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***Abstract* —This paper describes CoZi, a new packet scheduling mechanism for large scale ZigBee networks. CoZi aims at enhancing the reliability of the data delivery and the bandwidth utilization of the network. Based on simple network coding, instead of the classic packet forwarding, our algorithm takes advantage of the shared nature of the wireless medium as well as the cluster-tree topology of IEEE 802.15.4 networks to increase the global throughput and to reduce transmissions in end-to-end and dissemination-based communications.**

***Index Terms*—Network coding, wireless sensor networks, IEEE 802.15.4, ZigBee**

I. Introduction

The emergence of standardized new communication protocols and network architectures exclusively designed for low-power devices and wireless sensor networks (WSNs) is a significant indicator of the degree of maturity attained by these technologies. ZigBee [20] and the IEEE 802.15.4 [9] represent some of these important standards that have contributed to the development of WSNs and Low-rate Wireless Personal Area Networks (WPANs). Based on the underlying cluster-tree topology of the IEEE 802.15.4 standard, ZigBee allows low data-rate wireless communications for energy-constrained devices to provide a variety of applications for health-care, home automation, energy management, remote monitoring and other domains. Ensuring efficient and reliable communications in such erratic environments as wireless networks is a very challenging issue. Indeed, the inherent properties of radio channels can alter communications in terms of delay, data delivery and energy consumption. Nonetheless, a smart utilization of the wireless medium can also drastically improve the network's performances. [4] has shown the potential benefits of taking advantage of the shared nature characteristic of wireless links in order to enhance data delivery and global throughput of wireless networks.

Throughout this article, we describe CoZi (Coding for ZigBee) a coding scheme capable of improving 802.15.4 communications by exploiting the network coding theory innovative concepts [4]. The topology of ZigBee networks consists on abstractly separated clusters built depending on nodes' profiles. The clusters are often physically overlapped, i.e., nodes may frequently receive packets from nodes that are not in the same cluster, via what we designate as overhearing links. We thus propose to exploit these overheard packets with a distributed one-hop coding system as described in [10] to avoid the channel overhead induced by the brute force replication and to improve the global network throughput for both *end-to-end* and *dissemination* data-delivery scenarios.

The key target of our work resides on optimizing the global throughput of ZigBee networks. This can be tackled as a scheduling problem which is known to be hard to solve. Therefore, we propose a network coding scheme based on proactive local topology inferring mixed with the utilization of our distributed packet scheduling system in order to improve end-to-end and dissemination based communications in ZigBee wireless sensor networks. We evaluate our solution through simulations considering different network densities and data traffic scenarios. Our performance study shows an important improvement of the global network throughput under high load and a significant gain in terms of delay for both end-to-end and dissemination-based communications

The reminder of the paper is organized as follows: Section II discusses related work of 802.15.4/ZigBee optimization algorithms and network coding techniques for wireless networks. Section III describes the system's characteristics. In section IV we define CoZi, our coding scheme for ZigBee sensor networks, followed in Section V by a detailed performances evaluation. The paper concludes with a brief discussion in Sections VI.

II. Background

The IEEE 802.15.4 is extensively employed in WSNs. It is the underlying standard of several well-known technologies such as ZigBee or 6LoWPAN [13]. TinyOs [5] and Contiki [6] are two operating systems for sensing devices that provide full or partial implementation of the 802.15.4 MAC and PHY layers. Many researchers have investigated the dissemination and data–delivery in 802.15.4 based networks. Both Deluge [8] and Typhoon [15], for example, consider data dissemination for *on-the-air* reprogramming of large scale 802.15.4 sensor networks. Kim *et al*. described in [12] a routing protocol based on the neighbor table originally defined in the ZigBee specifications to cope with the insufficiencies inherent to tree-routing. Also, in [19], J. Zheng *et al*. propose a dissemination-based algorithm to build a mesh network upon a ZigBee topology. More recently, authors of [3] have presented a deterministic algorithm which optimally configures ZigBee parameters (beacon intervals, super-frame durations, and guaranteed time-slots) in order to guarantee end-to-end deadlines for real-time packets delivery. All these works aim at optimizing the throughput and the data delivery reliability in ZigBee. We can however notice that none of them exploits the redundant links created by the broadcast nature of the radio channel and thus the extra bandwidth provided by these links.

Independently, recent advances in the applications of the Network Coding theory introduced by Ahlswede *et al*. in [4] are refining some of the conventional techniques in communication networks. Joint work of both the wireless network and the network coding communities shows in [16] the potential benefits of using coding operations at packet level to increase the performances of wireless networks. Many protocols such as, Avalanche [2], CodeTorrent [14], or CodeCast [17] have used random linear coding or simple XOR operations to improve routing, forwarding and dissemination schemes over MANETs, by dividing streams of data into blocks and encoding them before transmissions. In all these cases, the network coding provides a significant gain in terms of reliability, delay and throughput. Different network coding mechanisms have been proposed since the emergence of the concept. For instance, [2] uses linear network coding, in which packets are encoded using randomly selected coefficients. In this case, to decode packets nodes have to solve linearly independent equations, this solution is generally used to ensure better reliability and data-availability in large scale wired and wireless networks. In [10] and [11], authors use exclusively XOR operations instead of linear equations to facilitate the decoding operations. This coding technique has shown remarkable performances in the improvement of the global throughput in wireless ad hoc networks. In this paper, we extend the work of Katti *et al.* in [10] by exploiting the unique characteristics of the cluster-tree topology of ZigBee networks and by selecting the best code among the different coding possibilities, in order to allow a maximum number of neighbors to decode the packet.

III. System Description

The IEEE 802.15.4 standard defines Medium Access Control (MAC) and Physical Layer (PHY) specifications for Low-rate Wireless Personal Area Networks (WPANs). In a 802.15.4 network, devices can be classified in two categories, namely: full function devices (FFDs) or reduced function devices (RFDs). This distinction resides on the role that the node will play within the network. Indeed, FFDs can operate in three modes: PAN coordinator, coordinator, or end-device, whereas RFDs are used only for basic operations (e.g., scalar sensing or basic actuating) and can thus only be considered as end-devices. Note that 802.15.4 uses the roles and the addresses as defined in the ZigBee standard [20]. As depicted in Figure 1, ZigBee networks include the following roles:

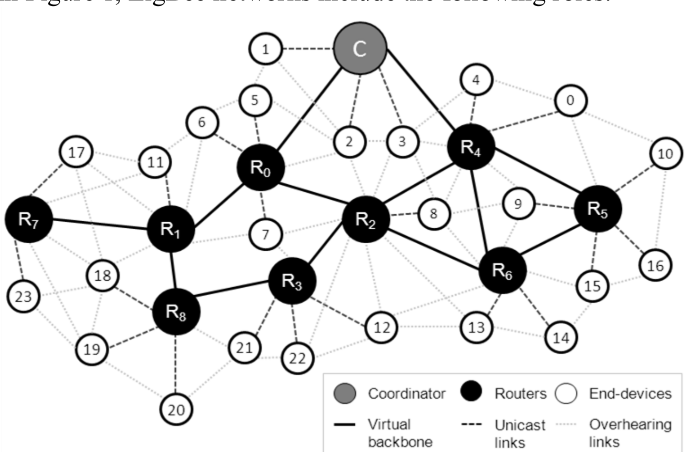

Fig. 1 – ZigBee network topology illustration

1) The Coordinator: it s a unique node in the network in charge of the connectivity with higher performance networks. ZigBee networks have to include at least one FFD operating as the coordinator. In a real application, the coordinator might represent a sink or a gateway in a WSN for instance.

2) Routers: they provide specific services to end-devices or other routers such as synchronization, data collection, and medium access scheduling. Every FFD in the network is eligible to be a router. The overlay network composed of the routers and the coordinator can be seen as a virtual backbone within the network.

3) End-Devices: they can communicate via unicast links exclusively with their unique associated parent, which allows them to minimize their energy consumption.

The routing algorithms provided in ZigBee are either cluster-tree based or table-driven. The tree-routing mechanism is based on the hierarchical block address allocation mechanism called Cskip [20], so each parent has an address interval to distribute to its children. While, table-driven routing is based on the Ad hoc On-demand Distance Vector (AODV) routing protocol [18] for multihop ad hoc network. In this paper, we focus on the cluster-tree topology, and the hierarchical routing, which is the default and economical routing mecnanism used in ZigNee networks. Nevertheless, our solution can be easily extended to a mesh routing scenario.

B. *ZigBee Network Formation*

In order to build the cluster-tree topology, each device goes through two phases before joining the network and starting to send its data (cf. Figure 2). Depending whether the beacon mode is activated or not, the construction of the hierarchy uses different algorithms, although both make use of signalization[1].

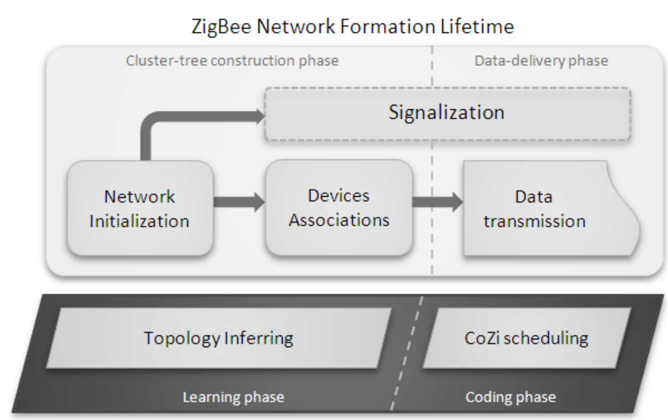

Fig. 2 – CoZi architecture overview

1) Network Initialization Phase: During this phase, the FFD defined as coordinator allocates to itself the network address 0x0000, and if the beacon mode is activated it starts sending beacon-frames to let the neighboring nodes know that they can associate with it. Otherwise, it waits for a beacon-request.

2) *Nodes Associations Phase:* Whenever a node is turned on, it waits for receiving a beacon from the coordinator or the closest router if the beacon mode is activated. Otherwise, it broadcasts a beacon request and chooses to associate with one

[1] We refer to signalization all the exchanged control frames and control packets used to build and to maintain the ZigBee cluster-tree topology (beacons, beacon-requests, association-requests, etc.).

of the responding routers (respectively the coordinator). At the end of the association phase, the node is associated with one unique parent and is given a network address.

3) *Data-Delivery Phase:* This phase can start if at least two nodes in the network are associated and thus have their network addresses. Since we are interested here in the use a cluster-tree routing algorithm, an RFD node has to transmit its packets to its parent. The latter will then, depending on the destination address, choose a route above the virtual backbone in order to reach the destination.

Our major contribution in this work consists on exploiting the signalization messages exchanged during the ZigBee network construction phase to infer the local network topology of the network at each node. This will allow intermediate nodes to take encoding decisions based on previously received information without any global knowledge of the network topology. To do so, we assume each node has overhearing capabilities i.e., is able to receive from its neighborhood unicast packets that are not directly addressed to him, which is a realistic assumption[2] since the wireless radio channel is by definition a shared medium. We also assume that nodes are capable of performing bit-wise XOR operations at the packet level to use one-hop coding as described in section IV. Note that we use the term "received" for the packets that are received and supposed to be handled by the node according to the routing process, and "overheard" for the packets that were not destined to the node.

IV. CoZi Overview

In this paper, we propose two coding strategies that can be used at each node to maximize the bandwidth utilization of a ZigBee sensor network depending on the nature of its data-traffic. To this end, any ZigBee router can perform network coding operations before data transmissions by combining packets using simple XOR operations. The coding decision takes into account that a maximum number of nodes have to be able to decode the outgoing coded packet.

A. CoZi Queuing System

As depicted in Figure 3 our scheduling system requires an overhearing queue (Q_{ovh}) in addition to the input queue (Q_{in}). While Q_{ovh} contains only overheard packets, Q_{in} can include packets in transit from other nodes or new packets from the node itself. Overheard packets are stored within a buffer for a period of time during which they will be used to decode incoming coded packets. Algorithm 1 describes the node functioning when a packet is received or overheard. It shows that whenever an intermediate node A receives a new packet p from its neighborhood, A checks whether p is non-coded, in which case A acknowledges the reception of p if it is destined to him, or stores p in its overhearing queue $Q_{ovh}(A)$ otherwise. In the case where p is coded and A succeeds to decode it using previously received packets, A either sends an ACK packet to the sender or stores p in $Q_{ovh}(A)$ depending on the destination field of the retrieved packet p_{dec}, as described from line 9 to 15 in Algorithm 1. Finally, if A is not able to decode p, it simply drops it from $Q_{in}(A)$.

Algorithm 1 Packet Reception at an Intermediate Node A

1: **for** each incoming packet p in $Q_{in}(A)$ **do**
2:     **if** p is non-coded **then**
3:         **if** p is destined to A **then**
4:             A sends an ACK to the sender
5:         **else** /* A overheard p */
6:             p is stored in $Q_{ovh}(A)$
7:         **end if**
8:     **else** /* p is coded */
9:         **if** p is decodable **then**
10:             $p_{dec} = Decode(p)$
11:             **if** p_{dec} is destined to A **then**
12:                 A sends an ACK to the sender
13:             **else** /* A overheard p */
14:                 p_{dec} is stored in $Q_{ovh}(A)$
15:             **end if**
16:         **else** /* p is not decodable */
17:             p is dropped from $Q_{in}(A)$
18:         **end if**
19:     **end if**
20: **end for**

The careful reader might wonder about the potential memory overhead induced by keeping overheard packets at each node and the additional computation delay due to coding operations. In fact, both the delay and the memory requirements for ensuring one-hop coding are negligible. Indeed, to save 117 overheard packets, which is equivalent to a 500ms bufferization period, in an 802.15.4 channel with a capacity of 250 kb/s, the total amount of required memory is less than 15 kilobytes. This is largely available in most ZigBee compliant devices. Concerning the computation overhead, since network coding consists only on atomic bitwise XOR operations, it does not alter the computation time.

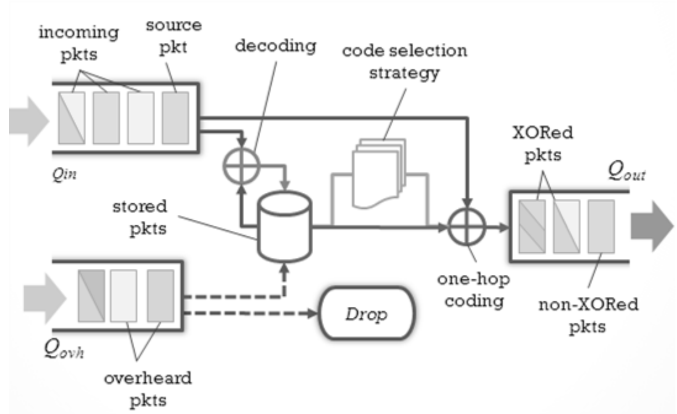

Fig. 3 – CoZi queuing system illustration

B. Topology Inferring

As detailed in [10], in one-hop coding, when a node A sends a coded packet p to the node B, A has to be sure that B will be able to decode it in our case. This can be done only if A guesses what B has already received and overheard from its neighbors. To do so, as stated in section III, our algorithm goes through a learning phase as the ZigBee network is constructed. During this period, the coordinator and the routers build decoding tables based on packets received from

[2] Overhearing can be easily implemented for 802.15.4 networks by activating the promiscuous mode in every node. We used the same procedure as the one proposed in [11] by Katti *et al.* for the IEEE 802.11 MAC.

their children that contain the list of the overheard links for every device. For example, consider the device number 18 in Figure 1. At the end of its association with the router R_8, 18 knows that he can overhear packets transmitted from the routers R_1, R_7 and from the devices $17, 19$ and 23 thanks to the signalization messages that have been exchanged since the initialization of the network. Node 18 will then send to R_8 a special packet with the addresses of R_1, $R_7, 17, 19$ and 23' indicating that it can overhear their packets. Note that this operation takes place only after the nodes' association with their parents, and thus does not imply a large overhead on the network traffic.

C. Packet Encoding

Knowing that intermediate nodes in the network are necessarily routers or the coordinator since ZigBee is based on a cluster-tree topology, we assume that network coding decisions are exclusively performed at intermediate nodes before any transmission.

Let us consider a node A that receives N packets in $Q_{in}(A)$ from its neighborhood and has to forward them to M other nodes. Whenever a packet p from $Q_{in}(A)$ has to be transmitted to its next-hop B, the node A chooses from $Q_{in}(A)$ depending on the coding strategy, packets that are supposed to be already overheard or received by B (side-packets) and XORs them with p into one coded packet that will be encapsulated in a special 802.15.4 CoZi frame (cf. Figure 4). The side-packets' identifiers are then listed into the special MAC footer field to allow packet decoding (c Figure 4). This operation will allow neighboring nodes to receive new packets without any additional transmissions. Note that the size of the coded packets identifiers field is at most equivalent to MCP (Maximum Coded Packets) which represents the maximum number of packet that a node can XOR together.

D. Packet Decoding

When a node A receives or overhears a coded packet p, it checks the *coded packet IDs field* of its containing frame to verify if it has already all the corresponding packets to decode it in $Q_{\text{ovh}}(A)$ and $Q_{\text{in}}(A)$. If it is the case, the node XORs p with all the corresponding packets to retrieve the original p_{dec}. After this operation, A verifies the *destination address field* of the decoded packet (cf. Figure 5). If it is destined to him, A sends an ACK message[3] to acknowledge the decoding and the reception of p_{dec}. If because of a link failure A happens not to have overheard a packet necessary to decode p and p is destined to him, the decoding operation will obviously fail and a retransmission of p_{dec} might be needed potentially encoded with a new set of packets.

E. Coding Strategies

Data-delivery schemes can notably vary depending on the application, the environment and the characteristics of the network, particularly in wireless sensor networks. In this work, we propose two code selection mechanisms for CoZi in order to take advantage of routing-based and dissemination-based ZigBee sensor network and thus ensure better bandwidth utilization.

[3] We make use of the asynchronous ACK mechanism proposed in [11].

Coded Packet

2	1	4 to 20	(102 to 118) - *MCP*	*MCP*	2
Frame control	Sequence Number	Addressing Fields	Data Payload	Coded Packet IDs	FCS
	MAC Fields			MAC Fields	
MAC Header			MAC Payload	MAC Footer	

Fig. 4 – CoZi data-frame and coded ZigBee packet scheme

2	2	2	1	1	(94 to 110) - MCP
Frame control	Destination Address	Source Address	Radius	Sequence Number	Packet Payload
	Routing Fields				
NWK Header					NWK Payload

Fig. 5 – CoZi ZigBee decoded packet

1) *CoZi for dissemination-based WSNs:* In a dissemination-based scenario, data packets have to be transmitted from one source node to the entire network. In this case, our code selection mechanism chooses between all the packets in $Q_{in}(A)$ so that a maximum of neighbor nodes can decode the coded packet regardless of the packet order in the queue.

2) *CoZi for routing-based WSNs:* In a routed WSN, data packets are sent from one source to a destination both designated by their network addresses. In such a scenario, intermediate nodes have to encode a packet so that the next-hop is assured to decode it. The set of coding opportunities in this case is more restricted than in a dissemination scheme.

For the sake of clarity and to illustrate our code selection mechanism, we consider a canonical example of four nodes A, B, C, D with the following queues configuration:

$$\mathrm{Q_{in}}(A) = \{p_1, p_2, p_3, p_4\}$$
$$\mathrm{Q_{ovh}}(B) = \{p_1, p_4\}$$
$$\mathrm{Q_{ovh}}(C) = \{p_1\}$$
$$\mathrm{Q_{ovh}}(D) = \{p_3\}$$

In a dissemination based network where the information has to be transmitted from A to a maximum number of nodes, it is more efficient to transmit p, with $p = p_3 \oplus p_1$, rather than p' for instance (with $p' = p_1 \oplus p_2$). Indeed, by sending p, A allows B, C and D to decode p (B, C can retrieve p_3, and D retrieves p_1) while by sending p' only B and C can decode it.

On the other hand, if we consider a routing-based network, our algorithm will be constrained by the fact that the destination has to be able to decode the packet. For example, if A has to transmit p_2 to C, the CoZi has to guarantee that C will be able to retrieve p_2. Thus, the selected code will be $p"$ instead of p, with $p" = p_1 \oplus p_2$. Note that in this case, only B and C are able to decode $p"$, since D does not have neither p_1 nor p_2 to perform the decoding.

V. Performance Evaluation

In this section, we evaluate the performance of CoZi in different data-delivery scenarios with two different network densities to quantify the network throughput, the data transmission reliability and the end-to-end delay. Then, we compare the results with the classical ZigBee routing.

A. Simulation environment

We use the Qualnet 4.5 simulation environment [7] to assess our solution, where the ZigBee and 802.15.4 protocols are fully implemented. We consider 50 and 100 nodes uniformly placed in a $100m \times 100m$ square area. The coordinator is placed in the center of the network and the rest of the nodes are either routers or end-devices. To implement CoZi, we modified the packet scheduling module of ZigBee and added our specific control and data frames to the 802.15.4 MAC of the simulation platform. Moreover, we developed an extension feature for Qualnet that picks randomly sources and destinations for end-to-end CBR (constant bit-rate) communications. The complete simulation attributes are presented in Table 1.

TABLE I – SIMULATION SETTINGS

Simulation time	600 s
Mobility model	*None*
Routing protocol	ZigBee cluster-tree
MAC protocol	802.15.4
Reflection model	Two-ray ground
Propagation model	Lognormal shadowing
Capacityy	250 $kbps$
Trans. rang.	$\sim$35 m
MCP (Maximum number of coded packets)	5
Overhearing buffering period	500ms
Packet size	116 Bytes
Promiscuous mode	Activated
Traffic nature	Constant Bit-Rate
Beacon Order (BO)	15
Super Frame Order (SO)	15
Number of router	80%
Number of end-devices	19%
Beacon mode	Disabled

B. Throughput

First, we compute the throughput versus the traffic load for the network with 50 and 100 nodes. Figure 6 shows that the achieved throughput remains stable (80-95%) using CoZi, while it drastically decreases when ZigBee routing is used, confirming that CoZi enhances significantly the network throughput in a routed data-delivery scenario, especially at high traffic loads where coding opportunities are more frequent.

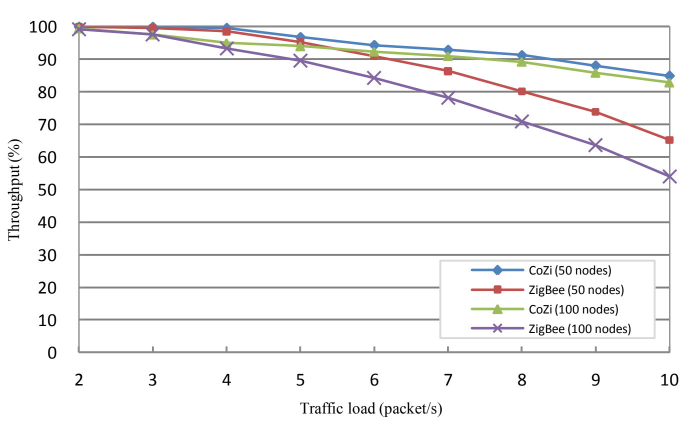

Fig. 6 – Throughput versus traffic load with various nodes densities

C. Convergence Time

The throughput is also improved in the dissemination-based scenario, reducing considerably the convergence time of the data-propagation. In fact, we can see from Figure 7 that the throughput in this case is slightly higher than in the routing scenario due to the larger coding possibilities inherent to dissemination-based networks as discussed in section IV.E. Moreover, we notice that the coding efficiency increases as the density of the network grows in both scenarios, i.e., when nodes overhears more packets within their neighborhood.

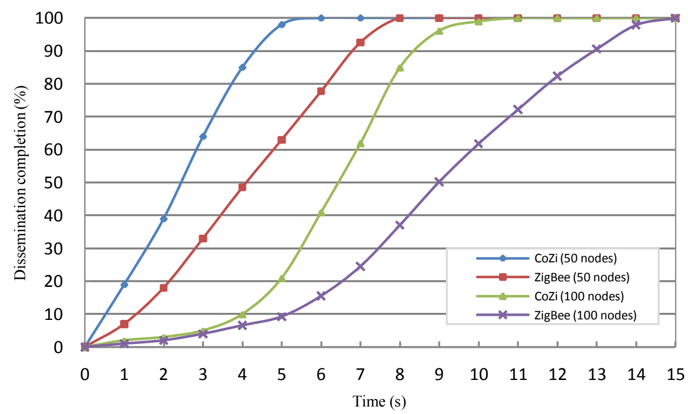

Fig. 7 – Data-delivery completion ratio versus time

D. Delay

To assess the end-to-end delay of communications, a constant traffic load of 8 packets per second is applied to routes between randomly selected end-devices across the network. We assume each router has to forward packets to their destinations using routes with a definite path length. Then, we compute the average latency of each end-to-end communications. The result of the experiment is plotted in Figure 8 (the number of nodes in this case is 100) and confirms the benefit of using CoZi for delay constrained applications. Indeed, thanks to overhearing and one-hop coding, nodes can receive packets sooner than in a ZigBee classical routing, which shortens certain routes and thus provides a substantial reduction of the latency within the network. We can conclude from these experiments that CoZi can be very efficient and convenient for large scale, relatively dense and delay constrained ZigBee-based sensor networks.

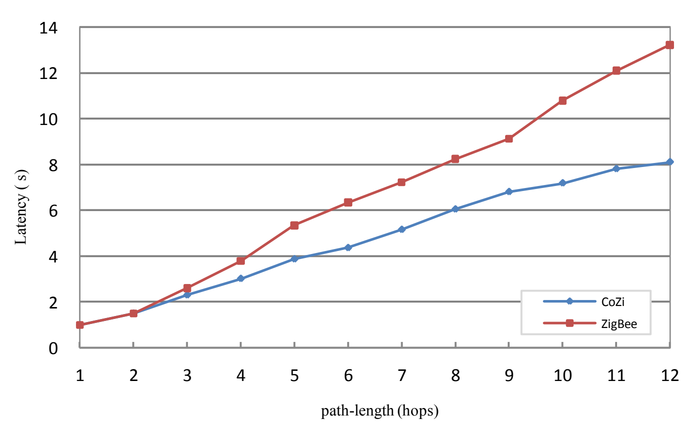

Fig. 8 – Latency versus path-length

VI. Conclusion & Future Work

Nodes in ZigBee sensor networks do not exploit the shared nature of the wireless medium, whether for routing or dissemination data-delivery schemes. This paper presents CoZi, a distributed packet scheduling based on simple network coding at intermediate nodes to offer better bandwidth utilization and more reliable communications with extremely negligible network overhead. Using clever topology inferring from ZigBee signalization messages, our solution helps to perform more optimized coding decisions in order to allow a larger range of decoding nodes whether for routed or dissemination based ZigBee sensor networks. Simulation results show that by using our enhancements, the network throughput and reliability are improved and the end-to-end delay reduced.

Other issues of interest have emerged while working on this solution. In fact, our future work will extend CoZi to include sleep-awake mechanisms for better energy efficiency and will focus on the implementation of our extension in an experimental ZigBee-based WSN platform.

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