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ABSTRACT

This paper focuses on the demodulation performance analysis of different CSK configurations coupled with different demodulation/decoding methods in urban environments. The tested CSK configurations are defined by the number of bits mapped by a CSK symbol, the number of PRN codes constituting a symbol, and the codeword source mapping. The tested demodulation techniques are the traditional non-coherent demodulation technique and a new proposed technique called 'non-coherent PRN code' which reduces the demodulation exposition to the carrier phase fast variations. The tested scenarios depend on the mobile speed and the Line-of-Sight received signal conditions. From all these parameters, a better overall view of the behavior of a CSK signal transmitted in urban environments is obtained and more tools are provided for the design of a GNSS CSK modulated signal.

INTRODUCTION

GNSS signals are designed in order to fulfill the special needs of a GNSS system: to provide the receiver with precise synchronization and to broadcast little essential information such as the satellites ephemeris, clock error correction, etc. The combination of these two elements allows a GNSS system to provide the user with its PVT (position, velocity, time) [1][2].

The GNSS signal communication part design consisted in the implementation of a BPSK modulation. The BPSK modulation was historically selected in order to allow the implementation of the key synchronization part: direct sequences-spread spectrum (DS-SS). At the epoch, the low BPSK modulation bandwidth efficiency **[**3] did not present any limitation to the signal design due to the low required bit rate.

Nowadays, the BPSK modulation choice can be questioned due to the introduction of a new dataless (pilot) component as well as the extension of the GNSS user community with high expectations in terms of new services and positioning capabilities in more challenging environments. On one hand, the introduction of a pilot component allows the receiver to achieve the precise synchronization on the pilot channel alone. On the other hand, new GNSS applications/services demand a much higher data rate which cannot be provided by classic GNSS BPSK modulated signals due to PRN code length and period restrictions [5]. In fact, the data rate increase of a GNSS BPSK modulated signal will lead to a new signal with a wider spectrum, or to a loss of PRN code isolation and orthogonality properties [5].

The use of a Code Shift Keying (CSK) modulation as a solution to increase the final signal data rate was proposed in [4][5] and has even been implemented on the LEX signal of the Japanese QZSS system. The CSK modulation, specially designed to increase the transmission rate of a spreading spectrum signal, consists in circularly shifting each transmitted PRN code in order to represent with each shifted PRN code a different CSK symbol mapping a set of bits.

Previous analysis of the introduction of a CSK modulation in a GNSS signal received in open-sky environments can be found in the literature [4][5]. However, only preliminary analysis of the GNSS CSK modulated signals reception in urban environments has been done [6] despite its interest:

1) Under-development applications target environments with difficult reception conditions such as urban areas.
2) GNSS BPSK modulated signal reception in urban environments is restricted by the carrier phase estimation performance (coherent demodulation) whereas GNSS CSK modulated signals are not (non-coherent demodulation)

The aim of this paper is to further analyze the performance of a GNSS CSK modulated signal received in an urban environment when using the non-coherent demodulation method presented in [6]. More specifically, this article inspects if a CSK demodulation is possible when the signal is transmitted through a mobile channel and inspects the best CSK configuration for a mobile channel. Additionally, this work also analyzes an alternative non-coherent method for the harshest mobile channels.

In this paper first, the CSK fundamentals and the two analyzed non-coherent demodulation methods are described. Second, the mobile channel mathematical model is defined. Third, the results obtained from numerical simulations of the transmission of a CSK signal through a mobile channel are presented. Finally, this paper is concluded.

CODE SHIFT KEYING MODULATION TECHNIQUE

CSK Definition

The CSK modulation technique is a DS–SS signaling method which overcomes the spreading gain versus data rate limitations [7]. The CSK is a form of orthogonal M-ary signaling over a communication channel [8] since M orthogonal signaling waveforms are used in order to transmit $U = \log_2(M)$ bits. The special characteristic of the CSK modulation with respect to the typical orthogonal M-ary signaling is that each waveform (or symbol representing a set of input bits) is obtained from a different circular cyclic phase shift of a single fundamental PRN sequence. Moreover, each circular cyclic phase shift is made by an integer number of chips [7] and is assumed to be a full period version of the fundamental sequence [7].

CSK symbol Mathematical Model

The CSK symbol mathematical model depends on the number of possible shifts of the fundamental PRN code, M, and on the number of identical shifted PRN codes which constitute a CSK symbol, N. The number of different circular shifts of the fundamental PRN code which are required to transmit U bits per CSK symbol is equal to M, where $M = 2^U$. The CSK fundamental code is called $c_d(t)$ and has a period length equal to T_{PRN} which spans over C chips. C is not necessarily equal to M and the chip interval is equal to T_c. From this fundamental code, $c_d(t)$, the modulator generates the M circular PRN code shifts, referred as $c_0(t)$ to $c_{M-1}(t)$. A mathematical expression of a generic circular PRN code shift is shown below:

$$c_x(t) = c_d(mod[t - m_x T_c, C \cdot T_c]) \quad c_x[m] = c_d(mod[m - m_x, C]) \quad x = 0 \dots M-1 \tag{1}$$

$$c_x(t) = \sum_{m=0}^{C-1} c_x[m] \cdot rect\left(\frac{t - mT_c}{T_c}\right) \tag{2}$$

Where m_x is the integer number representing the code shift of the x^{th} symbol and $mod(x, y)$ represents the modulus operation of y over x. The CSK symbol mathematical model, $s_x(t)$, is thus obtained by repeating N times the circular PRN code shift which represents the set of bits which are transmitted:

$$s_x(t) = \sum_{n=0}^{N-1} c_x(t - nT_{PRN}) \tag{3}$$

The CSK symbol length, T_s, is thus defined as $T_s = NT_{PRN}$. Finally, the bit rate increase of a CSK modulation with respect to a BPSK modulation where each BPSK symbols spans 1 fundamental PRN code is equal to:

$$Bit\ rate\ increase = U/N \tag{4}$$

The main idea driving the use of consecutive PRN codes in order to constitute a CSK symbol was the possibility of obtaining a relative small bit rate increase by using a CSK symbol mapping a large number of bits, U. In fact, in order to obtain a bit rate increase equal to n (xn), a CSK configuration, defined as $CSK(U, N)$ [5] has to be as follows: $CSK(U, U/n)$. Therefore, since in an AWGN channel, the demodulation performance of a CSK signal increases along the increase of U [5], a designer should use the largest possible value of U in order to obtain the best possible demodulation performance when targeting a bit rate increase of n. However, this conclusion was only valid for an AWGN channel where the signal carrier phase and the signal amplitude are considered constant along the time. In the case of a mobile channel where these two parameters can vary very fast, a longer CSK symbol duration could be detrimental as will be explained later.

CSK modulated signal mathematical Model

The equivalent low-pass CSK modulated signal at the emitter's antenna output is simply modelled as:

$$s(t) = \sqrt{2P_{trans}} \sum_{i=-\infty}^{+\infty} s_{x[i]}(t - iT_s) \tag{5}$$

Where P_{trans} is the transmitted CSK signal power, and $x[i] \epsilon [0, M-1]$ indicates the transmitted CSK symbol at instant i. The equivalent low-pass received signal at the receiver RF block output, $v(t)$, can be modeled when assuming the transmission of a CSK signal through a narrowband non-frequency selective channel [3] as:

$$v(t) = \sqrt{2P} \cdot c(t) \cdot s(t) + n(t) \qquad c(t) = a(t)e^{j\varphi(t)} \tag{6}$$

Where P is the received signal power (without taking into account the propagation channel influence), $c(t)$ is the complex envelope introduced by the propagation channel, $\varphi(t)$ is the instantaneous carrier phase introduced by the propagation channel, $a(t)$ is the amplitude introduced by the propagation channel, and $n(t)$ is the equivalent low-pass AWG noise with power equal to σ^2.

CSK Demodulator Output Mathematical Model

The principle of an orthogonal modulation demodulator consists in applying a matched filter for each symbol of the constellation. Therefore, the CSK demodulator consists in a bank of matched filters, one for each possible PRN code shift. Moreover, since each symbol is a circular shift of a fundamental sequence, a FFT-base demodulator conducting the time correlation process in the frequency domain [8] can also be applied.

The equivalent mathematical operation conducted by the k^{th} matched filter, which represents the k^{th} PRN code shift, in order to estimate the i^{th} transmitted CSK symbol is:

$$y_k^{I,i} = \frac{1}{T_s} \mathrm{Re}\left[\int_0^{T_s} v(t - iT_s) s_k(t) e^{-j\hat{\varphi}(t)} dt\right] \tag{7}$$

Where $\hat{\varphi}(t)$ is the carrier phase estimation, $y_k^{I,i}$ represents the in-phase output of the k^{th} matched filter at instant i. The vector $Y^{I,i}$ representing the in-phase outputs of the matched filters is thus defined as:

$$Y^{I,i} = \left[y_0^{I,i}, y_1^{I,i}, \dots, y_k^{I,i}, \dots, y_{M-1}^{I,i}\right] \tag{8}$$

Moreover, assuming a perfect code delay synchronization and assuming a perfect orthogonality between any two PRN code shifts, $y_k^{I,i}$ can modeled as:

$$y_k^{I,i} = \begin{cases} C_i^I + n_k^{I,i} & x = k \\ n_k^{I,i} & x \neq k \end{cases} \qquad k = 0 \dots M-1 \tag{9}$$

$$C_i^I = \mathrm{Re}\left[\frac{1}{T_s}\int_{(i-1)T_s}^{iT_s} a(t) e^{j\varepsilon_\varphi(t)} dt\right] \qquad \varepsilon_\varphi(t) = \varphi(t) - \hat{\varphi}(t) \tag{10}$$

Therefore, $n_k^{I,i}$ are independent (due to PRN code shifts orthogonality) narrow-band Gaussian noises with power equal to $\sigma^2 = (R_s \cdot N_0)/(2P)$, and, R_s is the CSK symbol rate ($R_s = 1/T_s$). For a coherent demodulation process, the in-phase outputs of the bank of matched filters suffices to demodulate the data [3]. However, for a non-coherent demodulation process, the receiver must also obtain the quadrature-phase outputs of the bank of matched filters. The mathematical model of the normalized quadrature-phase output of the k^{th} matched filter output at instant i, $y_k^{Q,i}$, can be modeled as:

$$y_k^{Q,i} = \frac{1}{T_s} \mathrm{Im}\left[\int_0^{T_s} v(t - iT_s) s_k(t) e^{-j\hat{\varphi}(t)} dt\right] = \begin{cases} C_i^Q + n_k^{Q,i} & x = k \\ n_k^{Q,i} & x \neq k \end{cases} \qquad k = 0 \dots M-1 \tag{11}$$

$$C_i^Q = \mathrm{Im}\left[\frac{1}{T_s}\int_{(i-1)T_s}^{iT_s} a(t) e^{j\varepsilon_\varphi(t)} dt\right] \tag{12}$$

Where $n_k^{Q,i}$ are independent narrow-band Gaussian noises with power equal to $\sigma^2 = (R_s \cdot N_0)/(2P)$. $n_k^{I,i}$ and $n_k^{Q,i}$ are also independent to the $n_k^{I,i}$ noises.

CSK Non-Coherent Demodulator Output Mathematical Model

In mobile channels, where the variation of the signal carrier phase can be too fast to be estimated or the signal power can be too attenuated to allow a PLL to be locked (or to provide signal carrier estimation with a desired level of accuracy), the coherent demodulation of the signal cannot be applied. Therefore, in these situations, the application of a non-coherent demodulation, which does not need to estimate incoming signal carrier phase, becomes an attractive method to demodulate the data.

The non-coherent demodulation method of a CSK modulated signal consists in recovering the entire power transmitted by the data component from a non-linear combination of the I and Q matched filter outputs. More specifically, for a non-coherent demodulation method, the received carrier phase is usually not estimated, $\hat{\varphi}(t) = 0$. But instead, each component of the $Y^{I,i}$ vector (in-phase output) is individually squared and added to the corresponding squared component of the $Y^{Q,i}$ vector (quadrature-phase output). Afterwards, a square-root is applied to each individual result. Therefore, the entire data component power is recovered by the following metric:

$$\left|y_k^i\right| = \sqrt{\left(y_k^{I,i}\right)^2 + \left(y_k^{Q,i}\right)^2}, \ \ k = 0, \dots, M-1 \tag{13}$$

Note that for an AWGN channel, the non-coherent demodulation is not interesting because the received signal carrier phase is easily estimated and because the C/N_0 value of $\left|y_k^i\right|$ is lower than the C/N_0 value of $y_k^{I,i}$ for an accurate estimation of the received signal carrier phase.

The limitation of the non-coherent demodulation can be observed from equation (10) and is given by the evolution of $a(t)$, $\varepsilon_\varphi(t)$ and the symbol duration T_s. Neglecting the noise in equation (9) and (11), $\left|y_k^i\right|$ can be expressed as (assuming $\hat{\varphi}(t) = 0$):

$$\left|y_k^i\right| = \frac{1}{T_s}\sqrt{\left|\int_{(i-1)T_s}^{iT_s} a(t)e^{j\varphi(t)}dt\right|^2} \tag{14}$$

Therefore, the metric $\left|y_k^i\right|$ is maximized when $\varphi(t)$ is constant inside the interval $[(i-1)T_s, iT_s]$. However, for a mobile channel, $\varphi(t)$ can vary very fast and thus, in the worst case scenario the integral could be destructive and the metric result around 0. Besides, T_s determines the integral duration and thus, it also controls the variation range of $\varphi(t)$ (determined by the mobile channel). In order to try to mitigate this negative effect, an alternative CSK non-coherent demodulation method is tested.

'Non-coherent PRN correlation' CSK Non-Coherent Demodulator Output Mathematical Model

Due to the repetition of N identical PRN codes in order to to constitute a CSK symbol, an alternative non-coherent demodulation method, referred as 'non-coherent PRN correlation', can be proposed for the CSK modulation. The 'non-coherent PRN correlation' demodulation reduces the integration time and thus reduces the exposition of the metric to the incoming carrier phase variation: exploits the fact that $y_k^{I,i}$ and $y_k^{Q,i}$ terms can be expressed as an addition of correlations between the incoming signal and the inspected PRN code shift (with $\hat{\varphi}(t) = 0$), $y_k^{I,i,n}$ and $y_k^{Q,i,n}$:

$$y_k^{I,i} = \frac{1}{N}\sum_{n=0}^{N-1} y_k^{I,i,n} \qquad y_k^{I,i,n} = \mathrm{Re}\left[\int_0^{T_{PRN}} v(t - iT_s - nT_{PRN})c_k(t)dt\right] \tag{15}$$

Where $y_k^{I,i,n}$ is referred as the inside in-phase PRN correlation of the n^{th} PRN code of the k^{th} CSK symbol at instant i. Making the same assumptions as before, a perfect code delay estimation and orthogonality between any two PRN code shifts, $y_k^{I,i,n}$ is equal to:

$$y_k^{I,i,n} = \begin{cases} C_i^{I,n} + n_k^{I,i,n} & x = k \\ n_k^{I,i,n} & x \neq k \end{cases}; \qquad C_i^{I,n} = \mathrm{Re}[C_i^n] = \mathrm{Re}\left[\frac{1}{T_s}\int_{(i-1)T_s+(n-1)T_{PRN}}^{(i-1)T_s+nT_{PRN}} a(t)e^{j\varphi(t)}dt\right] \tag{16}$$

Where $n_k^{I,i,n}$ are independent narrow-band Gaussian noises with power equal to $\sigma^2 = (R_{PRN}\cdot N_0)/(2P)$ with $R_{PRN} = 1/T_{PRN}$. Therefore, the new 'non-coherent PRN' demodulation method consists in generating the metric $\left|y_k^i\right|_{N_{nc}}$, which uses all the data component power by making different non-linear combinations of these new defined inside PRN correlations

$$\left|y_k^i\right|_{N_{nc}} = \sqrt{y_{k,N_{nc}}^{I,i} + y_{k,N_{nc}}^{Q,i}} \tag{17}$$

$$y_{k,N_{nc}}^{I,i} = \sum_{n'=0}^{N_{nc}} \left(y_{k,N_c}^{I,i}(n')\right)^2 \qquad y_{k,N_{nc}}^{Q,i} = \sum_{n'=0}^{N_{nc}} \left(y_{k,N_c}^{Q,i}(n')\right)^2 \tag{18}$$

$$y_{k,N_c}^{I,i}(n') = \sum_{n=0}^{N_c} y_k^{I,i,(n+n'\cdot N_{nc})} = \mathrm{Re}\left[\sum_{n=0}^{N_c} C_i^{(n+n'\cdot N_{nc})}\right] + \sum_{n=0}^{N_c} n_k^{I,i,n} \tag{19}$$

Where $N_c = N/N_{nc}$ is the number of coherently accumulated inside PRN correlations, and N_{nc} is the number of non-coherent accumulations. Note that when $N_{nc} = 1$, $\left|y_k^i\right|_{N_{nc}} = N \cdot \left|y_k^i\right|$ (factor N has been removed for simplification purposes).

Finally, comparing the expression of metric $\left|y_k^i\right|_{N_{nc}}$ to the expression of metric $\left|y_k^i\right|$, it can be observed that due to the shorter integral period, $T_{PRN} < T_s$, $\varphi(t)$ will vary less inside the integrals of $\left|y_k^i\right|_{N_{nc}}$ and thus fewer destructive correlations should be found. Therefore, for mobile channels with very fast variations of the channel phase, $\left|y_k^i\right|_{N_{nc}}$ could be more adapted than $\left|y_k^i\right|$. However, the noise power of $\left|y_k^i\right|_{N_{nc}}$ will be higher than the noise power of $\left|y_k^i\right|$ since $\left|y_k^i\right|_{N_{nc}}$ contains more quadratic noise terms: $\left|y_k^i\right|$ is a Rayleigh/Rician distribution whereas $\left|y_k^i\right|_{N_{nc}}$ is a non-central/central chi distribution. This means that the 'Non-coherent PRN correlation' demodulation method needs to overcome its larger noise power with the reduction of the carrier phase variation in order to obtain better performance than the traditional non-coherent demodulation method. Since the $\varphi(t)$ variation rate depends on the mobile channel, the performance of metric $\left|y_k^i\right|_{N_{nc}}$ with respect to metric $\left|y_k^i\right|$ will thus depend on the mobile channel model characteristics.

CSK bits likelihood ratios mathematical expression for non-coherent demodulation

The general expression of the likelihood ratio of the u^{th} bit of an orthogonal CSK modulation at the i^{th} interval for a non-coherent demodulation method has been derived as was explained in [4], but using non-central and central chi distributions:

$$LR(b_u^i) = \frac{\sum_{\substack{k \\ \sim b_u^i = 1}} \left(\left|y_k^i\right|_{N_{nc}}\right)^{-(N_{nc}-1)} \mathrm{I}_{N_{nc}-1}\left(\frac{\left|y_k^i\right|_{N_{nc}}}{\sigma}\lambda\right) \cdot p\left(\left|y_k^i\right|_{N_{nc}}\right)}{\sum_{\substack{k \\ \sim b_u^i = 0}} \left(\left|y_k^i\right|_{N_{nc}}\right)^{-(N_{nc}-1)} \mathrm{I}_{N_{nc}-1}\left(\frac{\left|y_k^i\right|_{N_{nc}}}{\sigma}\lambda\right) \cdot p\left(\left|y_k^i\right|_{N_{nc}}\right)} \tag{20}$$

$$\lambda = \frac{1}{\sigma}\sqrt{\sum_{n'=0}^{N_{nc}} \left|\sum_{n=0}^{N_c} C_i^{(n+n' \cdot N_{nc})}\right|^2} \tag{21}$$

Where, $\sum_{\substack{k \\ \sim b_u^i = b}} g\left(\left|y_k^i\right|_{N_{nc}}\right)$ represents the addition of all the elements $\left|y_k^i\right|_{N_{nc}}$, evaluated by function $g(\cdot)$, which represent a combination of bits where the u^{th} bit is equal to b at the i^{th} instant ($b_u^i = b$). $p\left(\left|y_k^i\right|_{N_{nc}}\right)$ is the a-priori probability of $\left|y_k^i\right|_{N_{nc}}$:

$$p\left(\left|y_k^i\right|_{N_{nc}}\right) = \prod_{z=0}^{U-1} p\left(b_z^i = y_{k,z}^i\right) \tag{22}$$

Where, $y_{k,z}^i$ is the value of the z^{th} bit, b_z, of the k^{th} CSK symbol at the i^{th} instant. Finally, σ is the noise standard deviation of $n_k^{I,i,n}$.

Codeword Source Mapping

The codeword source mapping of an orthogonal *M*-ary modulation is defined as the mapping between the bits carried by an orthogonal *M*-ary symbol and the bits belonging to a codeword. The codeword source mapping is a very important element of an orthogonal *M*-ary modulation since it determines the codeword duration and the signal demodulation performance. In this paper, two types of mappings are analyzed since they represent the most extreme cases.

- Mapping A: Each bit mapped by an orthogonal *M*-ary symbol belongs to a different codeword. Mapping A was shown to provide the best demodulation/decoding performance in [5] but requires more time to access the codeword.
- Mapping B: All the bits mapped by an orthogonal *M*-ary symbol belong to the same codeword. It provides the worst demodulation / decoding performance [5] but the fastest access to the codeword

Decoding Methods

Two decoding methods are used in this work for a CSKmodulation when implementing a binary LDPC channel code. A description of the two methods can be found on [5]. The decoding methods are:

- Classical CSK Decoding method

- Bit-Interleaved Coded Modulation – Iterative Decoding (BICM-IT)

LAND MOBILE SATELLITE CHANNEL MODEL

In this article, the inspected propagation channel is the Land Mobile Satellite (LMS) channel, and the selected mathematical model is the Perez-Fontan channel model [10]. The Perez-Fontan channel model is assumed to be non-frequency selective and thus, the received signal can be modeled as presented in equation (6), where the received signal complex envelope, $c(t)$, represents the influence of the channel on the received signal. Therefore, the channel model is completely characterized by the correct modeling of the coefficient $c(t)$.

The Perez-Fontan channel model characterizes the $c(t)$ values with a Loo distribution, as described in [10] and [11]. The Loo distribution models the addition of the two components of the received signal, the Line-of-Sight component which follows a log-normal distribution, and the multipath component which follows a Rayleigh distribution. The key parameters of the Loo distribution are (α, Ψ) which are the mean and the variance of the LOS component (log-normal distribution) and MP which is the multipath average power MP (Rayleigh distribution).

The value of the Loo parameters is not constant but evolves in time in order to take into account the variation of the scenario conditions. In fact, the Perez-Fontan channel model is a 3-state model, where each state corresponds to a certain level of shadowing/blockage of the direct signal component (LoS Conditions - LoS, Intermediate Shadowing - IS, Deep Shadowing - DS). A more detailed definition of the implemented channel model can be found in [6], and the algorithm used to implement the channel model is described in [9].

RESULTS

Assumptions, numerical values and results interpretation

Two main assumptions are made in the numerical simulations:

1- Propagation code delay is perfectly estimated
2- Channel state information (CSI) is available: the user can perfectly estimate the $|C_i^n|$ and σ values. The exact knowledge of these values is a key factor on the final demodulation performance. Therefore, a further analysis should be conducted in order to determine a real case scenario where $|C_i^n|$ and σ are estimated by the user (not known in advance).

The simulations do not change between mobile channel states. This means that the Loo parameters are fixed and the demodulation performances are given for these static scenarios. The choice of using static scenarios allowed a better inspection of the channel impact on the demodulation performance. The Loo parameter values of the Perez-Fontan mobile channel are given in Table 1, and these parameters represent an urban environment, with a satellite elevation angle of 40° and broadcasting in the S-Band.

The PRN code period used in this work is equal to 4ms and thus, the bit rate increase is given with respect to a BPSK modulation where each symbol spans 1 PRN code (4ms).

Finally, all the C/N_0 values given in the figures are for the data component alone. Therefore, additional power should be added in order to take into account the power required to implement the pilot.

CSK demodulation performance with traditional non-coherent demodulation method

Fig. 1 presents the demodulation performance of different CSK configurations which increase the bit rate by a factor of 2. The demodulation performance are presented only for the traditional non-coherent demodulation method and for classic and iterative decoding. The simulated scenario is a IS scenario. From Fig. 1, several conclusions can extracted. The first and most important conclusion is that non-coherent CSK demodulation is possible and it is possible for acceptable C/N_0 values. Second, mapping A still outperforms mapping B but the difference appears to be reduced with comparison to the AWGN case with non-coherent demodulation (Fig. 3). Third, better demodulation performance is obtained for higher user speeds: for higher speeds the correlation length of the multipath component decreases, the channel becomes whiter, and thus more similar to an AWGN noise (but with a higher noise variance). Fourth, it can be observed in mapping B that the best demodulation performance is no longer obtained by the CSK configuration with the higher U value (10b): the fast variation of the channel begins to make detrimental to have long CSK symbols. In fact, this effect is more evident on the 50 Km/h figure since the channel variation is faster than on the 5 Km/h case.

Fig. 2 presents the demodulation performance of different CSK configurations which increase the bit rate by a factor of 2. The demodulation performance are presented only for the traditional non-coherent demodulation method and for classic and iterative decoding. The simulated scenario is a DS scenario. From Fig. 2, the same conclusion from Fig. 1 can be extracted where the most important ones are: first, non-coherent CSK demodulation is even possible on the harshest scenarios but a large C/N_0 value is required, second, large U values are detrimental to the demodulation performance. In fact, in this DS scenario, the last conclusion is more evident since there are cases where the best CSK configuration has $U = 4$ and the worst has $U = 10$.

Comparison between non-coherent demodulation methods

Fig. 3 represents the application of the two methods to different CSK configurations which provide a bit rate increase of 2 when the propagation channel is assumed to be an AWGN channel: $N_{nc} = 1$ indicates the traditional method and any other value of N_{nc} determines the configuration of the 'non-coherent PRN correlation' method. From these figures, it can be verified that due to the existence of more quadratic noise terms, the 'non-coherent PRN correlation' demodulation method, either for classic or for iterative decoding, starts with some dBs of disadvantages with respect to the traditional method. Therefore, only in a mobile channel with a very fast variation of the incoming carrier phase, $\varphi(t)$, the "non-coherent PRN correlation" method will outperform the traditional method.

Fig. 4 represent the demodulation performance of a CSK modulated signal with CSK configurations using mapping B and providing a x2 bit rate increase. The CSK signal is received in a IS scenario for the left figure and in a DS scenario for the right figure. The receiver motion is equal to 50 km/h. From Fig. 4, it can be observed that the 'non-coherent PRN correlation" method can outperform the traditional non-coherent demodulation method but only for much degraded scenarios since only for the DS case, this outperformance is observed. Moreover, it can be observed that thanks to the new method, the CSK configurations having a large U continue to outperform CSK configurations with a low U. Therefore, it can be concluded that a signal designer could still use CSK configurations with large U values and could provide the best demodulation performance in any kind of scenario if the receiver implements the proposed "non-coherent PRN correlation" method. However, the remaining difficulty will be to choose between the two methods at a given instant.

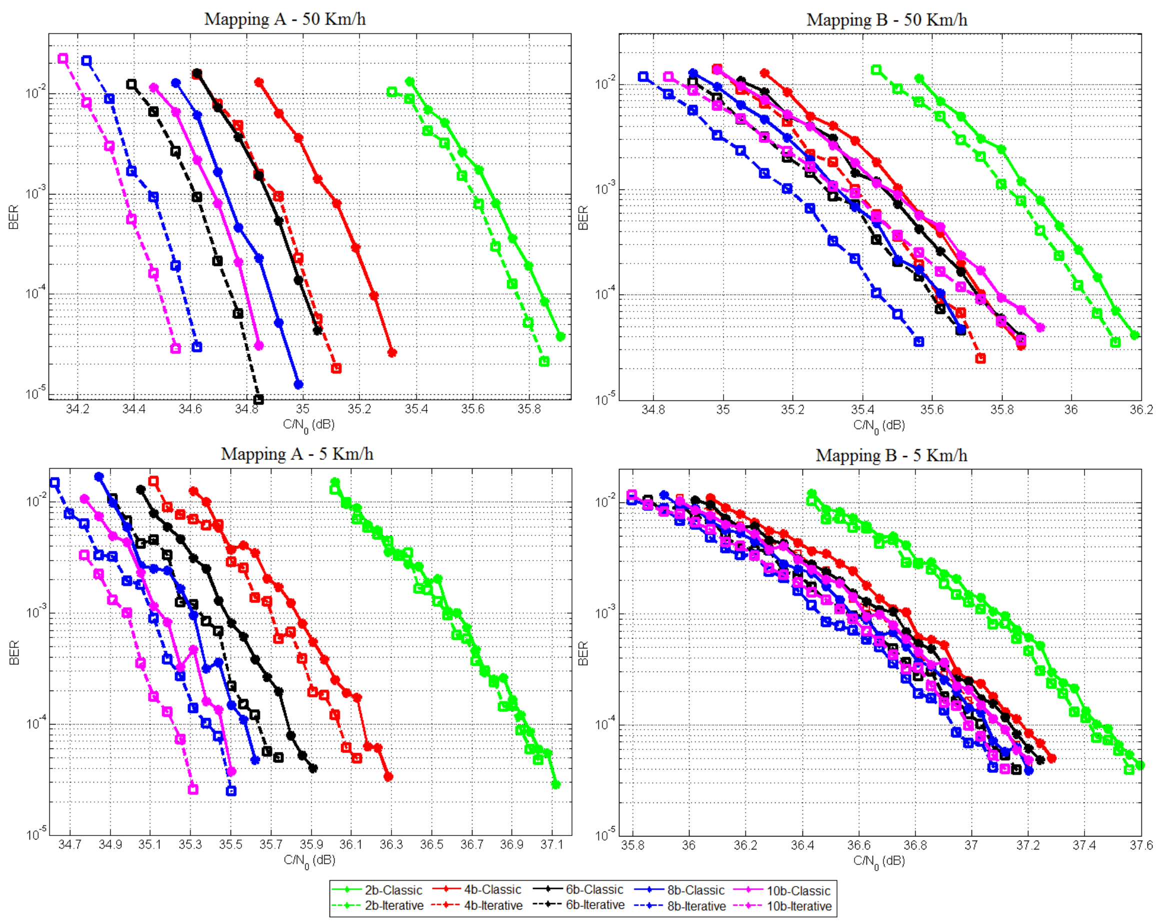

Fig. 1: Traditional non-coherent demodulation of different CSK configurations with x2 bit rate increase in a mobile channel (IS scenario).

Table 1: Loo parameters of the Perez-Fontan channel model for an urban environment, 40° elevation and S-Band

LOS Reception Conditions	LoS Conditions (LOS)	Intermediate Shadowing (IS)	Deep Shadowing (DS)
α (dB)	-0.3	-8.0	-24.4
Ψ (dB)	0.73	4.5	4.5
MP (dB)	-15.9	-19.2	-19.0

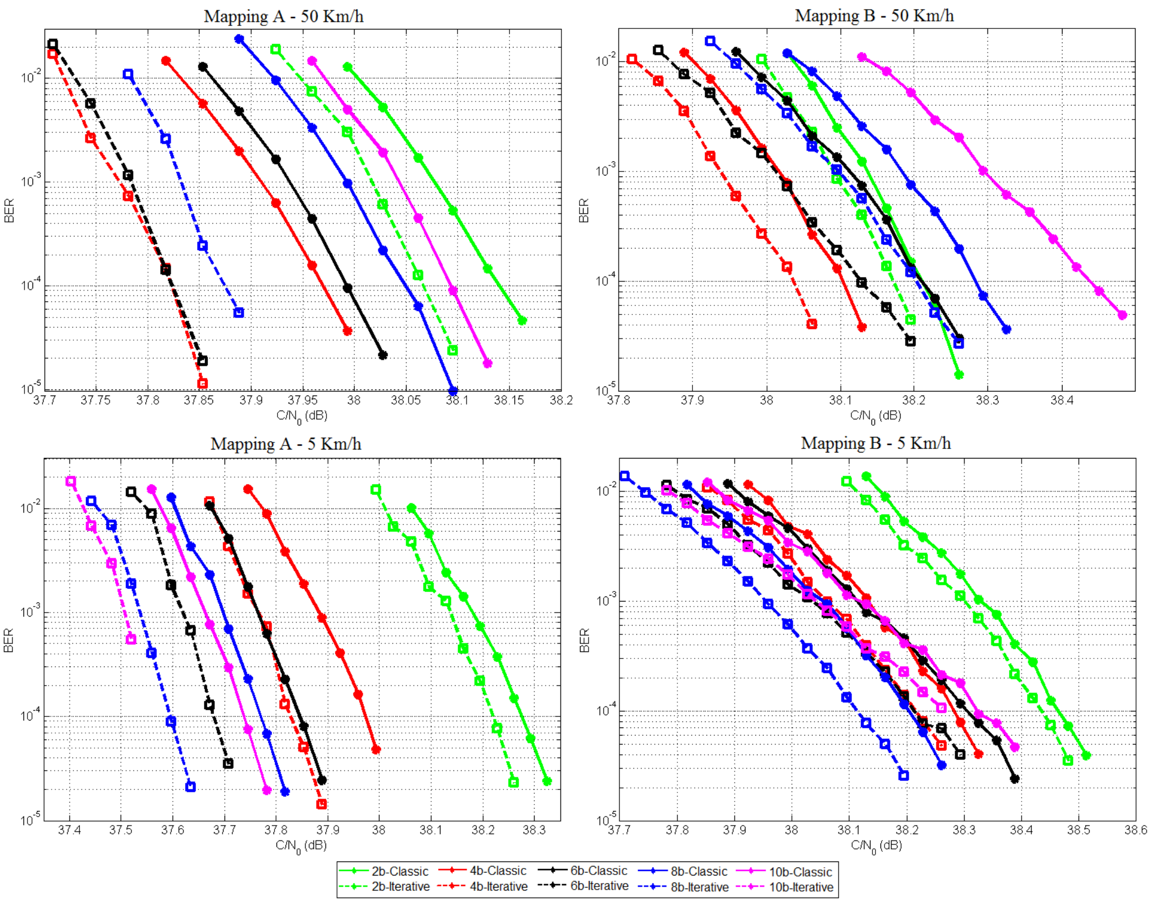

Fig. 2: Traditional non-coherent demodulation of different CSK configurations with x2 bit rate increase in a mobile channel (DS scenario).

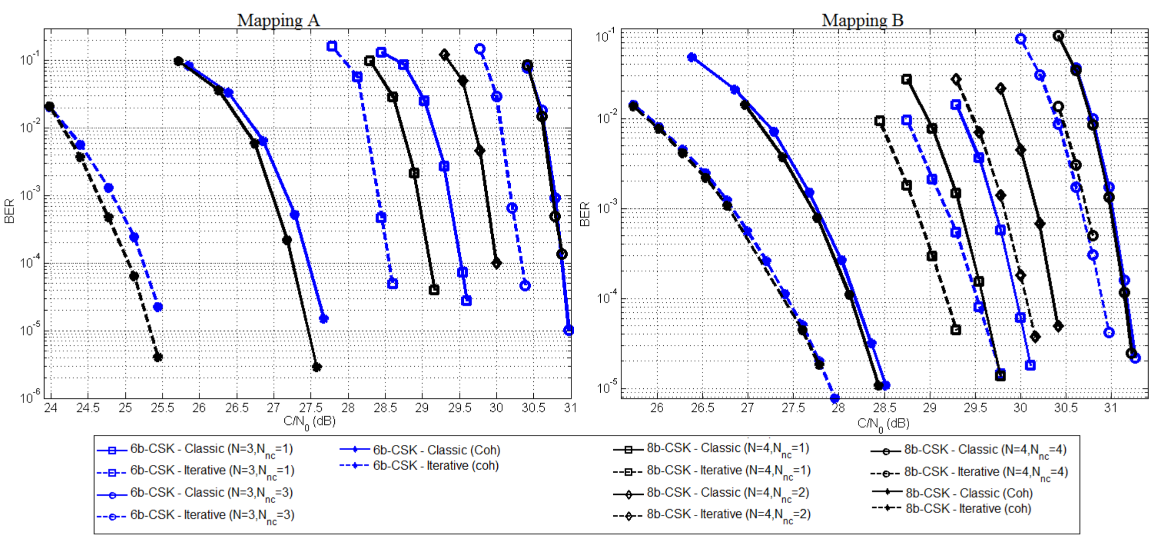

Fig. 3: CSK demodulation in an AWGN channel with both non-coherent demodulation methods

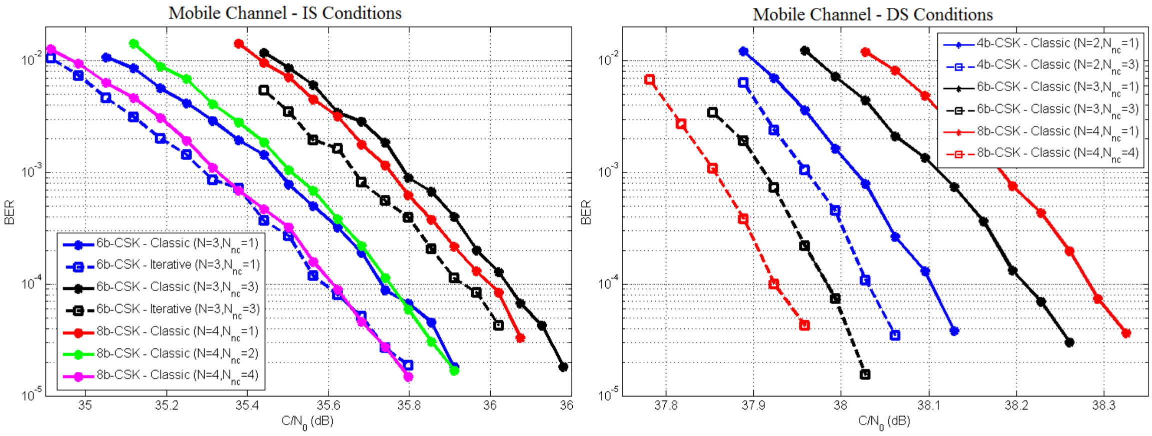

Fig. 4: CSK demodulation in a mobile channel with both non-coherent demodulation methods (x2)

CONCLUSION AND PERSPECTIVE

The demodulation performance of a CSK modulated signal received in an urban environment has been analyzed for CSK configurations with a bit increase rate of 2. From this performance, it has been concluded that the demodulation process is possible using a non-coherent demodulation method. Moreover, it has been observed that for harsh signal received conditions, as opposite to the AWGN channel, having a long CSK symbol (long N which is related to U) is detrimental to the demodulation performance since the fast channel phase variations can destroy the coherent accumulation of the N consecutive PRN codes constituting the symbol. A new non-coherent demodulation method, referred as "non-coherent PRN correlation", has been defined. In harsh environments, this method has been shown to obtain better demodulation performance when using high N (or U) values than the traditional method when using any possible CSK configuration. Therefore, from the signal design point of view, if the receiver can guarantee to use the new non-coherent demodulation method at the required time, the best CSK configuration to implement is a CSK configuration with a high U value (other factors to take into account as complexity, etc). The entire study of this article is based on the CSI availability assumption. However, in reality, the final user must estimate the channel and thus a new study which takes into account the channel estimation limitations should be conducted. Moreover, a criterion deciding which non-coherent method should be used at any epoch should also be searched.

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