Combining LT codes and XOR network coding for reliable and energy efficient transmissions in wireless sensor networks

Anya Apavatjrut
Computer Engineering
Chiang Mai University
50200, Chiang Mai, Thailand
Email: anya@eng.cmu.ac.th

Katia Jaffrès-Runser,
Université de Toulouse
IRIT ENSEEIHT
31061, Toulouse, France
Email: kjr@enseeiht.fr

Claire Goursaud and Jean-Marie Gorce
Université de Lyon, INRIA,
INSA-Lyon, CITI
F-69621, Villeurbanne, France
Email: surname.name@inria.fr

***Abstract*—This paper tackles the problem of providing end to end reliable transmissions in a randomly deployed wireless sensor network. To this aim, we investigate the simultaneous use of gradient broadcast routing (for its inherent adaptability to any network topology and its changes), fountain codes (for their universal property) and intra-flow network coding (to introduce packet diversity in redundant copies).**

We present the impact of the proposed XLT-GRAB strategy on a realistic network. This work permits to highlight that, compared to basic gradient broadcast routing, the strategy not only improves the reliability and the delay in the network but also clearly increases its lifetime.

I. INTRODUCTION

The topic of reliable transmission of sensed data across large-scale wireless sensor networks (WSN) has triggered a lot of effort in current research projects. Recent technologies offer low-cost and low-power chips that can be deployed for monitoring purposes in open fields. When a node senses some change in the environment, it advertises its data to one or several sink nodes. Due to the large scale of such networks, the transmission is multi-hop between the data source node and the sink. For some applications, the network must provide reliable end-to-end transmissions, meaning that the probability of one emitted packet to arrive at the sink must be equal or as close as possible to one. Reaching high reliability is getting challenging when nodes are deployed in environments with severe operational conditions (e.g. high temperature, fire, humidity...). In such conditions, nodes are prone to an increased number of failures and wireless transmission becomes less reliable.

A first mean to increase reliability is to introduce redundancy through *path diversity*. Indeed, multi-path routing outperforms single path approaches such as Directed Diffusion [11] under severe working conditions : since single-path approaches see their source-sink path often break, more flooding stages for route discovery are necessary. In multi-path routing, several copies of a *same* packet travel on multiple paths in parallel. With such option, more copies are sent through the network, increasing transmission reliability at the price of an increase in energy expenditure for redundant transmissions. Thus, there is a trade-off between the desired level of reliability and the life duration of the network.

Multi-path routing solutions divide into two classes. In the first class, the algorithm constructs à priori several disjoint routes that are maintained either with 'keep alive' packets [10] or by alternatively sending the data in a round robin manner on each path to reduce the route maintenance load [4]. The other class of algorithms is known as *gradient broadcast algorithms* (cf. [8], [12], [13], [27]). These algorithms do not set the routes à priori but allow several nodes at a time to forward a same packet *in broadcast* based on pre-defined set of forwarding rules. A cost field is set in an initialization stage where all nodes of the network get assigned a cost proportional to their distance to the sink. These algorithms have mainly been designed for severe operational conditions. Nodes are able to adjust locally to instantaneous changes in the network topology (node failure) or link quality (link failure). Thus, they are more flexible than the previous class of algorithms. However, this comes at the cost of an increased number of copies traveling in the network. Different forwarding policies have been considered to improve the energy reliability trade-off, adjusting the node's behavior for instance to the level of interference [12] or congestion [13] perceived.

A second mean to reach perfect reliability is to add a *coding layer* on top of the routing algorithm. In this case, each message m is encoded using a specific coding algorithm which adds redundancy to m to compensate for the losses in the network and still retrieve m at the sink. Widely used codes are based on Reed-Solomon or LDPC codes. An efficient design for such codes necessitates the knowledge of the losses incurred by the network. As such, these codes are usually implemented using Hybrid Automatic Repeat Request (HARQ) protocols where a forward error correction code in addition to an error detection code is appended to the transmitted packet. If complete packet recovery is not possible knowing the error correction code, an acknowledged is sent to retrieve the information missing to decode the original packet. Such a coding strategy is complementary to single-path routing protocols where packets can be acknowledged hop by hop along a pre-defined path. However, in highly versatile networks, implementing such coding still incurs an important overhead of control packets.

Fountain codes are a promising coding solution to guaranty reliability [2], [5], [7], [17]. Indeed, they are *rateless*, *i.e.* a source $\mathcal{S}$ can potentially generate a limitless number of encoded packets until it receives an acknowledgement from $\mathcal{D}$. They can adapt to the channel condition on the fly. Another advantage of fountain codes over schemes such as HARQ is the limited use of the feedback path: $\mathcal{D}$ only acknowledges end to end a successful decoding to $\mathcal{S}$ instead of hop by hop. As discussed in our previous work [3], LT codes are particularly suited for data dissemination in wireless sensor networks. It can be implemented over a single path routing algorithm as discussed in [3], [2] but we claim in this paper that fountain codes naturally provide a good solution for improving the reliability of gradient broadcast data dissemination as well. Contrary to single path routing, it is complex to implement a hop-by-hop acknowledgement for multi-hop broadcast transmissions as required by HARQ techniques. Fountain codes only require an end-to-end acknowledgement which can simply be broadcasted by the sink after m is decoded. To further reduce the control overhead, this acknowledgement can be merged with the gradient cost field maintenance packets of the protocol.

Adding fountain codes to a gradient broadcast algorithm provides perfect reliability as we will show in the first part of this paper. However, even though there is very little control overhead with this solution, the drawback is that lots of redundant packets travel in the network. The main contribution of this paper is to show that it is possible to leverage these copies through network coding. With network coding, relays re-combine the received packet along the multi-hop diffusion. This technique introduces diversity in the variety of packets present in the network and consequently reduces the number of redundant copies received at the sink. We refer to *packet diversity* to designate this type of diversity. Of course all packets received are not linearly independent, but some provide additional information for decoding, reducing the time needed to decode a message. We show in a simulation study how our implementation of a XOR network coding solution over an LT-code [2] performs over a simple gradient broadcast algorithm: reliability is maintained at a reduced energy and delay cost.

Section II concentrates on reaching reliable transmissions combining gradient broadcast and fountain codes. The next Section III focuses on the addition of XOR network coding in the data dissemination with the description of XLT-GRAB. Then, Section IV highlights the main achievements of the proposed strategy and finally section V concludes the paper.

II. REACHING RELIABILITY

A. Gradient broadcast routing

All transmissions in gradient broadcast routing are performed in a broadcast mode and any relay hearing a packet has to decide whether it can forward it or not. In order to push the packets towards the sink, only relays located closer to the sink than the previous hop relay are allowed to forward packets. The basic algorithm is composed of two stages:

a) Cost field setup: In this initialization step, the nodes distributively build the gradient cost field. In this paper, we use the implementation proposed by Ye et al. [26]. Here, flooding is initiated by the sink sending an advertisement (ADV) packet containing its own cost ($Q = 0$ for instance). All the other nodes have an initial cost $Q = +\infty$. A node A with cost Q_A that receives an ADV packet with packet cost Q_p updates its own cost if $Q_p + L < Q_A$, L being the link cost. If this condition is met, the new cost Q_A is set to $Q_p + L$ and a new ADV packet is sent with a new packet cost $Q_p = Q_A$. To reduce the flooding load, a back-off timer proportional to Q_A is decremented before sending the ADV packet. Consequently, the node with the lowest value of Q_A sends its packet first, acting as an implicit acknowledgement that prevents other nodes with higher costs from forwarding their ADV packet. With this algorithm, only one ADV packet per node is sent in the cost field setup stage. The link cost value can be expressed in various metrics (in hops, in meters, etc..). In this work, we consider a simple euclidian distance metric.

b) Forwarding stage: Once a sensor S has a packet to send to the sink, it appends its own cost Q_s to the packet and broadcasts it. All nodes receiving it decide to forward it if and only if their own cost Q_i is lower than Q_s.

This algorithm is particularly reliable compared to single path routing, has very low control overhead but at the price of a very high packet redundancy. Following works have concentrated on creating additional forwarding rules to improve the tradeoff between reliability and energy consumption [12], [13], [27]. In this paper, we use the basic algorithm and control the amount of redundancy by introducing a *forwarding probability* p_f. If the sensor is allowed to forward a packet based on its cost, it will do it with probability p_f. This probability is the same for all sensors in the network. More elaborated local optimization schemes of p_f can be found in [12], [13].

B. Through coding: LT codes

The concept of fountain codes was first presented by Byers et al in 1998 [5]. The most interesting benefit of fountain code is that transmission reliability can be assured without requiring channel state information. These codes provide both rate-less and universal property as it requires minimum transmissions to cope with error rate probability of the any type of channel. This induces higher performance in terms of energy and transmission time especially when losses persist in the transmission channel [18].

Fountain codes can be categorized, based on their encoding/decoding techniques, into several categories. We note, for example, Random Linear fountain codes, LT code [17], Raptor code [22], etc. Among these categories, Random Linear fountain codes provide the best code rate but at the cost of high computational complexity at the decoding. LT codes and Raptor codes are more lightweight and asymptotically optimal at a more reasonable cost. In this work, we consider an LT code because of its lower decoding complexity which

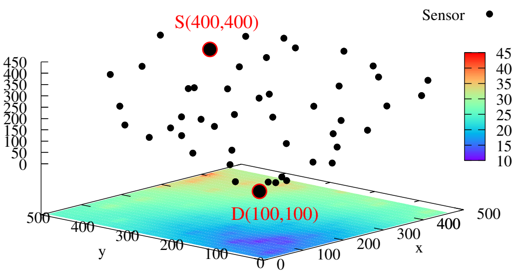

Fig. 1. Positions and costs of sensor nodes based on gradient broadcast routing

Layer	Configurations
Networking	MAC protocol: Unslotted IEEE 802.15.4 CSMA/CA Transmission period of source = 1s Coding: LT code K=100, $\delta = 0.5$, $c = 0.03$ PDU size = 128bytes
Radio	Radio device: Chipset CC1100 Modulation: BPSK, Frequency = 868MHz Transmitted power = 10dBm Transmission rate = 20Kbit/s
Propagation	Propagation model : pathloss, Rayleigh fading Pathloss exponent α = 2 White noise = -111dBm/Hz

TABLE I
SIMULATION PARAMETERS.

better suits the limited computing capabilities of sensors. The message *m* is divided into *K* fragments. These are randomly combined (XOR addition) such that the degree distribution follows the Robust Soliton Distribution defined in [17]

For a more detailed description of LT codes, we refer the reader to [17].

In the context of wireless sensor networking, most significant works using Fountain codes propose a data dissemination protocol for sensor reprogramming [21], [20]. The programs are split into R blocks, each block being encoded with a digital fountain code whose distribution is optimized using a genetic optimization algorithm. Dissemination in the multi-hop network of each block is performed hop-by-hop using an ADV/REQ/DATA communication paradygm.

C. Combining LT codes and gradient broadcasting

In this section, we study the benefits of using LT codes over a gradient broadcast routing algorithm. This algorithm provides high flexibility, but provides a limited reliability due to collisions or interference on the wireless channel [12], [13]. The use of LT should ensure a perfect reception of the original message m. Indeed, it was shown that fountain codes demonstrate high efficiency in terms of error probability in the case of cooperative communication in relay channels [6], [16], [18]. Besides, it has been recently proven in [19] that transmission with fountain codes called *Fountain-Coding-and-Forward* is more efficient than traditional relaying strategies.

We present here a preliminary study on a given network topology. To this aim, we have considered a wireless sensor network composed of a total of 50 nodes spatially distributed following a Poisson distribution in a 2 dimensional space of 500m×500m. Average node degree is of about three. A source S is located at coordinate (100,100) and the destination D at coordinate (400,400). The source first encodes the information with LT codes before broadcasting the encoded message. The message propagates in a relaying mesh from S to D following the gradient broadcast routing defined earlier. Fig. 1 illustrates our network of interest together with the costs of the nodes.

The following simulation results are obtained using WSNet event-driven simulator [24]. The MAC protocol considered follows the IEEE 802.15.4 standard where channel access is controlled by an unslotted CSMA/CA. At the physical layer, parameters from the TI CC1100 chipset are implemented. In this simulation, we assume a perfect feedback mechanism meaning that all acknowledgements encounter no loss during the transmission. Simulation parameters are given in Table I.

Fig. 2 illustrates the gain in reliability due to LT codes as a function of the forwarding probability. In the simulations, a message is decomposed into K fragments. In the LT-code simulation, the source creates a limitless flow of encoded packets. The reliability is evaluated with the message success rate. For the LT-coding case, the message success rate is either one or zero, depending if the sink has been able to decoded the message or not. For the no LT-coding case, the source sends directly the K packets. In this case, the message success rate is measured by the ratio between the correctly received packets to the number of packets originally sent (i.e. K). Results are averaged over 1000 subsequent transmissions. The results in this figure are regressed with linear bezier approximation.

We can first point out that, even if LT codes should ensure perfectly reliable transmissions, we do not always obtain a success rate equal to 1. This is due to the fact that, for bad transmission conditions, nodes can keep trying (unsuccessfully) to relay the new packets of the source. Of course, in practice, this can be avoided by limiting the number of transmissions of the source. However, we did not implement this solution in our simulations in order not to bias our results.

LT codes show a higher success rate on average for the same forwarding probabilities compared to the no coding case.

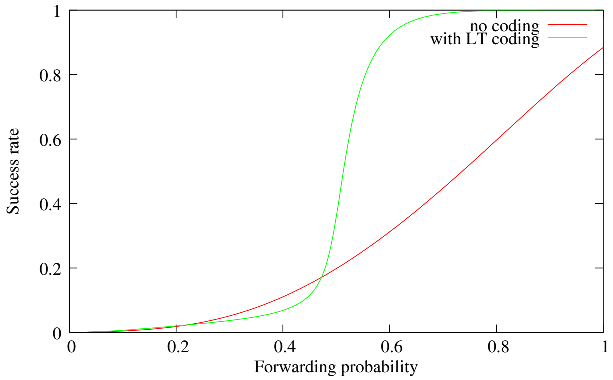

Fig. 2. Success rate as a function of the forwarding probability with and without LT codes over a gradient broadcast routing.

However, what is not shown in these results is the additional coding overhead of LT codes and the fact that a substantial amount of copies arrive at the sink node. Thus, the price to pay for reliability is a reduced network lifetime. The aim of the rest of the paper is to propose a solution to keep the same level of reliability at a reduced energy cost.

III. IMPROVING ENERGY WITH NETWORK CODING

A. *XOR network coding heuristic*

The term *network coding* has been first proposed by Ahlswede et al. in [1] in order to improve the transmission rate in a multicast scenario, which has been confirmed by subsequent studies [15], [14]. Transmission with network coding is also more scalable and can lead to the optimization of complexity, throughput, transmission delay and security. In opportunistic transmissions, packets received at the destination are usually redundant as the same packets are broadcast by several relay nodes and travel through multi-path propagation. It has been shown that if the relays can process information along the line, system capacity can be achieved [9].

We are particularly interested in this paper in applying *intra-flow* network coding to fountain encoded packets. In this case, network coding can play an efficient role to optimize the redundancy. For instance, in [25], two users exchange information before sending mutual encoded information towards the destination which results in a certain gain in redundancy. In our previous work [2], we have shown as well that network coding applied to an LT encoded flow of packets is beneficial in terms of energy expenditure and delay for a multi-hop *linear* network. However, to achieve such benefits, specific network codes have to be designed to maintain the degree distribution of LT coded packets at the sink [2], [7]. In the proposed algorithm, the degree d^* of the packet to be created at the relay node is chosen with respect to the Robust Soliton distribution [17]. Buffered packets are then randomly selected and XOR-ed together until degree d^* is obtained or a $MAXROUND$ value is reached. Since creating lower degree packets (e.g. degree 1 and 2) is not easily feasible with the previous algorithm, if $d^* \in \{1,2\}$ then a combination is only performed with probability $p = 0.2$ to preserve the Robust Soliton distribution.

In this paper, we investigate the efficiency of the network code defined in Algorithm 2 of [2] for data dissemination in a two-dimensional sensor network based on a gradient broadcasting scheme.

B. *XLT-GRAB*

Gradient broadcast routing inherently generates redundancy which is beneficial to the reliability of the transmission in severe working conditions. However, these multiple copies drain energy from the sensors and it is not easy to find the optimal trade-off between reliability and redundancy. Instead, we propose to take advantage of redundant packets through network coding by defining the XLT-GRAB algorithm. The XLT-GRAB combines the adaptability of gradient broadcast routing, the reliability of LT codes and the packet diversity introduced by network coding. Tong et al. [23] proposed as well to introduce intra-flow network coding using higher field sizes to gradient broadcasting schemes, however, their can not achieve the perfect reliability of LT-codes considered in this work.

XLT-GRAB uses the cost setup stage of [26]. It differs from previous approaches by the following points:

- the source sends each message m using an LT-code. In the following, we use $K = 100$ because packets are smaller in wireless sensor networks than in other types of applications. The sink acknowledges each message after successfully decoding it using an ADV message. This ADV message serves two purposes, namely acknowledging m and updating the costs to account for topology changes in the network. The source keeps transmitting coded packets until an acknowledgement is received.
- a relay node forwards a packet based on a pre-defined forwarding probability p_f as presented in Section II if it is located closer to the sink than the previous hop relay.
- a relay decides with a given *XORing probability* p_{xor} to apply network coding using Algorithm 2 of [2] to forward a network coded packet instead of the received one.

	p_f	p_{xor}
Increase	Improved reliability	Increased diversity
Decrease	Improved energy	Improved decoding efficiency

TABLE II
IMPACT OF p_f AND p_{xor} ON TRANSMISSION

A big picture of the effect of both p_f and p_{xor} parameters is given in Table II. In this study, we investigate the combined impact of both parameters on the transmission efficiency since their independent optimization would lead to suboptimal configurations.

IV. PERFORMANCE RESULTS

The pre-defined forwarding and XORing probabilities are varied to show the impact of redundancy and network coding on the following end-to-end performance metrics:

- the redundancy defined as the average number of identical (coded) packets received at the sink,
- the success ratio defined as the ratio between the number of correctly received messages to the number of transmitted messages,
- the end-to-end message transmission delay in seconds,
- the total energy consumed by all nodes of the network for emission and reception actions.

Performance results are averaged over 50 consecutive message transmissions, each message encoded with an LT code. We have first evaluated the impact of p_f and p_{xor} on the number of duplicated packets in Fig. 3. We present the results for different values of the XORing probability p_{xor}, $p_{xor} = 0$ corresponding to the non XORing case, and $p_{xor} = 1$ corresponding to the systematic XORing case. As expected, redundancy increases with the forwarding probability and decreases with the XORing probability as more diverse encoded packets are created through network coding.

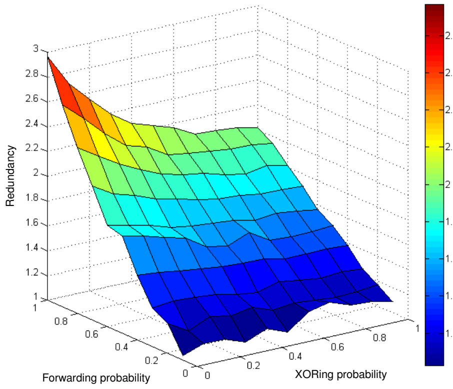

Fig. 3. Packet redundancy as a function of p_f and p_{xor}.

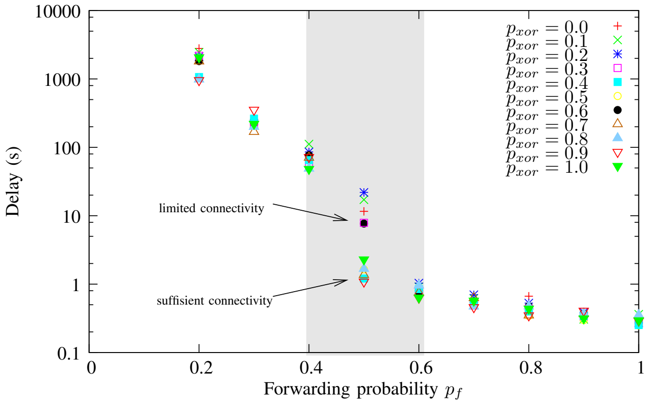

Fig. 5. End to end transmission delay.

Second, we have evaluated the success rate as a function of p_f and p_{xor}. Three regions of interest have been identified :

- for a low forwarding probability ($p_f < 0.4$), the network is not reliable at all for whichever XORing probability. Indeed, the destination receives very few packets with almost no redundancy among them. Thus, the XORing brings no further diversity in this case. The very poor performance is due to low connectivity,
- on the contrary, when the forwarding probability is high ($p_f > 0.6$), the network is reliable for whichever XORing probability. Indeed, the network is fully connected (all nodes have in average three neighbor nodes), and coding is useless.
- in between, ($0.4 < p_f < 0.6$), there is a transitory area, which is represented in Fig. 4. We can observe that the no XORing case is the worse, and that we get the best results for $p_{xor} = 1$. Thus XORing allows us to take advantage of all received packets at the sink, increasing about four times the success rate.

Fig. 5, which presents the end-to-end delay, gives results compliant with Fig. 4. Indeed, we can observe the same regions: for small p_f, the lack of connectivity induces high latency, while for the reliable network part, the delay converges to a lower value. However, it can be pointed out that in the transitory area, delay can be divided up to 10 times when using systematic XORing compared to the non XORing case.

The energy related results are provided in Figure 6. The same regions can be defined on this plot as previously. As soon as connectivity becomes sufficient, energy depletes by a factor of 10. Before connectivity is reached, the main energy consumption factor is due to the additional packets being sent by the network to compensate for the highly unreliable multi-hop transmissions. Once connectivity is reached (i.e. for $p_f > 0.6$), the energy increases again but more slowly because additional redundancy is introduced in the forwarding process, which positively impacts the delay on Fig. 5. Minimal energy consumption is obtained for $p_f = 0.6$, for all values of p_{xor}.

The effect of XOR network coding on highly and lowly connected networks is negligible. What is really interesting is that in the transitory area, diversity brought by the XORing permits to significantly reduce the energy consumption: for $p_f = 0.5$, up to eight times less energy is needed using our XOR network coding algorithm of [2]. And it concurrently increases reliability and reduces transmission delay.

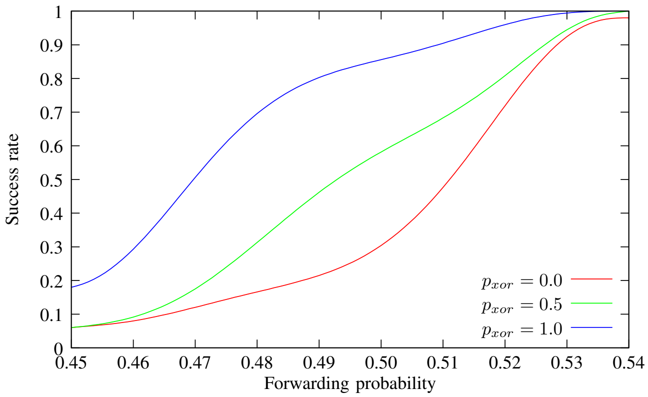

Fig. 4. Message success rate in the transitory area.

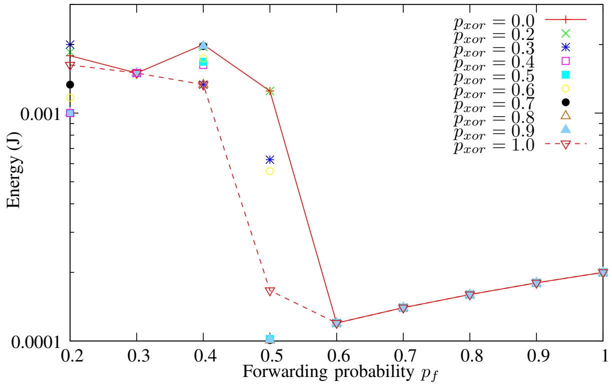

Fig. 6. Energy consumption.

		$p_f = 0.6$	$p_f = 1$
$E_{ini} = 0.6$	$p_{xor} = 0$	4.44E+4 s. / 3	3.94E+4 s. / 3
	$p_{xor} = 1$	5.09E+4 s. / 4	3.85E+4 s. / 3
$E_{ini} = 1$	$p_{xor} = 0$	9.25E+4 s. / 6	8.79E+4 s. / 6
	$p_{xor} = 1$	9.44E+4 s. / 6	7.78E+4 s. / 5

TABLE III
AVERAGE LIFETIME AND NUMBER OF MESSAGES DECODED FOR A FIXED INITIAL ENERGY OF 0.6 J AND 1 J.

Thereby, we can conclude that the use of intra-flow network coding is neutral for fully connected networks, but reduces the negative impact of reduced connectivity, hence increasing network lifetime as shown in Table III. In this table, an unlimited sequence of messages encoded with LT code ($K = 100$) is sent by the source and the initial energy of the sensors is fixed to 0.6 J. The transmission ends when the network is completely disconnected. Table III reports the average lifetime of the relaying sensors and the number of messages successfully decoded. The impact of p_f and p_{xor} is investigated. As shown earlier, $p_f = 0.6$ minimizes energy consumption and greatly improves network lifetime. For the case where $p_f = 1$, network coding reduces lifetime because less redundant packets can be disregarded by the relays (which is in line with the results of Figure 6). Most important is the impact of p_{xor} on $p_f = 0.6$: the systematic XORing of packets improves of up to 15% the life duration of the network compared to the no-xoring scenario with $p_f = 0.6$.

V. CONCLUSION

This paper studies the benefits for including intra-flow network coding into a classical gradient broadcast routing. This strategy is coupled to LT fountain codes at the source to ensure reliability in the transmissions. First results on the considered topology confirm that gradient broadcasting combined with LT codes ensure reliable transmissions while intra-flow network coding increases network lifetime by introducing packet diversity. Next, scenarios where multiple flows share the network will be studied. Main challenge will be to efficiently design inter-flow network coding for LT codes.

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