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***Abstract*—It has been analytically and empirically proved that Network Coding can significantly enhance wireless communications in terms of achievable throughput, data delivery and delay. While research in Network Coding has mainly addressed the problem of coding efficiency, buffer optimization and queuing, little attention has been paid to what we define as coding reliability, i.e., the ability for nodes to encode packets efficiently enough, so that a maximum number of its destinations can extract innovative data whatever the medium conditions can be. In this work, we investigate this concept in Wireless Sensor Networks (WSN) then we present Re-CoZi, a packet transport mechanism which enables robust XOR Coding for WSN using echo-feedback packet reception and decoding acknowledgement. Our performance analysis shows that Re-CoZi keeps the added value of NC in terms of bandwidth utilization and delay, while providing a more reliable coding.**

Keywords: Reliable Network coding, Wireless Sensor Networks, ZigBee, IEEE 802.15.4.

I. INTRODUCTION

This paper focuses on one promising and leading technology in WSNs and WPANs, alias, ZigBee [6] and its underlying Medium Access Control and physical layers, the IEEE 802.15.4 [4]. We investigated the impact of one-hop coding at the frame level to exploit the clustered hierarchy of 802.15.4-based networks. This utilization of network coding (NC) reveals significant results in terms of throughput, data-delivery and latency. However, in certain conditions, when a high loss rate is experienced due to interferences in the radio spectrum, we can notice that coding decisions often turn out to be non-optimal, which alters drastically the added-value of NC provoking series of coding and decoding failures and thus an important performance degradation in the network.

We describe what we define as the coding reliability of NC schemes [1]. We argue that this concept is an important feature for the assessment and the development of coding algorithms. Surprisingly, it is frequently not taken into account in the literature even if it may impact the efficiency of any coding algorithm designed for wireless networks wherein the medium is by nature unreliable. As an empirical example, we propose to study CoZi, our scheduling system for ZSNs. We show how interferences and collisions can impact the behavior of our algorithm, then we propose Re-CoZi (Reliable CoZi), a simple and yet efficient solution using echo-feedback acknowledgement mechanisms [2] and topology inference to improve the robustness of NC under erratic medium conditions. Finally, we show that Re-CoZi still outperforms classic ZigBee routing in terms of data-delivery, though, with a small trade-off in terms of end-to-end latency.

The rest of the paper is organized as follows: Section II gives a brief description of our prior work on XOR coding for WSNs. In Section III, we introduce the concept of network coding reliability. In Section IV, we present Re-CoZi, our new reliable routing protocol for 802.15.4, networks and then we show in Section V, by additional performance analysis involving ZigBee and CoZi the conclusive results that Re-CoZi offers. Section VI concludes the paper.

II. BACKGROUND

A. CoZi Overview

CoZi (Coding for ZigBee) is a simple one-hop coding scheme designed for ZigBee sensor networks to enhance bandwidth utilization and data delivery using the cluster-based topology of the IEEE 802.15.4. In CoZi, only routers can encode packets before data transmissions by combining those using XOR operations. Every coding decision is performed depending on a specific strategy, so that a maximum number of nodes can decode the outgoing packet. To decode a packet, nodes use what is defined in [5] as overhearing links (cf. Fig. 1). Indeed, since 802.15.4 clusters are physically overlapped, i.e., nodes may receive packets from nodes that are not in the same cluster, each node can exploit these links to overhear packets that are not destined to him in order to help decode forthcoming encoded packets. Fig. 1 illustrates an example of a 2 hop communication with CoZi, where the node *i* has to forward a maximum number of packets from nodes *a*, *b* and *c* to *j*, *k*, *l* and *m* within one transmission using XOR coding. The pool of available packets at *i* contains {A_1, A_2, B_1, B_2, C_1, and C_2}. Thanks to the neighboring table of ZigBee and to the topology inference system of CoZi, the node *i* knows that one of the optimal combinations of packets is to broadcast $A_1 \oplus B_1$ to all destinations, allowing them to decode either A_1 or B_1.

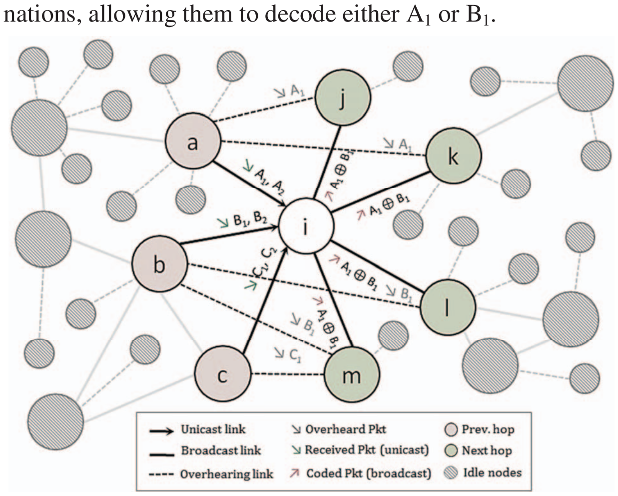

Figure 1 - ZigBee overhearing example

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DOI 10.1109/MASS.2011.122

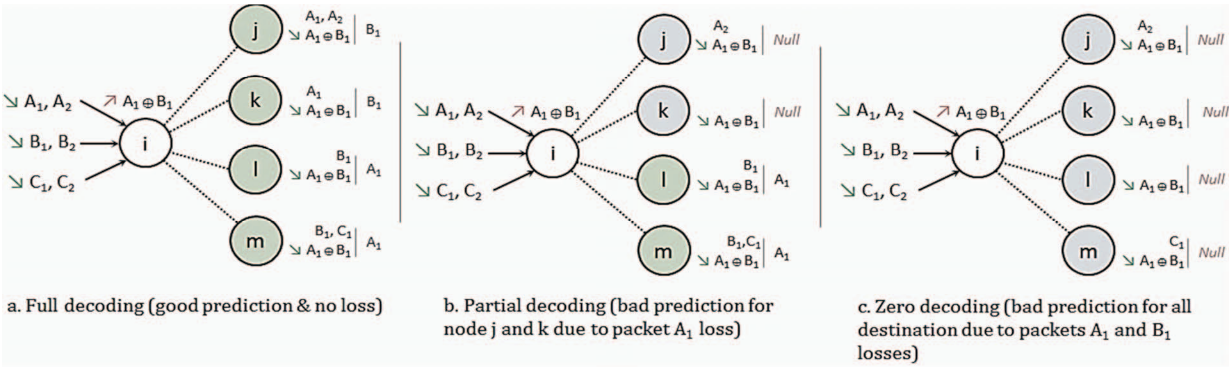

Figure 2 - Packet loss impact on coding efficiency illustration

III. CODING RELIABILITY

Reliability in wireless networks in general, refers to full or high data-delivery using retransmissions mechanisms, so that data traverse the network and arrive intact at their destination. While coding reliability rather concerns the ability for any node to encode packets efficiently enough so that a maximum number of its next hops can decode this packet, whatever are the network conditions (collisions, node failures, etc.). We classify the main criteria a network coding algorithm has to meet to ensure network coding reliability.

1) Topology Inference: It is one of the key parameters in the reliability of any network coding algorithm, since a bad prediction of local packet availability can lead to sub-optimal or even non-decodable packet combination. Fig. 2 shows situations where *i* selects packets based on inaccurate local topology feedbacks, which leads to, respectively, partial and impossible decoding at the destinations.

2) Decodability: We call decodability the probability of a selected code c used by a node s to be decoded by all its destinations. It is defined by the following equation:

$$\mathrm{Dec(c)} = \begin{cases} \sum_{i=0}^{N(s)} \frac{P_{dec_i}(c)}{N(s)}, N(s) \neq 0 \\ 0, \text{otherwise} \end{cases} \quad (1)$$

With $P_{dec_i}(c) = P[dec_i(c) \neq \emptyset]$ and $dec_i(c)$ is the set of decoded packets by node i from c. $P_{dec_i}(c)$ represents the probability of decoding a packet c by a node i, and $N(s)$ is the number of nodes that are supposed by s as able to decode c (and not the total number of s neighbors).

3) Innovativity: It represents the probability that a coded packet c produces at least one innovative packet at all its destinations. It is defined in the following equation:

$$Inn(c) = \begin{cases} \sum_{i=0}^{N(s)} \frac{P_{inn_i}(c)}{N(s)}, N(s) \neq 0 \\ 0, otherwise \end{cases} \quad (2)$$

With $P_{inn_i}(c) = P[\, dec_i(c) \notin (Q_{in}(i) \cup Q_{ovh}(i))]$. $P_{inn_i}(c)$ is the probability that the packet c is innovative for a node i. A node considers a packet as innovative if it has never received or overheard it. Fig. 2 plots an example where the exact same packet has different innovativity values depending on the packet loss rate. Where:

Fig. 2 (a) : $Inn(p_a) = 1$, when no losses
Fig. 2 (b) : $Inn(p_b) = ½$, when A_1 is lost
Fig. 2 (c) : $Inn(p_c) = 0$, when A_1, B_1 are lost

4) Optimality: The optimality of a code is the union of both its decodability and its innovativity, i.e. a code (combination of packets) is said optimal, if and only if it allows decoding a maximum number of packets and if it reaches its highest decodability and innovativity.

$$Opt(c_i) = Max\left[\, Dec(c_i) \times Inn(c_i) \times \frac{N_{dec_i}}{N_{pos_i}} \right] \quad (3)$$

Where N_{dec_i} is the number of distinct decoded packets and N_{pos_i} the number of possible decoded packets.

5) Fairness: To ensure reliable network coding, one has to guarantee a certain degree of equitability between data flows when selecting a combination of packets. While, coding unequivocally enhances the bandwidth utilization, it may also penalize flows depending on how the packet selection algorithm behaves. For example, if a coding node focuses only on the optimality of a code, it may overlook the fairness toward the different data flows it has to forward. In fact, by picking packets from the same flow(s) at each coding opportunity, it can delay the transmission of other flows and dramatically affects the data delivery rate of some end-to-end communications. Hence, we define $Fair_i$ (cf. Equation 4) the probability that the next outgoing packet c from node i contains at least one packet from the flow f_j.

$$\forall i \in N, j \in InFlows(i),$$
$$Fair_i(f_j) = P\left[c \in Q_{out}(i) \mid \exists\, p \in f_j, p \oplus c = c - p\right] \quad (4)$$

Where $Q_{out}(i)$ is the set of outgoing packets from node i, $InFlows(i)$ the set of the incoming flows f_j.

IV. RE-COZI

In this work, we propose Re-CoZi, a series of solutions to cope with coding failures due to unreliable medium conditions. Based on our definition of coding reliability, Re-CoZi keeps the performance gain ensured by network coding and provides coding efficiency using advanced acknowledgment techniques and link state awareness.

A. *Re-CoZi Acknowledgement System*

To avoid any loss of reliability under bad medium conditions, we add an echo-feedback field in transmitted packet to inform neighboring nodes about any overheard or received packet. This passive packet ACK approach consists in acknowledging the transmission over the previous hop by relaying an ACK field within the actual head of the transmission queue. Using this piggy-backing approach lowers the overhead induced by sending ACK packets at each decoding phase. As a result, the coding node can always know when a packet has been lost by checking into the echo-feedback field. Furthermore, a real gain can be expected because less short ACK packets are sent reducing the transmission overhead, especially under a very high loss rate where many packets are unnecessarily duplicated because of ACK loss.

B. *Link State Based Network Coding*

In order to ensure a maximum data-delivery under lossy conditions, new mechanisms must be designed for network-coding-based networks. Using the Received Signal Strength Indication (RSSI) field within received or overheard packets and the current Packet Loss Rate (PLR), each intermediate node can trigger the advanced acknowledgement mechanisms in order to cope with the rise of the packet loss rate.

$$\left[c_1.\left(\frac{\sum_N RSSI_i}{N}\right)+c_2.\left(\frac{\sum_N PLR_i}{N}\right)\right] < T \Rightarrow A\_ACK = 1 \qquad (6)$$

C. *Preventing Dead-End Paths*

To cope with the fairness issue, Re-CoZi adds a local queue management mechanism, where each node supervises its *Tx* queue, checking if packets from one flow remained a determined period of time without being sent; in which case, it suspends all coding operations to send these packets at the next transmission opportunity. This solution allows node to avoid applying unfair coding strategies that lower the data-delivery of certain end-to-end communications.

V. PERFORMANCE ANALYSIS

We use the Qualnet 4.5 simulation environment [3] to assess our solution. We consider 100 nodes randomly positioned in a $150m \times 150m$ area. The ZigBee coordinator is placed in the center of the network and the rest of the nodes are either routers or end-devices. The simulation environment triggers randomly an end-to-end communication between two arbitrary nodes. Each communication has a traffic load that varies from 25 to 100 packets per second.

VI. CONCLUSION AND FUTURE WORK

In this work, we define coding reliability: a series of metrics that allow reliable network coding over wireless networks. Then, we propose Re-CoZi, a one-hop coding scheme for ZSNs which uses medium aware advanced acknowledgement mechanisms to provide reliable network-coding-based communications over lossy environments. This work on network coding theory entails a wealth of new issues of interest. Our future works target the impact of characteristics such as, density and mobility on the coding reliability.

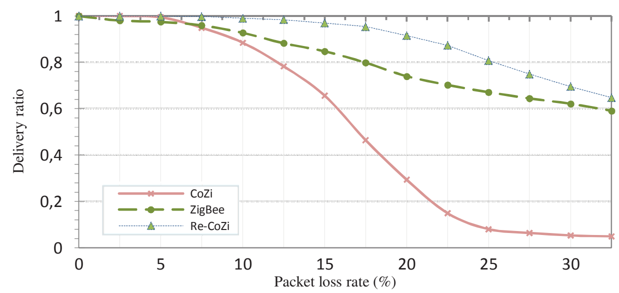

Figure 3 – Delivery ratio versus packet loss rate

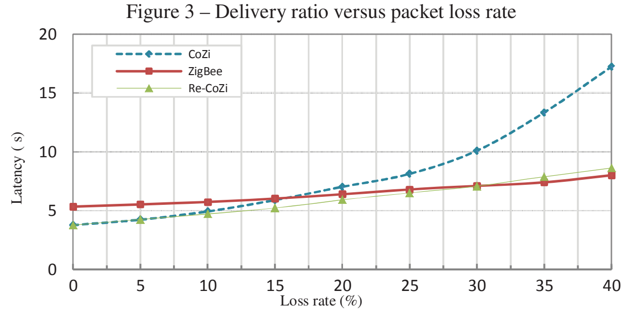

Figure 4 – Latency versus packet loss rate

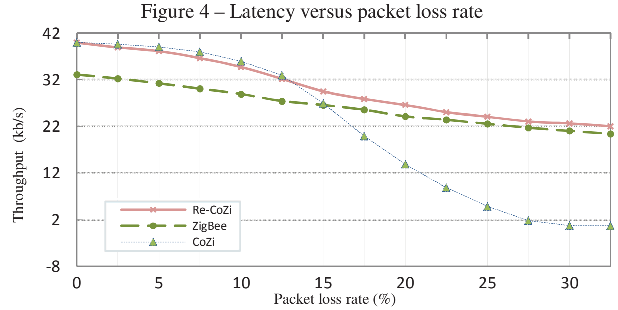

Figure 5 – Throughput versus packet loss rate

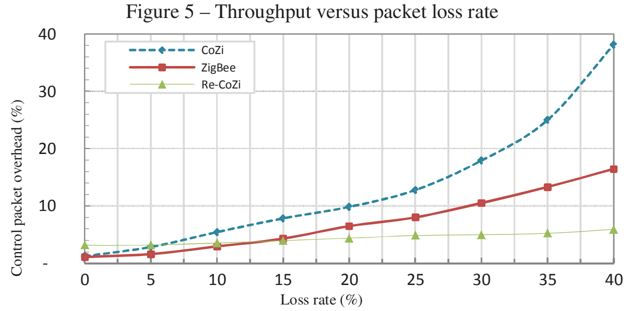

Figure 6 – Control packet overhead

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