On Link Layer Denial of Service in Data Wireless LANs

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Abstract:

In this paper we investigate the resiliency to jamming of data protocols, such as IP, over WLAN. We show that, on existing WLAN, an adversary can successfully jam data packets at a very low energy cost. Such attacks allow a set of adversary nodes disseminated over an area to prevent communication, partition an ad hoc network, or force packets to be routed over adversary chosen paths. The ratio of the jamming pulses duration to the transmission duration can be as low as 10^{-4}. We investigate and analyze the performance of combining a cryptographic interleaver with various coding schemes to improve the robustness of wireless LANs for IP packets transmission [1]. A concatenated code that is simple to decode and can maintain a low Frame Error Rate (FER) under a jamming effort ratio of 15%. We argue that LDPC codes will be very suitable to prevent this type of jamming. We investigate the theoretical limits by analyzing the performance derived from upper bounds on binary error-control codes. We also propose an efficient anti-jamming technique for IEEE802.11b based on Reed-Solomon Codes.

1 Introduction

Current standards for wireless data communications such as IEEE802.11 and Bluetooth are easy targets of denial of service attacks. For example, the physical layers of IEEE802.11 and IEEE802.11b do not have any error-correction scheme. If an attacker sends a strong jamming signal of duration ***one*** bit/symbol it will make the CRC computation wrong. Therefore the whole packet will be lost. If we assume that this wireless link is

used to transmit an IP data packet (usually 12000 bits long), the energy ratio between a jammer and user can be of the order of 1/10000 (which is equivalent to 40 dB gain for the jammer). Other wireless data standards that make use of error-correction codes can also be easily defeated as we will show in Section 2.2. The reason is that current systems are designed to resist non-malicious interference and noise. Even robust wireless links designed to resist jamming do not fully take into account the data aspect of the communication. Existing anti-jamming systems rely on an extensive use of spread-spectrum techniques [2]. These techniques *separately* protect *bits* against jammers. They are adequate for voice communication where the jammer has to keep jamming the channel to prevent a communication. In voice communication, when the communicating nodes use a high-gain spreading sequence, the energy of a jammer can be easily exhausted for a continuous jamming of the voice communication. Non-continuous jamming only results in a graceful degradation of the voice quality. In the context of data communication, spread-spectrum techniques are not sufficient because the jammer does not need to jam a data packet for a long period of time to be able to destroy it. In a "non error-correction" encoded data packet a single bit error generates a CRC error, leading to the loss of the entire packet. Our work aims at building on top of traditional anti-jamming techniques, used at the bit level (such as spread spectrum), to protect data packets.

In the context of a multihop ad hoc network a small number of smart jammers disseminated across a geographical area can last for a long period of time with limited energy resources. Since they only need short jamming durations, the remaining time and energy can also be used to jam other communication channels. They can even be coordinated to create an attack network targeting traffic between specific nodes. They can achieve several goals such as preventing all communication, partitioning a network at low energy cost, or forcing all packets to be routed over chosen areas. In the last case, the traffic will be forced over an area where the adversary has powerful nodes that do better channel decoding and traffic analysis. The adversary nodes can stay in sleep mode most of the time and be triggered to jam some communication between specific nodes. In this case, the attackers would only wake-up to detect some MAC/IP address and, if needed, jam only few bits of the packet to destroy. The attacking nodes receivers can be designed to consume very little energy because the goal is not to demodulate/decode correctly a packet but only to detect (or carrier sense),

with a reasonable probability, ongoing communication. These low-power jammers will be referred to as *cyber-mines.* Even if anti-jamming techniques, such as spread-spectrum, are used, the substantial gain achieved by having to jam only few bits out of 1500 bytes IP packets can be invested in a higher signal power (for direct-sequence spread spectrum) or multi-channel jamming (for frequency hopping spread spectrum). This gain in jamming effort can be invested by the attacker to circumvent the processing gain (usually 20 to 30 dB in the context of military communications) achieved by spread spectrum techniques.

In this paper, we show that it is easy to jam existing wireless data systems at low power cost. We will propose and analyze the performance of various techniques for making data communications reliable in the presence of such malicious attackers. Our techniques are based on the combination of error-correction codes and cryptographically strong interleavers (i.e., adversaries cannot guess the interleaving function). The underlying assumption to our work is that jamming a single bit has a constant cost. We investigate how this cost scales to destroying a complete packet. All existing techniques, such as spread spectrum, can be transparently combined with our approach for an increased resiliency.

We will focus on DoS targeting the physical/link layer. Previous research on physical layer jamming has only focused on bit anti-jamming [2, 3] and not on packet level anti-jamming. Other DoS techniques can be applied at higher protocol layers of systems such as IEEE802.11 (e.g., by forcing the backoff window to remain at its maximum) or Bluetooth MAC (e.g., by destroying some control packet), routing (e.g., by injecting erroneous or destroying control routing packets), and transport protocols (e.g., by forcing TCP multiplicative decrease to keep the congestion window small) [4-11].

In the rest of this section, we introduce the concepts behind reliable communications. In Section 2, we show how existing WLAN standards, such as IEEE802.11 and Bluetooth, can be jammed at very low energy cost. In Section 3, we present the bound on throughput under jamming. In Section 4, we analyze the performance of directly using known binary codes against jamming. In Section 5, we propose and analyze the performance

and the tradeoffs of two concatenated codes against jamming. In Section 6, we argue that LDPC codes are the best choice for long enough packet encoded using binary modulation. In Section 7, address the practical case of IEEE802.11b. Finally, we conclude and propose directions for future research.

1.1 Channel coding

Figure 1 describes a simplified architecture for the transmitter and receiver of a digital communication [2]. We only show the components relevant to our paper. Components such as equalizers, amplifiers, mixers, and antennas are omitted. We consider block codes, but convolutional codes use similar design. The stream of data bits is encoded, then interleaved, and finally modulated for transmission over the channel. The receiver demodulates the incoming signal, then it de-interleaves the bits, and finally error-decodes them.

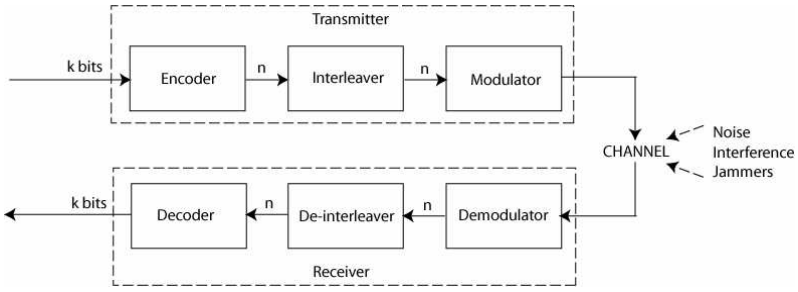
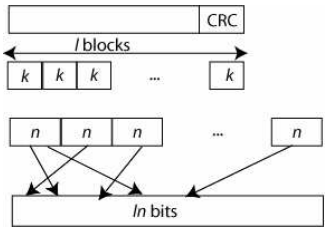


Figure 1: Simplified architecture of a communication link.

The channel encoding is achieved using an error-control code (ECC) [12, 13]. An error-control code can be defined as follows. Let's consider a set of symbols Σ, with cardinality q. A block error-control coding scheme is a function that maps a vector $u = (u_1, ..., u_k) \in \Sigma^k$ into a codeword $v = (v_1, ..., v_n) \in \Sigma^n$. When $q = 2$ the scheme is called a binary error-control code or binary code. The Hamming distance between two words $x, y \in \Sigma^n$ is the number of positions where x differs from y. It is denoted by $\Delta(x, y)$. A code C is a subset of Σ^n, whose minimum distance is defined by $\Delta(C) \stackrel{def}{=} \min_{x,y \in C; x \neq y} \{\Delta(x, y)\}$.

A code C is typically characterized by four parameters $(n, k, d)_q$. n denotes the codeword length, $k = \log_q|C|$ the uncoded word length, $d = \Delta(C)$ the code minimum distance, and $q = |\Sigma|$ the code alphabet size. To simplify the notation, we will omit q when addressing binary codes (i.e., $q = 2$). We usually also characterize a code by its code rate $r = k/n$, and its relative distance $\delta = d/n$. A $(n, k, d)_q$ code can correct at lease $\lfloor (d\text{-}1)/2 \rfloor$ symbols in error.

1.2 Packet encoding



Before transmission, the data information is formatted and processed for reliable error detection and correction. First, a checksum (or CRC) is appended to the data bits. Then, the data sequence is divided into one or several blocks of k bits. Each block is encoded into a codeword of n bits. Finally, the encoded bits are interleaved before being transmitted. The checksum is used by the receiver to verify that the de-interleaved/decoded steps did not lead to an uncorrectable error. We assume that the checksum length is s. In practice, s is usually between 16 and 32 bits.

1.3 Adversarial model

In our discussion, we assume that the physical communication channel is noiseless. We also assume the existence of an adversary. The adversary is capable of sending jamming signals of arbitrary length at any time. And for any bit that the attacker jams, that bit is flipped with probability 1. A more realistic assumption would be to assume that the flipping probability is 0.5. However, both for sake of simplicity and as a worst-case analysis, we assume that all jammed bits are flipped with probability 1. Considering a flipping probability of 0.5 will lead to a higher throughput under the same jamming effort.

Parameters: To quantify the jamming effort of the attacker, we use the sum of the duration of all the jamming signals sent by the attacker when a packet of length nl is being sent. This total duration, measured in bits, is denoted as e. In addition, we define the jamming effort τ as: $\tau = e/nl$. τ is constrained by the code rate and the relative distance of the code $C(n, k, d)$ being used. We will analyze this relation in the subsequent

sections. Our goal is to analyze the various techniques we proposed in terms of achievable throughput under a given jamming effort. We also talk about jamming efficiency which is defined as $1/\tau$.

1.4 Performance evaluation

We will evaluate the performance of the various schemes based on the overall achievable throughput. The throughput is the product of the code rate and the resulting frame success rate (i.e., 1-FER):

$$Throughput = \frac{(lk - s)(1 - FER)}{nl}.$$

(n, k, d) is the error-control code being used, l is the number of blocks in the packet, and s is the checksum length. The frame error rate is the probability that a packet cannot be correctly decoded. This is detected by checking the checksum. We will assume that the checksum is long enough such that all incorrectly decoded packets are detected by the checksum.

1.5 Traditional anti-jamming techniques

Traditional jamming techniques address the energy cost of jamming a single symbol/bit in a communication. The jamming capability of a single symbol is a function of the jammer power, the transmitter power, the antennas gains (from jammer to receiver, receiver to jammer, transmitter to receiver, and receiver to transmitter), the communication receiver bandwidth, the jamming transmitter bandwidth, the range between the transmitter and receiver, the range between the jammer and receiver, the jammer signal loss, and the communication signal loss [3]. Classical jamming consists in injecting an interfering signal that submerges the signal at the receiver. Several interfering waveforms can be used such as noise modulated FM, noise bursts, or continuous wave (CW) tone. The jammer can also play-back a previously recorded signal. Resistance to jamming is traditionally achieved by tuning various parameters such as transmission power, directional antennas, and receiver communication bandwidth. Traditionally, jamming strength is measured through the jamming-to-signal ratio defined as follows [3]:

$$\frac{J}{S} = \frac{P_j G_{jr} G_{rj} R_{tr}^2 L_r B_r}{P_t G_{tr} G_{rt} R_{jr}^2 L_j B_j}$$

P_j:	jammer power	P_t:	transmitter power
G_{jr}:	antenna gain from jammer to receiver	G_{tr}:	antenna gain from transmitter to receiver
G_{rj}:	antenna gain from receiver to jammer	G_{rt}:	antenna gain from receiver to transmitter
R_{tr}:	distance from transmitter to receiver	R_{jr}:	distance from jammer to receiver
L_r:	communication signal loss	L_j:	jammer signal loss
B_r:	communications receiver bandwidth	B_j:	jamming transmitter bandwidth

Transmission power level: Protection against jamming in wireless communication is usually achieved by reducing the jamming to signal ratio. The obvious techniques to reduce the jamming-to-signal ratio is based on increasing the transmission power level. However, this technique is not very efficient and is usually used as a last solution.

Spread-Spectrum: The most commonly used anti-jamming technique is *spread spectrum* [2]; it relies on reducing B_r/B_j. This techniqus force the jammer to spend much more energy than the sender. This is achieved by forcing the jammer to jam over a larger frequency band than the effective receiver/communication bandwidth. The typical value of the spread spectrum processing gain in military communication is between 20 dB and 30 dB. Spread spectrum technology uses a pseudorandom sequence to spread a signal over a much larger frequency band than what is required for its transmission. Correlating the received signal with the pseudorandom sequence carries out the dispreading operation. There are two main spread spectrum techniques, namely: the direct sequence technique and frequency hopping. If the pseudorandom sequence is unknown to the jammer, then the spreading operation achieves a processing gain G in the signal-to-jamming ratio. To successfully jam a communication the adversary would have to compensate this processing gain by increasing its transmission power. There are practical difficulties with high spreading factors such as time of acquisition (synchronization) and required bandwidth.

Directional antennas: Another technique to resist to symbol jamming is based on reducing the antenna gain from the jammer to the receiver. This can be achieved by using directional antennas, sectored antennas, or smart antennas creating reception beams centered on the transmitter.

It is worth noting that reducing the jamming-to-signal ratio does not necessarily lead to complete resiliency to jamming. This is due to other vulnerabilities introduced by higher protocol layers. Previous research in the area of anti-jamming has mainly focused on bit error probability of anti-jamming systems [14]. The main application being voice communication. In this paper, we are interested in techniques for *data packet* jamming. We assume that a bit-level anti-jamming technique, such as spread spectrum, or antenna directivity can be used. We assume that jamming a single bit requires some constant effort. We investigate how this effort scales when a data packet, such as in the IP protocol, is transmitted.

2 Jamming Data Communication

In this section, we show how an adversary can jam existing WLAN when used to transmit IP packets. We also present the jamming effort for various modes of IEEE802.11, IEEE802.11a/b, and Bluetooth.

2.1 Technique [Jamming no-ecc, ecc, interleaver+ecc]

A communication that is not protected with error-control codes (ECC) can be denied by destroying a single bit in each packet. However, even error-correcting codes have a bounded error-correction capability. Practical codes cannot tolerate bursts of errors that exceed some small bound (e.g., a Hamming code is only able to correct a single bit and cannot tolerate two bit errors in the same block). In practice, a combination of an interleaver and an error-correction code is used. The interleaver spreads the burst of errors over multiple blocks, which allows reducing the number of errors per time window (or block) below the error-correction capability of the code. These are known techniques in the context of non-malicious interference. In traditional communication systems, the structures of the interleaver and ECC are publicly known. Therefore the attacker can choose which bits to jam such that, when de-interleaved, they will result in a burst of errors that exceeds the ECC capability.

Figure 2 shows how an adversary can corrupt a data packet for three types of communication. A single interference pulse corrupts the packet when no error-correction is used. A jamming burst exceeding the error-correction capability of the code results in an unrecoverable error. Finally, if the structure of the interleaver is known, the adversary can choose a sequence of pulses that leads to uncorrectable errors.

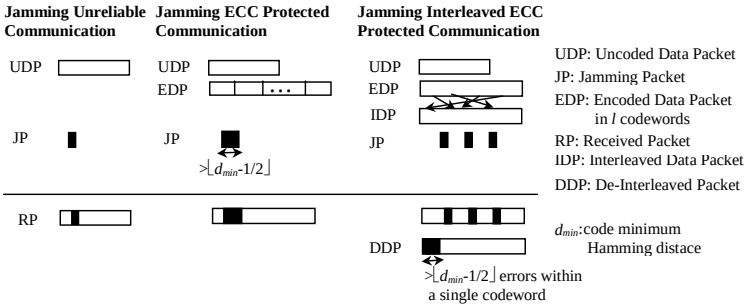


Figure 2. Low-power jamming of a data packet.

2.2 Jamming existing systems

2.2.1 IEEE802.11 and IEEE802.11b

IEEE802.11 sends the data using a Differential Binary Phase Shift Keying (DBPSK) modulation (1 Mbps) or Differential Quaternary Phase Shift Keying (DQPSK) (2 Mbps) [2, 15]. The bits are spread using an 11 chips Barker code. IEEE802.11 does not use any error-correction scheme. Therefore, a single interference pulse of length 1 bit (i.e., duration 1 μs) can destroy an IP packet of size 1500 bytes. As a result, the jammer saves energy by a factor of 1/12000 or 1/6000. Table 1 summarizes the jamming efficiency (i.e., 1/(jamming effort)) of an adversary for IEEE802.11 modes.

Modulation/coding Rate	**Packet length IP packet**	**Number of bits needed to jam**	**Jammer Efficiency**
BPSK	1500*8	1	12000
QPSK	1500*8	2	6000
CCK (5.5Mbps)	1500*8	4	3000
CCK (11Mbps)	1500*8	8	1500

Table 1: Jammer efficiency against IEEE802.11.

IEEE802.11b uses a *complementary code keying* (CCK) modulation [16]. CCK allows transmissions at data rates of 5.5 Mbps and 11Mbps. The data stream is divided into symbols of 4 bits for 5.5 Mbps data rate or

symbols of 8 bits for 11 Mbps data rate. If the jammer destroys one symbol, it will succeed in destroying the packet. Therefore the jammer effort is 4/12000 for 5.5 Mbps and 8/12000 for 11 Mbps data rate.

2.2.2 IEEE802.11a

IEEE802.11a has 8 possible data rates (i.e., 6 Mbps, 9 Mbps, 12 Mbps, 18 Mbps, … , 54 Mbps). It uses various modulation techniques (i.e., BPSK, QPSK, 16QAM, 64QAM) and convolutional coding with various coding rates (i.e., 1/2, 2/3, 3/4). IEEE802.11a also uses an interleaver. Both the convolutional code and the interleaver are applied to blocks of bits. Each block of bits is separately encoded as an OFDM symbol (Orthogonal Frequency Division Multiple Access) [17]. The size of these blocks varies from 48 to 288 depending on the modulation and coding rates. The 48 bits per symbol encoding provides a 6Mbps data rate, while the 288 bits per symbol provides 54 Mbps data rate. If the adversary successfully jams a whole OFDM symbol, the whole IP packet will be lost. Table 2 summarizes the jamming efficiency against IEEE802.11a modes for an adversary to successfully destroy a typical IP packet. To compute the jamming efficiency we divide the size of an encoded IP packet by the number of bits per OFDM symbol. This is only the worst case scenario from the jammer's perspective. More efficient jamming can be achieved by destroying sub-OFDM symbols to exceed the error correction capability of the used codes.

Data Rate (Mbps)	**Modulation**	**Coding Rate**	**Bits per Symbol**	**Encoded IP Packet length**	**Jammer Efficiency**
6	BPSK	½	48	1500*8*2	500
9	BPSK	¾	48	1500*8*4/3	333
12	QPSK	½	96	1500*8*2	250
18	QPSK	¾	96	1500*8*4/3	167
24	16QAM	½	192	1500*8*2	125
36	16QAM	¾	192	1500*8*4/3	83
48	64QAM	½	288	1500*8*2	62.5

54	64QAM	¾	288	1500*8*4/3	55.5

Table 2. Jamming efficiency against IEEE802.11a.

2.2.3 Bluetooth

Bluetooth uses a Gaussian Frequency Shift Keying (GFSK) modulation combined with slow frequency hopping spread-spectrum technique [18]. Since it is simple for an attacker to recover the frequency hopping sequence, we will ignore the spreading gain against a malicious attacker. Bluetooth recovers from errors using three techniques: ARQ retransmissions, (15, 10, 4) shortened Hamming code, or 1/3 repetition code. Only the (15, 10, 4) code and ARQ are used with data packets. The data packets have various sizes and error-coding schemes. They are designated by the standard as DH1, DH3, DH5, DV, DM3, and DM5. Table 3 summarizes these packet sizes and error-coding schemes. These coding schemes are easy to overcome. When the ARQ scheme is used, it is sufficient to destroy a single bit in order to systematically generate a CRC error. The (15, 10, 4) code has a minimum distance of 4 and therefore can be exceeded by jamming two bits. Bluetooth does not have any interleaving[1] scheme. Although DV packets have relatively good performance, they are not the preferred mode for data communication because of their high overhead.

Data Packet Type	Number of bits	Num of bits to jam	Jammer Efficiency
DH1 (no ECC)	28*8 = 224	1	224
DM3 (15, 10, 4)	123*8 = 984	2	984/2 = 492
DH3 (no ECC)	185*8 = 1480	1	1480
DM5 (15, 10, 4)	226*8 = 1808	2	1808/2 = 904
DH5 (no ECC)	341 * 8 = 2728	1	2728
DV (15, 10, 4)	150	2	75

Table 3. Jamming efficiency against Bluetooth data packets.

[1] Whitening is used against DC bias and is applied before encoding. It doesn't help against errors.

3 Performance bounds

In this section we discuss the interleaving technique that will be applied to all the coding schemes we will consider. Then we discuss the asymptotic bound of throughput under jamming.

3.1 Cryptographic interleaving

As discussed previously if the structure of the interleaver is public, the jammer can decide on which bits to jam to make one block uncorrectable at a minimum jamming cost. Therefore even if the remaining blocks are correctly decoded the CRC will still indicate an error. We define an interleaver as a permutation function π such that a packet of size m: $p_0, p_1, \ldots, p_{m-1}$ will be encoded into $p_{\pi(0)}, p_{\pi(1)}, \ldots, p_{\pi(m-1)}$. The ideal cryptographic interleaver is defined as a function Π that takes as parameter a key K and provides a permutation $\Pi(K) = \pi$, where π can be any permutation function over a set of size m, and there is no way to guess π for an adversary who does not know the key K. An additional parameter such as the current time can be provided to Π to allow the communicating ends to periodically change the permutation function. If the interleaving function is unknown to the adversary, a jamming of total duration e would be perceived by the receiver as a Binary Symmetric Channel (BSC) with Bit Error Rate (BER) e/m. The jammer cannot benefit from the knowledge of the error control code being used to do better than a BSC. The cryptographic interleaver is basically a transposition cipher except that the goal is not to provide confidentiality of data but to prevent the jammer from guessing which bits to jam.

3.2 Shannon's bound

Since the cryptographic interleaver transforms the effect of jamming into a binary symmetric channel, then the bound on the achievable throughput can be derived from Shannon's capacity for a BSC:

$$C = 1 - H(p)$$
$$C = 1 + p\log_2(p) + (1-p)\log_2(1-p)$$

where H is the entropy function and p the bit error probability.

4 Direct application of binary codes

In this section, we investigate a direct use of the performance of binary error-correction codes. We are interested in figuring out the best performance that could be achieved. Therefore, we do not consider issues related to actually constructing the best codes or being able to decode them. Subsequent sections will consider more practical constraints.

4.1 Single codeword binary code

The most direct approach to resist to jamming is to use the best known codes. In [19], a compilation of upper bounds on binary codes for values of n below 28 is presented. [13] provides a table of upper bounds on best known binary codes for values of n within the interval [28, 512] and for values of minimum distance $d \leq 29$. In order to assess the best we can do against jamming, we have plotted the coding rate required to resist a jamming effort of 15% and 20%. To be able to resist to a jamming effort of τ, the error code has to verify the following constraint: $d > 2*\tau*n$. **Figure 3** shows the upper bound on the coding rate derived from the upper bound on binary codes. Here the coding rate is computed as the ratio of k and n. We do not take into account the checksum overhead given the short length of the codes. Using only short codes per checksum would be inefficient. In Section 4.2, we analyze the use of multiple short codes combined with a single checksum. Only values up to $n = 95$ are used because longer codes, that resist to the jamming effort we consider, require higher minimum distance than given by the tables (i.e., the maximum distance given in [13] is 29). The up and downs in the curves are a result of the discrete characteristic of the codes.

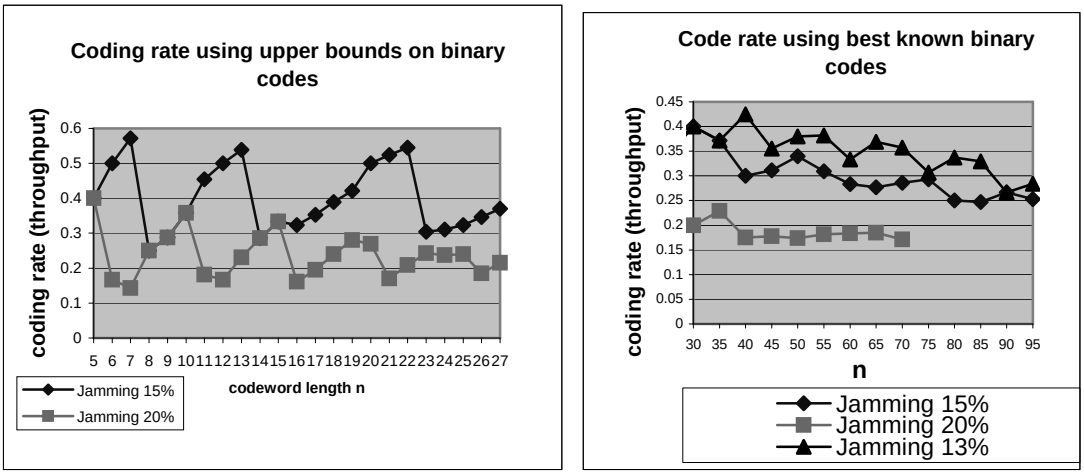


Figure 3: Upper bound on coding rate against jamming effort of 15% and 20%.

From Figure 3, we can conclude that reasonable throughput can be maintained against 20% jamming effort. This should be contrasted with the performance of existing WLAN. The latter would lead to a throughput that is almost zero for a jamming effort much lower than 10%. Also to understand why we claim that this performance is good, one can consider the theoretical asymptotic bound on capacity for a BSC channel of BER 20% is $C = 1\text{-}H(0.2) = 0.27$. The asymptotic bound for BER equal to 15% (13%) is 0.39 (0.44).

Even if the achievable throughput can be maintained at a reasonable value using best codes, it is both very difficult to find these codes, and also difficult to decode them efficiently. This becomes specially true when n is increased beyond 100 bits. Using only short codes (i.e., $n<20$) is not reasonable because of the checksum overhead. The following sections will investigate some alternatives.

4.2 Multiple codeword binary code

Because of the limitations of using a single codeword, it is natural to think of using multiple codewords that are interleaved together. The structure of the interleaver can be cryptographically. Therefore the effect of the jammer is seen as randomly picking e bits and flipping their values. We will keep this assumption in the remaining of the paper. The coding procedure is as follows:

1. The data packet (including a checksum) is divided into l blocks of k bits each.
2. Each block is encoded using a (n, k, d) binary code.
3. The nl bits are cryptographically interleaved with a secret shared key[2].

The decoding procedure is as follows:

1. The packet is deinterleaved.
2. Each block is separately decoded.
3. The packet is kept only if the checksum is correct.

The error-detection is achieved using the checksum. The probability of not detecting an erroneous decoding is considered to be negligible (in the order of 2^{-16}).

Proposition 1: Let e be the total number of bits that an attacker jams during the packet transmission, and X_i be the number of error bits in codeword i ($1 \le i \le l$). The distribution of X_i is multivariate hypergeometric:

$$\Pr[\prod_{i=1}^{l} X_i = e_i] = \frac{\prod_{i=1}^{l} \binom{n}{e_i}}{\binom{nl}{e}} \qquad (\sum_{i=1}^{l} e_i = e; 0 \le e_i \le n).$$

The probability that some specified codeword contains x errors is:

$$\Pr[X = x] = \frac{\binom{l}{x}\binom{(l-1)n}{e-x}}{\binom{nl}{e}}.$$

Proposition 2: The probability that a packet is dropped when e bits are jammed is the probability that at least one codeword has more than $t = \lfloor (d\text{-}1)/2 \rfloor$ errors (error-correction capability of the code) is:

$$\Pr[\bigvee_{i=1}^{l} X_i > t] \qquad (\sum_{i=1}^{l} X_i = e; 0 \le X_i \le n).$$

The probability in Proposition 2 can be evaluated using Proposition 1, which unfortunately is tedious [20]. Since it is very difficult to compute the packet error probability using a closed form formula or an analytical

[2] In this paper we do not address how this shared key can be established. One possibility is offline setup.

approach, we have simulated this probability for various values of *n*, *k*, *d*, and *l*. Figure 4 shows that the probability of packet error increases rapidly to 1 for a constant jamming effort (7%, 14%, and 28%). We simulated two short codes with good minimum distance and coding rates: the Hamming code which is perfect and a Preparata code (15, 8, 5).

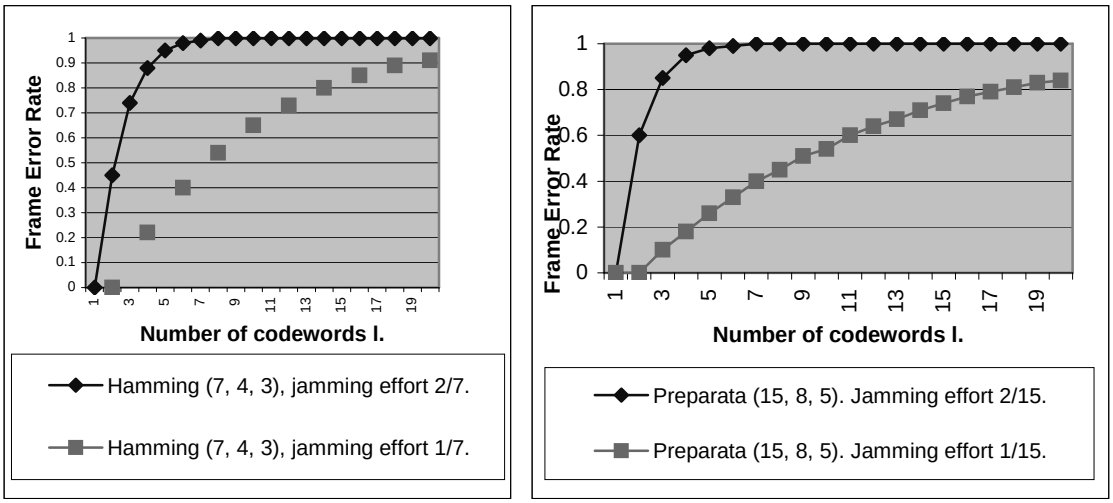


Figure 4: Frame error as a function of the number of codewords.

5 Concatenated Codes

Because of the difficulty to find and decode reasonably long binary codes and because of the poor performance of multiple short codewords, we propose to investigate a set of concatenated codes. The concatenated codes are defined as the use of two error correction codes in sequence. The first code $(n_2, k_2, d_2)_{q2}$ is called an outer code and the second code to be used is called an inner code $(n_1, k_1, d_1)_{q1}$ [2]. The sequence of symbols of the outer codeword is then encoded using the inner code.

For medium size packets, we propose a concatenated code using a Reed-Solomon (RS) code as the outer code and a good short block code as the inner code. The advantages of using RS codes [21-23] are its flexibility and easy decoding. The flexibility of RS codes allows us to adapt the code rate/error correction capability to the jamming effort. This can be done by retransmitting additional redundancy only when necessary (i.e., channel being jammed). This process is usually called Hybrid-ARQ type II. The overall coding rate of the

concatenated code is the product of the coding rate of the inner code by the coding rate of the outer code: $r = r_1 * r_2$ (i.e., $k_1 * k_2 / n_1 / n_2$). The throughput of a concatenated code is $r_1 * r_2 * (1\text{-FER})$. Finally, for a RS outer code, the frame-error rate of the concatenated code is FER = Prob[(number of inner code decoding errors) > $(n_2 - k_2)/2$].

We consider the generalization of RS-code that describes them as non-binary Maximum Distance Separable (MDS) code that can be characterized as $(n, k, n-k+1)_q$, such that $k \leq n \leq q$ [24]. For more information on the construction of RS-codes, the reader is referred to [21]. In this paper, we only consider their properties. RS codes flexibility proved to be useful in various contexts [25, 26]. When combined with an inner code, the number of codewords of the inner code limits the number of RS code symbols. Therefore the inner code cannot be too short. We have considered two inner codes taken from [19], namely: the Preparata code (15, 8, 5) and the (26, 10, 9).

The coding procedure is as follows:

1. The data packet (including a checksum) is divided into k_2 blocks of k_1 bits each.
2. Each block of k_1 bits is seen as a symbol of the outer-code (RS). These k_2 symbols are encoded using the $(n_2, k_2, n_2-k_2+1)_2^{k1}$ RS code. This results into n_2 symbols (blocks) of k_1 bits each. This can only be done if $n_2 \leq 2^{k1}$
3. Each block of k_1 bits is now encoded using the inner code leading to blocks of n_1 bits.
4. The resulting $n_{1*}\, n_2$ bits are cryptographically interleaved.

The decoding procedure is as follows:

1. The packet is deinterleaved.
2. Each (n_1, k_1, d_1) block is separately decoded.
3. The RS code is decoded.

We simulated this scheme under various jamming efforts. Figure 5 shows the performance of the two concatenated codes under 13% and 15% jamming effort. For each value of n_2 we choose the value k_2 that

maximizes the throughput function assuming a constant jamming effort of 13% or 15%. Figure 5 shows that the concatenated codes maintain good performance even for large values of $n=n_1*n_2$. For example, if we compare the best known code for jamming effort 13.3% to the performance of the concatenated RS-(15, 8, 5) code for length 105 bits we obtain the following[3]:

- The best known code that tolerates 13.3% jamming effort needs a minimum Hamming distance of 29 (105*0.133*2+1). From [13] this would correspond to a (105, 29, 29). Therefore its coding rate (or throughput under 13.3% jamming) would be 29/105 = 0.276.
- The best combination of RS-(15, 8, 5) would be with a $(7, 3, 5)_8$ RS code with symbols of 8 bits concatenated with the (15, 8, 5) code. From our simulation of 13.3% bits in error this code provides a throughput of 0.15 (see Figure 5).

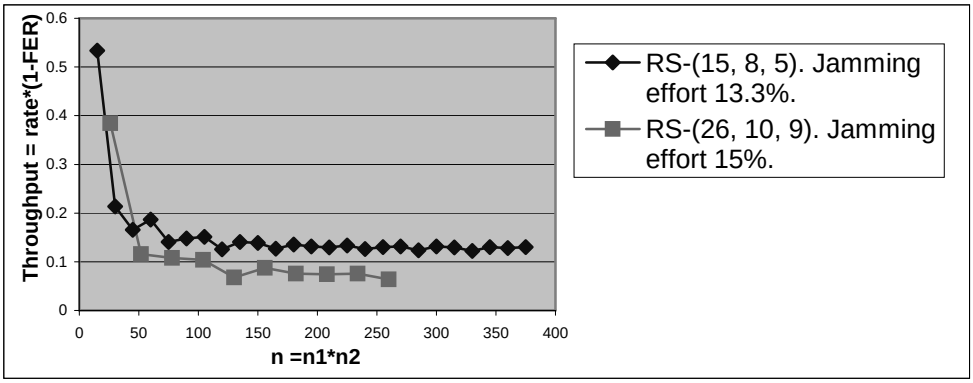


Figure 5: Concatenating Reed-Solomon codes with a short code maintains a 8% throughput even under 15% jamming effort, and a 13% throughput under 13.3% jamming effort.

The performance of the proposed concatenated code is 0.15, which is better than half the performance of the best known code (0.15> ½*0.276). Although the concatenated code is not the best in performance it has several advantages. It is much easier to decode (even in software) than a long best known code. Some of the best known codes can only be decoded using exhaustive search, which is unrealistic for practical applications. One of the most important advantages of RS codes is their flexibility in providing more error correction capability on demand. In the first transmission the sender only needs to send a small number of redundancy

[3] The values of n = 105, and jamming effort 13.3% are chosen in order to simplify the comparison by getting integer values.

symbols. If the receiver is unable to decode the packet than the transmitter can send additional redundancy symbols [21]. This property can be used to design an anti-jamming hybrid ARQ protocol that is adaptive to the jamming effort of the adversary.

6 Low Density Parity Check Codes

In this section, we argue that for packets that are in the order of 10000 bits LDPC codes are the most suitable. LDPC codes were initially introduced by Gallager [27] in 1962, but were forgotten for almost thirty years except for few exceptions. They were recently rediscovered [28] and attracted lot of interest because of their near Shannon limit performance. Good LDPC codes have high bloc size, which makes them impractical for short packets. However, they are perfect for long packets such as 12000 bits IP packets. LDPC codes have also low decoding complexity. Lot of research is being done in identifying good LDPC codes that can be efficiently implemented in hardware and software. Here we report on the performance of LDPC-like codes against various jamming levels. These values are derived from the achievable BER with some very good irregular LDPC codes under a BSC channel [29]. The code throughput is computed as 1-*FER*. The code length is 16000 bits.

Jamming Effort	Code Rate	Shannon Limit	Code Throughput
8%	0.5	0.598	0.5
17.4%	0.25	0.333	0.25

Table 4. Achievable throughput by some Irregular-LDPC codes under various jamming effort.

Table 4 shows that LDPC are suitable for long packets and can provide high throughput under high jamming effort (i.e., 17%). Even if LDPC codes use a single block-encoding scheme they still require the use of a cryptographic interleaver. This is due to the following facts. Firstly, LDPC codes correct errors beyond half of their minimum distance [28]. Which is a powerful characteristic of LDPC. Secondly, optimized LDPC codes can have a small effective minimum distance. Therefore there still exist a small set of low weight errors than cannot be corrected [30]. This effect is called the error floor. If no cryptographic interleaving is used than the adversary can induce such errors. Cryptographic interleaving prevents the jammer from generating pulses that

would result in such patterns. Another set of near-Shannon codes are Turbo-codes and are also a good alternative to LDPC codes specially for shorter packets.

7 The Case of IEEE802.11b

In this section we consider the special case of IEEE802.11b. The data packet is no more considered as a sequence of bits but as a sequence of symbols of 8 bits. We propose to use extended-Reed-Solomon codes against jammers. Reed-Solomon-like codes (RS-codes) are particularly efficient codes, however they are non-binary. A single bit error has the same effect as a symbol error. Therefore they are not suitable for correcting bit errors. However, combining RS-codes with modulation schemes that transmit multibit symbols can lead to efficient anti-jamming techniques. This is the case for IEEE802.11b. The assumption here is that the adversary destroys the whole symbol.

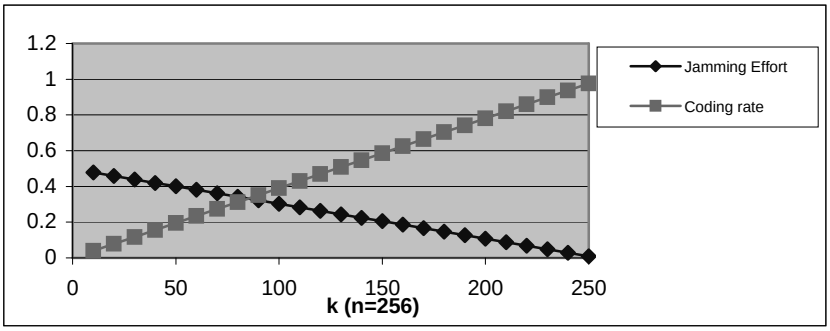


Figure 6: Jamming effort and coding rate (or throughput) for various RS encoding schemes.

CCK communication used in IEEE802.11b transmits 8 bits in each symbol (when used at 11Mbps). Since the symbol size is 8 bits, it is possible to create an extended-RS-code of maximum length 256 symbols. It is possible to resist to the jamming of j symbols out of N=256, if $k = 256-2*j$ symbols are used for data information. For example, if k is taken equal to 85, the adversary needs to jam (256-85)/2 = 85 bytes to destroy the data packet. Therefore, the jamming effort has to be 1/3. Furthermore, the data rate (or throughput) is still reasonable at 85/256 = 1/3. Figure 6 shows the jamming effort that can be tolerated and the corresponding data rate for various values of k. In other words, the throughput is a linear function of the jamming effort. It decreases from 1 to 0 when the jamming effort increases from 0 to 0.5.

8 Conclusion and future work

In this paper, we have investigated the problem of denial of service against data packets (e.g., IP packets) transmitted over WLAN protocols (i.e., IEEE802.11 and Bluetooth). Our results are as follows:

- We have shown that it is easy to jam such communications at an energy cost that is much lower than the transmitter's cost. Such attacks cannot only prevent communication within large areas for long periods of time but can also lead to other more elaborate and coordinated attacks such as partitioning of a multihop ad hoc network or forcing packets to be routed over chosen paths. Previous research in DoS has mainly focused on either bit-level anti-jamming or MAC/Routing layer issues.
- We investigated the use of cryptographically strong interleavers and error control codes to prevent low power jamming, and show that straightforward use of short codes interleaved together provides poor performance.
- We have analyzed the performance of the best-known binary codes and shown that, for binary modulation and long data packets, LDPC codes can sustain a good throughput under a reasonably high level of jamming.
- Finally, we have proposed and analyzed the performance of some Reed-Solomon concatenated codes. The advantages of such codes are their flexibility to achieve adaptive anti-jamming, long codewords, and simple decoding. We have also shown how to provide very efficient anti-jamming for 802.11b.

As future directions for research we plan to investigate the performance of hybrid-ARQ type II based on Low Density Parity Check codes (LDPC) against dynamic jamming efforts. In a practical setting, the communication is not always under attack. If the communicating nodes are always using excessive error-correction codes, then they will waste bandwidth. Therefore, the communicating nodes should use an adaptive scheme that increases the resistance to jamming whenever an attack is detected. Other directions of research are in the area of multi-layer DoS where the adversary can combine weaknesses of layers.

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