Jiménez *et al. EURASIP Journal on Wireless Communications and Networking* (2016) 2016:270
DOI 10.1186/s13638-016-0770-6

EURASIP Journal on Wireless Communications and Networking

RESEARCH **Open Access**

Novel orthogonal multi-sequences for an efficient jamming on the UMTS signal

Victor P. Gil Jiménez*, Ana Garcia Armada, Francisco Hernando Gallego and Nieves Sidney González Pizarro

Abstract

In this paper, a novel and efficient scheme for jamming the Universal Mobile Telecommunications System (UMTS) signal without the assistance from the base station or operator is proposed and evaluated. The scheme is based on new orthogonal multi-sequences developed in this paper. These sequences are specially designed to interfere all the Orthogonal Variable Spread Factor (OVSF) codes that are used in the UMTS transmission and thus, any signal spread by these multi-sequences will interfere all the transmitted data channels at the same time. A power gain of about 7 dB is obtained with respect to the traditional jamming method based on high power wide-band noise injection can be obtained when no channel is used and 10.4 dB in a more realistic scenario with multipath Rayleigh channel.

Keywords: OVSF, Multi-sequences, UMTS jamming

1 Introduction

Mobile communications are one of the most used technologies nowadays and with largest penetration. However, there are many situations where mobile transmissions are prohibited or need to be eliminated for security reasons, such as in dignitary's vehicles, penitentiaries, hospitals, or airplanes; and places where their use is annoying such as cinemas, theaters, or concert halls. For these reasons, it is important to provide inhibitors for such technologies. Indeed, several proposals and techniques can be found in the literature and in the market. Most of them require support from operators. For Global System for Mobile (GSM), in [1] and [2], it is the operator, relying on an external equipment (the inhibitor) who inhibits the signal. Other similar examples, now for Universal Mobile Telecommunication System (UMTS), can be found in [3–5]. However, most of the situations do not allow to get this support, especially in mobile scenarios where the inhibition area is moving such as in the case of dignitary's vehicles. In GSM, a simple transmission of additive white Gaussian noise (AWGN) in the whole band is enough to efficiently interfere the signal since it is a narrow-band technology [6, 7]. Unfortunately, the same technique is neither effective (it does not always work) nor efficient (it needs a lot of energy) [8] for a wide-band system such as UMTS because the bandwidth of UMTS is 5 MHz, so the bandwidth of the noise must be at least 5 MHz. Thus, a lot of power energy will be needed. Since power transmission is limited (because of regulations and safety), it must be used for inhibition not only UMTS but also other standards; more efficient jamming systems must be found. Although most of the common and commercial jammers for UMTS use the high power AWGN injection, their performance is neither energy efficient nor valid in terms of availability of the system [9]. Moreover, according to regulation [10], it might not be safe due to the high power demand. Recently, other smart strategies are being used for GSM [11] or UMTS [12].

In this paper, a novel smart approach is developed. It is specifically based on the UMTS signal properties, where the Orthogonal Variable Spreading Factor (OVSF) codes are used for spreading the signal. These codes, by spreading the signal, also protect the transmission against multi-path and narrow-band and wide-band interference. However, a narrow-band signal spread by an OVSF will fully interfere with the transmitted signal in that channel. Since there are many OVSF codes being used at the same time and, moreover, they are unknown, in order to avoid the transmission of hundreds of OVSF-spread signals, in this paper, a set of multi-sequences are developed

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*Correspondence: vgil@tsc.uc3m.es
Signal Theory and Communications, University Carlos III de Madrid, Madrid, Spain

with high interference capabilities yet reduced number of sequences.

Of course, since some of the jamming techniques are also used by malicious people, there are attempts to detect [13] or to reduce or mitigate such jamming techniques as in [14]. In this sense, our proposal holds unaffected by them because our signals will interfere any data spread within the cell and thus all the channels will be affected (control and data channels).

Notation: Throughout this paper, the following notation will be used. Boldface letters will be used for vectors and normal face for scalars and $(\cdot)^T$ denotes transposition.

2 UMTS signal basics

The UMTS signal is based on spread spectrum Code Division Multiple Access (CDMA) [15], i.e., the original narrow-band signal from each user or base station is spread into a wide-band signal by using a channelization code (c_i) and scrambled by another code $\left(S_{dl,n}\right)$, as it is depicted in Fig. 1. Then, all signals are multiplexed together with different gains (G_i) and transmitted at the same time and frequency. At the receiver, after synchronization process [16], the specific channel is decoded (despread) by using the same channelization code (c_i) used for spreading at the transmitter. Different users (or base stations) are separated by using different scrambling codes $\left(S_{dl,n}\right)$, and different channels from the same user (or same base station) are distinguished by different channelization codes (c_i). The scrambling codes are pseudo-noise (PN) gold sequences and do not spread whereas channelization codes are OVSF-based and provide the spreading of the transmission signal and thus the robustness against multi-path and interference. Both types of codes are sequentially applied to the data source. Each base station, denoted NodeB in UMTS, uses one and only one primary scrambling code for all the transmission (neighbor NodeBs use different scrambling codes). Then, after scrambling the signal, each different channel can be distinguished because each one uses a different OVSF spreading code. On the other side, each user transmits to the NodeB by using a different scrambling code, and their data channels are spread by different OVSF codes. Thus, once the scrambling code is known, in order to interfere all the channels in one cell for one user, we need to transmit by interfering all the possible OVSF to guarantee that the ones used in the cell (that are unknown) are being jammed. The effect of this action will be similar to a link layer denial of service [17] but at the physical layer and without the support neither from the operator nor from specific NodeB, common scenario in mobility cases. It should be noted that the scrambling code from the NodeB can be easily acquired like any UMTS terminal does. The first thing a UMTS terminal does when detecting the cell is to acquire the scrambling code by using the synchronization process. Thus, a jammer could perform this procedure before starting to interfere. These scrambling codes do not change very often for a cell, in fact, they can even not change at all during months.

3 Generation of orthogonal multi-sequences

3.1 Generation of sequences correlated with OVSFs

As explained before, each UMTS data channel is spread by one OVSF. Those OVSF codes are orthogonal to each other in order to avoid inter-channel interference. Any transmission using a specific OVSF will interfere this and only this channel and not the others. Since the NodeB or the mobile station can use any of the 512 or 256 OVSF codes, respectively (each parent OVSF of length less than 256 or 512 is interfered by its descendant), we would need to use all the OVSF in order to guarantee that the ones that are actually used are being interfered (a priori, it is not easy to know which ones they are). Moreover, the OVSF being used changes dynamically. Unfortunately, the transmission of all the OVSF codes will end up with very high power transmission requirements. In order to avoid this, multi-sequences have been developed in this paper. The idea is to generate a sequence with high interference capabilities to several OVSF at the same time. In this way, a noise signal spread by this multi-sequence will interfere all the channels spread by these OVSF. In the following, the generation of these multi-sequences will be described. Let us denote the maximum spreading factor 512 or 256 for the downlink and the uplink, respectively, as L.

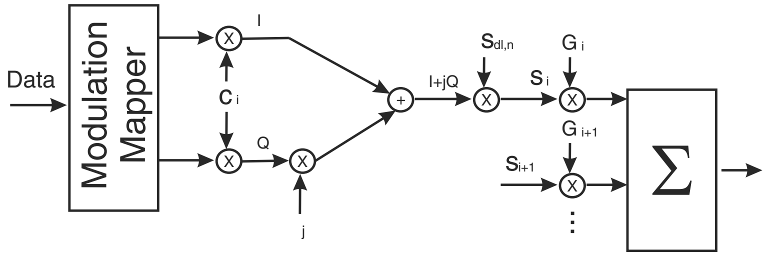

Fig. 1 Downlink UMTS spreading and scrambling process [15]

Let $\mathbf{a} \in \mathbb{R}^{(1\times SF)}$ and $\mathbf{b} \in \mathbb{R}^{(1\times SF)}$ be two OVSF codes of spreading factor (code length), $SF = L$. In order to generate another sequence highly correlated with both of them, we can rely on the Cholesky decomposition [18]. Let R

$$R = \begin{pmatrix} \alpha & \beta \\ \beta & \alpha \end{pmatrix} \tag{1}$$

be the correlation matrix, where α denotes the desired correlation for the new sequence with respect to **a** and β correlation with respect to **b**. It should be noted that $\beta < \alpha$, otherwise the matrix does not fit Cholesky properties. Then, a new sequence correlated with **a** and **b** can be obtained by

$$\mathbf{s} = \left[\mathbf{a}^T \mathbf{b}^T\right] \Lambda \ , \tag{2}$$

where Λ is the Cholesky decomposition of R [18], i.e., $R = \Lambda\Lambda^H$. It should be noted here that Λ is a lower triangular matrix with nonnegative diagonal entries. We found thus that the new sequence **s** will exhibit a correlation close to α and β with respect to **a** and **b**, respectively. Thus, a signal spread by **s** will interfere channels spread by **a** and **b** simultaneously. Since $\alpha > \beta$, the interference over **a** will be larger than over **b**. However, this sequence will still only interfere over two out of L available codes. In order to avoid the generation of $SF/2$ orthogonal interference sequences and thus the expenditure of too much power, a set of multi-sequences is developed as follows. Let $\mathbf{s}_1$ and $\mathbf{s}_2$ be two sequences generated by using Eq. 2 from arbitrary four OVSF codes **a** and **b** (two different OVSF codes per sequence). Summing up these two sequences (i.e., the mathematical addition), the resulting one exhibits high correlation with respect to the four used OVSF; however, the correlation will be lower than the one shown for $\mathbf{s}_1$ or $\mathbf{s}_2$. We can repeat this process to obtain a sequence that is correlated with respect to all the OVSF codes ($\mathbf{s}_{\mathrm{ALL}}$); however, the more sequences $\mathbf{s}_i$ will sum-up, the lower the correlation with respect each OVSF will be. This means that a signal spread by $\mathbf{s}_{\mathrm{ALL}}$ will interfere all the OVSF codes (thus all the possible channels) but in a very low ratio. Since there is a tradeoff between the correlation properties of the generated sequence and the number of OVSF codes that is able to interfere, we propose the use of multi-sequences instead.

3.2 Generation of OVSF codes

Before explaining the generation of multi-sequences, a summary on how the OVSF codes are generated is presented. Let $h_1 = 1$ the first OVSF code of length 2^0. Then, the two next OVSF codes of length 2^1 are generated like Hadamard matrix as

$$\mathbf{h}_2 = \begin{bmatrix} h_1 & h_1 \\ h_1 & -h_1 \end{bmatrix} , \tag{3}$$

with $\mathbf{h}_2 \in \mathbb{R}^{2\times 2}$. The matrix $\mathbf{h}_k$, with $k = 7, 8$ for $SF = 2^k = 256, 512$, respectively, can be recursively generated in the following way, similarly as how Hadamard matrix is built

$$\mathbf{h}_k = \begin{bmatrix} \mathbf{h}_{k-1} & \mathbf{h}_{k-1} \\ \mathbf{h}_{k-1} & -\mathbf{h}_{k-1} \end{bmatrix} , \tag{4}$$

being $\mathbf{h}_k \in \mathbb{R}^{2^k \times 2^k}$.

3.3 Generation of multi-sequences

Denoting $\mathbf{o}_j$ as the j-th row in $\mathbf{h}_k$ of length SF, we assign a multi-sequence $\mathbf{S}_i^{\mathrm{SF}}$, with $i \in \{0 \cdots N-1\}$ as the ith multi-sequence of spreading factor SF. It is built as follows. If we denote the jth out of SF OVSF codes as $\mathbf{o}_j$, the multi-sequence i is obtained as

$$\mathbf{S}_i^{\mathrm{SF}} = \sum_{l=i\frac{\mathrm{SF}}{N}, m=i\frac{\mathrm{SF}}{N}+\frac{\mathrm{SF}}{2}}^{(i+1)\frac{\mathrm{SF}}{N}-1, (i+1)\frac{\mathrm{SF}}{N}+\frac{\mathrm{SF}}{2}-1} \left[\mathbf{o}_l^T \mathbf{o}_m^T\right] \Lambda \ , \ i < \frac{N}{2} \tag{5}$$

$$\mathbf{S}_i^{\mathrm{SF}} = \sum_{l=i\frac{\mathrm{SF}}{N}, m=(N-i-1)\frac{\mathrm{SF}}{N}}^{(i+1)\frac{\mathrm{SF}}{N}-1, (N-i)\times\frac{\mathrm{SF}}{N}-1} \left[\mathbf{o}_l^T \mathbf{o}_m^T\right] \Lambda \ , \ i \geq \frac{N}{2} \tag{6}$$

where α and β—from (1)—will establish the performance and the range of utilization, as it will be shown in the next section, and N is the number of multi-sequences that we want to generate.

In order to clarify the expressions in Eqs. 5 and 6, a simple example is provided in the following. Assuming a spreading factor of $\mathrm{SF} = 16$ and the generation of $N = 4$ different multi-sequences, the first multi-sequence $\mathbf{S}_0^{16}$ will use sequences $\mathbf{o}_{1\cdots 3}$ and $\mathbf{o}_{8\cdots 11}$, the second multi-sequence $\mathbf{S}_1^{16}$ will use $\mathbf{o}_{4\cdots 7}$ and $\mathbf{o}_{12\cdots 15}$, the third multi-sequence $\mathbf{S}_2^{16}$ will use $\mathbf{o}_{8\cdots 11}$ and $\mathbf{o}_{4\cdots 7}$, and the forth multi-sequence $\mathbf{S}_3^{16}$ will use $\mathbf{o}_{12\cdots 15}$ and $\mathbf{o}_{0\cdots 3}$.

As it can be observed from Eqs. 5 and 6 and the above example, each multi-sequence uses $2 \times \frac{\mathrm{SF}}{N}$ of the available OVSF spreading codes, and there are overlaps in codes (sequences $\mathbf{o}_{0\cdots 3}$ are present in multi-sequences $\mathbf{s}_0^{16}$ and $\mathbf{S}_3^{16}$); that means that each OVSF code will be interfered by two multi-sequences S_i^{SF}, one of them with correlation factor α and the other with β. The lower and the upper limits in Eqs. 5 and 6 move along all the available SF codes. Thus, the proposal is the spreading of a narrow-band noise signal by our developed multi-sequences in order to interfere all the SF channels approximately two times each $N \times T_{\mathrm{Slot}}$, where T_{Slot} is the time duration of one slot in the UMTS frame, as it can be seen in Fig. 2.

A description of our scheme and a comparison to traditional one is depicted in Fig. 3. As it can be observed in this figure, our proposal avoids the use of wide-band noise generator, which is either energy inefficient and operational valid.

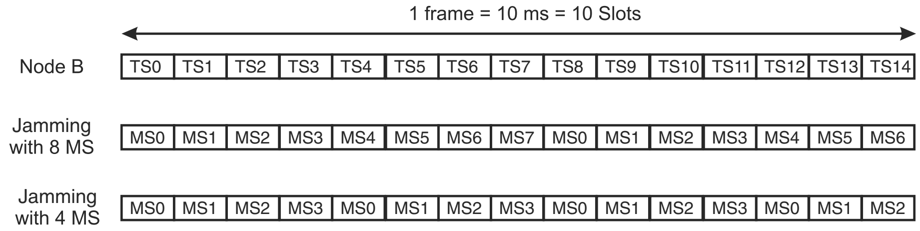

Fig. 2 Time structure for the proposed multi-sequence jamming system

4 Discussion on parameters α and β

As it has been aforementioned, two important parameters are α and β (correlation factors). Thus, in this section, the analysis and influence of both parameters will be carried out. Each multi-sequence will interfere two channels spread by two different OVSF. The amount of interference that each multi-sequence is able to obtain over a specific channel depends on the correlation between the OVSF code used for spreading this channel and the multi-sequence. In Fig. 4, the mean correlation over all the OVSF codes of different multi-sequences built with different values of α and β is shown.

It can be seen that, as expected, the correlation is higher for 8 multi-sequences (black solid curves) than for four multi-sequences (red dashed ones). The reason is that if the number of multi-sequences increases, it means that fewer number of OVSF is used on each multi-sequence, and therefore the achievable correlation can be higher. Besides, it can be observed that, for a specific value of α, the correlation has a maximum around $\beta = 0.7$ for $\alpha = 1$ and a little bit lower for $\alpha = 0.9$ or 0.8. The global maximum correlation is obtained for $\alpha = 1$ and $\beta = 0.7$ for both, 8 and 4 multi-sequences. The maximum correlation will produce the largest interference and thus, it is likely that the best performance, i.e., the highest symbol error rate (SER). However, the larger number of multi-sequences implies that they are repeated less often within a time, as it can be seen in Fig. 2.

As it has been explained before, each multi-sequence is built with $2 \times \frac{\mathrm{SF}}{N}$ OVSF codes, half of them will exhibit α correlation and the other β correlation. Coming back to the previous example, multi-sequence $\mathbf{S}_0$ will exhibit α correlation with respect to sequences $0 \cdots 3$ and β correlation with respect to sequences $8 \cdots 11$, whereas multi-sequence $\mathbf{S}_3$ will exhibit α correlation with respect to sequences $12 \cdots 15$ and β correlation with respect to sequences $0 \cdots 3$. Thus, using the transmission sequence in Fig. 2 when multi-sequence is being transmitted, there will be a high interference in OVSF codes $0 \cdots 3$ and lower interference to OVSF codes $8 \cdots 11$ during the first interval.

Thus, each multi-sequence will interfere approximately with α correlation (higher) to $\frac{\mathrm{SF}}{N}$ OVSF codes and with β correlation (lower) to the other $\frac{\mathrm{SF}}{N}$ OVSF codes. Therefore, there are high interference part (larger SER, i.e., SER_H), as shown in Fig. 5, and low interference part (lower SER, i.e., SER_L), in Fig. 6, depending on the OVSF. In this Fig. 5, the higher SER is plotted for different

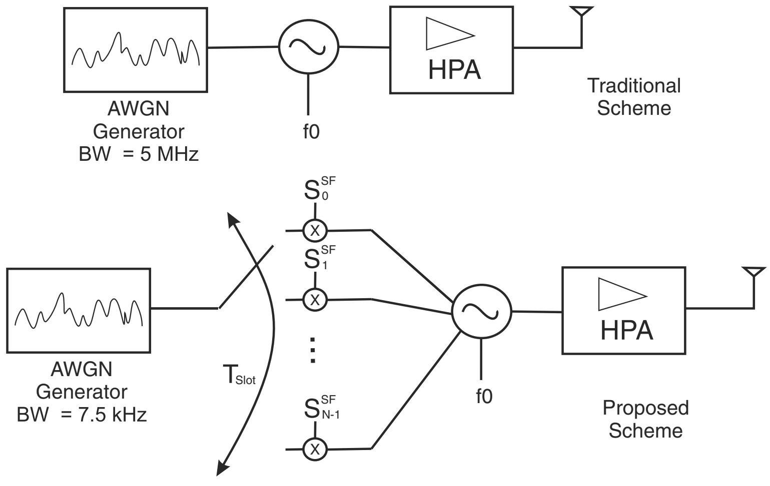

Fig. 3 Traditional and proposed system UMTS jamming model

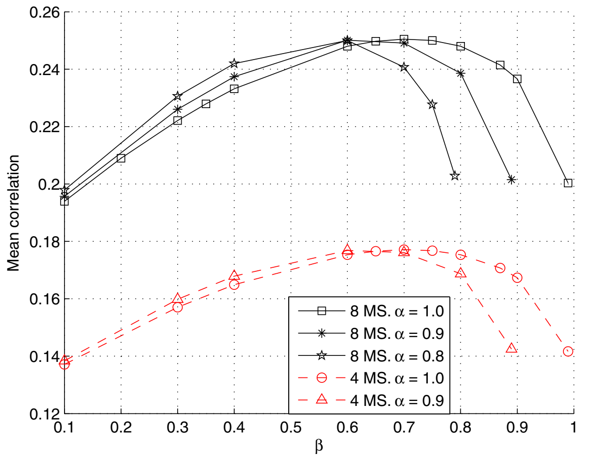

Fig. 4 Mean correlation for different multi-sequences and different α and β

multi-sequences and values of parameters α and β. In the same way, in Fig. 6, the lower SER is plotted. As it will be shown later, each multi-sequence has three regions of action, namely, *no interference, lower SER (SER*$_L$*), and higher SER (SER*$_H$*)*. As it can be observed in Fig. 5, the SER is almost constant for a wide range of values of parameter β^1, independently on the number of multi-sequences used, although the maximum SER value increases when lower number of multi-sequences is used. The reason is that although the correlation is lower for lower number of multi-sequences, the amount of time that is interfering the system is longer (see Fig. 2). On the other hand, in Fig. 6, it can be observed that the value of SER varies largely with parameter β obtaining a maximum when the correlation is the highest ($\beta \approx 0.7$ and $\alpha = 1$), as indicated in Fig. 6. It is interesting to highlight here that, since there are three regions (no interference, low interference, and high interference) due to the way the multi-sequences are built, the important threshold is the limit of the low interference because it will establish the interference range limit. In this sense, from the point of view of the jammer, the higher the SER$_L$ is, the better because it means that in the lower interference region, the error probability will be SER$_L$.

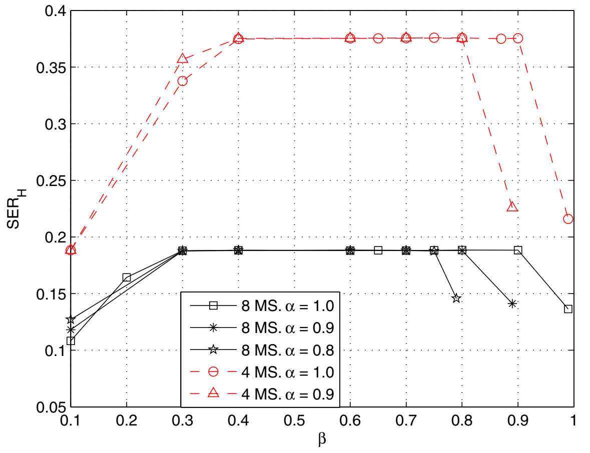

Fig. 5 Dependence of SER$_H$ with β and α

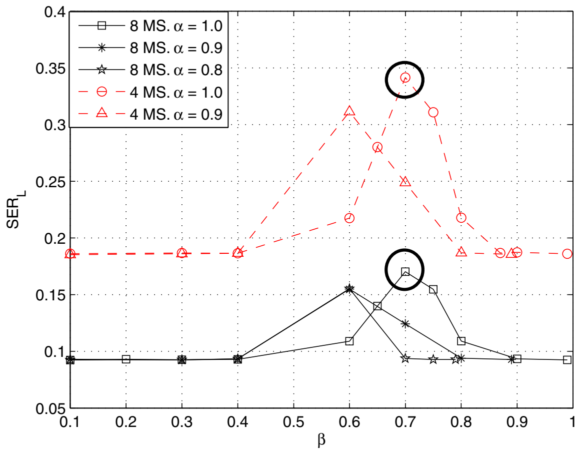

Fig. 6 Dependence of SER$_L$ with β and α

From Figs. 4, 5 and 6, it could be extracted that the best values for α and β are 1 and 0.7, respectively, and independently on how many multi-sequences are being used as it is shown in Fig. 6. As it will be shown in the following, taking into account the performance, those previous values give minimum working range.

Since UMTS uses spread spectrum, the E_c/I_0 is commonly used instead of the signal-to-noise ratio (SNR). The E_c/I_0 is the energy per channel over the total received energy (signal and interference) [15]. Since what is important here is not the total energy which will include all the channels' energy but the power per channel of interest, in the following, the E_c/I_0 will be used for the performance evaluation. As explained before, each channel is interfered by two multi-sequences, one with larger correlation than the other, that gives three regions: the first one is when the channel is being interfered by the multi-sequence with high correlation with it, the second, when the channel is being interfered by the multi-sequence with lower correlation, and the third one is when the multi-sequence being used does not interfere the channel. From an energy efficiency point of view, the goal is to be able to interfere the system with the lowest energy. A SER $\geq 10^{-1}$ is usually accepted to be large enough to block any protection coding scheme.

For evaluating the energy efficiency of our proposed inhibition scheme, several simulations have been carried out to evaluate how much energy is needed for the inhibition of the UMTS signal. We have denoted the working range as the E_c/I_0 range over where the scheme is able to obtain some interference.

In Fig. 7, this working range is displayed. It can be seen that the former best values ($\alpha = 1$ and $\beta \approx 0.7$) get a minimum in working range, i.e., the multi-sequences enter in the no interference region at lowest E_c/I_0. The I_0 in these figures only takes into account our interference. This is the worst case scenario from the point of view of interference because there is not extra interference due to other terminals, data channel or multi-path channel; all the interference comes from our jamming signal. That means that in a realistic scenario, the performance of our multi-sequences, from the point of view of interference, will start to work from a lower E_c/I_0 because I_0 will also contain the noise and other interference. Besides, since the error probability is the measure, anything that increases error probability such as noise or interference will push up the jammer's performance.

Since the energy efficiency is a must, from Fig. 7, the best values for α and β are 1 and 0.3, respectively, because they reach the maximum working region (up to −14 dB of E_c/I_0 for 8 multi-sequences) and, at the same time, get higher correlation and higher SER_L too. From the figure, it can also be extracted that the best number of multi-sequences is 8. A smaller number of N (number of multi-sequences) reduces too much the working range whereas a larger one reduces too much the SER. Thus, there is a tradeoff between working range and achievable SER.

A set of N multi-sequences can be easily obtained by using Eqs. 5 and 6. However, for smaller values of N, e.g. $N = 2$, it reduces too much of the working range (to −20 dB of E_c/I_0, which is even worse than traditional AWGN scheme). On the other hand, a larger number of multi-sequences ($N = 16$) will reach much longer working range (up to −13 dB of E_c/I_0) but however, the SER will be close to 10^{-2}, which is too low to be valid from an interference point of view. A good tradeoff is 8 multi-sequences because it gives a reasonable large working range and at the same time obtains a $SER \geq 10^{-1}$.

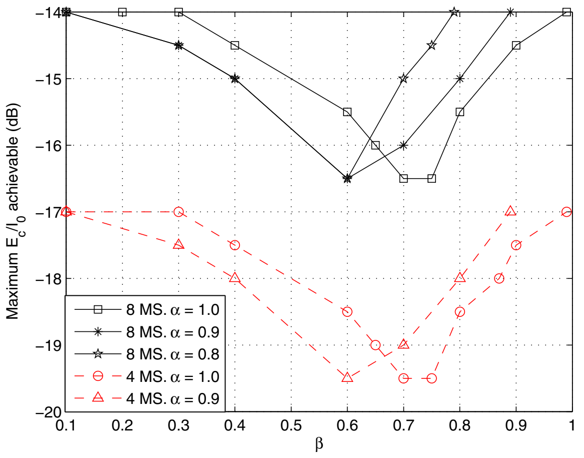

Fig. 7 Maximum achievable E_c/I_0 with α and β

5 Results

Since the goal is the interference of the UMTS signal, the setup has been designed for evaluating the interference capabilities of our proposal, i.e., the only transmitted signals are the information channel (OVSF) to be interfered and our jamming signal in an ideal wireless channel (no propagation channel effects). The only impairment that alters the transmitted signal and impacts into the performance is our proposed jamming signal. In a realistic scenario, with realistic channel effects, interference from other cells, multi-user interference, and near-far effect, the results, from the point of view of interference, would be much better. Our results should then be treated as lower bounds of achievable performance. At the end of the section, a more realistic scenario where a multi-path Rayleigh channel has been simulated too.

The proposed scheme spreads a random signal during a certain number of slots with the multi-sequence $\mathbf{S}_0^{512}$, then, with the multi-sequence $\mathbf{S}_1^{512}$ and so on until multi-sequence $\mathbf{S}_{N-1}^{512}$, and the process starts again with multi-sequence $\mathbf{S}_0^{512}$ (see Fig. 2). The number of slots used for each multi-sequence must be small (although it does not change results) because the larger number of slots used, the longer time until the repetition of the same multi-sequence. There are several communication procedures such as the authentication, the resource allocation or paging, among others, that use a reduced number of frames. Since the goal of multi-sequences is to interfere the transmission, these procedures and the others should be interfered. This is the reason why the number of slots of repetition have to be small, to be able to interfere these basic procedures. In our simulations, a reference time of one frame has been used. In Fig. 2, the multi-sequence pattern for $N = 4$ and $N = 8$ is shown. It can be observed that same multi-sequence is repeated several times within a frame. In order to obtain a fair comparison, the transmit power is always the same for the transmission of 4 multi-sequences or 8 multi-sequences.

The modulation used to obtain the results is QPSK which is the only modulation valid in UMTS. In this paper, High Speed Downlink Packet Access (HSDPA) has not been considered.

As anticipated in the paper, there are three working regions that can be observed in Fig. 8: *higher SER* (SER_H) below −24 dB, *lower SER* (SER_L) up to −14 dB, and *no interference* above −14 dB, all of them for the 8 multi-sequences and [$\alpha = 1, \beta = 0.3$] case. These thresholds are different for the other cases. It can also be seen in Fig. 8 that our proposal obtains a 7-dB gain with respect to the

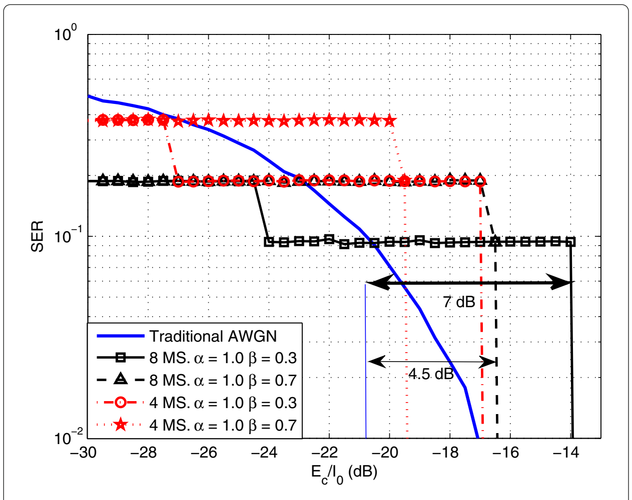

Fig. 8 SER for different multi-sequences and different β. $\alpha = 1$. No channel neither noise

traditional AWGN scheme since for a SER $= 10^{-1}$ (which makes data channel undecodable), our 8 multi-sequence scheme is able to work up to $E_c/I_0 = -14$ dB whereas AWGN only reaches -21 dB. If we use $\beta = 0.7$ instead, we get larger SER but the gain reduces to 4.5 dB.

In a more realistic scenario where a Rayleigh channel is used, it can be seen in Fig. 9 that results, in terms of inhibition, were improved compared to the previous scenario where neither channel nor noise where included. Now, the error probability is higher but also the working range. It has been highlighted in the figure that for the same configuration where previously we obtained 7 dB of gain, now a gain of approximately 10.4 dB is obtained.

Finally, for a realistic implementation of the jammer, the following procedures will be carried out. First, the jammer (as any UMTS terminal) will obtain the scrambling codes for all the cells that want to be interfered in the area (even for several operators). Then, it will start to transmit the multi-sequences in a row constantly and following the frame structure in Fig. 2 by using the spreading(s) code(s). In this way, the communication is interfered in the cell(s).

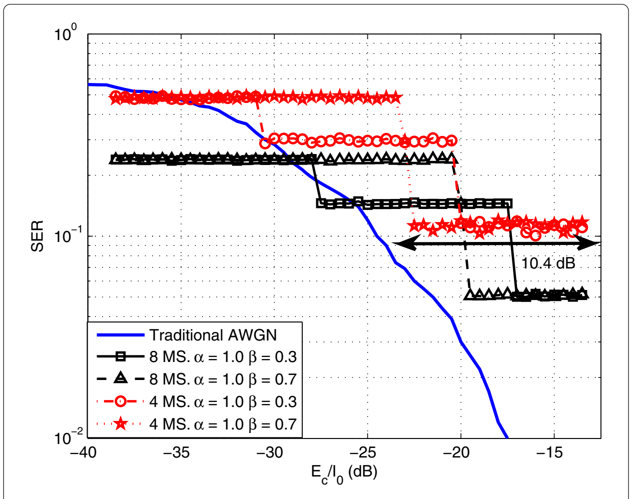

Fig. 9 SER for different multi-sequences and different β. $\alpha = 1$. Rayleigh channel

6 Conclusions

A set of orthogonal multi-sequences for interfering the UMTS transmission signal has been designed and evaluated. With these multi-sequences, the amount of energy needed to interfere the transmission is significantly reduced (more than 7 dB when no other sources of impairments are present and larger than 10.4 dB in Rayleigh channel). The procedure is simple and multi-sequences can be offline calculated and stored, thus, the real-time implementation of the inhibitor becomes trivial. By using these multi-sequences, all the communications are inhibited independently on which OVSF codes were being used. We have found that the best tradeoff between number of multi-sequences and interference capability is fulfilled with 8 multi-sequences, but, if the range of spreading codes is known, the set of multi-sequences can be reduced. Thus, the working range and the SER can be increased.

Besides, since our proposal is based on the interference of the OVSF codes, it can be selective and designed to only interfere a set of channels that provides more flexibility and usefulness to our proposal.

Endnote

[1] The range is 0.3 to 0.75 for 8 multi-sequences and 0.4 to 0.8 for 4 multi-sequences.

Acknowledgements
This work has been partially funded by the Spanish national project ELISA (TEC2014-59255-C3-3-R).

Competing interests
The author(s) declare(s) that they have no competing interests.

Received: 9 July 2016 Accepted: 9 November 2016

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