Direct-Sequence Spread Spectrum with Signal Space Diversity for High Resistance to Jamming

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***Abstract*—Jamming attacks can severely limit wireless networks availability and can cause serious damage, in particular for tactical applications. Over the past decades, Direct-Sequence Spread Spectrum (DSSS) has been used to enhance resistance to jamming. In this paper, we first analyze the performance of the DSSS modulation in the presence of malicious jamming; we take into account by considering different physical phenomena such as a large Doppler shift and we use at the receiver side robust synchronization algorithms. We then propose to consider jointly rotated constellations and the DSSS technique in order to enhance robustness against jamming, while keeping reasonable complexity. Simulations results underline the good performance of our proposal as it shows a gain of several dBs compared to the DSSS technique with conventional constellations.**

***Index Terms*—Direct-Sequence Spread Spectrum (DSSS), synchronization, Gaussian noise jammer, comb jammer, repeat jammer, Rotated and Cyclically Q-Delayed (RCQD), Signal Space Diversity (SSD).**

I. Introduction

Wireless communications systems communicate through open channels which make them sensitive to attackers malicious activities. Jamming attacks are one of the most straightforward and effective types of attacks: the jammer simply transmits jamming signal over the legitimate signal bandwidth so as to prevent the legitimate signal reception.
To face this issue, it is customary to use spread spectrum techniques. In particular, Direct Sequence Spread Spectrum (DSSS) techniques consist in multiplying the signal on the transmitter side by a sequence of N chips over time. Besides this technique traditionally offers a certain level of discretion, this also allows a certain resistance to jamming. Indeed, the power spectral density of the spread signal is divided by the spreading factor. For a fairly high spreading factor, the power spectral density of the transmitted signal is lower than that of the noise, thus making it quite difficult to detect the transmitted signal [1]–[3].

Thanks to an inherent increased modulation diversity (Signal Space Diversity (SSD)), Rotated and Cyclically Q-Delayed (RCQD) signals are able to allow a better system performance over fading channels compared to conventional constellations [4]–[7]. To construct the two-dimensional (2D) RCQD signal, one first needs to rotate the conventional signals with a proper rotation angle and then to interleave the Q components, so as to ensure that the I and Q components of a given symbol experience independent channels. At the receiver side, each component brings all the information carried by the original 2D symbol, which reduces the effect of random signal-to-noise losses. Rotated constellations have thus been considered in various situations such as the joint study with DSSS modulation for cellular networks [8] and with the OFDM modulation in the DVB-T2 standard [9].

In this paper, we first study the performance of the DSSS modulation with conventional QAM constellations in presence of different jamming waveforms. In our simulations, we have taken into account several physical phenomena and we consider the various stages of the whole communication chain, so as to be as close as possible to realistic environments. We then propose to use jointly the DSSS modulation with rotated constellations in order to enhance the resistance to jamming. We show that combining DSSS with SSD allows a gain of several dBs compared to the conventional DSSS.

The reminder of this paper is organized as follows. Section II reminds the DSSS principle and the system model. The algorithms that we used in our simulations are also presented in this section. Section III introduces several jammer models. The DSSS modulation with Signal Space Diversity is detailed in section IV. Some numerical results are presented in Section V, and finally Section VI concludes the paper.

II. DSSS principle and system model

A. System model with conventional DSSS

Figure 1 depicts the system model. First, the information bits are classically channel-encoded and then transformed into a series of symbols. These symbols are then multiplied by a high-rate pseudo-random sequence, resulting in a transmitted chip signal with a wider bandwidth. To reduce the detection threat, the spreading sequence is pseudo-random and changes at each symbol time [10]. The transmitter then adds a preamble at the beginning of each frame so as to allow good synchronization at the receiver side. Finally, both the preamble and the chips are filtered with a Raised Root Cosine Filter (SRRC), and are sent on a frequency carrier f_0.

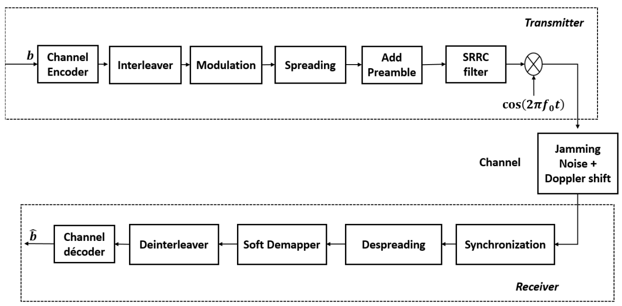

Fig. 1. System model.

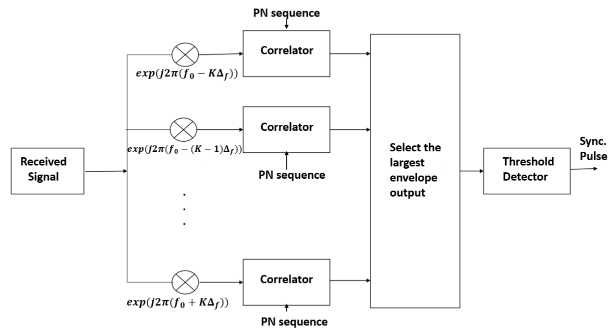

Fig. 2. Frame Synchronization and Initial search for Doppler frequency offset.

At the receiver side, the received signal is the superposition of three components; first, the desired signal which includes the information bits that may suffer from Doppler effect; this desired signal is also perturbed by two independent components : a Gaussian noise and also some jamming signal. In order to recover the information bits, the receiver first needs to use several synchronization algorithms. The synchronization algorithms are described in the following II.B subsection.
Thereafter, the receiver despreads the observations and computes the Log-Likelihood Ratio (LLR) for each received bit. Finally, the LLR values are fed to the channel decoder to estimate the transmitted information bits.

B. Synchronization algorithms

Synchronization is a critical step as it is proceeded at the front-end of the receiver. We now detail the various algorithms (frame, time, frequency and phase synchronization) used in our simulations.

1) Frame synchronization: Figure 2 presents the algorithm that we used in our simulations to perform frame synchronization. With this algorithm, the receiver first correlates the received signal with the known preamble at several frequency shifts centered around the carrier frequency $f_0 - K\Delta_f, f_0 - (K-1)\Delta_f, \cdots f_0 + K\Delta_f$ (i.e. we consider $2K+1$ Doppler hypothesis) [3]. A correlation peak is then selected; thus, this algorithm both allows frame detection and coarse initial estimation of the Doppler shift. One can remark that the RAKE receiver structure [3] can be inappropriate to the tactical communication canvas because of false alarm detection in a jamming environment. Indeed, in the case of several correlation peaks, the receiver only considers the first one as some of the other peaks may be due to the repeat jammer. Finally, it is worth noting that the legitimate signal is most likely to be received before the repeat jammer signal due to the jammer processing time and the larger propagation time.

2) Time synchronization: After frame synchronization, uncertainties often remain regarding the optimal sampling instants. Hence, the receiver needs to perform time synchronization. This step is of utmost importance to the reception quality of the transmitted symbols and impacts the overall system performance. To face this issue, several algorithms have been proposed in the literature, such as the Delay Locked Loop (DLL), the Early Late Detector (ELD), and the Zero Crossing Delay (ZCD). These algorithms are inspired by approximations of the Maximum Likelihood (ML) approach [11]–[14]. With the ML approach and the Data Aided (DA) mode, the receiver estimates the delay $\hat{\boldsymbol{u}}_{ML}$ that maximizes the probability of the received symbols $\boldsymbol{r}$ given the known transmitted symbols:

$$\begin{aligned}\hat{\boldsymbol{u}}_{ML} &= \underset{u}{\operatorname{argmax}} P(\boldsymbol{r}|\boldsymbol{a},u) \\ &= \underset{u}{\operatorname{argmax}} \Lambda_L(\boldsymbol{r}|\boldsymbol{a},u) \\ &= \underset{u}{\operatorname{argmax}} \frac{1}{\sigma_n^2}\sum_{j=1}^{N} \Re\{a_j^* x_j(u)\} - \sum_{j=1}^{N}\frac{|a_j|^2}{2\sigma_n^2},\end{aligned} \tag{1}$$

where $\boldsymbol{a} = [a_1, a_2 \cdots, a_n]$ stacks the transmitted symbols a_j, $x_j(u)$ is the j-th received observation, $\Re\{z\}$ denotes the real part of z and σ_n^2 is the noise variance.
Furthermore, the derivative of $\Lambda_L(\boldsymbol{r}|\boldsymbol{a},u)$ with respect to u can be written as:

$$\frac{\partial \Lambda_L(\boldsymbol{r}|\boldsymbol{a},u)}{\partial u} = \sum_{j=1}^{N} \frac{\partial \Re\{a_j^* x_j(u)\}}{\partial u} \tag{2}$$

Using the gradient descent algorithm, the delay can be obtained with the following recursive algorithm [11]–[13]:

$$\hat{u}_n = \hat{u}_{n-1} + \mu e_n(\hat{u}_{n-1}, a_n), \tag{3}$$

where :

$$e_n(\hat{u}_{n-1}, a_n) = \Re\{a_j^* \frac{\partial x_j(u)}{\partial u}|_{u=\hat{u}_{n-1}}\}. \tag{4}$$

3) Phase synchronization: The performance of digital transmission systems depends on many factors, among which, phase synchronization is critical. Indeed, with a poor phase offset estimation, the overall system performance can rapidly be deteriorated [15].
To face this issue, several algorithms have been proposed in the literature [15]–[21]. With the ML criterion and in DA mode, the receiver estimates the phase sequence $\hat{\boldsymbol{\beta}}$ as:

$$\hat{\boldsymbol{\beta}}_{ML} = \underset{\boldsymbol{\beta}}{\operatorname{argmax}} P(\boldsymbol{r}|\boldsymbol{\beta},\boldsymbol{a})). \tag{5}$$

After some mathematical derivations, Eq. (5) becomes:

$$\hat{\boldsymbol{\beta}}_{ML} = \underset{\boldsymbol{\beta}}{\operatorname{argmax}} \sum_{i=1}^{N} \Re\left\{r_i a_i^* e^{-\beta_i}\right\}. \tag{6}$$

With a Phase-Locked Loop (PLL), the phase error estimation (6) is performed in a recursive manner [20], [21]:

$$\hat{\beta}_{k+1} = \hat{\beta}_k + \mu \Im\left\{r_k a_k^* e^{-j\hat{\beta}_k}\right\}. \tag{7}$$

where $\Im\{z\}$ denotes the imaginary part of z.

III. Jammer models

Jamming attacks are one of the most straightforward and efficient attacks; the jammer has free access to the wireless channel and can transmit jamming signals so as to prevent the legitimate signal reception. In this paper, we assume that the jammer knows the center frequency and bandwidth of the signal. To make jamming as effective as possible the attackers can use numerous types of jammers that have been studied in the literature [22], [23]. In our simulations, we consider three kinds of jammers, namely the Gaussian noise jammer, the comb jammer and the repeat jammer.

A. Gaussian noise jammer

The jammer signal can be written as:

$$j_G(t) = \sqrt{2J} p_G(t) cos(2\pi f_0 t), \tag{8}$$

where $\sqrt{2J}$ is the amplitude of the jammer signal and $p_G(t)$ is a band-limited Gaussian noise.
The Gaussian noise jammer places noise energy across the entire bandwidth of the legitimate signal.

B. Comb jammer

The comb jammer can be written as

$$j_C(t) = \sqrt{2J} \sum_{i=-N_R}^{N_R} cos(2\pi(f_0 + i\delta_f)t), \tag{9}$$

where N_R and δ_f are chosen so that the jamming signal covers the entire bandwidth of the legitimate signal.

C. Repeat jammer

This jammer simply repeats the legitimate signal and can be written as:

$$j_R(t) = \sqrt{2J} x(t - \tau), \tag{10}$$

where τ is a time delay due to an additional propagation time and processing time and $x(t)$ is the legitimate signal.

IV. DSSS with rotated constellations

A. Signal Space Diversity (SSD)

Rotated and cyclic Q-delayed (RCQD) modulations also called Signal Space Diversity (SSD) techniques [4], [5] outperform conventional constellations over fading channels thanks to some inherent diversity.
To obtain RCQD signals, one first has to rotate the conventional symbol so as to correlate the In-phase (I) and Quadrature (Q) components of the conventional symbol:

$$s = \boldsymbol{R} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}, \tag{11}$$

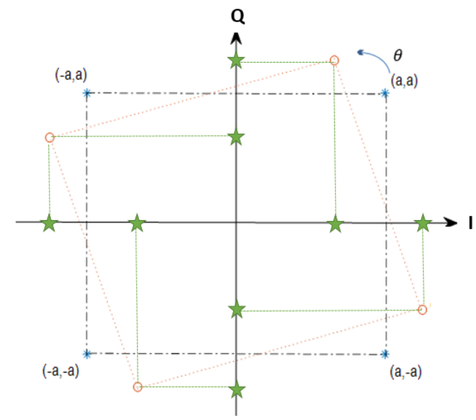

Fig. 3. Conventional (in blue) and rotated (in red) QPSK constellations.

where a_1 (resp. a_2) is the I (resp. Q) component of the conventional QAM symbol and $\boldsymbol{R}$ is the rotation matrix:

$$\boldsymbol{R} = \begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix}, \tag{12}$$

where θ is the rotation angle.
Then, the transmitter sends the components s_1 and s_2 of the rotated symbol s on two independent channels.
Figure 3 illustrates the key simplifying idea of Signal Space Diversity. If we suppose that one of the components of the transmitted RCQD symbol is erased, we can see that, differently from a conventional constellation symbol (see blue stars of Fig. 3), with the rotated constellation the receiver is able to recover the original information because the I (resp. Q) component of any rotated constellation points are distinct.

B. System model with rotated constellations

In order to improve the resistance to jamming, we propose to use rotated constellations and spread spectrum techniques jointly. First, we consider that the transmitter frames are sent on two independent channels, for instance, at two different carrier frequencies. With conventional constellations, the transmitter send two independent frames over these two channels. However, with rotated constellation, the symbols of the two frames are first rotated with the rotation angle $\theta = \text{atan}(1/\sqrt{M})$, where M is the constellation size; indeed, this so-called Uniformly Projected (UP)-RCQD [24], [25] rotation angle allows good Bit Error Rate (BER) performance and can be decoded with low computational complexity. The rotated symbol at time instant n of the i-th frame, with $i \in \{1, 2\}$, $s^i(n)$ can be written as:

$$s^i(n) = s_1^i(n) + js_2^i(n) = a(n)exp(j\theta), \tag{13}$$

where $a(n)$ is the information symbol at time n, belonging here to a conventional M-QAM constellation.
Thereafter, the I components of the first frame rotated symbols are transmitted with the Q components of the second frame

rotated symbols over the first channel. The transmitted signal over the first channel can therefore be written as:

$$x^1(n) = x_1^1(n) + jx_2^1(n) = s_1^1(n) + js_2^2(n). \tag{14}$$

Similarly, the I components of the second frame symbols are transmitted with the Q components of the first frame symbols over the second channel. The transmitted symbols over the second channel can therefore be written as:

$$x^2(n) = x_1^2(n) + jx_2^2(n) = s_1^2(n) + js_2^1(n). \tag{15}$$

Assuming perfect synchronization for the purpose of obtaining the expression of the ideal detection, the received symbol at time n on the i-th channel can be written as:

$$y^i(n) = x^i(n) + v^i(n) + J^i(n), \tag{16}$$

where $v^i(n)$ is an Additive White Gaussian Noise (AWGN) and $J^i(n)$ is a potential jammer signal at time n.
Then, the proposed receiver deinterleaves the received components in order to obtain the observations $r^i(n)$ on each transmitted rotated symbol $s^i(n)$, with $i \in \{1, 2\}$. Afterwards, analogously to [6], [25], it computes the log likelihood ratio (LLR) for each received bit on the first channel. For instance, for the BPSK constellation, the LLR can be computed as:

$$\begin{aligned}\Lambda\left(b^1(n)\right) = &\left[\frac{|r_1^1(n)-s_1^{(1)}|^2}{N_1(n)} + \frac{|r_2^1(n)-s_2^{(1)}|^2}{N_2(n)}\right] \\ &- \left[\frac{|r_1^1(n)-s_1^{(0)}|^2}{N_1(n)} + \frac{|r_2^1(n)-s_2^{(0)}|^2}{N_2(n)}\right],\end{aligned} \tag{17}$$

where $s_1^{(k)} = s_1^{(k)} + js_2^{(k)}$ is the rotated symbol associated with the bit k in $\{0, 1\}$, and $N_i(n)$ is the total variance of the Gaussian noise and the jamming signal on the i-th channel.
Two points should be noted; in order to accurately compute the LLR values, the receiver needs to first estimate $N_1(n)$ and $N_2(n)$ using conventional estimation algorithms [3]. In addition, if we want that the rotated constellations perform better than the conventional constellations, $N_1(n)$ and $N_2(n)$ must be independent variables; this condition can easily be fulfilled in practice by transmitting the components of the rotated symbols over independent channels. Similarly, one computes the LLR for each received bit on the second channel.

V. Simulation Results

This section is divided into two parts. The first part discusses the performance of DSSS with conventional constellations. The second part compares the DSSS system with Signal Space Diversity (see section IV), to the DSSS system with conventional QAM constellations in terms of jamming resistance. Simulations parameters are summarized in Table 1.

A. The conventional DSSS

Figures 4 and 5 show the BER performance as a function of P_J/P_u, where P_J is the jamming signal power and P_u is the legitimate signal power. These figures are obtained over the Gaussian channel (i.e. only one channel) with a constant

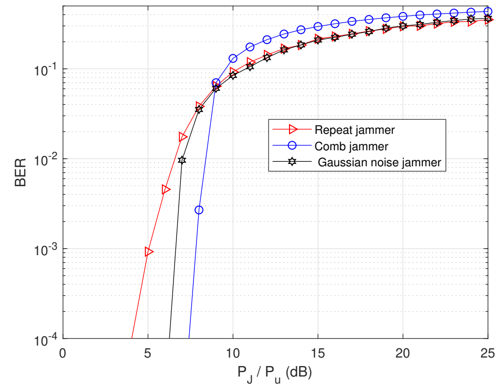

Fig. 4. BER comparison between the repeat jammer, the comb jammer and the Gaussian noise jammer with the conventional BPSK constellation for SF=4.

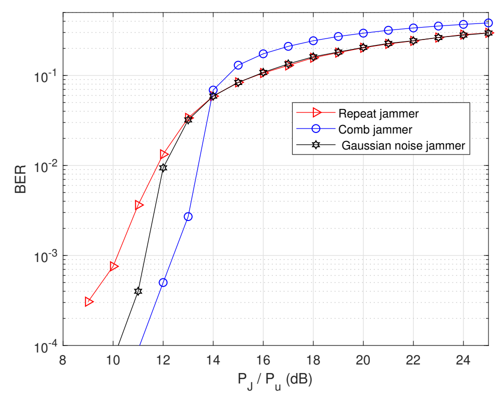

Fig. 5. BER comparison between the repeat jammer, the comb jammer and the Gaussian noise jammer with the conventional BPSK constellation for SF=16.

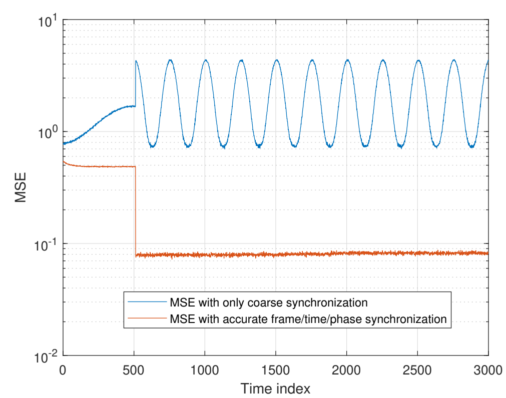

Fig. 6. Comparison of synchronization Mean Square Error with the repeat jammer and the conventional QPSK constellation for $SF = 16$ and $P_J/P_u = 9$ dB.

TABLE I
SIMULATION PARAMETERS

Parameters	
Preamble	511 symbols
chip rate	10^7 chip/s
Number of information bits per packet	1000 bits
Channel coding	Turbo (13,15)
Code rate	1/3
Roll-off factor	0.5
Doppler shift / Carrier frequency	$\approx 10^{-3}$
N_R (comb jammer)	200
K (Frame synchronization)	8

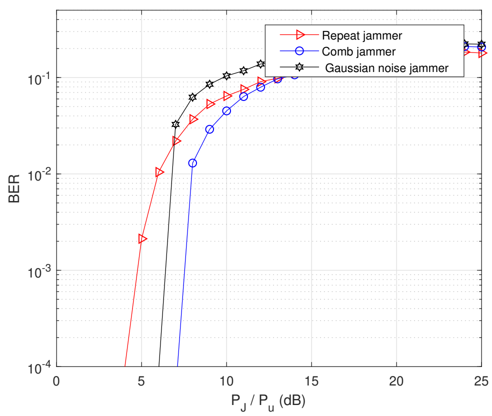

Fig. 7. BER comparison between the repeat jammer, the comb jammer and the Gaussian noise jammer in the first scenario and for the conventional BPSK constellation.

signal to noise ratio equals to 10 dB for a Spreading Factor (SF) equal to 4 and 16 respectively. Moreover, we assume in our simulation that the jamming delay is larger than the chip duration and less than the symbol duration.

We can observe that, among the considered jammers, the repeat jammer is the most detrimental to the system performance. In addition, regardless of the type of interference, increasing the spreading factor logically results in a signif-

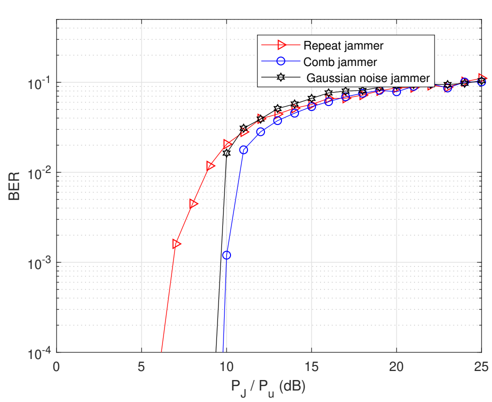

Fig. 8. BER comparison between the repeat jammer, the comb jammer and the Gaussian noise jammer (first scenario and rotated UP-RCQD BPSK).

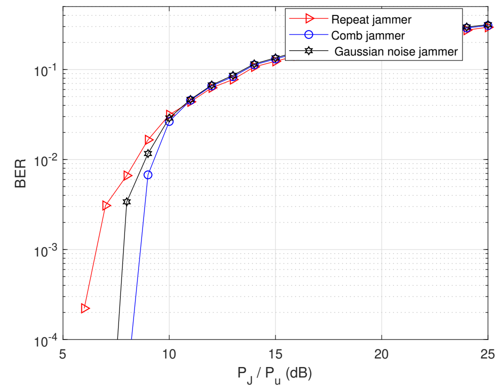

Fig. 9. BER comparison between the repeat jammer, the comb jammer and the Gaussian noise jammer (second scenario and conventional BPSK).

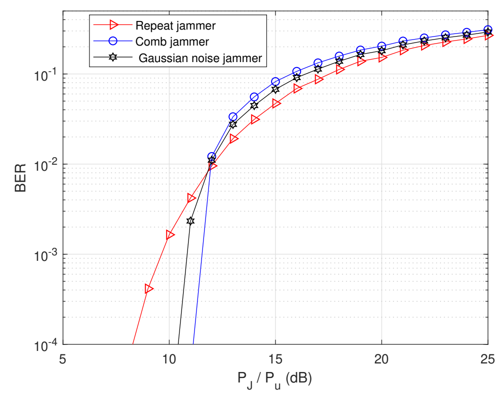

Fig. 10. BER comparison between the repeat jammer, the comb jammer and the Gaussian noise jammer in the second scenario and for the rotated UP-RCQD BPSK constellation.

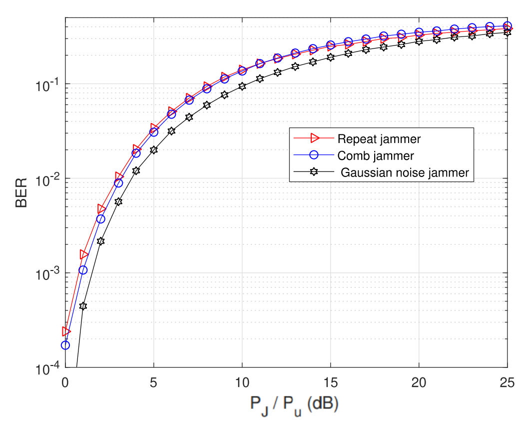

Fig. 11. BER comparison between the repeat jammer, the comb jammer and the Gaussian noise jammer in the in the second scenario, for the conventional QPSK constellation and $SF = 4$.

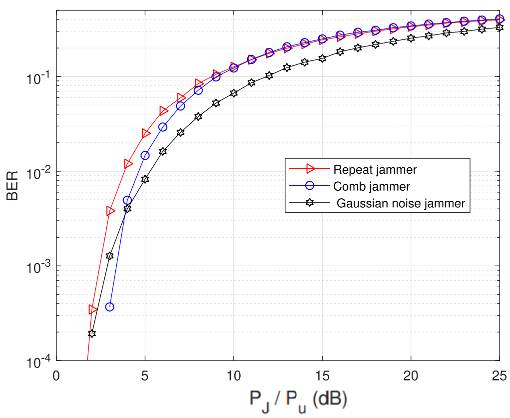

Fig. 12. BER comparison between the repeat jammer, the comb jammer and the Gaussian noise jammer in the second scenario, for the rotated UP-RCQD QPSK constellation and $SF = 4$.

icant improvement of the system performance. Furthermore, Fig. 6 displays typical synchronization Mean Square Error (MSE) curves obtained in the case of the repeat jammer and the conventional QPSK constellation for $SF = 16$ and $P_J/P_u = 9$ dB. We can observe that with only a coarse synchronization, the MSE performance is not sufficient to obtain a good BER performance. On the other hand, with all the considered synchronization algorithms, we obtain good MSE performance at $P_J/P_u = 9$ dB. Similar results are obtained with other system parameters; finally, it may be worth mentioning that the MSE performance, with all the considered synchronization algorithms, can be seriously deteriorated for a large P_J/P_u, leading inherently to a poor BER performance. In the next subsection, we compare the performance of the conventional DSSS to the DSSS with Signal Space Diversity in the same simulation conditions.

B. Comparison of DSSS with rotated and non rotated constellations in two scenarii

In our simulations, we consider two scenarii. In the first one, the two channels are independently jammed with probability $p = 0.5$ and the jammer on both channels have the same power P_J. In the second scenario, both channels are always jammed and the total jammer power on both channel P_J is constant, however the jammer power on each channel varies randomly, obeying a uniform distribution.

For the first scenario, Figure 7 (resp. Fig. 8) shows the BER performance with the three considered jammers, obtained with a spreading factor equal to 4 with a conventional BPSK constellation (resp. a UP-RCQD BPSK constellation). We observe that the rotated BPSK DSSS outperforms the DSSS with the non-rotated BPSK by a gain of about 2 to 3 dB according to the different types of jamming.

Now considering the second scenario, Figure 9 (resp. 10) shows the BER performance for the three considered jammers, obtained with a spreading factor equal to 4 with a conventional BPSK constellation (resp. a UP-RCQD BPSK constellation). We can observe that Signal Space Diversity also allows about a 3 dB gain in BER performance compared to conventional constellations. Finally, similar results are obtained with other constellations sizes. For instance, Figure 11 (resp. Figure 12) shows the BER performance for the three considered jammers with a conventional QPSK constellation (resp. a UP-RCQD QPSK constellation). We can observe again that the DSSS with the UP-RCQD QPSK constellation outperforms the conventional DSSS by about 2 to 3 dB depending on the type of jammer.

VI. CONCLUSION

To work around the high vulnerability to jamming attacks, wireless communications systems often uses Direct Sequence Spread Spectrum techniques. We first studied the resistance to jamming of the DSSS modulation, including the influence of a Doppler effect and imperfect synchronization. Then, the use of DSSS with signal space diversity is proposed in this paper. Simulation results clearly show that the proposed technique achieves a gain of several dBs in performance compared to the conventional DSSS.

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