

Silence is Golden

exploiting jamming and radio silence to communicate *

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ABSTRACT

Jamming techniques require just moderate resources to be deployed, while their effectiveness in disrupting communications is unprecedented. In this paper we introduce several contributions to jamming mitigation. In particular, we introduce a novel adversary model that has both (unlimited) jamming reactive capabilities as well as powerful (but limited) proactive jamming capabilities. Under this powerful but yet realistic adversary model, the communication bandwidth provided by current anti-jamming solutions drops to zero.

We then present Silence is Golden (*SiG*): a novel anti jamming protocol that, introducing a tunable, asymmetric communication channel, is able to mitigate the adversary capabilities, enabling the parties to communicate. For instance, with *SiG* it is possible to deliver a 128 bits long message with a probability greater than 99% in 4096 time slots in the presence of a jammer that jams all the on-the-fly communications and the 74% of the silent radio spectrum—while competing proposals simply fail.

The provided solution enjoys a thorough theoretical analysis and is supported by extensive experimental results, showing the viability of our proposal.

1. INTRODUCTION

Wireless communications are prone to several kinds of attacks due to the shared nature of the radio channel. *Jamming* is one of the most effective denial of service attack that might be performed in such a scenario [20]. Jamming is a general term that refers to several disruptive radio activities aiming at either to interfere or to prevent communications. While jamming originated in the military scenario, it is nowadays a threat also to civilian communications [19]. There are mainly two reasons for the widespread diffusion of jamming as a DoS attack in the wireless scenario: the first

one is its effectiveness; the other one is that its implementation does not require specialized hardware. For instance, a cheap WiFi radio can be used to generate collisions with the on-the-fly packets so that the receiver cannot decode them [4]; or, the same radio might be used to occupy the transmission channel in such a way that the transmitter cannot even start a new communication [23]. In the last decade, jamming devices have been evolved into high power random noise transmitters, making the activity of jamming a dreadful threat for wireless communications. As an example, we observe that military equipments implement band jamming by transmitting a white noise signal of 100W power over several frequency bands between 20 and 2483 Mhz [15].

Different jamming strategies have been deployed during the years [6]. The jammer might target the transmitter side by performing the so called noise-spoofing, i.e., the transmitter never senses a clear radio channel and therefore never starts a new transmission. Conversely, the jammer might target the receiver side, i.e., noise jamming. Noise jamming interferes with the current on-the-fly message introducing several errors or even making it not receivable. Different radio techniques are possible in order to interfere with the transmitter and the receiver radios [20]: the jammer might perform a tone jamming by generating a sinusoidal waveform whose power is concentrated on the target carrier frequency or it might perform a band jamming by spreading a flat spectrum power in the bandwidth of interest.

Jammers can be categorized in two main families: *proactive* and *reactive*. The proactive jammer randomly jams A of the F available frequencies in the radio spectrum, and therefore, the transmitter/receiver pair has only $F - A$ frequency bands in order to communicate. The solutions dealing with the proactive jammer implement a strategy based on a trial-and-fail communication process in random frequency slots. Conversely, the reactive jammer is more effective, in fact, it jams the communication after it has sensed it. The reactive jammer senses the radio spectrum and jams the communications as soon as they appear on-the-air. Dealing with a reactive jammer is more difficult: the sense-and-jam behavior is always disruptive, and so far, all the proposed solutions leverage a bounded jammer model, e.g., the size of the jammed area, the reaction time, the number of the jammed frequencies.

Contribution. In this work we provide several contributions: first, we introduce a novel type of adversary. Our adversary combines both *reactive* and *proactive* jamming capabilities. As a reactive jammer, it is able to disrupt all

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the on-the-air communications in the available spectrum. In fact, in this capacity, we assume it is able to perform both a network and a spectrum wide sensing and to react with a jamming signal emitted without delay with respect to the transmission sender. As a proactive jammer, our adversary is able to jam additional (apparently) not used frequency slots in the radio spectrum. To the best of our knowledge, these are the most strongest assumptions ever made in the literature for a radio jammer. The second contribution is the definition of the *SiG* protocol. Our proposal is, to the best of our knowledge, the only one able to thwart the powerful, yet viable, adversary above introduced. For instance, against the introduced adversary, the *SiG* protocol enables the transmitter to successfully deliver a 128 bits long message within 4096 time slots while other solutions in the literature, cannot guarantee any communications at all. Further, the *SiG* protocol is fully detailed, showing how to tune its parameters in order to trade-off communication capabilities with an efficient usage of the transmission slots. Moreover, a thorough analysis of its capabilities is provided, together with a comparison against anti-jamming state of the art solutions. Finally, an extensive simulation campaign supports our findings.

Section 3 introduces our reference scenario, defining the transmitter, the receiver, and the adversary model. Section 4 presents a simplified version of the *SiG* protocol, which is subsequently detailed in Sections 4.1 and 4.2, that introduce the frequency hopping scheme and the error correcting codes, respectively. Section 5 provides a detailed decryption of the *SiG* protocol and Section 6 shows the performance of *SiG* by means of a theoretical analysis and simulation results. Finally, Section 7 compares *SiG* with other recent solutions to jamming attacks. Some concluding remarks are reported in Section 8.

2. RELATED WORK

In the following, we review the most relevant anti-jamming techniques. We consider both proactive and reactive anti-jamming techniques, and finally, we recall an early solution that leverages jamming to communicate between peers.

2.1 Proactive jamming

An early analysis on the feasibility of launching and detecting jamming attacks in wireless networks is proposed in [25]. Authors provide an in-deep study about the problem of conducting radio interference attacks on wireless networks, and examine the critical issue of diagnosing the presence of jamming attacks. They consider different adversarial models and run real test-beds to measure the adversarial performance. They show that by using signal strength, carrier sensing time, or the packet delivery ratio individually, it might difficult to conclude the presence of a jammer.

Many solutions have been proposed against proactive jammers. We identify two main families: the “keyed” [11] and the “key-less” [17]. The former leverages a pre-shared secret in order to generate frequency hopping sequences (unknown to the jammer), while the latter leverages a delay between the sender and receivers in order to make them converging on a shared transmission frequency. Authors in [12][11] propose the Time Delayed Broadcast Scheme (TDBS): a broadcast communication is achieved by means of a sequence of unicast communications—sometimes assisted by proxies. The

solution relies on long frequency hopping sequences that are pre-loaded in each sensor belonging to the network before nodes deployment. A key-less solution is presented in [17]. Authors propose to deliver a message between two peers by an uncoordinated spread spectrum technique while introducing a delay between the transmitter and the receiver in order to have them synched. Finally, an early key-less solution is from [2]. Authors leveraged specialized ultra-wide band radios in order to transmit short impulses. Such communication scheme is difficult to jam, i.e., so far radio impulse cannot be cancelled with an inverse waveform. Each bit of the message is coded with a time-delayed radio impulse, nevertheless spurious impulses (errors) might appear at the receiver side due to noise fluctuations or malicious entities, and the previous produces an enormous increase in the computational cost that is exponential in the size of the message.

2.2 Reactive jamming

Reactive jamming involves the activity of sensing the channel and subsequently switching the radio to the jamming status. As for reactive-jamming, the current state of the art solutions do not deal directly with the jammer but leverage either space or temporal bounds the adversary is subject to. Authors in [13] propose to exploit the reaction time of the reactive jammer in order to enable communication; they argue that the jamming activity needs more than $t_s = 1ms$ while radio switching needs other $t_c = 50\mu s$, while the transmitter has already sent $R(t_s + t_c)$ bits—assuming a transmission rate R . The receiver collects all the bits that are transmitted by the sender but not jammed by the reactive jammer, and assembles them to construct the original message.

In [26], author propose a combined solution that involves both locating the reactive jammer and deactivating the nodes that trigger its activity. Authors observe that the reactive jamming activity is particularly disruptive in dense WSNs. Indeed, the reactive jammer is triggered by a specific node, while the jamming signal will eventually prevent all the communications of the nodes in the jammer neighborhood. In order to avoid this, authors propose a solution where nodes cooperate in order to estimate the jammer position, and subsequently enforce the radio-silence of the nodes that trigger the jamming activity.

Another solution to reactive jamming is POWJAM [9]. Author proposes short-distance transmissions (with low power) between peers in order to hidden the transmitter to the reactive jammer. Each long-range communication turns out to be implemented by a sequence of multi-hop transmissions characterized by low-distance propagation and therefore a low probability to be sensed by the jammer.

An efficient and fair MAC protocol robust to reactive interference has been proposed in [1] and subsequently extended in [19]. The proposed protocol is robust to both internal and external interference requiring no knowledge about the number of participants, nevertheless the authors bound the reactive jamming activity to $(1 - \epsilon)$ -portion of the available time slots.

Another interesting solution comes from [24]. There, authors design, prototype, and evaluate a system for cancelling the jamming signal: the system combines a mechanical beam-forming design with an auto-configuration algorithm and a software radio digital interference cancellation algorithm. The mechanical beam-forming uses a custom-designed two-

elements antenna architecture and an iterative algorithm for jammer signal identification and cancellation.

Finally, an interesting solution is provided in [3]. The scenario involves 4 nodes and a slotted channel: two legitimate peers communicate to each others by transmitting messages on the shared channel, while one of the illegitimate users interferes/jams the legitimate messages. Now, the other illegitimate peer decides a reception of a “1” when a collision is detected, while decides for “0” when the slot is empty or filled up by a legitimate message. Authors prove that the status of the channel, i.e., jammed or not-jammed, can be used to communicate one bit of information.

3. SCENARIO

We consider a wireless communication scenario constituted by a point-to-point link between a transmitter (T) and a receiver (R), where T wants to deliver a message m constituted by L_m bits to R . We assume $m \in \Phi$, where Φ is a dictionary shared between T and R (note that such a dictionary could be the set of correct English words). Further, we assume the radio spectrum as constituted by F different frequency bands (channels), i.e., $\{f_0, \dots, f_{F-1}\}$. Both the transmitter and the receiver share a pre-loaded secret s_0 .

Generally speaking, R could receive from T —due to the jamming activity and the radio noise— a message m' , such that $m' \neq m$. The *SiG* protocol guarantees (with a given, tunable, probability) to recover m . In the following, we assume m to be constituted by a few bits, e.g., $L_m \in \{128, 256, 512\}$ bits—e.g. m could carry commands or geographical coordinates.

Further, we assume that T and R are loosely time synchronized [8] and that time is divided into slots, i.e., $i \in [0, \dots, \infty[$. Finally, we do not assume any specific or powerful hardware configuration at both T and R — the *SiG* protocol only needs the computation of a cryptographically secure hash function [7] and the capability to run a symmetric encryption algorithm such as AES [14].

Table 1 shows a resume of the symbols and acronyms used throughout this paper.

3.1 Transmitter and Receiver: Software and Hardware Assumptions

Transmitter. We consider a standard off-the-shelf radio transmitter such as a WiFi, or a GPRS/UMTS radio device. Without loosing of generality, in the following we consider a radio technology characterized by $F = 124$ different communication channels (like in the GSM-850). At each time slot i , the transmitter chooses a pseudo-random frequency $f_i \xleftarrow{\$} [f_0, \dots, f_{F-1}]$, and as it will be clear in the following, it decides whether to stay silent or to transmit the message m , i.e., $\text{transmit}(m, f_i)$.

Receiver. In our model, the receiver might reconstruct the transmitted message m in mainly two ways: by either simply receiving (during a time slot) the transmitted message m or, as it will be clear in the following, by estimating the energy associated to the frequency f_i . In this latter case,

Table 1: Notation summary.

T, R, \mathcal{J}	transmitter, receiver, and jammer
m, m'	transmitted and received messages
Φ	message dictionary
m_e, m'_e	transmitted and received encrypted messages
L_m	length of the messages $m, m_e, m',$ and m'_e
m_{ec}, m'_{ec}	transmitted and received encoded encrypted messages
L_c	length of the messages m_{ec} and m'_{ec}
M_i, M'_i	transmitted and received codewords associated to the message bit m_i
i	slot time
s_i	one time password
f_i	frequency used at slot time i
$F, (A)$	number of available (jammed) frequencies
$E(f_i)$	physical layer function for estimating the energy of the frequency slot f_i
τ	threshold for signal/jamming detection
$H_1(\cdot), H_2(\cdot)$	cryptographically secure hash functions
p_A	proactive jamming probability
n	codeword length
C_n^Δ	error correction code
$ECC(\cdot)$	C_n^Δ encoding algorithm
$ECC^{-1}(\cdot)$	C_n^Δ decoding algorithm
$ENC(\cdot)$	symmetric encryption algorithm
$DEC(\cdot)$	symmetric decryption algorithm
\bar{p}_A	maximum jamming probability resiliency
ϵ	probability of successful message jamming
$ \cdot $	size of the bit-string

recovering m requires multiple time slots — one of such estimations *per* time slot.

We envisage a very simple receiver equipped with a radio and able to estimate the *received signal strength*, hereafter RSS, i.e., we assume R is provided with a radio physical layer function $E(f_i)$ which returns an average estimation of the RSS values experienced during the frequency slot f_i . RSS estimation is a common feature in all the radio devices in order to implement the medium access control. RSS provides an estimation of the current channel energy. Note that recent papers have leveraged this information to detect the presence of a jamming signal [22] [25], i.e., when a powerful jamming attack is performed, the receiver experiences high RSS values.

Therefore, in addition to the standard receiving behavior, our receiver also senses and logs (into m') whether the energy associated to that frequency exceeds a given threshold τ . As a toy example, let us consider Fig. 1. For each time slot $i \in [0, \dots, 7]$, the receiver assesses the channel status and sets $m'_i = 1$ if the RSS overcomes the threshold τ (this is the case if there is a transmission, jamming, or environmental noise), while it sets $m'_i = 0$ if it senses only noise floor (RSS under τ). Communicating leveraging radio silence leads to the following definition:

DEFINITION 1. We refer to slot i as a **silent slot** if the energy detected by the receiver on the associated frequency f_i is below the threshold τ .

3.2 Adversarial model

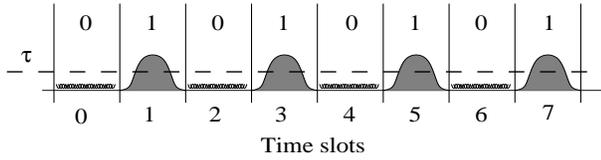


Figure 1: Energy detection capability of the receiver: At each time slot, the receiver translates the measured channel energy (RSS) to a bit value, i.e., it decides for “0” when the measured energy is under the threshold τ , “1” otherwise.

We confront our solution against what, to the best of our knowledge, is the most powerful adversary presented in the literature. In particular, our adversary (\mathcal{J}), combines the capability of the proactive jammer, of the reactive jammer, and also network wide eavesdropping capabilities. In particular:

- \mathcal{J} as a **global eavesdropper**. It is able to eavesdrop all the communications in the network. In order to achieve this, \mathcal{J} might deploy multiple eavesdropping stations all over the network, and moreover, we assume each station is able to monitor the overall radio spectrum.
- \mathcal{J} as a **reactive jammer**. It is able to sense the ongoing communication and to jam it instantaneously, while at the same time switching between the sensing and the jamming procedures. Note that considering this powerful (but yet realistic) type of adversary we assume a conservative stance as for the security of communications. To the best of our knowledge, this is the strongest adversarial configuration ever assumed in literature for a reactive jammer.
- \mathcal{J} as a **proactive jammer**. At each time slot, \mathcal{J} randomly chooses A among the F available frequencies and jams them.

Therefore, at each time slot, if T is performing a transmission, \mathcal{J} successfully jams it (whatever the transmission frequency is). Otherwise, \mathcal{J} jams A out of the F available frequencies.

As a toy example, let us assume $F = 1$ and the communication scenario in Fig. 2. The transmitter sends to the receiver 4 messages and the jammer successfully jams all of them at time slots $i \in \{1, 3, 5, 7\}$ (reactive jamming). Moreover, \mathcal{J} generates a jamming signal during the time slot 2 (proactive jamming). Proactive jamming might appear useless in our adversarial model (all the communications are already assumed as successfully jammed), nevertheless, as it will be clear in the following, the silent slots are important to our solution and therefore a proactive jammer has an incentive in jamming them.

4. SiG PRELIMINARIES

In this section we introduce the rationales of the SiG protocol, while a detailed description will be provided in the following section. Let us assume T has to transmit an 8 bits

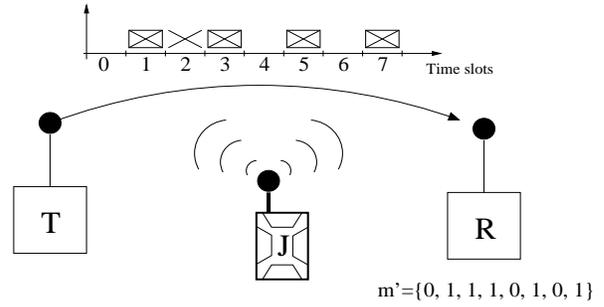


Figure 2: Communication scenario: The transmitter (T) delivers a sequence of messages to the receiver (R). The jammer (\mathcal{J}) successfully jams all the messages. R logs to m' the status of each time slot: 1 for jammed, 0 otherwise.

message ($L_m = 8$), that is: $m = \{0, 1, 0, 1, 0, 1, 0, 1\}$ (Fig. 1). The transmitter behaves as follows: at each time slot i with $0 \leq i \leq 7$, if $m_i == 1$ than T transmits the whole m , otherwise it waits for the next time slot.

As for the receiver, there can be three cases: if R correctly receives the message m (benign scenario) than it stops the SiG protocol, otherwise, the receiver sets $m'_i = 1$ if the RSS exceeds the threshold τ , otherwise R sets $m'_i = 0$. However, recalling Section 3.2, \mathcal{J} (being also a perfect reactive jammer) is assumed to jam all the slots used by T to transmit the message, as well as (being a proactive jammer) a few more randomly selected slots (where some of them could be silent slots). Therefore, let us consider again Fig. 2: \mathcal{J} successfully jams the slots $i \in \{1, 3, 5, 7\}$ and also slot 2 (this latter one was intended by T to be a silent slot). We observe that, although all the messages are successfully jammed, after 8 time slots R is able to recover the bit string $m' = \{0, 1, 1, 1, 0, 1, 0, 1\}$ that differs from m for only one bit — the silent slot ($i = 2$) jammed by \mathcal{J} .

Similar to the Definition 1, we define an *active* slot as follows:

DEFINITION 2. Slot i is an **active** slot if, on the associated frequency f_i , the transmitter T is carrying out an active communication by transmitting a message.

Silence is Golden. The SiG protocol interleaves silent slots with active slots—slot i will be an active one if $m_i == 1$, a silent one otherwise. Both of them are fundamental for the successful message transmission. In particular, while active slots carry the message (or the “1”s of the message, if the frequency f_i is jammed) the silent slots carry the “0”s of the message (or an error if the frequency f_i is jammed).

In the following, we show how multiple transmissions can be leveraged to mitigate the (proactive) jamming activity. This feature, combined with channel-idiosyncratic error-correcting code capabilities enable the full recovery of the original message (m).

4.1 Leveraging frequency-hopping

In the following, we refine the baseline communication scheme above introduced.

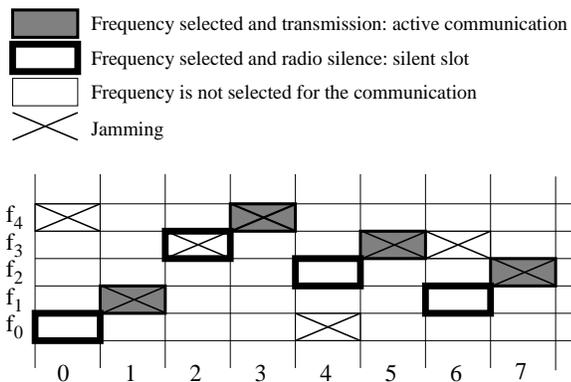


Figure 3: Communication by frequency hopping: T and R share a secret (s_0) that is leveraged to generate the frequency hopping sequence.

As stated before, T and R choose in a pseudo-random fashion the current communication channel within a set of $F \geq 1$ frequencies. Increasing F makes the proactive jamming of the current communication channel more difficult, since a larger F decreases the probability of \mathcal{J} to jam the silent slots (communicating the “0”s of m).

In detail, T and R implement a frequency hopping scheme [16] that makes the current communication frequency unpredictable to the entities that do not share the initial secret s_0 . A few solutions have been proposed in order to generate a pseudo-random (shared) frequency starting from a shared secret. In this work, we adopt the following formula:

$$f_i = H_1(s_i | i) \pmod F$$

where $H_1(\cdot)$ is a cryptographically secure hash function, e.g., SHA-1 [7], i is the current time slot, s_i is the shared secret at time slot i and, finally, F is the total number of available frequencies.

Figure 3 shows an example of transmission of an 8 bits message. In particular, the frequency hopping sequence is constituted by $\{f_0, f_1, f_3, f_4, f_2, f_3, f_1, f_2\}$, while the bits involved in the communications are $m = \{0, 1, 0, 1, 0, 1, 0, 1\}$. Each of the above frequency f_i might experience one of the following three different states: silence (white box)—that is, the sender intends to send a 0—; pure jamming (cross)—that is, the frequency is not used by T , but it is jammed by \mathcal{J} —; or, jammed transmission (grey box with cross). We recall that \mathcal{J} is able to jam all the transmissions that appear in the radio channel, therefore none of the messages sent by the transmitter will be correctly received by the receiver. Nevertheless, at each time slot the receiver could still retrieve the bit-message m_i by assessing the status of the current frequency slot f_i . In fact, when $m_i = 1$: T transmits the message, \mathcal{J} jams it, and finally, R detects that the RSS associated to f_i exceeds τ (indeed, frequency f_i has been jammed) and sets $m'_i = 1$. Whereas, for each $m_i = 0$: T selects the radio channel f_i but does not transmit the message. R monitors f_i and if no power is detected, decides for $m'_i = 0$. This is the case for time slots $i \in \{0, 4, 6\}$. However, we observe that \mathcal{J} might jam a silent slot (frequency f_i used for a silent slot is randomly selected by the jammer as well), as it happens in our example for time slot $i = 2$ —causing a one bit error (m'_2) in the received sequence m' .

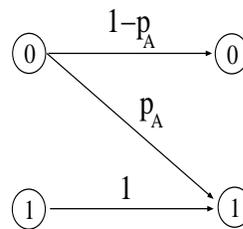


Figure 4: The inverted Z-channel: $P(0 \rightarrow 1) = p_A$ and $P(1 \rightarrow 1) = 0$

Therefore, assuming F available frequencies and an adversary able to jam A of them at each time slot, the probability for a silent slot to be jammed (flipping a bit from 0 to 1) is given by $p_A = \frac{A}{F}$. Moreover, we highlight that, regardless of \mathcal{J} activities, the receiver is anyway able to retrieve at least all the “1”s of the message.

4.2 Binary asymmetric error correcting codes

As stated in Section 4.1, \mathcal{J} can always prevent the correct reception of the messages, given its perfect reactive jamming capabilities. However, R is still able to recover all the “1”s of m . We stress that \mathcal{J} cannot prevent the (active) communication of the “1”s, in fact the only way to achieve this is to remove the message from the radio spectrum, e.g., generating an inverse waveform to have the RSS sensed by T resulting below the threshold τ . However, in the literature this feature is considered very difficult to achieve [2]; therefore, in the following we will assume such an event as impossible—i.e. experiencing a bit transition from “1” to “0” has associated probability 0. Nevertheless, \mathcal{J} has a probability p_A to jam a silent channel, that is changing the bit value from “0” to “1”.

Communication channels characterized by an asymmetric probability to experience a transition between zeros and ones, such as the one above described, are said *binary asymmetric channels* [10], hereafter BAC. In particular, BAC characterized by $P(0 \rightarrow 1) = p_A$ and $P(1 \rightarrow 1) = 0$ are said *inverted Z-channels* [10], see Fig. 4. The inverted Z-channel shows a perfect fit to model our communication channel. Mostly important, the error correcting codes (ECC) specifically designed for this channel might be used to recover the error bits due to jamming over silent slots.

Let x and y be two bit strings (codeword) of n bits each belonging to the code C . Let δ be the asymmetric distance, i.e., the number of i 's such that $m_i = 0$ and $m'_i = 1$. Let also $\Delta = \min_{\{x, y \in C, x \neq y\}} \delta(x, y)$ be the minimum asymmetric distance. A fundamental theorem of the ECC theory [5] follows:

THEOREM 1. *An asymmetric binary code of minimum asymmetric distance Δ is capable of correcting t or fewer errors of type $0 \rightarrow 1$, where t is fixed and satisfies $t \leq \Delta - 1$.*

Authors in [5] provide several constructions for asymmetric binary error correction codes C_n^Δ , given the codeword length n and the minimum asymmetric distance Δ .

In the following, we consider the most resilient configuration, i.e., $n = \Delta$, that is able to correct up to $n - 1$ errors. Now, let us assume a bit string m_e of L_m bits. In order to be resilient to $n - 1$ consecutive jamming hits, each bit m_{e_i} of the message m_e is encoded with a codeword M_i of length n bits, i.e., repeated n times. We adopt

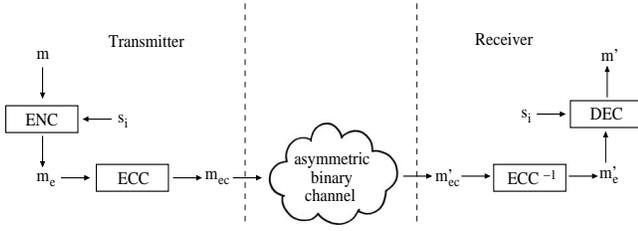


Figure 5: The SiG protocol: Transmitter and Receiver model. $|m| = |m_e| = |m'| = |m'_e| = L_m$ and $|m_{ec}| = |m'_{ec}| = L_c$.

the following notation: $m_{ec} = ECC(m_e)$ where m_e and m_{ec} are bit-strings of L_m and $L_c = nL_m$ bits, respectively, and $m_{ec} = \{M_0, \dots, M_{L_m-1}\}$. In particular, the i^{th} bit of the message m_e is encoded into the n bits codeword M_i , i.e., $M_i = \{0, \dots, 0\}$ if $m_{e_i} == 0$, else $M_i = \{1, \dots, 1\}$ if $m_{e_i} == 1$. Conversely, the receiver runs the decoding algorithm, i.e., $m'_e = ECC^{-1}(m'_{ec})$, where $m'_{ec} = \{M'_0, \dots, M'_{L_m-1}\}$ and decides for $m_{e_i} == 1$ if $M'_i = \{1, \dots, 1\}$, otherwise it sets $m_{e_i} == 0$.

5. THE SiG PROTOCOL

The SiG protocol guarantees both confidentiality and integrity of the transmitted message. Each message m , before being transmitted, is encrypted with a one-time-password (OTP) s_i , i.e., $m_e = ENC(m, s_i)$, where $ENC(\cdot)$ is a symmetric encryption algorithm (such as AES[14]), encrypting message m with key s_i . At each time slot a new (shared) secret key s_i is generated by both parties computing $s_i = H_2(s_{i-1})$, with $i \geq 1$ — where $H_2(\cdot)$ is a cryptographically secure hash function [7]. Conversely, the receiver computes $m' = DEC(m'_e, s_i)$, where $DEC(\cdot)$ is the symmetric decryption algorithm.

Figure 5 shows the overall model, while details are provided in Section 5.1 and 5.2, respectively.

5.1 Transmitter

Algorithm 1 shows the sequence of steps performed by T in order to transmit the bit-string m to the receiver R . The transmitter algorithm needs as input the message m and the shared (with R) secret s_{i-1} ($i \geq 1$). Assuming the current time slot as i , the first step is to generate a new OTP, i.e., s_i at line 9. The new shared secret s_i will be used to both encrypt the message m and generate the next transmission frequency. The message encryption is obtained by means of $m_e = ENC(m, s_i)$ while the encoding is performed as: $m_{ec} = ECC(m_e)$, obtaining a bit-string of $L_c = nL_m$ bits (line 11). Now, for each time slot i (in the next L_c slots), the transmitter decides whether to transmit the message m_e (line 16) or to stay silent (according to the bit value $m_{ec}[i]$ (line 18–19)). Each frequency slot is chosen according to $f_i = H_1(s_i | i) \bmod F$ (line 13).

Eventually, m is transmitted to R after nL_m time slots with an average of $\frac{nL_m}{2}$ transmissions, assuming the distribution of the bit values $\{0, 1\}$ as uniform¹.

5.2 Receiver

¹We recall that m_e is encrypted, therefore we would expect a uniform bit distribution [21].

Algorithm 1: Transmitter side

Input: Shared secret: s_{i-1} , Message: m

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1 let  $m$  be a bit-string of  $L_m$  bits.
2 let  $s_{i-1}$  be the shared secret with  $R$  at time slot  $i - 1$ .
3 let  $i$  be the current time slot.
4 let  $m_e$  be a bit-string of  $L_m$  bits.
5 let  $m_{ec}$  be a bit-string of  $L_c$  bits.
6 let  $ECC(\cdot)$  be the ECC encoding algorithm.
7 let  $ENC(\cdot)$  be a symmetric encryption algorithm.
8 let  $F$  be the number of available frequencies.

/* Generate a new OTP. */
9  $s_i = H(s_{i-1})$ ; /*
/* Encrypt the message  $m$  into  $m_e$  */
10  $m_e = ENC(m, s_i)$ ;
/* Encode the bit-string  $m_e$  into the bit-string
    $m_{ec}$  */
11  $m_{ec} = ECC(m_e)$ ;
12 for  $i = 1 \dots L_c$  do
    /* Select the communication frequency */
13  $f_i = H_1(s_i | i) \bmod F$ ; /*
    /* Retrieve one bit from  $m_{ec}$  */
14  $c = m_{ec}[i]$ ;
15 if  $c == 1$  then
    | /* Transmit  $m_e$  at frequency  $f$  */
16 | transmit( $m_e, f_i$ ); /*
17 end
18 else
    | /* Wait till the next time slot */
19 end
20 end

```

The receiver algorithm (Algorithm 2) starts by syncing with T on the new shared secret key, i.e., $s_i = H(s_{i-1})$, where i is the current time slot (line 10). If all the transmitted messages have been successfully jammed by \mathcal{J} , for each of the next L_c time slots, R performs three steps: frequency selection (line 13), channel energy measurement (line 20), and decision on the value of the current bit (line 21–27).

The receiver syncs with the transmitter on the correct frequency by means of $f_i = H_1(s_i | i) \bmod F$. The receiver performs the message reception by means of $m'_e = receive(f_i)$, decrypts m'_e obtaining m' , and finally, if the integrity check of m' is successful ($m' \in \Phi$), it sets the rx variable to true (line 17). Nevertheless, our adversarial model assumes that none of the message can be received correctly, i.e., \mathcal{J} is able to jam all the active communications.

Therefore, R leverages the channel energy in order to reconstruct the transmitted message. The receiver retrieves the estimation of the energy on the current frequency slot f_i by means of the radio function $e = E(f_i)$. If the estimated energy e overcomes the threshold τ , the receiver sets $m'_{ec}[i] = 1$, otherwise $m'_{ec}[i] = 0$. Eventually, after L_c time slots, the receiver firstly decodes the collected bits (m'_{ec}) into the bit-string m'_e , and subsequently decrypts m'_e obtaining the message m' .

Finally, the receiver checks for the message integrity, i.e., $m \in \Phi$, and returns $m = m'$ if the message is correct, otherwise error (lines 33–38).

Packet loss. Generally speaking, packet loss is due to ra-

dio noise that corrupts the transmitted packets [18]. In our communication model the correct reception of a bit at slot i depends on the energy sensed over frequency f_i . Hence, in principle it could be possible that random energy fluctuations in the channel might produce destructive interference, causing the energy associated to frequency f_i to be below the threshold τ , eventually generating a crossover $1 \rightarrow 0$. However, in our reference scenario (that is, assuming the presence of \mathcal{J}), we observe that our adversarial model involves a reactive jammer that (when a transmission is sensed) jams the overall network with a very powerful signal. Since the energy over frequency f_i is increased by the jammer, the jammer itself makes the probability of a crossover $1 \rightarrow 0$ negligible.

Finally, we stress that in any case a corrupted message cannot be accepted as a genuine one. Indeed, the receiver R eventually checks for the integrity of the message (line 33 in Algorithm 2), and discards the message if it does not pass the check.

5.3 Wrap up

The *SiG* protocol combines two key elements that make itself robust to jamming: (i) frequency hopping makes the communication of the “0”s unpredictable, while (ii) the (active) communication of “1”s cannot be prevented by \mathcal{J} (i.e. the transmission of “1”s is transparent to jamming).

We consider a simple example of the *SiG* protocol in Fig. 6. In order to ease the discussion, we do not consider the encryption step, therefore the bit-string m is directly encoded into the bit-stream m_{ec} . Further, we assume a code C_n^Δ , such that $\Delta = n = 8$, and consequently able to recover $t \leq \Delta - 1 = 7$ errors, see Section 4.2 for the details. Therefore, the initial bit-string $m = \{0, 1, 0, 1, 0, 1, 0, 1\}$ of length $L_m = 8$ bits is encoded into the bit-stream m_{ec} of length $L_c = nL_m = 64$ bits. The communication channel is constituted by $F = 5$ frequencies: at each time slot the transmitter and the receiver sync on one of them, and subsequently, either a transmission or a radio silence is performed as function of the current value of the bit to be transmitted.

The jammer jams both all the transmitted messages and (proactively) $A = 1$ of the $F = 5$ frequencies when no communications appear on the radio spectrum. We observe that \mathcal{J} hits the 5^{th} , 8^{th} , 23^{rd} , 37^{th} , and the 54^{th} silent slot, and consequently, the bit-string m'_{ec} differs from m_{ec} of 5 bits. Nevertheless, the ECC code is able to correct up to $t = 7$ errors per codeword, and eventually the received message m'_{ec} allows to recover m .

We stress that under a standard proactive adversary (that is, an adversary that with not zero probability fails to jam an active communication), the *SiG* protocol delivers the message m with the first not-jammed active communication. Whereas, our adversary \mathcal{J} successfully jams all the active communications, and therefore *SiG* accomplishes the correct delivery of a single bit (“1”) per active communication. Although \mathcal{J} cannot prevent the delivery of the “1”s, it can jam the transmission of the “0”s, changing their value to “1”.

6. PERFORMANCE EVALUATION

In the following, we present the performance analysis of the *SiG* protocol. We start our analysis from a theoretical point of view providing a closed formula for the probability that R , having derived m' from the received message m'_{ec} , cor-

Algorithm 2: Receiver side

Input : Shared secret: s_{i-1}

Output: Message m' if $m' = m$, otherwise **error**

```

1 let  $m'$  be a bit-string of  $L_m$  bits.
2 let  $s_{i-1}$  be the shared secret with  $R$  at time slot  $i - 1$ .
3 let  $i$  be the current time slot.
4 let  $m'_e$  be a bit-string of  $L_m$  bits.
5 let  $m'_{ec}$  be a bit-string of  $L_c$  bits.
6 let  $ECC^{-1}(\cdot)$  be the ECC decoding algorithm.
7 let  $DEC(\cdot)$  be a symmetric decryption algorithm.
8 let  $F$  be the number of available frequencies.
9 let  $\tau$  be the energy decision threshold.

/* Generate a new OTP. */
10  $s_i = H(s_{i-1});$ 
11  $i = 0; rx = \text{false};$ 
12 while  $i < L_c$  and  $\text{not}(rx)$  do
    /* Select the communication frequency */
13  $f_i = H_1(s_i | i) \bmod F;$ 
    /* Receive the message  $m'_e$  at the freq.  $f_i$  */
14  $m'_e = \text{receive}(f_i);$ 
    /* Decrypt  $m'_e$  with  $s_i$  */
15  $m' = DEC(m'_e, s_i);$ 
    /* Check  $m'$  integrity */
16 if  $m' \in \Phi$  then
    | /* Message has been correctly received. */
17 |  $rx = \text{true};$ 
18 end
19 else
    | /* Retrieve the channel energy. */
20 |  $e = E(f_i);$ 
21 | if  $e \geq \tau$  then
22 | |  $m'_{ec}[i] = 1;$ 
23 | end
24 | else
25 | |  $m'_{ec}[i] = 0;$ 
26 | end
27 end
28 end
29 if  $\text{not}(rx)$  then
    | /* Decode  $m'_{ec}$  into  $m'_e$  */
30 |  $m'_e = ECC^{-1}(m'_{ec});$ 
    | /* Decrypt  $m'_e$  with  $s_i$  */
31 |  $m' = DEC(m'_e, s_i);$ 
32 end
    /* Check  $m'$  integrity */
33 if  $m' \in \Phi$  or  $rx$  then
34 | return  $m'$ ;
35 end
36 else
37 | return error;
38 end

```

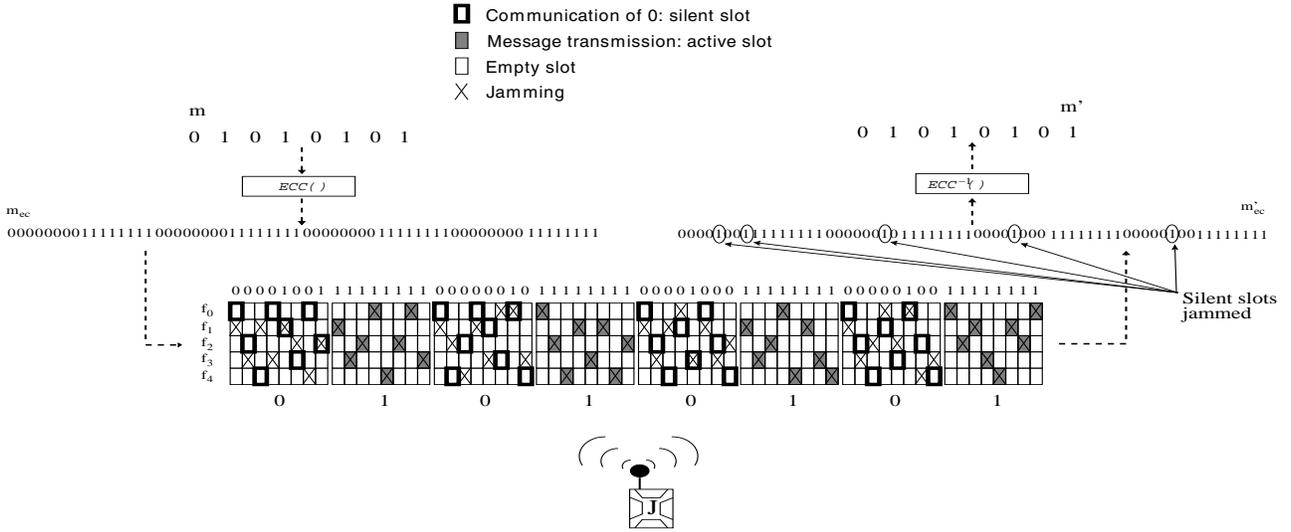


Figure 6: An example of message transmission, jamming, and reception: the bit-string $m = \{1, 0, 1, 0, 1, 0, 1, 0\}$ is encoded into the bit-string m_{ec} , and subsequently transmitted into a radio spectrum with $F = 5$ frequencies. The jammer jams all the messages and a few silence slots flipping one or more bits (from 0 to 1). Finally, the receiver recovers the original bit-string m by leveraging the error correcting code.

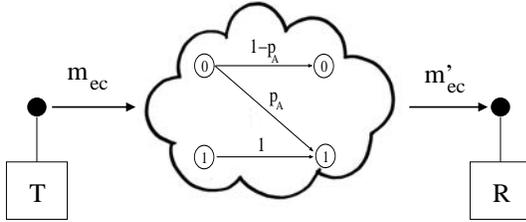


Figure 7: The communication reference model for the theoretical analysis.

rectly recovers the message m originally sent by T (we will refer to this probability as $P(m' = m)$). Such a probability will be dependant on the (proactive) jamming probability p_a . We will assume, coherently with our adversary model, that the reactive capabilities of the jammer allow it to jam all the transmissions of T —hence, all the 1s of message m are correctly received (cfr. Section 3.2). Subsequently, we show and discuss the results of an extensive simulation campaign—confirming our theoretical findings and the quality and viability of our proposal.

6.1 Theoretical analysis

Figure 7 recaps our communication reference model for the theoretical analysis. In particular, we recall that each bit of the message m , i.e. m_i , is encoded into a codeword M_i of n bits (as per Section 4.2), that is, $m_{ec} = ECC(m)$, where $m_{ec} = \{M_0, \dots, M_{L_m-1}\}$. The probability $P(M_i = M'_i)$ that the codeword M_i , with $i \in [0, L_m - 1]$, is correctly delivered to R assuming the channel model of Fig. 7, is:

$$P(M_i = M'_i) = P(\delta(M_i, M'_i) < n) \quad (1)$$

where $\delta(M_i, M'_i)$ is the asymmetric distance computed between M_i and M'_i , i.e., the number of “0”s belonging to M_i

that change their value to “1” in the bit-string M'_i . We recall that, according to our communication model—justified in previous sections and synthesized in Fig. 7—the only possible bit crossover is $0 \rightarrow 1$, while $1 \rightarrow 0$ is not possible. Therefore, since the frequencies jammed by a proactive jammer in any time slot are independent from the frequencies jammed in other time slots, Eq. (1) can be rewritten as:

$$P(M_i = M'_i) = 1 - P(\delta(M_i, M'_i) = n)$$

The probability to experience exactly one crossover $0 \rightarrow 1$ at a given time slot of codeword M_i is given by the probability p_a that \mathcal{J} successfully jams exactly that time slot (out of the n silent slots) belonging to the codeword M_i . Therefore, the probability to have the codeword M_i correctly decoded at the receiver, yields:

$$P(M_i = M'_i) = 1 - p_a^n$$

Further, the probability to correctly deliver the bit-string m_{ec} , i.e., $P(m_{ec} = m'_{ec})$, can be computed as:

$$P(m_{ec} = m'_{ec}) = \prod_{i=0}^{L_m-1} P(M_i = M'_i)$$

Assuming the message m enjoys a uniform distribution of zeros and ones (similar considerations expressed in footnote 1 do support this assumption) and recalling that, as justified in Section 5.2 $P(M_i = M'_i | m_i = 1) = 1$ —no crossovers $1 \rightarrow 0$ occur—, the above equation can be rewritten as:

$$\begin{aligned} P(m_{ec} = m'_{ec}) &= \prod_{i=0}^{\frac{L_m-1}{2}} P(M_i = M'_i | m_i = 0) \\ &= (1 - p_a^n)^{\frac{L_m}{2}} \end{aligned} \quad (2)$$

The probability that R could recover an L_m bits long message m sent by T and encoded with an ECC code C_n^Δ , yields:

$$P(m = m') = (1 - p_a^n)^{\frac{L_m}{2}} \geq e^{-p_a^n L_m} \quad (3)$$

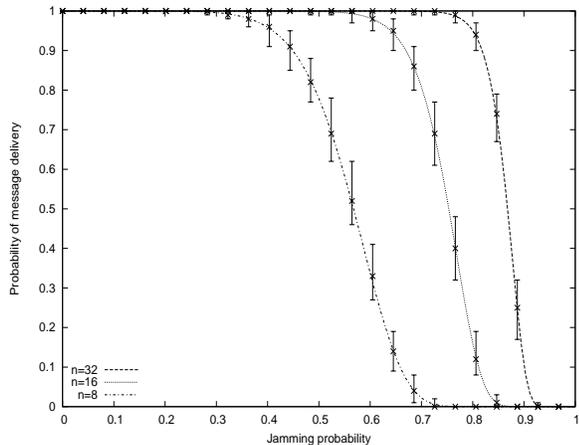


Figure 8: Message delivery probability ($P(m = m')$) with the *SiG* protocol: the message length is $L_m = 128$ bits, while the jamming probability has been obtained by fixing $F = 124$ and varying A in $[0, \dots, 124]$. We consider both experimental (error-bars) and theoretical (curves) results for different codeword lengths, i.e., $n \in \{8, 16, 32\}$.

Table 2: Bounds for the maximum jamming probability resiliency (\bar{p}_a) varying the codeword length $n \in \{8, 16, 32\}$ and fixing $\epsilon = 10^{-2}$.

n	\bar{p}_a
8	0.30
16	0.55
32	0.74

Therefore, if we set to ϵ the upper bound on the probability for \mathcal{J} to successfully jam the message m (i.e. $P(m' \neq m) \leq \epsilon$), the maximum jamming probability \bar{p}_a the protocol is resilient to can be computed as:

$$\bar{p}_a = \sqrt[n]{-\frac{1}{L_m} \ln(1 - \epsilon)} \quad (4)$$

6.2 Simulation results

We consider the reference scenario of Fig. 7, and the transmission of a message m of length $L_m = 128$ bits. Figure 8 shows both theoretical and simulated results of the *SiG* protocol. Errorbars show the quantile 5, 50, and 95 of 10,000 simulated transmissions of the message m . For each configuration, we derived the jamming probability p_a by setting the number of available frequencies to the constant $F = 124$, while we varied the number of jammed frequencies A from 0 to 124. Moreover, we consider three different codeword lengths, i.e., $n \in \{8, 16, 32\}$. Finally, the pointed curves represent the theoretical predictions provided by Eq. (3).

Table 2 shows the bounds on \bar{p}_a fixing $\epsilon = 0.99$ and varying $n \in \{8, 16, 32\}$; recalling Eq. (4), we can observe in Figure 8 how the bounds perfectly fit the experimental results. For instance, note that *SiG* is able to deliver a 128 bit-string with probability at least 99% ($P(m = m') \geq 1 - \epsilon$), using a codeword length of $n = 16$ in the presence of a jammer \mathcal{J} which proactively jams the 55% of the available frequencies. Finally, we want to stress that our results are obtained

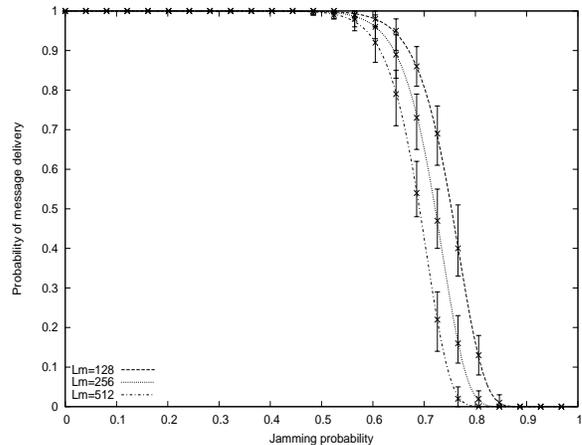


Figure 9: Message delivery probability ($P(m = m')$) with the *SiG* protocol: the message length spans in the range $L_m \in \{128, 256, 512\}$ bits, while the jamming probability has been obtained by fixing $F = 124$ and varying A in $[0, \dots, 124]$. We consider both experimental (errorbars) and theoretical (curves) results for a fixed codeword length $n = 16$.

assuming that the jamming is performed successfully on all the active communications and on a subset ($p_a = \frac{A}{F}$) of the silent radio channels.

Varying the message length L_m . Figure 9 shows both theoretical and simulated results of the *SiG* protocol varying the message length $L_m \in \{128, 256, 512\}$. We fixed the codeword length to $n = 16$, and we set the jamming probability by fixing the number of available frequencies to $F = 124$, while we varied the number of jammed frequencies A from 0 to 124. Errorbars show the quantile 5, 50, and 95 of 10,000 simulated transmissions of the message m , while the curves are obtained by plotting Eq. (3). Recalling Eq. (4), we observe that the bounds in order to guarantee a message delivery with at least 99% probability ($P(m = m') \geq 1 - \epsilon$), are given by $p_a \leq \bar{p}_a = \{0.55, 0.53, 0.51\}$ for a message of $L_m = \{128, 256, 512\}$ bits, respectively, and a codeword length $n = 16$.

Varying the threshold ϵ . Finally, we consider how the successful message jamming probability $\epsilon = P(m \neq m')$ affects the performance of the *SiG* protocol. Equation (4) can be rewritten as function of the codeword length, yielding:

$$n = \frac{\ln\left(-\frac{1}{L_m} \ln(1 - \epsilon)\right)}{\ln(p_a)} \quad (5)$$

Figure 10 shows Eq. (5) varying p_a for different values of the threshold $\epsilon \in \{10^{-2}, 10^{-4}, 10^{-6}\}$, with a message length $L_m = 128$ bits. For instance, assuming a (proactive) jamming probability $p_a = \frac{A}{F} = 0.8$, we observe that a codeword length n ranging in the interval $[40, 80]$ assures a message delivery probability of $1 - \epsilon$, where ϵ ranges in $[10^{-2}, 10^{-6}]$.

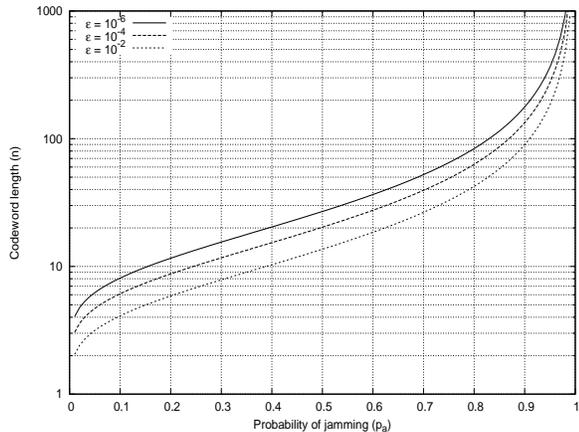


Figure 10: Choosing the codeword length (n) as function of the probability of jamming (p_a). We fixed the message length $L_m = 128$ bits and considered different values for the threshold $\epsilon \in \{10^{-2}, 10^{-4}, 10^{-6}\}$.

7. COMPARISON WITH OTHER SOLUTIONS

In this section we compare our solution with other anti-jamming techniques: Table 3 compares *SiG* with other works as function of the adversarial behavior. Firstly, we recall that —to the best of our knowledge— the adversary considered in this work (\mathcal{J}) is the most powerful ever considered in the literature (see Section 3.2). Standard techniques as [11][17] assume a “pure” proactive adversary, and therefore cannot deal with \mathcal{J} , in fact, both TDBS [11] and UFH-UDSSS [17] are useless against a reactive jammer that promptly interferes with the transmitted message. In particular, TDBS changes the transmission frequency of the peers according to a pre-loaded sequence; nevertheless, the simple frequency hopping is useless against \mathcal{J} , which reactively jams the transmitted message as soon as it appears on the channel. Similarly, UFH-UDSSS combines both uncoordinated frequency hopping and uncoordinated direct spread spectrum: although this approach does not need a pre-shared secret between the peers, a reactive adversary like \mathcal{J} disrupts the communications and prevents message delivery.

A few solutions have been proposed in order to mitigate the effects of a reactive adversary. The solution presented in [22] introduces a novel technique to detect a reactive jammer and raise a jamming suspicion alarm. Authors leverage the combination of bit errors and RSS readings in order to infer on the current presence of a jamming signal. Although, this solution is optimal for the protection of a reactive alarm system, it does not solve the problem of communicating in the presence of a reactive jammer. A similar solution is proposed by [26]: nodes that trigger the reactive jammer are switched off and the messages are routed in order to avoid the nodes close to jammers. This solution involves mainly the identification of jammers’ position and does not deal directly with the jamming attack, yet authors assume the jammed area is a subset of the network deployment, and therefore, the proposed solution is not effective against a \mathcal{J}

Table 3: Comparison with other solutions as function of the \mathcal{J} ’s behavior.

Name	Proactive adversary	Reactive adversary	Multiple adversaries
TDBS [11]	✓	×	✓
UFH-UDSSS [17]	✓	×	✓
[22]	×	✓	✓
[26]	×	✓	✓
BitTrickle [13]	×	✓	×
AntiJam [19]	×	✓	✓
[24]	✓	✓	×
<i>SiG</i>	✓	✓	✓

that can jam the whole network. An interesting solution that directly deals with a reactive jammer is BitTrickle [13]. The solution leverages the delay experienced by a jammer to switch between the sensing and the jamming phase in order to correctly deliver a few bits per packet. Although the authors assume a reactive jammer with unlimited spectrum coverage and transmission power, the proposed solution is not resilient to \mathcal{J} . Indeed, in our adversarial model \mathcal{J} experiences a theoretically zero delay to switch between sensing and jamming. e the frequency slots used for the transmissions). A MAC level solution is proposed in [19]: authors design a protocol that guarantees fair channel access probabilities among nodes in the presence of a reactive jammer. Nevertheless, as for the previous solutions, even AntiJam [19] cannot deal with \mathcal{J} , in fact, to the best of our knowledge, none of the solution proposed in the literature can deal with the reactive jammer introduced in this paper. Finally, the solution presented in [24] is the only one that can be adopted in order to deal with a combined proactive-reactive adversary. The solution is mainly based on a novel mechanical beam-forming design with a fast auto-configuration algorithm, i.e., the geometry of a two-element antenna is controlled by an algorithm in order to obtain a destructive interference for the received jamming signal. Nevertheless, such an approach cannot deal with multiple deployed adversaries or even against a single mobile adversary: indeed, antenna cancellation is achieved with respect to only a specific (static) adversarial position.

8. CONCLUSIONS

In this paper we have introduced a powerful (yet realistic) jammer that is able to reduce to zero the communication bandwidth between two communicating parties, even when state of the art anti-jamming solutions are adopted. To cope with this novel adversary model, we have introduced a brand new communication protocol: Silence is Golden (*SiG*). Implementing a tunable, asymmetric communication channel between communicating parties, *SiG* is able to restore an effective bandwidth between them. We have provided a thorough analysis of the *SiG* protocol, as well as the results of an extensive simulation campaign that do support our theoretical findings and the viability of the *SiG* protocol.

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