Lecture Notes in Networks and Systems 1040

Marcelo Zambrano Vizuete · Miguel Botto-Tobar · Sonia Casillas · Carina Gonzalez · Carlos Sánchez · Gabriel Gomes · Benjamin Durakovic *Editors*

Innovation and Research – Smart Technologies & Systems

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Preface

The 4th edition of the International Research and Innovation Congress – Smart Technologies and Systems, CI3 2023, took place from August 30 to September 1, 2023, at the facilities of the Instituto Tecnológico Universitario Rumiñahui, located in the city of SangolquÍ, Pichincha, Ecuador.

The conference was organized by the Red de Investigación, Innovación y Transferencia de Tecnología RIT2, made up of the most relevant university institutes in Ecuador, among which are ITCA, BOLIVARIANO, ARGOS, VIDA NUEVA, ESPÍRITU SANTO, SUDAMERICANO, ISMAC, SAN ISIDRO, ARTES GRÁFICAS, ORIENTE, HUMANE, SUCRE, CENTRAL TÉCNICO, POLICÍA NACIONAL and RUMIÑAHUI.

Additionally, the event is sponsored by the Secretaría de Educación Superior, Ciencia, Tecnología e Innovación SENESCYT, Labortorio de Comunicación Visual de la Universidad Estatal de Campinas—Brazil, Universidad Ana G. Méndez—Puerto Rico, Centro de Investigaciones Psicopedagógicas y Sociológicas—Cuba, Instituto Superior de Diseño de la Universidad de La Habana—Cuba, GDEON and the Corporación Ecuatoriana para el Desarrollo de la Investigación y la Academia—CEDIA.

The main objective of CI3 2023 is to generate a space for dissemination and collaboration, where academia, industry and government can share their ideas, experiences and results of their projects and research.

"Research as a pillar of higher education and business improvement" is the motto of the Conference and suggests how research, innovation and academia must coincide with the productive sector to leverage social and economic development.

CI3 2023 had 145 papers submitted, of which 52 were accepted for publication and presentation. To guarantee the quality of the publications, the event has a staff of more than 70 experts, from different countries such as Spain, Argentina, Chile, Mexico, Peru, Brazil, Ecuador, among others, who carry out an exhaustive review of each proposal sent.

Likewise, during the event a series of keynote conferences were held, given by both national and international experts, allowing attendees to get in touch with the latest trends and technological advances around the world. Keynote speakers included: Ph.D. Carina González, University of La Laguna, Spain; Ph.D. Gabriel Gómez, State University of Campinas, Brazil; Ph.D. Carlos Sanchez, University of Zaragoza, Spain; Ph.D. Juan Minango, Instituto Tecnológico Superior Rumiñahui; Dr. Iván Cherrez, Universidad Espíritu Santo, Ecuador; and Ph.D. Nela Paustizaca, Escuela Politécnica del Litoral, Ecuador.

The content of this proceeding is related to the following topics:

- Smart Cities
- Innovation and Development
- Applied Technologies
- Economics and Management
- ICT for Educations.

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Contents

Performance Analysis of Coherent and Non-coherent Detection Techniques in Chirp Spread Spectrum for Internet of Things Applications

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Abstract. This paper presents an analysis of Chirp Spread Spectrum (CSS) for Internet of Things (IoT) applications, focusing on the performance of coherent and non-coherent detectors in various channel environments. The study evaluates scenarios with additive white Gaussian noise (AWGN), frequency-selective channels, and Rayleigh fading channels, considering a system with 10 receiving antennas. The results demonstrate that the coherent detector outperforms the non-coherent detector in terms of performance. However, the non-coherent detector offers the advantage of lower complexity. To further improve the performance of non-coherent detection in CSS-based IoT systems, the need for exploring new techniques is emphasized. Future research should aim to bridge the performance gap between coherent and non-coherent detection, considering adaptive signal processing algorithms, advanced filtering techniques, or hybrid detection schemes. By addressing the challenges associated with non-coherent detection, CSS can become a reliable and efficient modulation scheme for low signal-to-noise ratio conditions in IoT applications. This research contributes to the advancement of CSS in IoT, enabling seamless connectivity and data exchange in diverse IoT scenarios.

Keywords: Chirp Spread Spectrum (CSS) · Internet of Things (IoT) · Coherent detection · Non-coherent detection · Performance analysis

1 Introduction

In recent years, the Internet of Things (IoT) has emerged as a transformative technology, connecting an unprecedented number of devices and enabling a wide range of applications that enhance efficiency, convenience, and productivity in

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various domains. With the explosive growth of IoT deployments, there is a pressing need for robust and efficient communication protocols that can handle the unique challenges posed by IoT environments. Chirp Spread Spectrum (CSS) has emerged as a promising modulation technique for overcoming some of these challenges, providing a reliable and versatile solution for IoT communication [1].

The concept of Chirp Spread Spectrum dates back to the early 1940s when it was initially used in military applications such as radar systems. However, it is only in recent years that CSS has gained significant attention as a viable modulation technique for IoT applications. Unlike traditional modulation schemes like frequency shift keying (FSK) or amplitude shift keying (ASK), CSS employs a unique approach that allows for increased range, improved robustness, and enhanced coexistence with other wireless systems [2].

CSS utilizes the principles of spread spectrum communication, which involves spreading the signal energy across a wide frequency band. This spreading not only provides inherent resistance to interference but also enables multiple devices to transmit simultaneously without causing significant mutual interference [2,3]. By employing linear frequency modulation, known as chirping, CSS achieves enhanced spectral efficiency and resilience against fading and multipath effects.

The Internet of Things, often referred to as the "network of smart devices," encompasses a vast ecosystem of interconnected sensors, actuators, and embedded systems, all working together to gather and exchange data. From smart homes and industrial automation to healthcare monitoring and environmental sensing, the IoT promises to revolutionize how we interact with technology and the world around us [4]. However, the massive number of IoT devices, their varied communication requirements, and the presence of other wireless systems demand innovative solutions to ensure reliable and efficient data transmission.

This is where CSS shines. By leveraging its unique characteristics, CSS addresses several key challenges encountered in IoT deployments. Its inherent resistance to interference makes it particularly suitable for crowded frequency bands, where numerous devices coexist, such as in urban environments or industrial settings. The low power requirements of CSS enable energy-efficient operation, making it well-suited for battery-powered IoT devices that are often deployed in remote or inaccessible locations [5].

Moreover, CSS enables long-range communication, allowing IoT devices to transmit data reliably over extended distances. This capability is especially valuable in applications such as environmental monitoring, precision agriculture, and asset tracking, where seamless connectivity across large areas is essential.

The purpose of this paper is to explore the applications and advantages of Chirp Spread Spectrum in the Internet of Things domain, with a specific focus on the comparison between coherent and non-coherent detection in CSS. We will investigate the performance of these detection schemes in two different environments: one with only noise and another with additive white Gaussian noise (AWGN) and Rayleigh fading.

The structure of the rest of the paper is as follows. Section 2 provides an in-depth explanation of Chirp Spread Spectrum modulation, including its principles, signal processing techniques, and advantages over traditional modulation schemes. In Sect. 3, the concept of coherent and non-coherent detection in CSS is discussed focusing on their benefits and limitations. Section 4 analyzes the performance comparison in terms of bit error rate (BER) between coherent and non-coherent detectors in the presence of additive white Gaussian noise (AWGN) and Rayleigh fading. Finally, the conclusions are presented in Sect. 5.

2 Chirp Spread Spectrum Concepts

From a mathematical standpoint, Chirp Spread Spectrum (CSS) is a modulation technique that utilizes linear frequency modulation to spread the signal energy across a wide frequency band [5]. This spreading technique provides inherent resistance to interference and enables multiple devices to transmit simultaneously without significant mutual interference [6]. In this introduction, we will explore the mathematical concepts underlying CSS and its advantages in the context of the Internet of Things (IoT).

CSS modulation is based on the principle of linear frequency modulation, also known as chirping. It involves sweeping the frequency of the transmitted signal linearly over time, resulting in a chirp waveform. Mathematically, the chirp waveform can be described as:

$$s(t) = \cos\left(2\pi\left(f_c t + \frac{K}{2}t^2\right)\right) \tag{1}$$

where $s(t)$ represents the chirp signal as a function of time t, f_c is the carrier frequency, and K represents the chirp rate. The chirp rate, defined as the change in frequency over time, determines the spread of the signal across the frequency band. A larger chirp rate results in a wider spread, providing increased resistance to interference.

CSS offers several advantages in IoT applications. Firstly, its resistance to interference allows for reliable communication in crowded frequency bands where multiple devices coexist [7]. By spreading the signal energy over a wide frequency band, CSS reduces the impact of narrowband interference sources, enabling robust communication in challenging environments. Additionally, CSS enables long-range communication, making it ideal for IoT deployments requiring connectivity over extended distances. The ability to transmit data reliably over larger distances enhances the coverage and scalability of IoT networks.

Furthermore, CSS exhibits low power requirements, making it energy-efficient and well-suited for battery-powered IoT devices. The efficient utilization of power resources ensures prolonged battery life, enabling long-term operation and reducing maintenance needs. This characteristic is particularly valuable for IoT deployments in remote or inaccessible locations, where frequent battery replacement or recharging may not be feasible.

Firstly, it is important to note that Chirp Spread Spectrum (CSS) is closely related to orthogonal Frequency Shift Keying (FSK) modulation, as both techniques employ orthogonal modulation schemes in different domains. While FSK modulation operates in the frequency domain, CSS operates in the time domain [8].

In FSK modulation, the transmitted signal is modulated by switching between different discrete frequencies, with each frequency representing a specific symbol. This modulation scheme is widely used in various communication systems, including wireless networks and digital audio broadcasting. FSK enables efficient transmission of digital data by using a set of orthogonal frequency carriers, ensuring minimal interference between symbols [3].

On the other hand, CSS takes a different approach by modulating the transmitted signal using linear frequency modulation, also known as chirping, in the time domain. This linear frequency sweep creates a chirp waveform, which spreads the signal energy across a wide frequency band. The spreading of the signal in CSS provides inherent resistance to interference and allows for the simultaneous transmission of multiple devices without significant mutual interference.

Despite the differences in the modulation domains, CSS and FSK share similarities in terms of their use of orthogonal modulation. Both techniques aim to minimize interference and improve the reliability of data transmission. While FSK achieves orthogonality in the frequency domain through the use of orthogonal frequency carriers, CSS achieves orthogonality in the time domain through the spreading of the signal energy [9].

Understanding the relationship between CSS and FSK can provide valuable insights into the principles and benefits of CSS modulation. By leveraging the orthogonal modulation characteristics, CSS enables robust and efficient communication in IoT applications, overcoming challenges such as interference, multipath fading, and coexistence with other wireless systems.

The complex base-band of the basic chirp $x_0(t)$, which has a frequency that linearly increases from $\frac{-BW}{2}$ at $t = \frac{-T}{2}$ to $\frac{BW}{2}$ at $t = \frac{T}{2}$ is given by:

$$x_0(t) = \exp\left\{ j\pi \frac{BW}{T} t^2 \right\} p_T(t), \quad \forall t \in R \tag{2}$$

where BW denotes the bandwidth of the signal, and T the time to transmit a symbol, then $\log_2(BW.T) = SF$ is the spreading factor which gives the number of bits carried by a single symbol that can take $M = BW \times T = 2^{SF}$ values and $p_T(t) = 1$ for all $t \in [-T/2, T/2[$, and $p_T(t) = 0$ otherwise.

To modulate a symbol $m \in M$, the initial frequency of $x_0(t)$ is shifted by $m\frac{BW}{M} = \frac{m}{T}$ Hz and the chirp must be wrapped between $[-BW/2; BW/2]$, that we have:

$$x_m(t) = \exp\left\{ j2\pi(\frac{BW}{2T} + \frac{m}{T})t \right\} \exp\left\{-j2\pi lBWt\right\} p_T(t), \tag{3}$$

$$\forall t \in Rl \in Z \quad \text{s.t.} \frac{BW}{T}t + \frac{m}{T} \in [lBW - \frac{BW}{2}; lBW + \frac{BW}{2}].$$

Thus, the modulated signal consists of multiple symbols sent sequentially, with a time spacing of T seconds:

$$s(t) = \sum_{n=0}^{L/SF} x_{\mathbf{m}_n}(t - nT), \forall t \in R, \tag{4}$$

where $\mathrm{m}_n \in M$ is the n-th element of $\mathbf{m}$.

To obtain the discrete-time of $s(t)$, we must sample at the rate $F_{samp} = \frac{1}{T_samp} = BW$. Using the relation $BWT = M$, we have $T = MT_{samp}$. Thus, the discrete-time expression of $s(t)$ is:

$$s[k] = s(kT_{samp}) = \sum_{n=0}^{L/SF} x_{\mathbf{m}_n}(kT_{samp} - nT) = \sum_{n=0}^{L/SF} x_{\mathbf{m}_n}[k - nM] \quad \forall k \in Z. \tag{5}$$

Therefore, the discrete-time expression of a modulated chirp is:

$$\begin{aligned} x_m[k] &= x_m(kT_{samp}) \\ &= \exp\left\{j2\pi\left(\frac{BW}{2T}kT_{samp} + \frac{m}{T}\right)kT_{samp}\right\} \\ &\quad \times \exp\left\{-j2\pi lBWkT_{samp}\right\} \\ &\quad \times p_T(kT_{samp}), \end{aligned} \tag{6}$$

$$\forall k, l \in Z \ \text{ s.t.} \frac{BW}{kT_{samp}} + \frac{m}{T} \in [lBW - \frac{BW}{2}; lBW + \frac{BW}{2}].$$

where $p_T(kT_{samp}) = p_{\frac{T}{T_{samp}}}(k) = p_M[k]$ and $\exp\left\{-j2\pi lBWkT_{samp}\right\} = \exp\left\{-j2\pi lk\right\} = 1 \forall l, k \in Z$. Thus, the expression of $x_m(t)$ is simpler in the discrete-time domain:

$$x_m[k] = \exp\left\{j2\pi(\frac{B}{2T}kT_{samp} + \frac{m}{T})kT_{samp}\right\}p_M[k] = \exp\left\{j\pi\frac{k^2}{M}\right\}\exp\left\{j2\pi\frac{m}{M}k\right\}p_M[k]. \tag{7}$$

$$x_m[k] = \exp\left\{j2\pi(\frac{B}{2T}kT_{samp} + \frac{m}{T})kT_{samp}\right\}p_M[k] = \exp\left\{j\pi\frac{k^2}{M}\right\}\exp\left\{j2\pi\frac{m}{M}k\right\}p_M[k]. \tag{8}$$

Incorporating (8) in (5), we obtain:

$$s[k] = \sum_{n=0}^{L/SF} p_M[k - nM]\exp\left\{j\pi\frac{(k - nM)^2}{M}\right\}\exp\left\{j2\pi\frac{\mathbf{m}_n}{M}(k - nM)\right\} \tag{9}$$

$$s[k] = \underbrace{\exp\left\{j\pi\frac{k^2}{M}\right\}}_{Chirp}\underbrace{\sum_{n=0}^{L/SF} p_M[k - nM]\exp\left\{j2\pi\frac{\mathbf{m}_n}{M}k\right\}}_{M-FSK} \tag{10}$$

The Eq. 10 shows that CSS signals are basically chirped versions of M-arry Frequency Shift Keying (M-FSK) signals [6].

3 Coherent and Non-coherent Detector in CSS

Considering an AWGN channel, we have that:

$$y[k] = s[k] + z[k] \quad \forall k \in Z, \tag{11}$$

where $z[k]$ is a zero-mean, complex-circular white Gaussian noise. Later, we proceed with dechirping operation:

$$y_d[k] = y[k]\text{exp}\left\{-j\pi\frac{k^2}{M}\right\} \quad \forall k \in Z, \tag{12}$$

where $y_d[k]$ is the dechirped observed signal. This process does not change the statistical properties of the noise, thus, the system involving $y_d[k]$ instead of $y[k]$ is equivalent to $M - FSK$ over AWGN.

3.1 Coherent Detector

Coherent detectors play a crucial role in Chirp Spread Spectrum (CSS) by extracting the transmitted information from the received CSS signal. These detectors rely on maintaining phase and frequency coherence between the transmitted and received signals, enabling precise demodulation and recovery of the original data [1].

In CSS, coherent detection involves aligning the carrier frequencies of the received signal with a replica of the transmitted chirp signal. This alignment is achieved through carrier synchronization, ensuring that the local replica of the transmitted chirp signal is accurately matched in frequency and phase with the received signal. By multiplying the received signal with the synchronized replica, the coherent detector can extract the information embedded in the CSS signal [1].

Coherent detection is essential for separating the desired signal from other interference sources, as it takes advantage of the alignment of the carrier frequencies. This alignment allows for precise demodulation, resulting in accurate recovery of the original data. It is particularly useful in environments with low signal-to-noise ratio or when dealing with interfering signals that are closely located in the frequency spectrum.

Overall, coherent detectors in CSS enable reliable and accurate demodulation, making them an important component in the successful implementation of CSS-based communication systems.

Over perfect AWGN channels, it allows for maximum likelihood detection (MLD). Its use is mandatory for demodulating derivative of CSS that use the phase to encode symbols [16]. Thus, a MLD strategy for M-CSS in the presence of AWGN is to find the symbol m whose associated signal $\exp\left\{2\pi\frac{m}{M}k\right\}$ correlates the best with the observed signal $y_d[k]$. This is given by:

$$\hat{\mathbf{m}}_n = \text{argmax}\ Real\left\{\sum_{k=-\infty}^{\infty} p_M[k]\text{exp}\left\{-2\pi\frac{m}{M}k\right\} y_d[k+nM]\right\}. \tag{13}$$

From the above expression, we observe the term in the real part is the M point Discrete Fourier Transform (DFT), denoted by $F_M\{.\}$ of the received signal:

$$\hat{\mathbf{m}}_n = \text{argmax } Real\left\{F_M\left\{y_d[k+nM]\right\}[m]\right\}. \tag{14}$$

Expanding (16), we have:

$$\begin{aligned} F_M\left\{y_d[k-nM]\right\}[m'] &= F_M\left\{s[k-nM]\right\}[m'] + F_M\left\{z[k]\right\}[m'] \\ &= M\delta_{n-n'}\delta_{m_n-m'_n} + F_M\left\{z[k]\right\}[m'], \end{aligned} \tag{15}$$

where $\delta_n = 1$ if $n = 0$ and zero otherwise. As we can see, the correlator output corresponding to the symbol that was sent has its amplitude augmented by M, as opposed to the other correlators. This means that this modulation, along with coherent demodulation gets more robust to noise as M increases.

3.2 Non-coherent Detector

In Chirp Spread Spectrum (CSS), a non-coherent detector is an alternative to the coherent detection scheme. Unlike coherent detection, which relies on maintaining phase and frequency coherence between the transmitted and received signals, non-coherent detection does not require such synchronization [5].

In non-coherent detection, the received CSS signal is processed without aligning the carrier frequencies or maintaining phase coherence. Instead, the detector focuses on extracting the modulating information from the received signal using techniques that do not rely on precise carrier synchronization [6].

One common non-coherent detection technique used in CSS is energy detection. This technique involves measuring the energy level of the received signal over a certain integration period. By comparing the energy level to a predetermined threshold, the detector makes a decision on the presence or absence of the transmitted signal.

Since non-coherent detection does not require precise synchronization, it offers several advantages in certain scenarios. Non-coherent detectors are more robust in environments where carrier frequency offsets or phase variations occur, as they are not affected by these impairments. They also eliminate the need for complex carrier recovery circuits, simplifying the receiver design and reducing implementation complexity.

However, non-coherent detection typically has lower performance compared to coherent detection, particularly in terms of signal detection sensitivity and demodulation accuracy. Non-coherent detectors may suffer from higher detection error rates and reduced data throughput, especially in low signal-to-noise ratio (SNR) conditions. Additionally, non-coherent detection may have limitations in scenarios where high-precision demodulation or decoding is required [4].

Nonetheless, non-coherent detection is suitable for applications where carrier synchronization is challenging or not feasible, or when the emphasis is on simplicity and robustness rather than achieving the highest possible performance. It offers an alternative approach for CSS systems in certain environments where precise synchronization is difficult to achieve or maintain.

Non-coherent detector replaces the real part operator by the magnitude operator in (16):

$$\hat{\mathbf{m}}_n = \text{argmax } |F_M \{y_d[k + nM]\} [m]|. \tag{16}$$

3.3 Quadrature Demodulation

In sub-section, we have included the description about quadrature demodulation for comparison purposes which is a technique used in communication systems to extract information from a modulated signal. It is commonly employed in various modulation schemes, including amplitude modulation (AM), frequency modulation (FM), and phase modulation (PM).

The term "quadrature" refers to the use of two separate signal paths, known as the in-phase (I) and quadrature (Q) channels, which are 90° out of phase with each other. The modulated signal is split into these two channels, allowing for simultaneous processing of both the in-phase and quadrature components.

The quadrature demodulation process typically involves two main steps: mixing and low-pass filtering. In the mixing stage, the received signal is multiplied by two local oscillators, one in-phase and one quadrature, which are synchronized with the carrier frequency of the modulated signal. This mixing process results in the separation of the modulated signal into its in-phase and quadrature components.

After mixing, the resulting signals are passed through low-pass filters to remove high-frequency components and noise. These filters are designed to allow only the baseband information, typically the amplitude, frequency, or phase modulation, to pass through. The filtered in-phase and quadrature signals can then be further processed or demodulated to recover the original modulating information.

Quadrature demodulation offers several advantages in communication systems. By using the I/Q channels, it enables the receiver to capture both the amplitude and phase characteristics of the modulated signal simultaneously. This allows for accurate demodulation and recovery of the original information, even in the presence of noise and interference.

Additionally, quadrature demodulation is compatible with various modulation schemes, making it a versatile technique in modern communication systems. It is widely used in applications such as wireless communication, software-defined radio (SDR), and digital broadcasting.

Quadrature demodulation can be used in M-CSS signal, once the M-CSS signal has passed by the dechirping process, we have a M-FSK signal which can be seen as frequency modulated M-arry Amplitude Shift Keying (ASK) modulations. Thus, we have two-stage demodulation process. The first stage performs quadrature detection of the frequency variation in $y_d[k]$, and the second performs M-ASK demodulation on this frequency variation.

Quadrature demodulation computes the product of $y_d[k]$ with a unit delayed and conjugated version of itself. In order to determine its frequency variation. Thus, we have:

$$a[k] = \arg \{y_d[k] y_d^*[k - 1]\}. \tag{17}$$

Once the frequency is the derivative of the phase, we have that quadrature demodulator corresponding to the digital derivative of the phase of $y_d[k]$. After quadrature detection, the signal is analogous to an M-ASK modulated signal:

$$a[k] = \frac{2\pi}{M} \sum_{n=0}^{L/SF} p_M[k - nM]\mathbf{m}_n + z'[k], \tag{18}$$

where $z'[k]$ has no guarantee to be Gaussian nor white. Later, a hard decision by comparing its amplitude to $M - 1$ thresholds can be taken in order to obtain the transmitted symbols $\mathbf{m}$.

4 Performance Results Comparisons

In this section, we analyze and compare the performance of CSS in different physical environments, such as AWGN, frequency-selective and Rayleight channels. We evaluate the performance metrics, including signal-to-noise ratio (SNR) and bit error rate (BER).

4.1 AWGN Channel

Figure 1 compares the three demodulators described in Sect. 3 for a CSS with SF = 9. We note that quadrature demodulation has the worst performance, which can however be improved by oversampling the received signal with a factor of 2. However, quadrature demodulation continues to present an E_b/N_0 difference as high as 23 dB for a BER of 10^{-4} in comparison with coherent demodulation.

4.2 Frequency-Selective Channel

In a frequency-selective channel in order to evaluate the performance of coherent and non-coherent demodulation, we have considered a static frequency-selective channel with impulse response $h[k] = 0.407\delta_{k-1} + 0.815\delta_k + 0.407\delta_{k+1}$ with $\delta_k = 1$ if $k = 0$ and $\delta_k = 0$ otherwise. Note that this channel is non-invertible. The received signal is given by:

$$y[k] = \sum_{l=-\infty}^{\infty} h[l]s[k - l] + z[k] \tag{19}$$

From Fig. 2 we note that CSS performs better than FSK on this channel due to the fact that it is better at spreading the information in frequency.

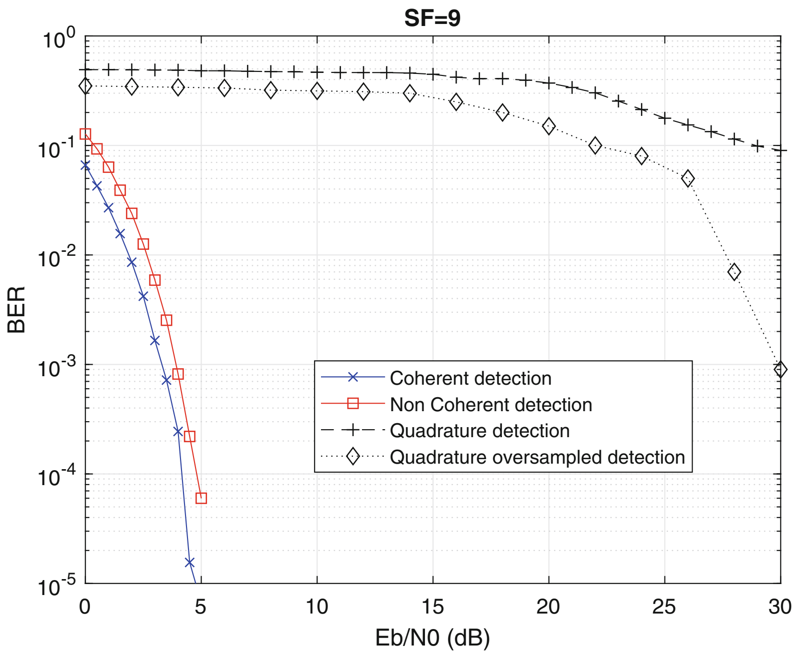

Fig. 1. Comparison between different detectors for CSS with SF = 9 in an AWGN channel

4.3 Rayleigh Channel

In this analysis, a slow and flat fading channel is assumed. Thus, the received signal is given by:

$$y[k] = h[k]s[k] + z[k], \tag{20}$$

where $h[k] = \alpha[k]\exp\{j\theta\}$ with $\alpha[k]$ and θ being attenuation factor and uniformly distributed phase variations.

Figure 3 shows the comparison between coherent and non-coherent CSS modulation with SF = 6 in a Rayleigh channel. As it is evident coherent detection presents a better performance of about 0.5 dB in comparison with non-coherent detection. For the theoretical non-coherent detection BER curve the 'beading' tool from Matlab was used. However, this same tool for the case of the theoretical coherent detection BER curve is only defined for $M = 2$.

Figure 4 compares the performance of a CSS modulation with SF = 6 employing $N_r = 1$ and $N_r = 10$ receive antennas for coherent and non-coherent detection. We can observe better performance when we use more than 1 receive antenna. For this case, we note that the performance difference between coherent and non-coherent detection increase as N_r increase. Thus, for $N_r = 10$ the performance difference is about 4 dB for a BER$= 10^{-3}$.

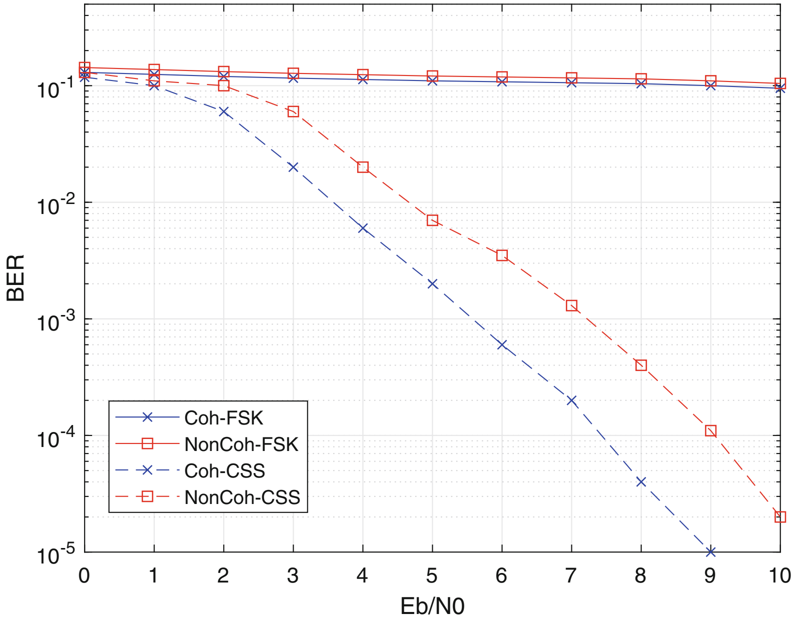

Fig. 2. Comparison between CSS and FSK in a Frequency-selective Channel.

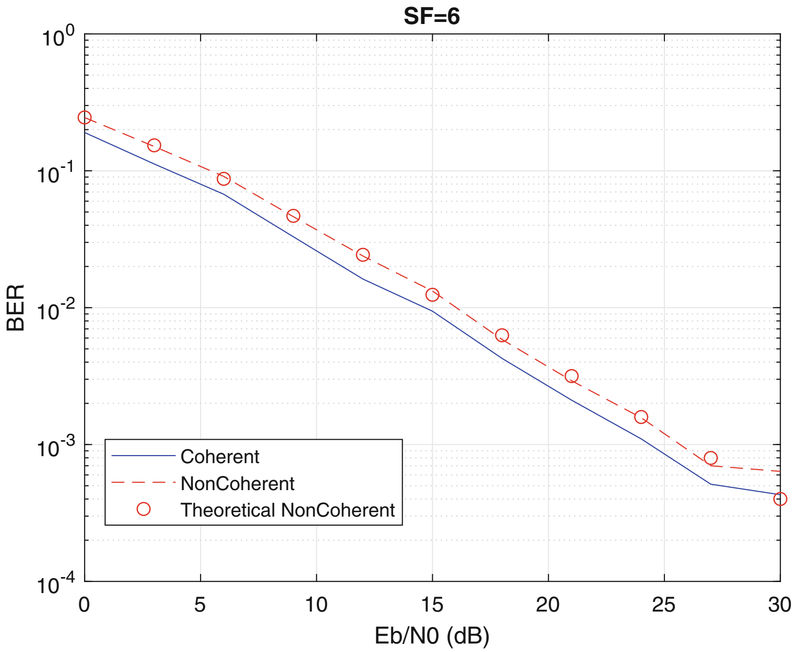

Fig. 3. CSS with coherent and non-coherent detection in a Rayleigh Channel.

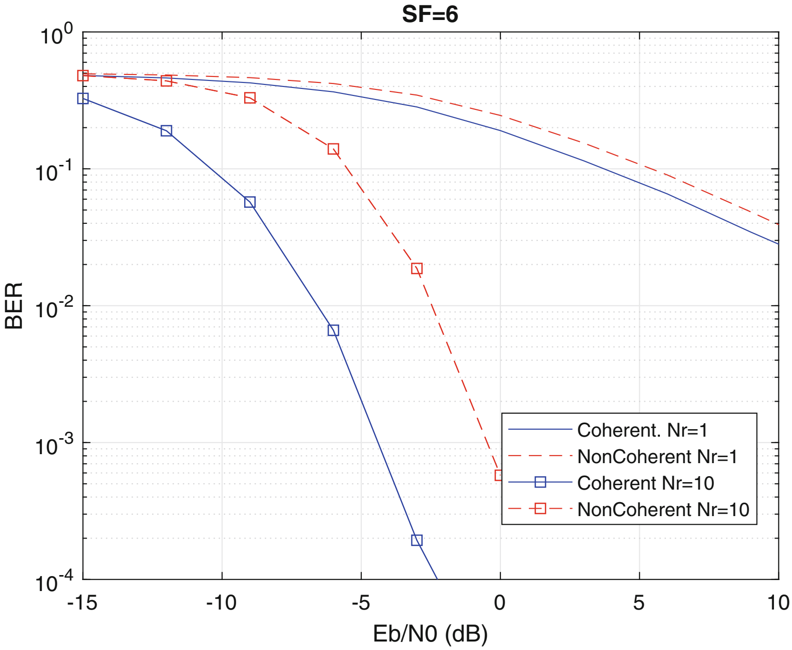

Fig. 4. CSS with coherent and non-coherent detection and diversity $N_r = 10$ receive antennas in a Rayleigh Channel.

5 Conclusion

In conclusion, the utilization of Chirp Spread Spectrum (CSS) in Internet of Things (IoT) applications has been presented and discussed in this paper. The performance of both coherent and non-coherent detectors was thoroughly analyzed in various channel environments, including scenarios with additive white Gaussian noise (AWGN), frequency-selective channels, and Rayleigh fading channels.

The results demonstrate that the coherent detector exhibits superior performance compared to the non-coherent detector in the studied system with 10 receiving antennas. The coherent detection scheme, with its ability to maintain phase and frequency coherence between the transmitted and received signals, proves to be more effective in extracting the desired information from the CSS signal.

However, it is worth noting that the non-coherent detector offers the advantage of lower complexity due to its independence from precise carrier synchronization. This makes it an attractive option for resource-constrained IoT devices or scenarios where maintaining synchronization may be challenging.

Nevertheless, to further enhance the performance of non-coherent detection in CSS-based IoT systems, it is essential to explore and evaluate new techniques. Future research should focus on developing innovative methods that can mitigate the performance gap between coherent and non-coherent detection. These advancements may include adaptive signal processing algorithms, advanced filtering techniques, or hybrid detection schemes that combine the strengths of both coherent and non-coherent approaches.

By addressing the challenges associated with non-coherent detection, such as increased bit error rates or reduced data throughput, the potential of CSS in low signal-to-noise ratio conditions can be fully realized. This will contribute to the advancement of reliable and efficient IoT communication systems, enabling seamless connectivity and data exchange in diverse IoT applications.

In summary, this study highlights the significance of coherent and non-coherent detectors in CSS-based IoT systems. While the coherent detector currently demonstrates superior performance, the exploration of new techniques for improving the performance of non-coherent detection holds great promise. By bridging the performance gap, we can leverage the advantages of both detection schemes and unlock the full potential of CSS in IoT applications.

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