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Efficiency of two decoders based on hash techniques and syndrome calculation over a Rayleigh channel

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ABSTRACT

The explosive growth of connected devices demands high quality and reliability in data transmission and storage. Error correction codes (ECCs) contribute to this in ways that are not very apparent to the end user, yet indispensable and effective at the most basic level of transmission. This paper presents an investigation of the performance and analysis of two decoders that are based on hash techniques and syndrome calculation over a Rayleigh channel. These decoders under study consist of two main features: a reduced complexity compared to other competitors and good error correction performance over an additive white gaussian noise (AWGN) channel. When applied to decode some linear block codes such as Bose, Ray-Chaudhuri, and Hocquenghem (BCH) and quadratic residue (QR) codes over a Rayleigh channel, the experiment and comparison results of these decoders have shown their efficiency in terms of guaranteed performance measured in bit error rate (BER). For example, the coding gain obtained by syndrome decoding and hash techniques (SDHT) when it is applied to decode BCH (31, 11, 11) equals 34.5 dB, i.e., a reduction rate of 75% compared to the case where the exchange is carried out without coding and decoding process.

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1. INTRODUCTION

In radio mobile links, the transmission channels evolve with time due to the random movements of the communicating entities and the existence of obstacles all along the road that links the transmitter and receiver. As a result, a transmitted signal may follow several paths before reaching the receiver, leading to significant variability in the received signal owing to the addition of several phase-shifted signals. A Rayleigh channel allows to take into account a number of effects such as multiple reflections, fading, and large and small scale fluctuations. The amplitude and phase of the received signal appear as random variables that follow the Rayleigh law. This model is particularly suitable for a statistical representation of a mobile radio channel.

Several recent studies have been interested in the investigation of additive white gaussian noise (AWGN) and Rayleigh channels in different environments [1]–[8]. Mattera *et al.* [1] presented a filter bank multicarrier layout at the base of a sine model filter adopting an overlapping factor equal to 2. To test their solution, they have used it on a frequency-selective Rayleigh fading channel. The originators have investigated a wiretap form of secondary fading multiple access channels to be secondary multiple access wiretap channel over Rayleigh/Rayleigh and Rayleigh/Nakagami fading [2]. A comparison of bit error rate (BER) performance had been done by Khansa *et al.* [3] between non-orthogonal multiple access-2000

(NOMA-2000) and power-domain NOMA employing many types of channels. As regards Rayleigh transmit channel, they considered at the same time static and dynamic user grouping. Zhang *et al*. [4] introduced multi-user orthogonal high efficiency differential chaos shift keying scheme. Moreover, they have offered a BER expression for multiple-input single-output of their scheme taking into account the Rayleigh transmit channel. Liao *et al.* [5] presented multi-time channels predictions scheme at the base of backpropagation neural networks and multi-hidden layers. Moreover, they had introduced a technique to construct sparse channels samples. This technique is able to save in an effective way the systems resources while maintaining strong results. Gomez-Deniz *et al.* [6] proposed a new distribution to model fading-shadowing wireless channel. Their proposed solution has presented many benefits on Rayleigh-lognormal distributions, in addition to K distributions. Bouabdellah *et al*. [7] examined the secrecy outage probability in addition to intercept probability trough Rayleigh channel for two-hop cognitive radio transmission layout. Grant [8] studied the flat fading channels with multiple antennas.

Tasneem *et al.* [9] presented a comparison of the performance of worldwide interoperability for microwave access (WiMAX), a wireless metropolitan area networking-based system, over AWGN, Rayleigh, and Rician fading channels. Vidhya and Kumar [10] implemented AWGN, Rayleigh, and Rician channel models by using least square (LS), LS-modified, and minimum mean square error (MMSE) algorithms. Yang *et al.* [11] investigated the AWGN and Rayleigh fading channels capacity employing phase-shift keying (PSK) in addition to quadrature amplitude modulation (QAM). They adopted successive interference cancellation in addition to an entropy power Gaussian approximation. Al-Hussaibi and Ali [12] presented a method to simulate equal/unequal concerning the generation of power-correlated Rayleigh fading channels..

Moreover, we found some decoders developed at the base of syndrome decoding and hash techniques over AWGN channel employing a binary phase-shift keying (BPSK) modulation [13], [14]. Moreover, the Gaussian transmit channel was the subject of work [15]. We should also note the presence of works that have explored the impact of both AWGN and Rayleigh transmit channels like [16]–[18].

Moreover, the Rayleigh channel has been the subject of several recent works [19]–[25]. Shaik and Dhuli [19] evaluated outage performances concerning multi-cell NOMA networks over interference-limited scenarios through Rician/Rayleigh fading channel. Raza *et al*. [20] unified the radio frequency energy-harvesting layouts over a combined Rayleigh-Rician faded channel. Nguyen *et al*. [21] analyzed the performances of a new energy-harvesting layout concerning two-way half-duplex relay networks, having two source nodes that exchange information thanks to a single relay through block Rayleigh channels. Le [22] proposed a novel single-integral and infinite-summation selection of multivariate equally correlated generalized Rayleigh faded to the multiuser-multiple-input-multiple-output system. Mamidi and Sundru [23] presented throughput study for cooperative spectrum sensing networks adopting enhanced energy detector layout through Rayleigh channel. Ying *et al*. [24] exploited a learning algorithm to propose detector to Rayleigh flat-fading channels having non-Gaussian interferences. In study [25], a performance analysis of orthogonal frequency division multiplexing at the base of 3-hop amplifies in addition to forward relaying network through mixed Rician/Rayleigh fading channel.

In order to judge the efficiency of a given decoder and its ability to be deployed in a reliable telecommunication system, we must determine its BER results in terms of signal-to-noise ratio (SNR) values. The present paper provides a global study of two decoders hard decision decoder based on hash and syndrome decoding (HSDec) [13] and syndrome decoding and hash techniques (SDHT) [14], which are developed at the base of syndrome decoding and hash techniques, over Rayleigh channel with a BPSK modulation. This work gives concrete results to the researchers of the field since it puts at their disposition practical results. These results are the fruit of numerical simulations of decoding of linear block codes, especially some Bose-Chaudhuri-Hocquenghem (BCH) and QR codes on Rayleigh channel adopting BPSK modulation.

The rest of this work is structured: section 2 gives the syndrome decoding principle, those of studied decoders, and describes AWGN and Rayleigh channels. Section 3 offers simulation findings and comparisons. In the end, a conclusion and prospective directions for our work are given in section 4.

2. METHOD

2.1. Syndrome decoding principle and the studied decoders

2.1.1. Syndrome decoding principle

How can we ensure that a received sequence «r» corresponds to the codeword sent by the transmitter? The answer to this question represents the syndrome decoding principle. Because of noise in the channel, the sequence that the recipient gets is not constantly similar to the one transmitted by emitter. Let *«h»* be the binary version of the received sequence *«r»*, the polynomial representation of *«h»* can be written as (1),

$$h(X) = c(X) + e(X) \quad (1)$$

where *c(X)* is a codeword in polynomial representation and *e(X)* is error added by the channel in polynomial representation. The syndrome vector «s» in representation form:

$$s(X) = h(X) \bmod g(X) = e(X) \bmod g(X) \quad (2)$$

where, *g(X)* is the generator polynomial. The computation of the syndrome vector «*s*» associated to the sequence «*h*» by the control matrix (parity check matrix) *H* proceeds as:

$$s(h) = s(c) + s(e) \quad (3)$$

$$s(h) = h.H^t = c.H^t + e.H^t = e.H^t \quad (4)$$

where, H^t is the transpose of a parity check matrix of the code.

Syndrome decoding is a very efficient method for decoding linear codes. Its principle is to calculate the vector syndrome «*s*» (using (2) or (4)) of the received word to determine whether an alteration has taken place or not. Accordingly, two cases must be distinguished:

- If the syndrome is zero, then most likely there was no error in the transmission operation.
- If the syndrome is not zero, then there was an error vector added to the codeword transmitted by emitter. In this situation, we must look for an error pattern «e», having a weight less than or equal to the correction capability of the code «t», which has the same syndrome value as that of the received word h. Therefore, the decoder corrects the received word «h» by the error vector «e».

2.1.2. The HSDec decoding algorithm

The hard decision decoder based on hash and syndrome decoding (HSDec) [13] represents a decoding algorithm based on syndrome computation and on the hash technique. The principle of the HSDec decoder is as:

- Building the hash table (TH) to store all corrigible error patterns: the storage position of every corrigible error pattern equals the decimal value of its binary syndrome.
- Using a powerful hash function, which finds error patterns immediately from received word syndrome. On a word reception, the receiver calculates the value of his syndrome «*S*» and instead of making an exhaustive search in the TH table; it directly accesses the line corresponding to «*S*». This greatly reduces the search time of the decoding algorithm.

Algorithm 1. The HSDec algorithm

```
The HSDec decoder works as follows:
            Input:
              b: binary word to decode of length n
              TH: Hash table
            Output:
              c: The corrected word
            Begin
               Compute syndrome «S» of «b» using formulas (2) or (4).
               Compute «index» the hash value of the syndrome «S».
               Correct the received binary word «b» by the error pattern stored in the line
               number «index» in the «TH» table.
            End
The function "Hash" was introduced as following:
```

Algorithm 2. The hash function algorithm

```
Function Hash(S: binary vector of n-k digits): integer
            Index ← ∑_{i=0}^{n-k-1} S[i] * 2^{n-k-i-1}
            Return Index
End Function
```

The hash table TH contains all the error patterns whose weights are less than or equal to the correction capacity of the studied code. Therefore, line number «*m*» contains the error pattern «*e*», such as *m=Hash* (syndrome value of «*e*»). The use of the hash function makes it possible to determine the storage position of a given error pattern.

2.1.3. Syndrome decoding and hash techniques decoder

The super digital hand tester (SDHT) [14] decoder is a soft in hard out (SIHO) decoding algorithm based on syndrome computation and hash techniques. The use of hashing techniques made it possible to minimize the execution time of the algorithm. With the use of the hash techniques, the determination of the row that contains all the possible error patterns whose weight is less than or equal to the threshold Th is directly determined. Therefore, the codeword closest to the received word can be found easily.

The decoding steps of the SDHT algorithm are detailed in Figure 1. SDHT decoding algorithm is able to correct up to *Th* $(Th \geq t)$ errors. It means we must stock up more than one error pattern per row in the hash table. The common factors between error patterns stocked up in the same row «*L*» are: i) they have a weight less than or equal to Th value and ii) they have the same return value of hash function. For an error pattern «e», we define the following relation: L=Hash (Syndrome value of «*e*»).

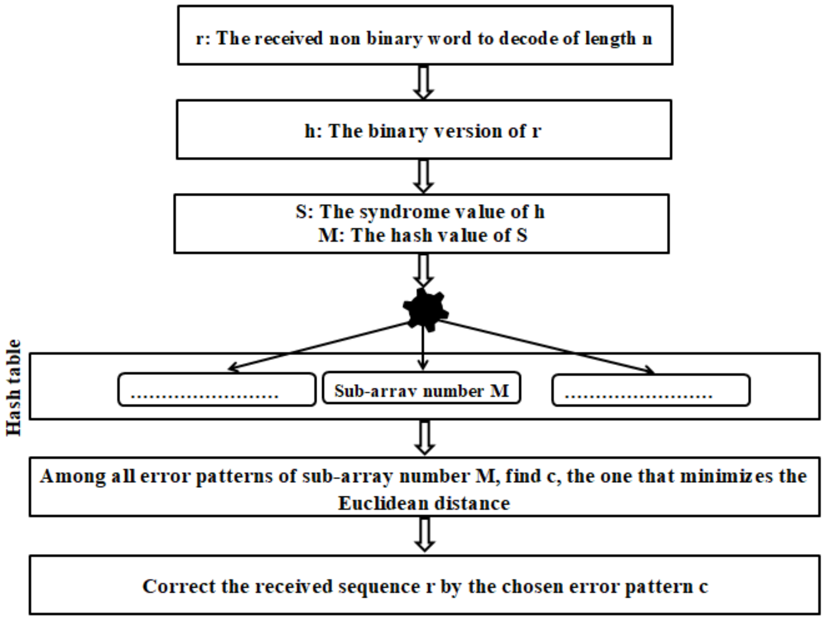


Figure 1. The SDHT principle

2.2. AWGN vs Rayleigh channel

2.2.1. AWGN channel

The AWGN channel represents a non-discrete and memoryless channel, called a Gauss channel, with binary input and analog output presented by continuous random variable *y(t)* [9]:

$$y(t) = x(t) + b(t) \quad (5)$$

where *x(t)* is the binary symbol emitted and *b(t)* represents a centered Gaussian random variable of variance σ^2 corresponding to the noise of the channel. Figure 2 represents the BER for BPSK modulation in terms of SNR over Gauss channel and Rayleigh channel. According to Figure 2(a), we deduce that BER achieves 10^{-5} when SNR equals 9.6 dB.

2.2.2. Rayleigh channel

In the conditions of mobile radio communication, the signal attenuation varies with the speed of the receiver (laptop, and vehicle) and the nature of the obstacles. In this type of channel called multipath fading channel, the amplitude a_k of the signal is modeled according to Rayleigh's or Rice's law. In the case of Rayleigh, the received signal can be modeled by (6),

$$r_k = a_k x_k + n \quad (6)$$

where x_k represents the modulated signal at the input of channel and «*n*» is Gaussian white noise with zero mean and variance σ^2 [8], [16], [26].

Figure 2(b) clearly shows that the BER achieves 10^{-5} when SNR equals 46 dB. With the channel effect, we need a lot more energy to reach an acceptable BER than in the case of AWGN channel. For this, the Rayleigh fading is most applicable when there is no line of sight (LOS) between the transmitter and receiver [27].

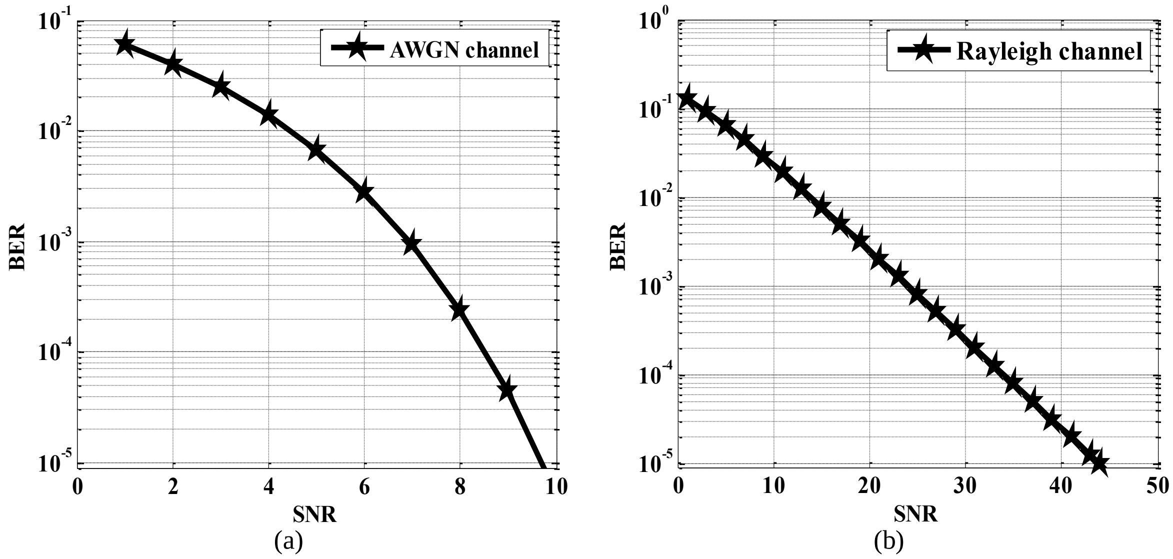


Figure 2. BER in terms of SNR over (a) an AWGN channel and (b) Rayleigh channel

3. RESULTS AND DISCUSSION

In this section, we are going to present simulation findings of HSDec and SDHT decoders of certain linear codes over Rayleigh channel adopting a BPSK modulation. We shall note that BER is measured, for each bit energy to noise power spectral density ratio $\left(\mathrm{SNR} = \frac{E_b}{N_0}\right)$, at the base of a minimum number equal to 200 residual errors and to 1,000 transmitted blocks. The totality of findings is obtained by a computer simulation program written using C programming language. Using MATLAB 13, we plotted the results of variation of $\frac{E_b}{N_0}$ versus BER. It should be noted that when the exchange is done without coding by emitter and without decoding by receiver, BER achieves 10^{-5} for an SNR value equal to 46 dB. A linear code is denoted by *C (n, k, d)* where n represents the length of the code, *k* represents its dimension and d forms the minimum distance among all its codewords.

3.1. Simulation results of HSDec and discussion

In Figure 3(a), we present the HSDec decoding algorithm performances for certain BCH codes having a length equal to 31. This figure shows that HSDec decoder guarantees a coding gain of 31 dB for BCH (31, 11, 11). We also deduce that the performance improves with the increment of the minimum distance and also the number of parity bits. For example, when switching from BCH (31, 26, 3) to BCH (31, 11, 11), the coding gain reaches 13 dB.

In Figure 3(b), we plot error correction performance of hash and syndrome decoding (HSDec) applied to certain BCH codes having a length equal to 63. This figure shows that the best results are obtained by the BCH (63, 45, 7) that assures coding gain of about 4 dB compared to the BCH (63, 51, 5) and about 10 dB compared to BCH (63, 57, 3) code. Moreover, we note that the HSDec decoder guarantees a coding gain of 27 dB for BCH (63, 45, 7).

Figure 4 presents performances of HSDec decoder applied to certain BCH codes having a length equal to 127. From this figure, it can be noticed that BCH (127, 113, 5) guarantees coding gain approximately equal to 6 dB compared to BCH (127, 120, 3) code. Figures 3 and 4 clearly show that the BCH (31, 11, 11) code assures the best error correction performance compared with the studied codes when it is used with the HSDec decoder over Rayleigh channel. Also, we note that with a BER value equal to 10^{-5}, the coding gain guaranteed by this code reaches 31 dB compared to the case where the exchange is done without coding by transmitter and without decoding by receiver.

Table 1 summarizes the error correction performance of HSDec decoder for decoding BCH codes of lengths 31, 63, and 127 over a Rayleigh channel. We denote the reduction rate of the quotient between the coding gain and 46 dB. We recall that all the values presented as coding gain are measured when BER equals 10^{-5} where the corresponding SNR value is 46 dB in the case of an exchange that is done without coding by transmitter and without decoding by receiver.

From Table 1, we deduce that the error correction performance of the hash and syndrome decoding (HSDec) decoder over a Rayleigh channel improves with the increase of the code correction capacity. Thus, the coding gain guaranteed by the BCH (31, 11, 11) code reaches 31 dB, i.e., a reduction rate which exceeds 67%. We also note that for the BCH code of length 63, the reduction rate varies between 39.13% and 58.70%.

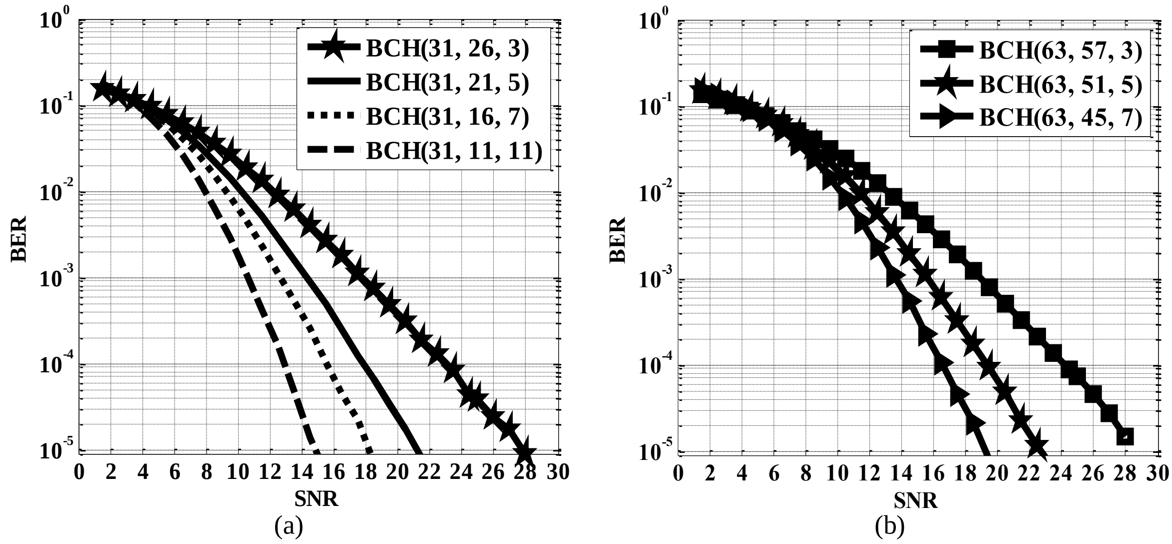


Figure 3. The HSDec performance over Rayleigh channel for BCH codes of length (a) 31 and (b) 63

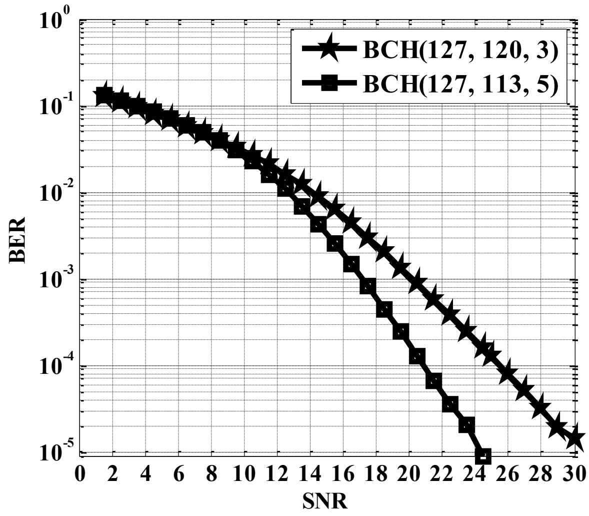


Figure 4. The HSDec performance over Rayleigh channel for BCH codes of length 127

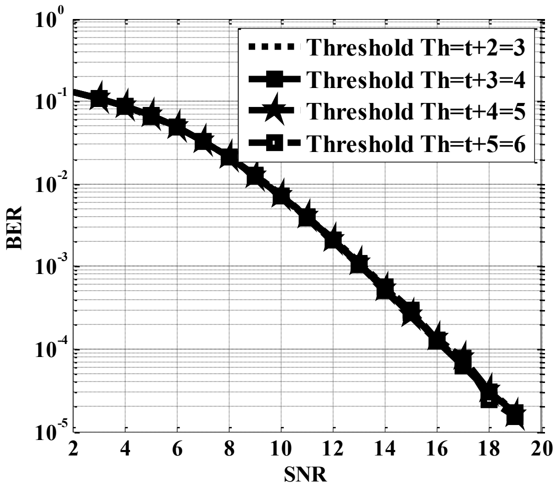
Table 1. Coding gain and reduction rate of the HSDec decoder applied to decode BCH codes of lengths 31, 63 and 127 over a Rayleigh channel

n	k	d	Coding gain	Reduction rate (in %)
31	26	3	18	39,13
31	21	5	24,5	53,26
31	16	7	28	60,87
31	11	11	31	67,39
63	57	3	18	39,13
63	51	5	23	50,00
63	45	7	27	58,70
127	120	3	16	34,78
127	113	5	21	45,65

3.2. Simulation results of SDHT and discussions

In this subsection, we give the simulation findings of SDHT decoder over the Rayleigh channel. We applied it to decode some BCH and quadratic residue (QR) codes of different lengths. For each code, we varied the coding threshold to analyze its effect on error correction performance.

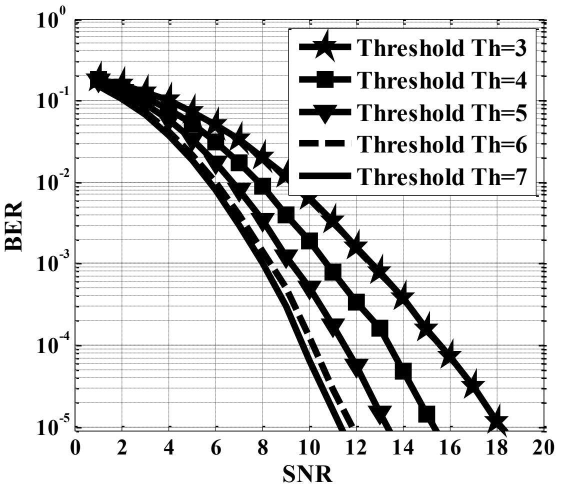
In Figures 5(a), 5(b), and 6(a), we present respectively the performance of SDHT decoder applied to decode BCH (31, 26, 3), BCH (31, 21, 5), and BCH (31, 16, 7) codes using different thresholds Th. From Figure 5(b) we can deduce that for a Th value equal to 5, the coding gain is about 3.5 dB if we compare it to Th value equal to 3.



(a) (b)

Figure 5. The SDHT performance over Rayleigh channel for (a) BCH (31, 26, 3) and (b) BCH (31, 21, 5) codes

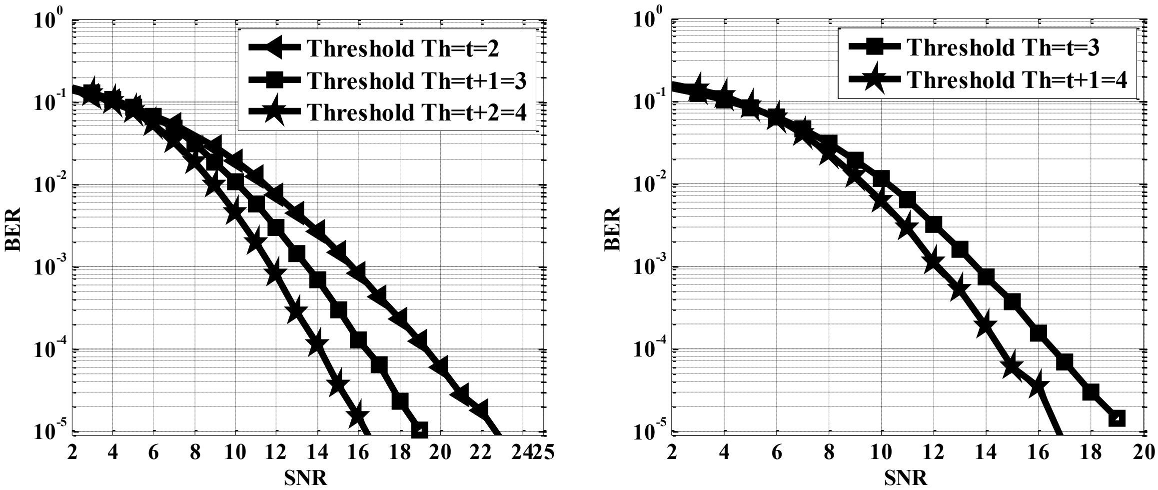
Figure 6(a) shows that the error correction performance improves by increment of coding threshold Th. For example, by varying the coding threshold from 3 to 7, the achieved coding gain is more than 6 dB for BCH (31, 16, 7) code. From Figures 5 and 6(a), we notice that the best error correction performance by SDHT for BCH codes of length 31 are those guaranteed by the BCH (31, 16, 7) with a threshold equal to 7. In Figures 6(b), 7(a), and 7(b), we plot error correction performance of the SDHT decoder to decode respectively the BCH (63, 57, 3), BCH (63, 51, 5) and BCH (63, 45, 7) using different thresholds Th.



(a) (b)

Figure 6. The SDHT performance over Rayleigh channel for (a) BCH (31, 16, 7) and (b) BCH (63, 57, 3) codes

Figure 6(b) shows that the coding gain for BCH (63, 57, 3) code, is about 2 dB when the threshold value is switched from 2 to 4. From Figure 7(a) we notice that coding gain is approximately equal to 6 dB when the threshold value is varied from 2 to 4. Figure 7(b) shows that the coding gain guaranteed by SDHT decoder applied to BCH (63, 45, 7) is about 2 dB when the threshold is varied from 3 to 4. From Figures 6(b) and 7, it can be deduced that the best error correction performance by SDHT for BCH codes of length 63 are those guaranteed by the BCH (63, 51, 5) and BCH (63, 45, 7) with a threshold equal to 4.



(a) (b)

Figure 7. The SDHT performance over Rayleigh channel for (a) BCH (63, 51, 5) and (b) BCH (63, 45, 7) codes

In Figure 8, we present the performance of SDHT decoding algorithm adopted for decoding BCH (127, 113, 5) using thresholds equal to 2 and 3. From this figure, we can deduce that with a Th value equal to 3, coding gain exceeds 3 dB compared to Th value equal to 2. We present in Figures 9(a) and 9(b) the error correction performance of the SDHT decoder to decode respectively the QR (23, 12, 7) and QR (31, 16, 7) codes with different thresholds Th.

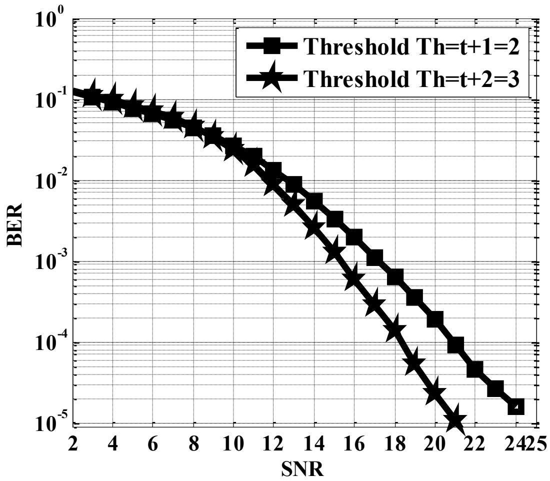


Figure 8. The SDHT performance over Rayleigh channel for BCH (127, 113, 5) code

From Figure 9(a), we can conclude that a coding gain, approximately equal to 2.4 dB, is guaranteed by SDHT decoder when the Th value is varied from 4 to 6. Figure 9(b) shows that for QR (31, 16, 7), the coding gain is more than 2 dB when the threshold value is switched from 5 to 7. From Figures 9(a) and 9(b), we notice that the SDHT decoder respectively applied to QR (23, 12, 7) and QR (31, 16, 7) codes with a Th value equal to 6, permits to reach a BER=10^{-5} for an SNR value equal to 12 dB.

An important result is that the BCH (31, 16, 7) and QR (31, 16, 7) codes assure the same results with a threshold value equal to 7. This means when the same code parameters are used, the SDHT decoder can guarantee the same performance for QR and BCH codes. In addition, we note that for BER equal to 10^{-5}, the coding gain guaranteed by these two codes exceeds 34 dB compared to the case where the exchange is done without coding by transmitter and without decoding by receiver.

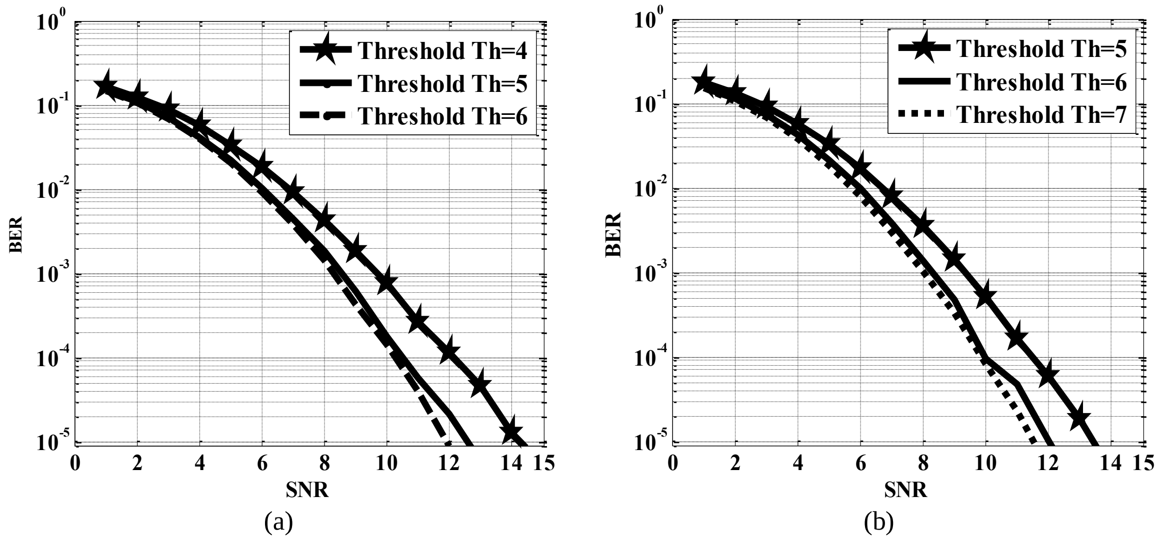


Figure 9. The SDHT performance over Rayleigh channel for (a) QR (23, 12, 7) and (b) QR (31, 16, 7) codes

From Figures 6 to 9, we deduce that we can improve the obtained results through the same code by increasing the threshold Th. For example, by increasing the threshold Th from 3 to 7, we can improve the correction results by more than 6 dB for BCH (31, 16, 7) and by 6 dB for BCH (63, 51, 5) when the threshold Th goes from 2 to 4. Thus, for the QR (31, 16, 7) code, the gain exceeds 2 dB when the threshold Th is incremented from 5 to 7. Table 2 summarizes the error correction performance of SDHT decoder to decode BCH codes having lengths equal to 31, 63, and 127 and QR codes of lengths 23 and 31 over a Rayleigh channel.

From Table 2, we conclude that the best results are those guaranteed by the BCH (31, 16, 7) and QR (31, 16, 7) codes. The coding gain guaranteed by these codes exceeds 34 dB, i.e., a reduction rate which exceeds 75%. We also note that for the BCH code of length 63, the reduction rate varies between 54.35% and 63.04%.

Table 2. Coding gain and reduction rate of the SDHT decoder applied to decode BCH and QR codes of different lengths over a Rayleigh channel

Code	n	k	d	Th	Coding gain	Reduction rate (in %)
BCH	31	26	3	6	26.5	57,61
	31	21	5	5	32	69,57
	31	16	7	7	34,5	75,00
	63	57	3	4	25	54,35
	63	51	5	4	29.6	64.34
	63	45	7	4	29	63,04
	127	113	5	3	25	54,35
QR	23	12	7	6	34	73,91
	31	16	7	7	34,5	75,00

4. CONCLUSION

In this paper, we have presented a study concerning error correction performance over a Rayleigh channel, of two decoders that have been developed at the base of hash technique and syndrome decoding. The results analysis shows that these studied decoders guaranteed the best performance in terms of the bit error rate. The study carried out in this article of HSDec and SDHT decoders shows their great success even in a different context from the one which they were initially developed from. As a perspective, we envisage conducting similar studies about other codes and decoders family.

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