0$ (0 %) and $e_B = 1$ (100 %), like [28]. In our analysis, we took an approach similar to [29]. Sojourn times in the two states are exponentially distributed and we varies T_G and T_B to obtain different values of PER.

According to this approach, when a node receives a message, it will decide if the message is corrupted or not. Corrupted messages are discarded (if the case, no ACK is sent). We assume that PER ranges from 0 to 50%, and that any packet could be lost, regardless if the message is originated from sensor nodes or the coordinator. It should be noted that this high level of losses (50%) is impracticable for many networks and applications.

Fig. 9 illustrates the success ratio between data sent by sensor nodes and data that actually reached the coordinator, either in first or in the second chance. Results highlight that, in general, all techniques have a better performance than the basic TDMA. The `Redundant TDMA` technique has the highest probability of successful transmissions, due to the fact that messages are not required to return, with no linked events.

Fig. 10 presents the average delay (measured in *number of slots*). This metric was obtained computing the dif-

[3] http://nescc.sourceforge.net/
[4] http://www.tinyos.net/
[5] http://www.microchip.com

[6] http://www.diodes.com/datasheets/ZXCT1022.pdf
[7] http://www.ni.com/pdf/manuals/371303l.pdf

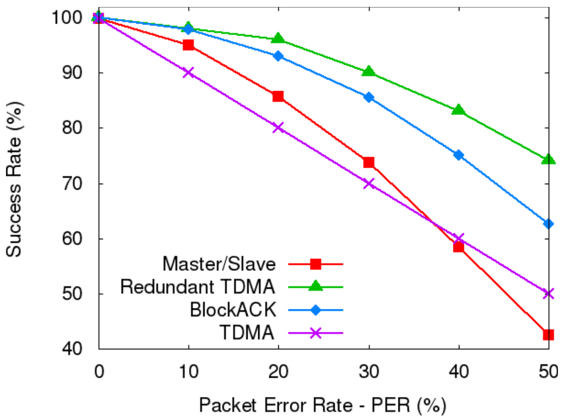

Figure 9. **Success rate.**

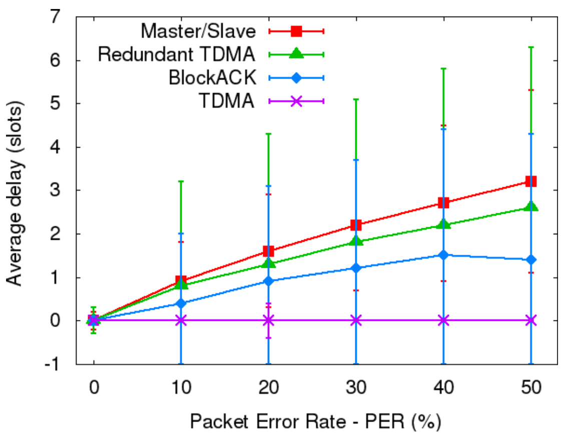

Figure 10. **Average delay of the messages containing effective data.**

ference between the instant of the first transmission attempt until its arrival at coordinator. In a scenario without errors, the transmission is performed within one slot, and consequently the delay is zero. In this context, this metric can be used to evaluate the `release jitter`. This Figure also illustrates the standard deviation of the results, using vertical bars.

Experimental results show that these techniques have a behavior that is about the opposite of the one shown in Fig. 9. In order of best performance in what considers the average delay: `BlockACK`, `Redundant TDMA` and `Master/Slave`. Depending on the application, it may be more interesting to prioritize lower losses or lower latencies. We can also observe that, the greater the delay, the greater is its variability. We can understand this by looking at the slot usage timelines, where we can observe a greater or lesser distance between the first and second chance of transmission, which will generate as a consequence, a greater or lesser delay jitter variation. Note that the average delay is computed using data from all nodes, and consequently it hides the individual behavior of each node. For example, in the case of `BlockACK` the first node has a higher delay than the last one, because the last

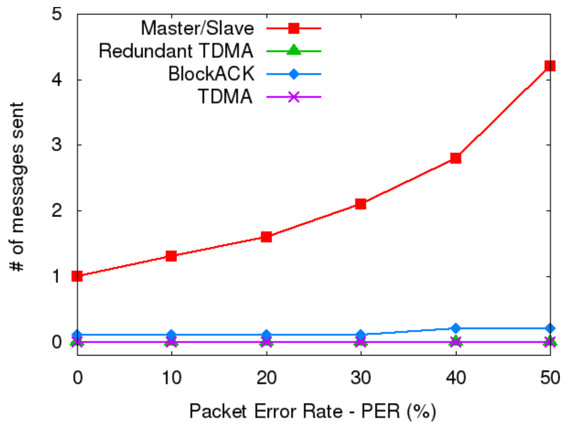

Figure 11. **Messages sent by the coordinator for each received message.**

will retransmit as soon as possible after the `BlockACK` frame; this can happen in the next slot and the delay will be just 2 slots. At the other end, the delay of the first node will be 10 slots.

Finally, the basic TDMA technique has no delay because the message transmission is always performed within a slot. However, this implies a higher loss level as it could be observed in Fig. 9.

In Fig. 11, it is presented the number of messages that the coordinator must send to each message actually received. This is an information that reflects a greater or lesser workload for the coordinator. `Master/Slave` is the technique that overloads more the coordinator with respect to the amount of messages sent. For the case of `Redundant TDMA` and `TDMA` the number of additional messages is zero. For the case of `BlockACK` is very low and inversely proportional to the number of sensor nodes. For instance, for 0% loss, the total number of messages sent by the nodes was 2580, while the coordinator itself sent 323 messages. The same ratio can be seen between the number of nodes and the coordinator (8 to 1). If the number of sensor nodes become larger than the workload of coordinator will become proportionally smaller, because the ratio (e.g. 20, 30 . . . to 1) became smaller.

The energy consumption of a sensor node for the different techniques is presented in Fig. 12. In all experiments the power consumption with the radio turned off was about 22 mW and with the radio turned on was about 68 mW. This is slightly higher than the specified by the manufacturer. All the experiments have showed similar results to [30]. Each presented result was computed as an average value of 550000 collected samples, which represents about 303 macro-cycles. It can be observed that every retransmission scheme has a higher consumption than `TDMA`. This was expected, because the second chance transmission is enabled.

The `TDMA Redundant` is insensitive to variation of losses, i.e., the power consumption of nodes stays the same in all levels of losses because the nodes always

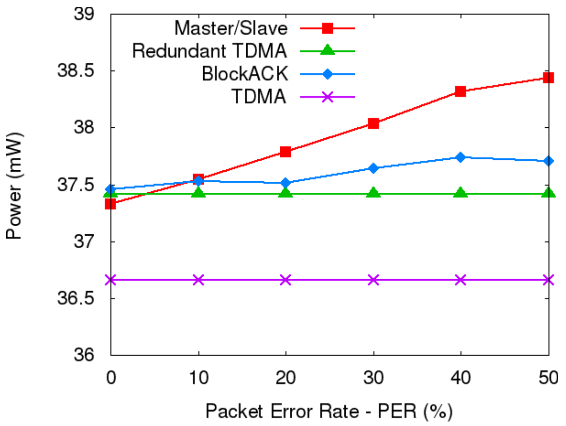

Figure 12. Power consumption of node.

Table 1. Estimated lifetime of node (hours) for different message loss rates.

Loss rate	Master/ Slave	Redundant TDMA	BlockACK	TDMA
0%	434	433	432	442
50%	421	433	430	442

retransmit the message. On the other hand, Master/ Slave and BlockACK are more sensitive to losses, being Master/Slave more sensitive. We do not present the standard deviation of the results because there are two very different states of energy consumption and this masks the value. In Table 1, we present an estimated lifetime of node with 2x2700 mAh battery.

The NetCod retransmission scheme has not yet been fully assessed. Fig. 13 illustrates a comparison of this implementation with the TDMA Redundant. It can be seen that, we can already achieve better results than those presented so far, with a lower rate for both the medium and resources usage. The number of cooperate workers by the coordinator was calculated on average: 1, 2.5, 4.4, 6.2, 7.5, 7.9 for loss rates ranging from 0% to 50% respectively.

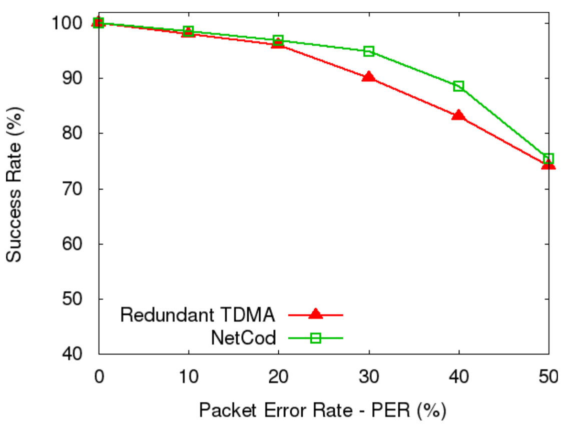

Figure 13. Success rate.

In Fig. 14 we can observe the performance improvement in the success rate as we change the number of cooperating nodes. It is clear that with higher number of cooperating nodes we have better performance. However, the higher processing and transmitting costs result in higher energy consumption. The upper curve shows the upper bound that can be achieved with NC in one retransmission schema, ie, this curve is to be pursued. On the other hand, for a good balance between the environment use, saving energy and success rate should be achieved by gradual migration between the various curves, ie, as the success rate decreases increases the number of cooperating nodes (to compensate).

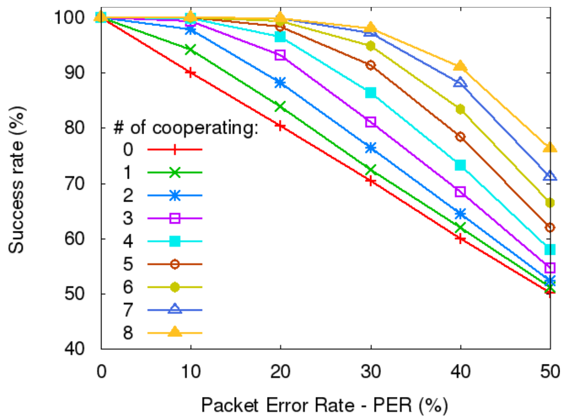

Figure 14. Success rate with variation in the number of cooperating nodes.

In what concerns the other metrics, the tests are still being executed. However, we believe that the NetCod retransmission scheme presents similar results to the BlocACK scheme, with regard to power consumption, average delay and the load of workload of the coordinator, with a slight increase in computational cost during regular operation.

7 Conclusions

In this work, we proposed, implemented and experimentally tested four message retransmission schemes for WSNs: BlockACK, Redundant TDMA, Master/ Slave and innovative NetCod.

Among all the assessed schemes, the one that presented the best performance was the NetCod. Though not yet thoroughly tested, the available results already highlight that this retransmission scheme has a lower packet loss rate and, by similarity with the technique BlockACK, it provides acceptable rates of energy consumption and average delays of messages.

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