Packet Error Recovery via Multipath Routing and Reed-Solomon Codes in Underwater Networks

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Abstract—Channel variability and a high level of noise lead to a significant probability of packet loss in many underwater networks. Techniques based on packet-level Forward Error Correction (FEC), such as Reed Solomon (RS) codes, can be used to offer an effective protection against excessive packet losses that would be generated by noise. In this paper, we propose a new error recovery scheme based on RS codes to be used in conjunction with multipath routing. We discuss several routing policies to take advantage of the inherent redundancy of multipath routing coupled with a suitable RS code. We evaluate the performance of these policies through simulation and compare them with the Multi-Sink Routing Protocol (MSRP). Results show that our policies outperform MSRP in term of packet delivery ratio (PDR), and that our solution strikes a balance between the achieved PDR and the overhead introduced by packet replication.

Index Terms—Underwater communications, multipath routing, Forward Error Correction, Reed-Solomon codes.

I. INTRODUCTION

The interest in Underwater Sensor Networks (UWSNs) has recently increased due to the possibility of using Autonomous Underwater Vehicles (AUVs) and sensors to explore the oceans and monitor underwater equipment. A UWSN consists of a certain number of sensors and vehicles interacting to perform collaborative tasks such as target detection and tactical surveillance. In these applications, there is the need to establish wireless acoustic communications such that a sufficient large area can be monitored with a limited number of nodes. Such communications, along with suitable networking protocols, should be able to overcome the multiple limitations of underwater channels and scenarios (i.e., limited bandwidth, long propagation delay, low throughput, high bit error rates and temporary loss of connectivity due to the time-varying channel and noise) [1]. In order to enable point-to-point communications over distances of up to a few km, the nodes may be configured to operate in the 4 to 8 kHz band [2]. However, the main drawback of this band is that it is highly affected by man made noise caused by machinery (pumps, reduction gears) or by the environment (waves, currents, etc.) [1], [3]. These effects may lead to a significant probability of losing packets during underwater transmissions, thereby reducing the reliability of UWSNs. In this paper, we consider the recovery of packet losses via a coded multipath routing scheme.

Many techniques have been proposed in the literature to combat packet losses in underwater networks. They can be classified into three categories:

(1) *Automatic Repeat reQuest (ARQ)*: require the receiver to detect packets in error and request the sender to retransmit them. This may lead to a long delay before a packet is delivered successfully due to the slow propagation that takes place in acoustic channels.

(2) *Erasure coding*: as an alternative to ARQ schemes, packet-level Forward Error Correction (FEC) has been proposed as a solution to combat packet loss in underwater networks. In packet-level FEC, source packets can be recovered at each receiving node from a subset of the encoded packets that are successfully received by that node [4]. This technique is proactive because nodes add redundant packets so that the receiver may successfully decode the original packets and thus reduce the need for retransmission.

(3) *Network coding*: nodes transmit packets which are composed partially with information originating from that node, and partially from information received from other nodes.

In this paper, we propose a new error recovery scheme relying on Reed Solomon codes (RS) [5], to be used in conjunction with multipath routing. RS codes are defined by the set of three parameters (n, k, t), k and n being the number of packets respectively before and after encoding, and $t = \frac{n-k}{2}$ the number of erroneous packets which can be recovered. RS codes are particularly useful for burst-error correction and perform well against burst noise and jamming because one of the effects of such noise is to generate errors over a contiguous set of bits which typically results in the loss of a few contiguous packets: the RS decoder can then recover the k original packets by leveraging on the redundant transmission of n packets.

The rest of this paper is organized as follows. In Section II, we review the main related work on packet error recovery in underwater networks. In Section III, we describe the problem and our scenario. Section IV presents our framework based on $RS(n, k, t)$ codes. Section V presents the results of our

simulations. Finally, conclusions and future directions are discussed in Section VI.

II. RELATED WORK ON PACKET ERROR RECOVERY IN UWSNs

Several techniques have been proposed to control packet losses in underwater networks, in order to improve the robustness of the network and increase the packet delivery ratio (PDR). Among these techniques, FEC coding is expected to reduce the need for retransmissions and thereby to save energy. However, several drawbacks may occur when these techniques are applied to USWNs. For instance, in [6], [7] the authors have proposed multipath forwarding techniques which use redundant packets through multiple paths to improve the PDR. This technique can recover erroneous packets, but may not be energy efficiency because multiple copies of packets coming from multiple paths are straightforwardly re-broadcast locally, and duplicated packets are discarded at the final destination.

In [8], Ahlswede et al. have been the first to use network coding to achieve the broadcast capacity in multicast tree networks. Afterwards, Li et al. [9] investigate the possible use of linear network codes in multicast networks whereas [10] showed how to find coefficients of the linear coding and decoding functions. In [11], the authors proposed a network coding scheme for UWSNs and evaluated its performance through simulations. They have built their scheme on top of multipath instead of single-path routing, in order to take advantage of the inherent broadcast property of underwater acoustic channels. Another reason to do so is that multipath increases the collaboration among the nodes. Their results show the importance to couple network coding and routing. However, the authors in [11] do not consider the effect of heterogeneous link loss probabilities, the topology of typical underwater deployments and the simultaneous transmissions by multiple sources.

The same authors have extended their work in [12] by taking into consideration the above drawbacks. Their solution relies on efficient packet error recovery using network coding in multipath UWSNs with the objective to improve the PDR and the energy consumption. The authors considered a routing technique based on broadcasting, called Vector-Based Forwarding (VBF) [6], and compared their proposed solution to ARQ and FEC. The authors showed that the network coding based solution was able to transfer data more efficiently than all other techniques under consideration, and provided guidelines for choosing the right protocol parameters (number of generated packets and number of relays). However, the network coding solution proposed in [12] is tailored around a specific network topology and routing protocol, which makes it difficult to generalize to the problem of data transfer in a small network with high packet loss. Furthermore, in all these proposed techniques based on FEC and network coding, only the error correction function is addressed. Exploiting multipath diversity using packet coding in underwater communications remains challenging.

To address this issue, in this paper we propose a new packet error recovery scheme in multipath underwater networks using Reed-Solomon (RS) codes. The contributions of this work are to propose a modified version of a multipath Multi-Sink Routing Protocol (MSRP) presented in [2], and to couple this protocol with a packet-level FEC technique based on RS codes. We compare the performance of our solution in terms of PDR, expected delay to obtain an (uncoded) packet at the destination and duplication overhead. These metrics will be computed for different levels of noise and for different topologies, and compared against the previous version of MSRP.

III. SCENARIO AND PROBLEM STATEMENT

We assume that a UWSN, deployed in the proximity of a harbor to be surveilled, communicates with multiple surface sinks through acoustic communications. The nodes in this network are static and bottom-mounted. We consider a grid topology, where nodes are arranged in a grid over a rectangular region of 3×4 km^2. In order to better explain the type of grid scenarios considered in this paper we refer to Fig. 1. The area is divided into cells, and one node is placed uniformly at random within each cell. Two sinks are placed at the middle of the left and right sides of the grid topology. These sinks collaborate over a separate reliable channel (e.g., a radio satellite link): therefore, from the point of view of the underwater network, a packet may be routed towards either sink.

We assume that two intruders move along a straight trajectory that crosses the network. These intruders create a field of interference during their movement, as their propeller noise falls within the communications band. Each node placed in the grid, upon detecting the presence of one of the two intruders, generates a set of k packets containing movement readings, encodes them into a group of n packets via a packet RS code, and transmits them to the sinks via multipath routing (described latter in Section IV-A). In this scenario, most of the time, the channel is characterized by a poor quality, caused by noise and interference, both generated by the intruders and caused by the concurrent transmissions of different nodes. As a result, the Packet Error Rate (PER) of the acoustic links is often high. Moreover the PER can vary over time as the intruders move. To cope with these impairments, the redundancy and diversity offered by multipath routing can be exploited in order to recover the resulting packet errors.

IV. PROTOCOL DESCRIPTION

In this section, we discuss several ways to take advantage of multipath routing coupled with packet RS codes.

A. Multipath Routing Protocol

In underwater networks, multipath routing is a suitable way to enhance the robustness of communications, especially against interference. We propose a proactive routing protocol called Reed-Solomon Multi-Sink Routing Protocol (RS-MSRP), based on MSRP. For the full description of MSRP we
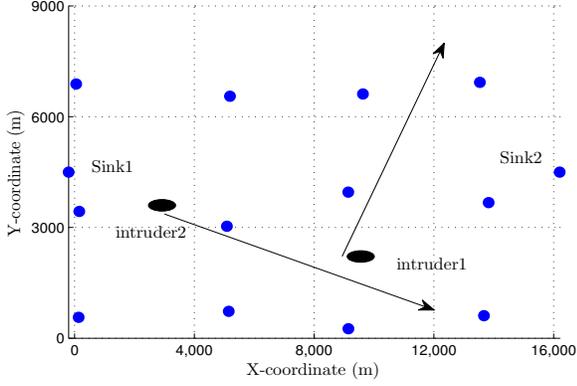
Fig. 1. Example of network realization with 12 nodes, 2 sinks and 2 intruders.

Fig. 2. Packet distribution in network A and B, where $p_A = 0.2$ and $p_B = 0.3$.

refer the reader to [2]; here, suffice it to recall that the sinks broadcast control packets containing the graph topology and the Signal-to-Noise Ratio (SNR) value experienced over each link. Each node implementing RS-MSRP receives duplicated control packets from other routes: these packets are merged to yield more complete topology information and transmitted forward. Once a source node receives an RS-MSRP control packet, it retrieves disjoint routes from the graph structure with the minimum SNR of each route. The benefit of selecting disjoint routes has been widely explained in [13]. sink. In order to guarantee that the data packets are routed along these paths, we employ source routing, which means that a complete path description to multiple sinks is included in the packet headers, and only the nodes listed there may cooperate in the routing process.

B. Error Recovery Scheme

In order to explain how data packets are grouped, encoded and transmitted from the source through disjoint routes, we first present the mechanism of recovering erroneous packets using an $\mathrm{RS}(n,k,t)$ code.

At the transmitter side, we employ an $\mathrm{RS}(n,k,t)$ code. In order to generate the RS codewords, we wait for the application layer to originate k packets, and collect them at the routing layer, where they are then encoded into n packets. This allows to leverage on the error recovery capability introduced by the RS code, at the price of a non-zero buffering delay at the transmitter. The encoded packets are sent to one or more sinks via multipath routing and collectively decoded (we assume that sinks collaborate by exchanging the received packets through a separate channel). At the decoder side, the information can be reconstructed as long as at least k out of the n packets of each group are correctly received. If the number of collected packets is less than k no group is created and thus no packet is transmitted. Assume that there are m paths available. Assume also that a packet is lost over a given path ℓ, $\ell = 1, 2, \ldots, m$ with probability p_ℓ, the Successful Recovery Rate ($rmSRR_\ell$)
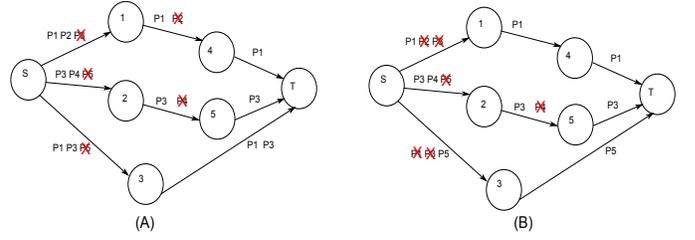
over that path can be found as:

$$\mathrm{SRR}_\ell = 1 - \sum_{i=0}^{k-1} \binom{n}{i} p_\ell^{n-i}(1-p_\ell)^i \qquad (1)$$

In case of multipath, the SRR over all the paths is given by the following equation:

$$\mathrm{SRR} = 1 - \left[\sum_{i_1=0}^{u_1} \cdots \sum_{i_m=0}^{u_m} B(v_1, i_1, p_1) \ldots B(v_m, i_m, p_m) \right], \qquad (2)$$

where

$$B(n, k, p) = \binom{n}{k} p^{n-k}(1-p)^k, \qquad (3)$$

$u_j = \min(k-1, v_j) - \sum_{t=0}^{j-1} i_t$, and v_i is the number of packets transmitted over path i. We note that for the computation of (2), the sum $i_1 + i_2 + \ldots + i_m$ of the packets recovered over all path must not exceed $k - 1$.

From (2) and (3), it can be observed that the SRR is a function both of the packet error rate (PER) over each path and of the redundancy introduced by the RS code. Thus, it is important to carefully choose how many packets should be transmitted over each path. Fig. 2 illustrates the benefit of using different packet distribution strategies at a source node. Suppose that A and B are two networks where source S uses an $\mathrm{RS}(5,3,1)$ code and transmits one group of 5 packets through 3 disjoint routes: {S-1-4-T, S-2-5-T, S-3-T}. Assume also that in network A the PER of all routes is equal to p_A (respectively, p_B in network B), and that $p_A < p_B$. We can see from Fig. 2(A) that only 2 distinct packets are received by node T, hence T is unable to recover the group of source packets. Conversely, in network B in Fig. 2(B), node T receives 3 distinct packets and can thus recover the group even if $p_B > p_A$. Hence, it is worthy to note from this illustration that the efficiency of the error recovery mechanism depends on the quality of paths and on the distribution of packets transmitted through these paths. For these reasons, we consider different packet distribution strategies for multipath routing protocol.

C. Routing Decision and Packet Assignment

With RS-MSRP, each source node transmits a group of encoded packets through different paths, and distributes the packets over the set of known paths using one of five policies, which are designed based on different routing metrics: the

minimum SNR experienced over the link of each path, the number of packets in a group for each path, the number of overlapped packets (defined as those packets that are replicated over more that one path), as well as a random packet distribution policy. These policies are presented in the following.

1) Equal distribution without overlapping: packets are distributed equally and contiguously (i.e., blocks of $\frac{n}{L}$ packets are sequentially transmitted) through L paths without replicating any packets over more than one path (no overlap). The advantage of this technique is that it causes no replication overhead, whereas its disadvantage is that the robustness against noise and interference comes only from the RS code.

2) SNR distribution without overlapping: packets are distributed contiguously but the number of packets in each path depends on the minimum SNR over that path. Call $\gamma_\ell^{\min}$ the minimum SNR across all links of path ℓ; then, $\text{int}[n\gamma_\ell^{\min}/\sum_{\ell=1}^{L}\gamma_\ell^{\min}]$ packets are transmitted over path ℓ. The advantage of this technique is that it achieves a higher PDR than the previous technique, because most packets are transmitted through better quality links. However, this also means that the use of multipath routing is limited, which may make the policy prone to losses if unpredicted interference affects the most paths carrying most packets.

3) SNR distribution with overlapping: this technique is similar to policy 2, where a fraction θ of the encoded packets is replicated over all paths and the others are divided across the paths so that most packets are sent over the most reliable path, as in policy 2. The advantage is a higher PDR than achieved by policy 2, but a replication overhead is introduced due to the transmission of some packets over more than one path.

4) Random distribution: packets in each group are transmitted by a source over every path with probability p_d. In order to control the number of transmitted packets, we choose two different probabilities, namely $p_d = 0.5$ and $p_d = 0.7$. These values have been chosen so that the expected number of packets sent by the source is never less than k in the considered network topology.

5) RS-MSRP: all encoded packets are replicated over all available paths. The advantage of RS-MSRP is that it outperforms all other techniques in terms of PDR because of the full packet replication. However, for this same reason, it is expected to be subject to the highest replication overhead.

V. SIMULATION RESULTS

In the following, we present a performance comparison for the routing policies described above. We will consider the PDR, the recovery ratio (RR), and the packet delivery and decoding delay (PDD). The RR is defined as $\text{RR} = D/(kG)$, where D is the number of packets correctly decoded by the sinks, and G is the number of transmitted sets of n packets: as each set should lead to the correct decoding of k packets, the RR is basically the ratio of all correctly decoded packets to all source packets that are actually buffered, encoded and sent. The PDD is defined as $\text{PDD}_G = T_{D_G} - T_{E_G}$, where T_{D_G} is the successful decoding time of the packets of a given group

G, and T_{E_G} is the instant of time when k distinct packets from that group G are collected at the source and encoded. Furthermore, we will consider the redundancy overhead (RO) ratio defined as the number of packets exceeding k packets per group divided by the number of received packets. The RO tells whether the redundancy introduced by the RS code is required or not, and is higher when more than k distinct packets are received to decoded a given group: in fact, the packets received after the kth are considered redundant, since they are not strictly required for the decoding process.

We assume that the nodes are placed according to the grid scenario presented in Section III, where 2 sinks and 2 intruders are used. We use an $\text{RS}(10, 6, 2)$ in all our simulations with a code rate of 0.6 and a redundancy rate of 0.4. The packets containing data are 16 Bytes long, and are generated periodically with a packet generation rate of 2 pkt/min. Such packets are small and transmitted rarely, hence the generated traffic is limited: this makes the ALOHA protocol suitable for this kind of scenario, as previously discussed in [2], [3]. All nodes transmit at the same power $P_t = 153$ dB re μPa. This value makes the grid scenario in Fig. 1 strongly connected, which creates significant interference between the multiple paths. To avoid this interference, we select two paths from the graph (one for each sink), instead of routing data towards the same destination over multiple routes. The curves are plotted as a function of the noise power, between 120 and 180 dB re μPa. We draw 2 sets of lines: the solid lines refer to the RS-MSRP, SNR with overlap and Random policies, that can lead to packet overlapping (i.e., the replication of the same packet over more than one path), whereas dashed lines refer to policies without overlapping (i.e., Equal and SNR). All simulation results are averaged over 100 network realizations, and the evaluation has been carried out using the nsMiracle simulator [14]. In order to consolidate the benefit of using our multipath routing protocols with a FEC code, we have compared the PDR, the PDD and PRO of each routing policy against the version of MSRP presented in [2].

We start from Fig. 3, which depicts the PDR of each policy. The first observation is that RS-MSRP performs better than the other policies. In fact in RS-MSRP, all packets are transmitted simultaneously over all disjoint paths achieving high robustness against losses. On the contrary, in the Equal and in the SNR policies, the packets are transmitted separately through the paths, with no replication. The random distribution policy achieves an intermediate PDR, regulated by the probability that a packet is sent over a given path, p_d. In this case, a packet may be replicated over different paths leading to a higher PDR than achieved by the Equal and SNR policies. The second observation from Fig. 3 is that when the noise power caused by the intruder is high, the SNR policy performs slightly better than the Equal policy because most of the packets are routed through the best quality links. In addition, when the intruder power is higher than the transmission power of the nodes, the sinks are still able to receive packets from the source nodes. This is explained by the fact that the intruders have straight trajectories where only a subset of nodes are
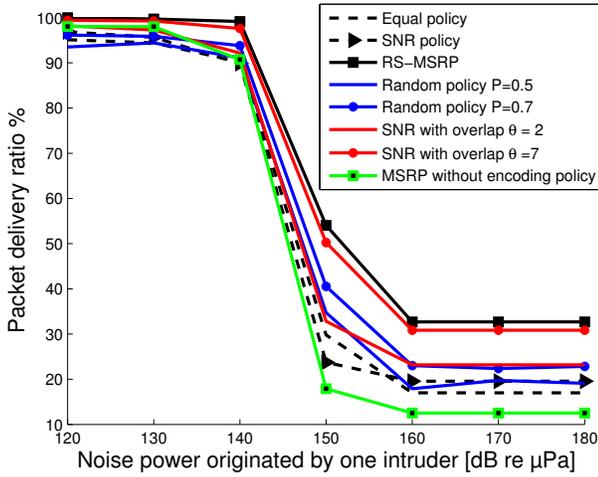
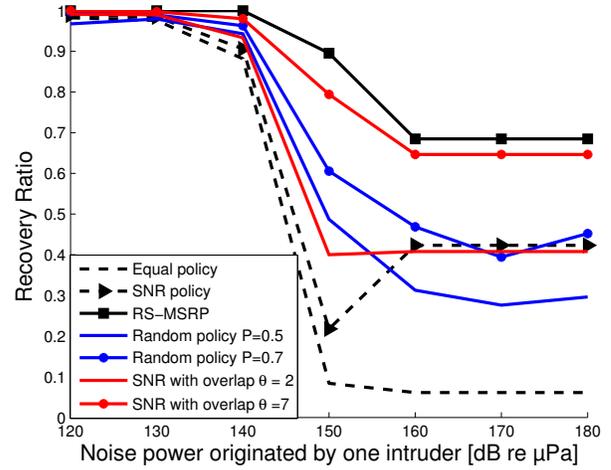Fig. 3. Packet delivery ratio vs. noise power for all policies.

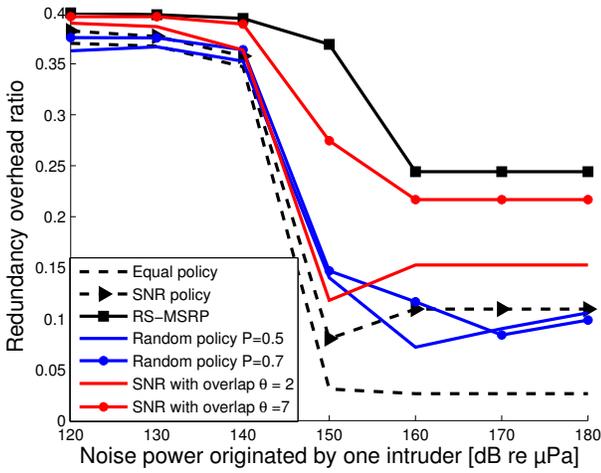Fig. 4. Recovery ratio vs. noise power for all policies.

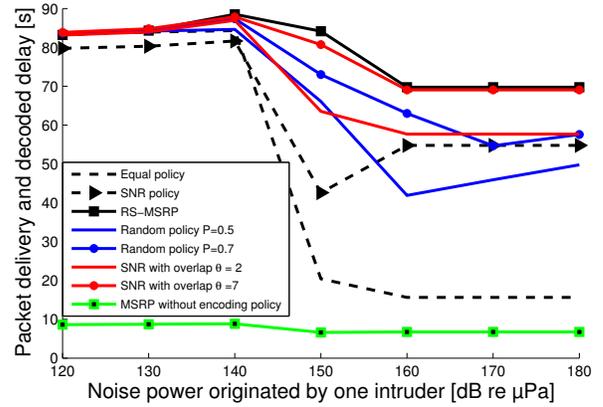Fig. 5. Redundancy overhead ratio vs. noise power for all policies.

Fig. 6. Packet delivery and decoding delay vs. noise power for all policies.

affected by the interference caused during their movements. Multipath routing, in these cases, helps the transmissions avoid interference.

To highlight the benefit yielded by the RS codes, we evaluate the RR in Fig. 4. We observe that RS-MSRP achieves the best RR as all packets are duplicated according to the number of paths. We also observe that in the SNR policy, when the power of noise increases and becomes comparable with the transmission power, the routing protocol tries to change routes, but fails because the noise power prevents control messages from being received correctly. When the intruder power is very high, exceeding the transmission power employed in the network, safe routes are created directly at the very first stages of route discovery, leading to more packets reaching the sinks, and hence to a higher RR. We note that in the Equal policy, the distribution of packets remains the same despite the intruder power, and this leads to more packet losses. Therefore, the RR is lower for the Equal policy than for the SNR policy.explained

in Section IV-C2). Hence, more packets are decoded correctly in the SNR policy than in the Equal policy.

In Fig. 5, we consider the RO for all policies. In these two plots, the Equal and SNR policies achieve the lowest overhead, as no packet is replicated over different paths. On the contrary, RS-MSRP and SNR with overlapping achieve the highest RO. The behavior of the SNR policy (for which the RO decreases until the noise power reaches 150 dB re μPa and then increases, is explained in the same way as in Fig. 4.

We conclude our evaluation by considering the PDD of the routing policies. The results are reported in Fig. 6. The MSRP policy achieves the lowest PDD because, in this policy, the packets are sent directly through multiple paths without any coding/decoding phases and with no need to wait until k data packets are buffered for RS encoding and decoding. We notice that, for high values of the intruder noise power, the PDD is generally lower for policies exhibiting a low PDR. This is because the PDD is computed only for the packets that are

correctly received and the RS packet groups that are correctly decoded. In case of high intruder noise, it is highly likely that the packets that make it through to the sinks are those that experienced favorable channel conditions and thereby incurred low delay. This reduces the average PDD.

From this evaluation, we can conclude that the RS-MSRP routing policy achieves the best PDR and RR at the expense of a high duplication overhead and a long delivery delay. However, as robustness is the most important criterion considered in this work, we have shown that using a $\mathrm{RS}(10, 6, 2)$ code with a redundancy rate of 0.4 can improve the packet delivery ratio in the considered topology.

VI. CONCLUSIONS

In this paper, we discussed packet error recovery in underwater networks using packet Reed-Solomon (RS) codes and multipath routing. We started from the observation that the recovery of packets using RS codes depends not only on the quality of the paths, but also on the distribution of the packets through these paths. We have then designed several multipath routing policies. Our comparison shows that our routing policies outperform the Multi-Sink Routing Protocol (MSRP) in terms of packet delivery ratio in a grid scenario, where two fixed sinks and two intruders are deployed. We have also shown that it is possible to trade off this packet delivery ratio with a lower packet overhead, if we send packets over different paths depending on the minimum SNR over each path, and then vary the number of packets that are replicated over the paths.

Future work on this topic includes an analytical study that can provide guidance on how to choose the RS code parameters in our scheme and demonstrate that the scheme is efficient in both packet error recovery and packet delivery delay.

VII. ACKNOWLEDGMENTS

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