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Analysis of the use of CSK for future GNSS Signals

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BIOGRAPHY

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Thomas Grelier has been a radionavigation engineer at CNES since 2004. His research activities focus on GNSS signal processing and design, development of GNSS space receivers and radiofrequency metrology sensor for satellite formation flying. He graduated from the French engineering school Supelec in 2003 and received a M.S. in electrical and computer engineering from Georgia Tech (USA) in 2004.

ABSTRACT

This paper presents an extended analysis on the implementation of a Code shift Keying (CSK) or Code Cyclic Shift Keying (CCSK) modulation on a GNSS signal: an orthogonal *M*-ary modulation specifically designed to increase the bandwidth efficiency of direct-sequence spread spectrum (DS-SS) signals. This paper provides a brief description of a CSK modulator as well as the description of two possible demodulators: a bank of correlators and a FT-based demodulator which simplifies the receiver complexity. The advantages and drawbacks of using a CSK modulation instead of a BPSK modulation in a GNSS signal are discussed.

Four different pairs "channel codes – decoding methods" are presented as suitable candidates to be implemented by a CSK modulation. For a binary channel, the classical sequential decoding is presented altogether with two iterative methods, Horizontal Dimension Multistage Decoding (HDMD) and Bit-interleaved coded Modulation – Iterative Decoding (BICM-ID). For a *Q*-ary channel, a Reed-Solomon channel code is proposed with the typical Berlekamp-Forney decoding algorithm.

Afterwards, this paper presents the methodology used to construct CSK signals which pursue two different objectives, to keep the same useful bit rate as a reference BPSK signal and to increase the useful bit rate with respect to a BPSK signal but maintaining the same symbol rate. This methodology includes the calculation and comparison of signal demodulation performances, the generation of CSK symbols allowing the desired bit rate and the determination of the codeword durations. The methodology has been applied to the different pairs "channel codes – decoding" methods in order to compare them and proposals for real signals have been made.

Finally, this paper has analyzed the impact of processing a CSK modulated signal on a GNSS receiver with respect to a BPSK signal. This analysis includes the increase of complexity of the demodulator block and the

possible performance degradation of the acquisition and, the carrier and code delay tracking.

I. INTRODUCTION

GNSS signals are designed (in order to fulfill the special needs of a GNSS system) to provide the receiver with precise synchronization or pseudo-range measurements and to broadcast limit amount of 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 historical design choice for the GNSS system synchronization part consists in implementing direct sequence-spread spectrum (DS-SS) characterized by a very narrow autocorrelation function. Additionally, the introduction of several almost orthogonal direct sequences, one for each satellite, was used to implement the simultaneous access of the original GPS system constellation satellites; this technique is known as Code Division Multiple Access (CDMA) [3]. Therefore, the use of direct sequences in a GNSS system has become a key element and an inherent part of the signal design.

The historical design choice of the GNSS signal communication part is the implementation of a BPSK modulation (be aware that a BOC modulation is a BPSK modulation from the demodulation point of view) [3]. This choice was made in order to allow the easy implementation of the synchronization part: direct sequences. Moreover, the low bandwidth efficiency of a BPSK modulation (number of bits/second/Hz) [3] did not present any limitation to the signal design: the low power of the received signal added to the limited required information imposed a low bit rate.

However, nowadays this choice of hybrid signal structure can be adapted due to the introduction of a new dataless (pilot) channel on all the new civil GNSS signals 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 pilot channel introduction to a GNSS signal and the possibility for the receiver to generate pseudo-range measurements from this channel implies that the data channel is no longer necessarily restricted by the GNSS system special hybrid characteristics [2]. Therefore, the data channel can be looked at as a more traditional communication channel. One example is the LEX signal of the Japanese QZSS system [5]. Another example could be the GPS L1C signal: 75% power allocation to the pilot channel [6] could lead to receivers discarding the data channel for synchronization purpose.

On the other hand, nowadays new applications and new services such as precise positioning, safety-of-life, etc., demand a much higher data rate (currently obtained via other systems) [7][8]. Moreover, a higher data rate can improve the signal demodulation performance by, for instance, means of increasing the transmitted information temporal diversity: more repetitions of the ephemeris data allow the receiver to obtain the information more quickly or to accumulate the information for a lower demodulation C/N_0 threshold.

The main limitation of using a BPSK data modulation to increase the signal data rate is the signal design choice of employing direct sequences (necessary for CDMA and precise pseudo-range measurements). The PRN code is limited by the data symbol duration which must decrease in order to increase the data rate and thus either the chipping rate or the PRN code must also be modified.

In this paper, the modulation known as Code Shift Keying (CSK) [9][10][11][12], specially designed to increase the transmission rate of a spread spectrum signal [9], is inspected.

In this paper, first, the CSK modulation and its fundamentals are defined. Second, the advantages and disadvantages of using a CSK modulation on a GNSS signals are presented. Third, the different pairs channel codes–decoding methods implemented for a CSK modulation are described. Fourth, the objectives and the methodology used to design a CSK signal are given. Fifth, real numeric propositions of CSK signals are made. Sixth, the impact of a CSK modulated signal on a GNSS receiver is analyzed. Seventh, the conclusions are given.

II. CODE SHIFT KEYING MODULATION TECHNIQUE

The main characteristics of a CSK modulation are given in the following subsections.

II.A. CSK Definition

The CSK modulation technique is a DS–SS signaling method which overcomes the spreading gain versus data rate limitations [9].

The CSK is a form of orthogonal *M*-ary signaling over a communication channel [10] 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 [9] and is assumed to be a full period version of the fundamental sequence [11]. Figure 1 provides a graphical explanation of the CSK modulation.

II.B. CSK Modulation Mathematical Model

Each single CSK symbol modulates U bits. The number of circularly shifted versions of the fundamental code 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 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 circularly shifted versions, which are called $c_0(t)$ to $c_{M-1}(t)$. A mathematical expression of a generic circularly shifted version of the code is shown below:

$$c_x(t) = c_d(mod[t - m_x T_c, N \cdot T_c]) \;\; x = 0 \dots M-1 \quad (1)$$

$$c_x[m] = c_d(mod[m - m_x, N]) \quad x = 0 \dots M-1 \quad (2)$$

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 received signal at the receiver antenna output, $v(t)$, can be modeled assuming the transmission of a CSK signal through an AWGN channel as:

$$v(t) = A \cdot c_x(t) \cdot \cos(\omega_0 t) + n(t) \quad (3)$$

Where A is the received signal amplitude and $n(t)$ is the AWG noise with power equal to σ^2. A possible CSK modulator block scheme is given in Figure 2.

II.C. CSK Demodulator Output Mathematical Model

In order to estimate which CSK symbol is transmitted, a matched filter should be implemented for each component (symbol) of the signal space basis [3]. For a CSK modulation, since each symbol is a circular shift version of the fundamental code, each matched filter output is equivalent to the evaluation of the correlation between the received signal and the fundamental spreading sequence at a different shift, the bank of matched filters can be replaced by Fourier Transform and Inverse Fourier Transform blocks which conduct the correlation in the frequency domain [12]. Figure 3 shows the CSK FT-based demodulator block scheme and equation (4) shows the conducted mathematical operation:

$$Y^i = IFFT\big(FFT(v[k]) \times FFT(c_d[k])\big) \quad (4)$$

The mathematical model of the normalized demodulator output at the ith interval (or instant), Y^i vector, can be modeled as:

$$y_k^i = \begin{cases} 1 + n_k^i & x = k \\ h_{kx} + n_k^i & x \neq k \end{cases} \qquad k = 0 \dots M-1 \quad (5)$$

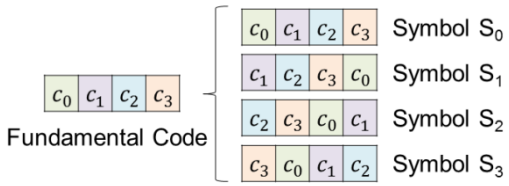


Figure 1: Example of CS K Modulation with M=4 (and U = 2 bits)

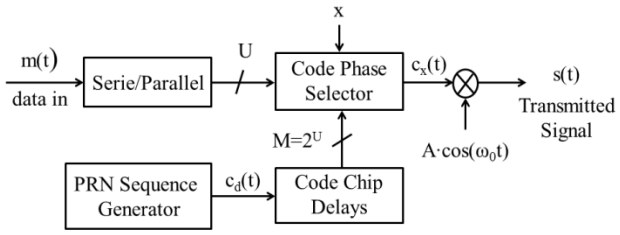


Figure 2: CSK modulator block

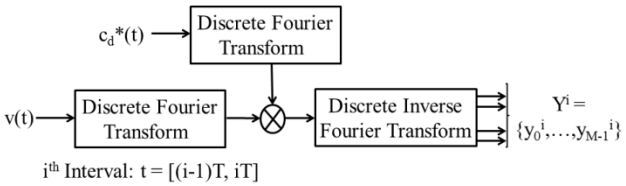


Figure 3: CSK FFT-base demodulator block [12]

Where, h_{kx} is the normalized value of the circular correlation function of the fundamental spreading sequence at point $(k\text{-}x)$. The h_{kx} value depends on the nature of the fundamental spreading sequence (M-sequence, Gold, Kasami, etc) but it is always fulfilled that $h_{kx} \ll 1$. n_k^i are independent narrow-band Gaussian noises with power equal to $\sigma^2 = (R_s \cdot N_0)/A^2$, and, R_s is the CSK symbol transmission rate.

The noises n_k^i are assumed to be independent because the correlation between two different circular shifted versions of the fundamental spreading code, is very low, $h_{k_1 k_2}$. In this paper, the cross-correlation value, $h_{k_1 k_2}$, is assumed to be 0 for all k_1 and k_2 values with $(k_1 \neq k_2)$.

II.D. CSK bits likelihood ratios mathematical expression

The general expression of the likelihood ratio of the uth bit of an orthogonal CSK modulation at the ith interval is [13]:

$$LR(b_u^i) = \frac{\sum_{\substack{k \\ \sim b_l=1}} \exp\left(-\frac{y_k^i}{\sigma^2}\right) \cdot p\left(y_k^i\right)}{\sum_{\substack{k \\ \sim b_l=0}} \exp\left(-\frac{y_k^i}{\sigma^2}\right) \cdot p\left(y_k^i\right)} \quad (6)$$

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

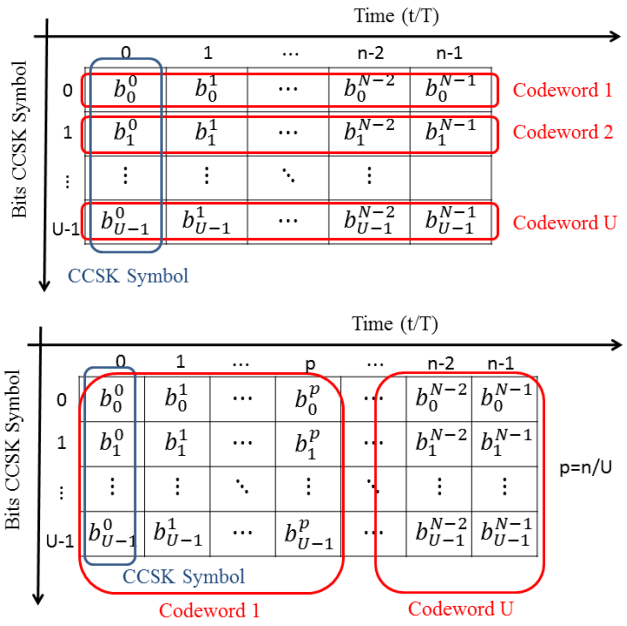


Figure 4: Codeword source mapping A (above) and codeword source mapping B (below) of a CSK modulation

$$p(y_k^i) = \prod_{z=0}^{U-1} p(b_z^i = y_{k,z}^i) \quad (7)$$

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.

Equation (6) shows that depending on the a-priori probability of the different correlator outputs y_k^i, the likelihood ratio of the bits vary. In fact, depending on this probability, more weigh is given to certain correlator outputs and thus, if this a-priori probability is reliable, the likelihood ratio expression should also be more reliable in average. This means that a way to improve the demodulation/decoding performance of a CSK signal consists in determining reliable symbol a-priori probabilities.

II.E. 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. Both mappings are represented in Figure 4.

- 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 [13] 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. This codeword source mapping provides the worst demodulation/decoding performance [13] but the fastest access to the codeword.

III. ADVANTAGES AND DRAWBACKS OF A CSK MODULATION WITH RESPECT TO A BPSK MODULATION

In this section, the main advantages and drawbacks of a CSK modulated signal with respect to a BPSK modulated signal are presented.

III.A. Advantages

The first and most important advantage is the possibility of implementing a non-coherent demodulation since a CSK modulation is a kind of orthogonal *M*-ary modulation [3][9]. A non-coherent demodulation process consists in demodulating the received signal without estimating the signal carrier phase by means of non-coherently adding the in-phase and quadrature-phase signal components [3]. Therefore, a non-coherent modulation may enable CSK signal demodulation in harsh environments (such as mobile channels representing urban or indoor environments) whereas for a BPSK signal the demodulation would not be possible unless the PLL has achieved lock. However, the exact gain of this advantage must be quantified (through simulations).

The second advantage is that the symbol rate, chipping rate and PRN code length of a reference signal must not be modified when the original coded bit rate is increased: the coded bit rate increase is simply achieved by introducing a CSK modulation in the reference signal (instead of a BPSK modulation) or by increasing the number of bits mapped by a CSK symbol (within a limit).

In fact, for a BPSK signal, the only possibility of increasing the coded bit rate consists in increasing the symbol rate (decreasing the symbol period). Therefore, two scenarios are possible. On one hand, the PRN code length can remain constant but this implies that the chip rate must be increased. However, if the chip rate is increased, the total signal bandwidth is increased, which implies the generation of interferences on the adjacent bands and the requirement of a wideband receiver with the consequent increase of the number of operations. On the other hand, the PRN code length can be decreased but this implies a degradation of the PRN code performance: isolation and near/far effect.

The third most important advantage is the flexibility of the coded bit data rate provided by a CSK modulation: the coded bit data rate of a CSK modulated signal can dynamically change at any moment of the signal transmission in order to be adapted to the kind of broadcasted data and its priorities (slow and thus more

robust for the ephemeris, clock error corrections, etc., and faster for less essential information such as precise positioning, etc.). In fact, the CSK modulation should only change the number of bits mapped by each symbol (or change the number of coherently accumulated PRN codes as shown in section V.C-1). Moreover, the dynamic change of the coded bit rate can follow a predetermined structure (signal known in advance) or could even be changed on-the-fly (through some information provided by the signal itself). On the opposite side, the coded bit rate of a BPSK signal is fixed although some flexibility could be given by allowing the coherent accumulation of consecutive PRN codes.

III.B. Drawbacks

The main drawback of a CSK modulated signal is that the synchronization process is extremely hard to achieve: due to each different PRN code cyclic shifted version found in each received symbol, the receiver cannot know which cyclic shifted local replica must be generated in order to synchronize the signal. This means the receiver would need first to demodulate the CSK signal. But the demodulation process is not possible without first acquiring the signal and tracking the code delay. Therefore, from the previous explained reasons, a CSK modulated signal needs a pilot signal in order to achieve the synchronization required to demodulate (either coherently or non-coherently) the signal and to provide the essential pseudo-range measurements.

The second drawback is the increase of the receiver complexity, more specifically the demodulator part: the introduction of a CSK modulation implies that instead of only using one correlator which output is fed to the decoder/detector block, M correlators are necessary (with the consequent complexity increase). However, this comparison is not fair since the coded bit rate is different for both modulations. A more fair comparison could be made between a CSK signal mapping U bits per symbol and a BPSK signal having a symbol rate and a chipping rate U times faster than those of the CSK signal. In this case, although there still is a difference on the number of required correlators (1 correlator to M correlators), the number of operations per second of the BPSK signal is increased by U. Therefore, the increase of complexity of a CSK receiver with respect to a BPSK is not so high as originally thought.

Finally, the introduction of a FFT-based demodulator for a CSK signal reduces the complexity (and number of operations) of the receiver as shown later in section VII-VII.C. However, a FFT-based signal presents some problems which must be further analyzed.

IV. DECODING METHODS

In this section, the different pairs channel code - decoding methods proposed for a CSK modulated signal are described. The pair choice plays a very important role on the final signal structure design:

- Determine the demodulation performance
- Determine the receiver's complexity
- Determine the codeword duration

Therefore, the final pair channel code – decoding method will be a trade-off between the previous 3 factors and the signal needs.

Four pairs have been proposed, three when a binary channel code is implemented, more specifically the GPS L1C subframe 2 LDPC (1200, 600) [6], and one when Q-ary channel code, more specifically Reed-Solomon channel code [4], is used.

The binary channel code decoding methods are:

1) Classical CSK Decoding method
2) Iterative Decoding methods:
   a. Horizontal dimension multistage decoding (HDMD)
   b. Bit-Interleaved Coded Modulation – Iterative Decoding (BICM-IT)

The Q-ary channel code decoding method is:

1) Reed-Solomon with Berlekamp / Forney algorithm

IV.A. Classical CSK Decoding Method (CD)

The classical CSK decoding method of the j^{th} codeword is simply the traditional sequential decoding method used in [13]: first the bits Likelihood Ratio (LR) or Log LR of the transmitted bits of the j^{th} codeword are calculated and second, the j^{th} codeword is decoded using the previous calculated LR values:

1) Apply equation (6) in order to calculate the LR of the bits transmitted in each CSK symbol. The symbols a-priori probabilities are assumed equiprobable.
2) Gather the LR values of all the bits belonging to the j^{th} codeword.
3) Decode the j^{th} codeword using the LR values.
4) If there still are LR values belonging to other un-decoded codewords, go to step 2 in order to decode them. In Mapping A, steps 2 to 4 are repeated as many times as bits mapped by a CSK symbol.

IV.B. CSK Iterative Decoding

The fundamental idea consists in iterating/mixing the decoding of the parallel codewords transported by a CSK modulation with the calculation of the LR of the CSK symbols bits. More in detail, the iterative decoding methods consist in first using the extrinsic information

provided by the decoding of the parallel codewords transported by the CSK symbols as a-priori bit probabilities on the calculation of the CSK symbols bits LR. Second, the new bits LR are used as new inputs to the channel code decoder of the transported codewords.

This principle can be easily understood from the original expression of the CSK symbols bits LR (equation (6)): depending on the a-priori probability of the different matched filter outputs at instant ith, y_k^i, the LR of the bits vary. In fact, depending on this probability, more weigh is given to certain matched filter outputs and thus, if this a-priori probability is reliable, the LR value should also be more reliable in average. This means, that a soft input decoding process using these new LR values should perform better than another one that does not use them. Therefore, the remaining question is how to obtain reliable a-priori probabilities.

An iterative decoding method will obtain better demodulation performance than the classical decoding method but the receiver complexity will grow: the LR calculation and the decoding of the codewords are executed more than once.

V.B-1. Horizontal Dimension multistage decoding (HDMD)

The Horizontal Dimension Multistage Decoding obtains the a-priori probabilities of equation (6) from the successful verification of CRC channel codes: the a-priori probabilities (values) of the bits protected by the CRC are determined when the CRC verification is successfully achieved. Therefore, in order to implement this decoding method, a CRC must be specifically introduced in each one of the parallel transmitted codewords. Moreover, a HDMD decoding method cannot be implemented for mapping B (at least two codewords must be simultaneously transmitted).

The HDMD algorithm for mapping A and a *(n, k)* channel code is given below. N_{nd} is the number of codewords having yet to succeed the CRC verification:

1) Calculate the bits LR (using equation (6) and assuming equiprobable bits) of *n* CSK symbols. N_{nd} is set to *U*.
2) Decode the N_{nd} codewords having yet to succeed the CRC verification.
3) Check the CRC of the N_{nd} decoded codewords. The interactive algorithm stops if:
   i. All the N_{nd} CRCs are correct: receiver assumes that all the codewords are correctly decoded.
   ii. All the N_{nd} CRCs are incorrect: no new information to be used on the LR calculation.
4) N_{nd} is updated to the number of remaining codewords having yet to succeed the CRC verification.

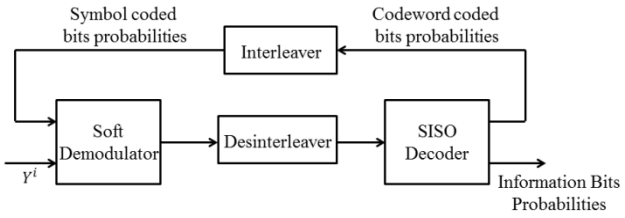


Figure 5: BICM-ID scheme

5) Calculate the bits LR of the N_{nd} codewords having yet to succeed the CRC verification. This calculation is made by using equation (6) and by determining the a-priori probabilities from:
   i. The bits value if the codeword (in which the bit is) has succeeded the CRC verification.
   ii. Otherwise, the a-priori probabilities are assumed equiprobable.
6) Go to step 2).

V.B-2. Bit-Interleaved Coded Modulation – Iterative Decoding (BICM-ID)

The original BICM was discovered by [15], which give its name, and the complete iterative method, BICM-ID, was conceived by [16]. Moreover, this method was proposed for orthogonal *M*-ary modulations and non-coherent demodulation in several papers [17][18][19].

For a BICM-ID method, the CSK symbol a-priori probabilities of equation (5) are provided by the same channel codes implemented on the transmitted codewords: assuming that each channel code (implemented on each one of the transmitted codewords) can provide the codeword bit probabilities after the execution of its decoding process (partially or totally), the application of the BICM-ID method consists in using these output bit probabilities (or LR) provided by each channel code as inputs to the general LR bit calculation formula (equation (5)) in the form of CSK symbol a-priori probabilities (equation (6)). Then, the new bits LR values are calculated and are fed again to the decoders of the implemented codewords which will execute again the decoding process (partially or totally). Finally, the process will repeat itself until all the codewords are successfully decoded or a certain number of iterations is reached. A scheme of the BICM-ID method is presented in Figure 5.

One of the main requirements of the BICM-ID consists in implementing channel codes which accept Soft Input - Soft Output (SISO) decoding methods. In the case of a LDPC channel code, the SISO method is called message-passing or propagation-belief [20]. The BICM-ID algorithm is presented next:

1) Calculate the bits LR of all the bits constituting the codewords transmitted in parallel using equation (5) and using the CSK symbol a-priori probabilities (equiprobable for the first iteration).

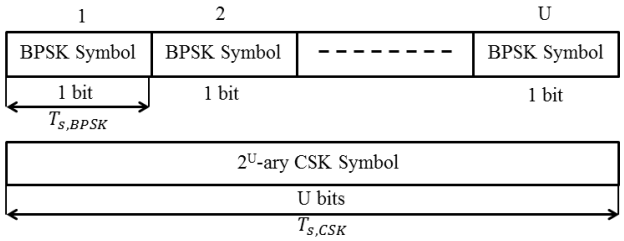


Figure 6: CSK symbol with respect to a BPSK symbol when keeping the coded bit data rate

2) Use the bits LR calculated in step 1) as inputs to the codewords decoding algorithms and execute the process (totally or partially).

3) Inspect if all the codewords are correctly decoded.

   i. Yes → The iterative process is ended

   ii. No → Use the bit probabilities obtained in step 2) from the decoding process execution in order to calculate the CSK symbol a-priori probabilities. Go to step 1)

IV.C. *Q*-ary channel code: Reed-Solomon

A *Q*-ary channel code is a code which uses symbols (representing a set of bits) instead of bits as basic units of information. The implementation of a *Q*-ary channel in an orthogonal *M*-ary modulation consists in fully represent a *Q*-ary symbol with a symbol of the orthogonal *M*-ary modulation (*Q=M*).

In this paper, the chosen *Q*-ary channel code family is the Reed-Solomon (RS) channel codes. A RS*(n, k)* channel code is a systematic block channel code which is able to correct until $t = (n - k)/2$ symbol errors [4].

The RS decoding method selected in this paper is the standard Berlekamp – Forney algorithm [4]. Finally, as opposite to the implementation of a binary channel code, a Reed-Solomon channel code uses a hard output CSK demodulator.

V. CSK SIGNAL DESIGN

In this section, the methodology used for designing a CSK modulated signal is presented. The design of a signal consists in determining the signal parameters in order to fulfill certain objectives or requirements. Two different signal objectives are proposed in this work:

1) Signal keeping a predefined useful bit rate with respect to a reference BPSK signal

2) Signal increasing a predefined useful bit rate with respect to a reference BPSK signal but keeping the same symbol duration (or rate).

The CSK signal parameters to be determined are the number of bits mapped by a CSK symbol, the number of consecutive PRN codes constituting a CSK symbol, the pair channel code – decoding method and the codeword duration. Moreover, these parameters also determine the signal BER and WER, and thus they have to be dimensioned in order to target a BER of 10^{-5}.

V.A. Reference BPSK signal

The chosen reference signal is based on the GPS L1C signal since this signal implements the most powerful channel code among all the defined GNSS signals at the epoch of this study.

Therefore, the selected channel code is the LDPC (1200,600) of subframe 2. The application of this channel code generates codewords with a duration of 1200 symbols ($1200 \cdot T_s$).

V.B. CSK signal with the same useful bit rate

In this section, the methodology used to design a CSK signal keeping the same useful bit rate as a reference BPSK signal is presented and its application to the proposed pair channel codes –decoding methods is given.

V.B-1. Methodology

A CSK signal keeping the same useful bit rate as a reference BPSK signal is created by mapping *U* bits per CSK symbol and by increasing *U* times the length of the CSK symbol period with respect to the BPSK signal symbol duration (see Figure 6). In doing so, the final useful bit rate of the CSK modulated signal is the same as the BPSK signal: although the rate is increased by *U* due to the introduction of a CSK modulation, the rate is also divided by *U* due to the increase of the CSK symbol duration.

In order to generate the extended CSK symbol, there are 2 possible options. On one hand, the CSK symbol can be generated from a long PRN code spanning the entire CSK symbol. On the other hand, the CSK symbol can be generated by consecutive PRN codes with the same length as the BPSK signal original PRN code and having all of them the same circular cyclic shift (the demodulator must coherently accumulate consecutive PRN codes in order to recover the power of the entire CSK symbol).

Moreover, if the CSK modulated signal introduces a new channel code different from the reference BPSK signal (only in the RS case), the useful bit rate of the CSK modulated signal will vary: the number of coded bits representing a useful bit is different for both modulated signals. Therefore, taking into account the CSK modulation and the change of channel code, in order to keep the same useful bit rate of a reference BPSK signal, a CSK signal must have a symbol duration equal to:

$$T_{s,CSK} = \frac{r_{code,CSK}}{r_{code,BPSK}} \cdot U \cdot T_{s,BPSK} \quad (8)$$

Where r_x represents the channel code rate of the channel code x and $T_{s,y}$ represents the symbol duration of modulation y.

The new codeword duration, $T_{cw,CSK}$, will depend on the number of bits constituting the codeword, n, the number of bits mapped by a CSK symbol which belong to the same codeword, S (S=1 for mapping A and S=U for mapping B) and the CSK symbol duration:

$$T_{cw,CSK} = \frac{n}{S} \cdot T_{s,CSK} \tag{9}$$

For a Reed-Solomon channel code, since the number of bits of a codeword is defined by construction, equation (9) can be expressed as:

$$T_{cw,CSK} = (2^U - 1) \cdot T_{s,CSK} \tag{10}$$

The analysis of the demodulation performance of a GNSS signal is usually done by expressing the BER (or WER) as a function of the signal C/N_0. However, in the digital communication field, the comparison between modulations (or modulations plus channel codes) is made using the E_b/N_0 since this figure of merit subtracts the demodulation performance dependence on the useful bit rate (or symbol rate). In this paper, the comparison is also made through the E_b/N_0 since this will allow presenting the CSK signal design parameters regardless of the final selected useful bit rate. Equation (11) shows that if the BPSK and CSK signals have the same useful bit rate, R_b, having the same C/N_0 value at the RF block output is equivalent to have the same E_b/N_0:

$$\frac{C}{N_0} = \frac{E_b}{N_0} + 10\log_{10}(R_b) \tag{11}$$

V.B-2. Application

The demodulation performance (BER vs E_b/N_0) of the reference BPSK signal and the demodulation performance of a CSK signal implementing a LDPC (1200, 600) channel code and using the classical decoding method, the HDMD method and the BICM-IT method for mappings A and B are presented in Figure 7, Figure 8 and Figure 9. In these figures, the demodulation performance is presented for different number of bits mapped by a CSK symbol, U.

From Figure 7 and Figure 8, it can be observed that a CSK signal using CD and mapping A has worse demodulation performance (BER=10^{-5}) than a reference BPSK signal for $U < 11$. Besides, Figure 9 shows that using mapping B, the BPSK signal always outperforms the CSK modulated signal with CD by at least 0.7dB. From Figure 7 and Figure 8, it can also be observed that a CSK signal using HDMD or BICM-ID outperforms a CSK signal using CD when mapping A is implemented. In fact, improvements of about 0.7-0.9 dBs are found between BICM-ID and CD. The recommendation from Figure 8 is to use U = 6 or 8 bits at most if possible. Moreover, BICM-ID always outperforms HDMD.

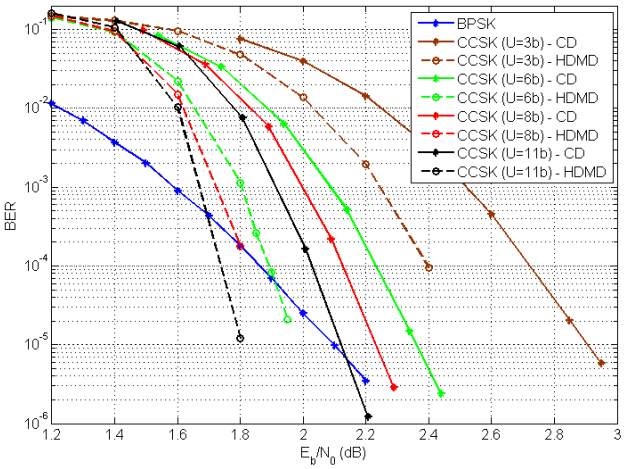


Figure 7: BER vs E_b/N_0 for a reference BPSK signal and for a CSK signal using Classical Decoding method (CD) and Horizontal Dimension Multistage Decoding (HDMD) with mapping A.

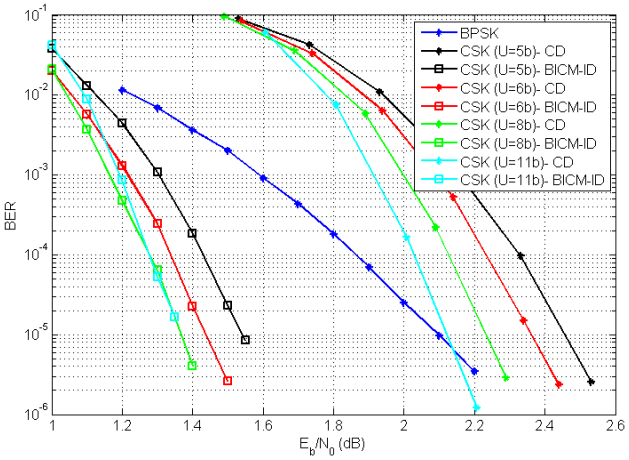


Figure 8: BER vs E_b/N_0 for a reference BPSK signal and for a CSK signal using Classical Decoding method (CD) and Bit-Interleaved Coded Modulation - Iterative Decoding (BICM-IT) with mapping A.

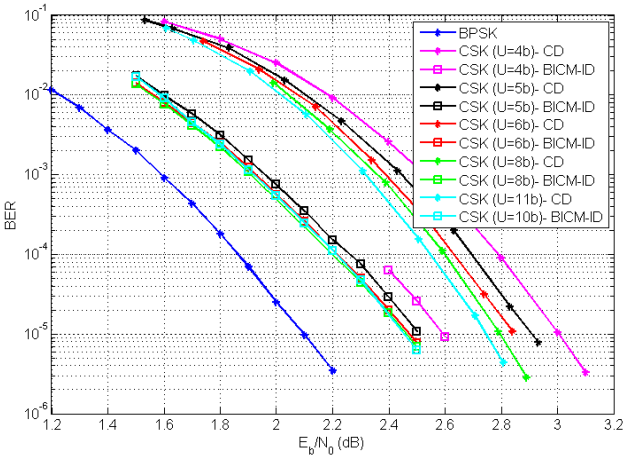


Figure 9: BER vs E_b/N_0 for a reference BPSK signal and for a CSK signal using Classical Decoding method (CD) and Bit-Interleaved Coded Modulation - Iterative Decoding (BICM-IT) with mapping B.

Table I: Codeword duration of a CSK signal implementing a LDPC(1200, 600) channel code when keeping the same useful bit rate of a reference BPSK signal

		Mapping A	*Mapping B*
Bits per CSK symbol, U	**5**	6000·Ts	1200·Ts
	6	7200·Ts	
	8	9600·Ts	
	11	13200·Ts	
	12	14400·Ts	

Table II: Symbol and codeword duration of a CSK signal implementing an optimal Reed-Solomon channel code

Channel Code	*U*	$T_{s,CSK}$	$T_{cw,CSK}$
RS (63,45)	6	8.3·Ts	522.9·Ts
RS (127,91)	7	10.04·Ts	1275.08·Ts
RS (255,191)	8	11.98·Ts	3054.9·Ts
RS (511,391)	9	13.78·Ts	7041.6·Ts
RS (1023,799)	10	15.62·Ts	15979.26·Ts

Finally, from these two figures it can be observed that a CSK signal using HDMD outperforms the reference BPSK signal when at least 6 bits are mapped by a CSK symbol (4 or 5 bits should be tested), and that a CSK signal using BICM-ID always outperforms the reference BPSK signal with mapping A. More specifically, a BPSK reference signal needs at least 0.6dB more than a CSK signal with BICM-ID to obtain a BER of 10^{-5}. In any case, this comparison is not entirely fair since the use of iterative decoding methods makes that the equivalent channel code implemented in a CSK signal has a size equal to $U \cdot n$ coded bits whereas the BPSK signal channel code only has a length of n coded bits (the receiver should wait the same exact amount of time, or in other words, the same number of bits, before being able to decode the codeword). Therefore, an entirely fair comparison should be done with a reference BPSK signal having a channel code of $U \cdot n$ coded bits.

From Figure 9, it can be seen that the reference BPSK signal still outperforms a CSK signal with BICM-ID with mapping B by about 0.4-0.5dB when a BER equal to 10^{-5} is targeted. Besides, BICM-ID improves CD by about 0.2-0.4dB for a BER equal to 10^{-5}. In fact, since the BICM-ID methods reaches a saturation when U=6 bits, the recommendation is to use U equal to 5 or 6 bits if possible.

Table I shows the codeword duration of a CSK signal implementing the LDPC (1200,600) channel code and keeping the useful bit rate of the reference BPSK signal. The codeword duration only depends on the implemented mapping. From Table I, it can be seen that although mapping A provided better demodulation performance than mapping B, its codeword duration is longer. Mapping B has the same codeword duration as the reference BPSK signal.

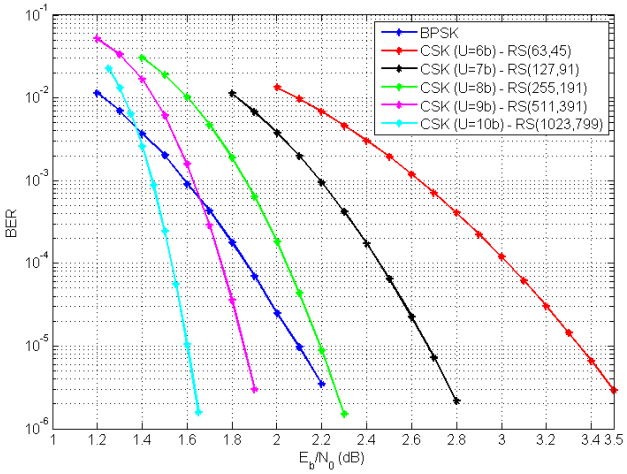


Figure 10: BER vs E_b/N_0 for a reference BPSK signal and for CSK signal with Reed-Solomon channel codes.

The demodulation performance (BER vs E_b/N_0) of the reference BPSK signal and the demodulation performance of a CSK signal implementing a Reed-Solomon (RS) channel code is presented in Figure 10. In these figures, the demodulation performance is presented for different number of bits mapped by a CSK symbol, U.

The RS codes presented in Figure 10 are the RS channel codes which present the better demodulation performance for each different number of bits mapped by a CSK symbol, U. In fact, a channel code increases is demodulation performance when the code rate is decreased, which implies a lower E_s/N_0 when E_b/N_0 is fixed (as in this case) [3]. However, an orthogonal M-ary modulation increases its demodulation performance when E_s/N_0 increases as well [13]. Therefore, the RS channel codes which better fulfill the trade-off between these two aspects, CSK modulation and channel code, have been searched and are presented in Figure 10. These RS channel codes have a code rate equal to about 3/4.

From Figure 10, it can be observed that when U=8, a CSK signal implementing a RS channel codes has about the same demodulation as a reference BPSK signal, and it is even better when U is larger. However, a CSK signal with LDPC(1200,600) using BICM-ID with mapping A outperforms a CSK signal with a RS channel for the inspected U values.

Table II shows the symbol duration and the codeword duration of a CSK signal implementing an optimal Reed-Solomon Channel code (depending on U) and keeping the useful bit rate of the reference BPSK signal. From Table II, it can be seen that when U is equal to 7 the codeword duration of the optimal Reed-Solomon and the reference BPSK signal codeword are about the same. However, U has to be at least equal to 8 to obtain the same demodulation performance for both types of signals. But when U=8, the codeword duration of the CSK signal implementing an optimal RS channel code is about 3 times longer than the BPSK signal codeword duration.

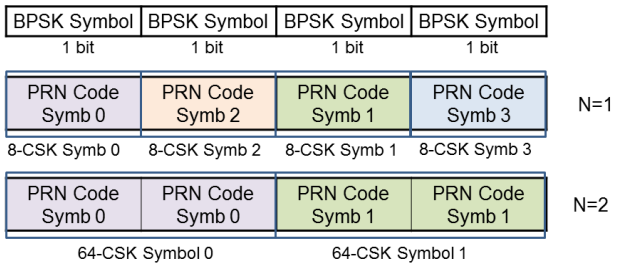


Figure 11: Different possible combinations of CSK symbols producing a bit rate increased by a factor of 3 with respect to the original BPSK signal

V.C. CSK signal with increased useful bit rate

In this section, the methodology used to design a CSK signal increasing the useful bit rate of a reference BPSK signal but keeping the same symbol rate (or duration) is presented and its application to the proposed pair channel codes –decoding methods is given.

V.C-1. Methodology

The increase of the useful bit rate is obtained by simply applying the CSK modulation instead of the BPSK modulation and thus, the useful bit rate is increased by a *U* factor.

Moreover, although one of the signal hypotheses is to keep the original signal symbol duration, a CSK symbol can be artificially extended by coherently accumulating *N* consecutive identical circular shifted PRN codes. In fact, the original signal parameters which should remain constant in order to maintain the original signal spectrum and original inter and intra interference characteristics are the chipping rate and the PRN code length. Therefore, there is no impediment to coherently accumulate *N* PRN codes to construct a new symbol with a larger duration, $T_{s'}$ (see equation (12)).

$$N \cdot T_s = T_{s'} \qquad N \in \mathbb{Z} \tag{12}$$

The new signal bit rate is thus equal to:

$$R_{s,CSK} = \frac{U}{N} \cdot R_{s,original} \tag{13}$$

And this means that whereas for a BPSK signal the accumulation process results into a decrease of the bit rate, for a CSK modulation the final bit rate is still increased if $N < U$. From now on, in this paper, the choice of the *U* and *N* parameters is called the CSK configuration of a CSK signal. Moreover, this paper calls *equivalent* the CSK configurations which provide the same bit rate but using different *U* and *N* values ($U/N = U'/N'$).

Figure 11 presents an example of two equivalent CSK configurations which increase the original BPSK signal bit rate by a factor of 3. The first configuration consist in simply changing the original BPSK symbol by a 8-ary CSK symbol (*U*=3 bits, *N*=1, for 3 bits/symbol), whereas the second one consist in accumulating 2 consecutive identically shifted PRN codes which represent a 64-ary CSK symbol (*U*=6 bits, *N*=2, for 3 bits/symbol).

Finally, equation (13) is only valid when the BPSK signal and the CSK signal implement a channel code with the same code rate. However, this does not have to be the case for the inspected Reed-Solomon channel code and thus equation (13) is generalized to:

$$R_{s,CSK} = \frac{r_{code,CSK}}{r_{code,BPSK}} \cdot \frac{U}{N} \cdot R_{s,original} \tag{14}$$

The comparison among the demodulation performance of different pair channel – decoding methods is made by comparing the BER vs normalized C/N_0 ($C/N_0|_n$). In this case, the C/N_0 is still not used since it is preferred to express the final demodulation performance independently from the symbol rate (easier to generalize the results to any PRN code period). Moreover, the E_b/N_0 cannot be used since the comparison is also made between different useful bit rates and the term which is originally fixed is the E_s/N_0. However, due to the possibility of artificially extending the CSK symbol, the E_s/N_0 varies among different CSK configurations. Therefore, this paper has decided to express the demodulation from an artificial figure of merit which is simply the C/N_0 normalized by the rate of the original BPSK symbol (or PRN code).

$$\left.\frac{C}{N_0}\right|_n = \frac{E_b}{N_0} + 10\,log_{10}(r_{code}) + 10\,log_{10}(U/N) \tag{15}$$

$$\frac{C}{N_0} = \left.\frac{C}{N_0}\right|_n + 10\,log_{10}(R_S) \tag{16}$$

Finally, the normalized C/N_0 required for an artificially extended CSK symbol can be calculated from the normalized C/N_0 of the original CSK symbol:

$$\left.\frac{C}{N_0}\right|_n (p/N) = \left.\frac{C}{N_0}\right|_n (p) - 10\,log_{10}(N) \tag{17}$$

Where $C/N_0|_n(x)$ is the normalized C/N_0 associated to a signal with a factor of increased data rate of *x*.

The duration of the new codewords of the CSK modulated signal with increased useful bit rate are easily determined from the codeword duration of the CSK signal with the same useful bit rate (see equation (8)). The only difference is that the CSK symbol is not expanded by the number of bits mapped by a CSK but by the number of coherent accumulated PRN codes:

$$T_{cw,CSK} = \frac{n}{S} \cdot N \cdot T_{s,BPSK} \tag{18}$$

As well as in the previous case, this expression can be customized by a Reed-Solomon signal:

$$T_{cw,CSK} = (2^U - 1) \cdot N \cdot T_{s,BPSK} \tag{19}$$

V.C-2. Application

The demodulation performance (BER vs norm C/N_0) of a CSK signal implementing a LDPC (1200, 600) channel code and using the classical decoding method for mapping A is presented in Figure 12. In this figure, different CSK configurations (*U* and *N* pair of values) are used in order to attain an increase of twice the original bit rate. From Figure 12, it can be seen that configurations with larger *U* and *N* values outperform configurations with smaller values. However, the former configurations increase the receiver complexity (*U* is larger).

The demodulation performance (BER vs norm C/N_0) of different CSK signals with increased bit rate with respect to a reference BPSK signal is presented in Figure 13. These CSK signals implement a LDPC (1200, 600) channel code and use the classical decoding method and the BICM-IT method for mappings A and B. The CSK configurations (*U, N*) implemented for these CSK signals always have a coherent accumulation number of PRN codes equal to 1 (*U, N=1*). From Figure 13, the same conclusions from Figure 7 and Figure 8 can be extracted: BICM-IT outperforms Classical Decoding and mapping A outperforms mapping B.

Table III shows the codeword duration of a CSK signal implementing the LDPC(1200,600) channel code and increasing the useful bit rate of the reference BPSK signal by a factor of *U/N*. The codeword duration is given as a function of the number of bits mapped by a CSK symbol, *U*, the number of PRN codes coherently accumulated, *N*, and the implemented mapping. From Table III, the same conclusions from Table I can be extracted: mapping A has longer codewords than mapping B. Moreover, it can be observed that although using CSK configurations with high *U* and *N* values provide better demodulation performance (regardless of the implemented mapping), when using mapping A these configurations have longer codewords than equivalent CSK configurations with lower *U* and *N* values. Therefore, a trade-off between demodulation performance and codeword duration / receiver complexity is found when using mapping A. However, when using mapping B, the codewords have exactly the same duration when using equivalent CSK configurations. Therefore, the previous trade-off is limited between the demodulation performance and the receiver complexity.

The demodulation performance (BER vs normalized C/N_0) of different CSK signals with increased bit rate with respect to a reference BPSK and implementing a Reed-Solomon (RS) channel code is presented in Figure 14. The CSK configurations (*U, N*) implemented for these CSK signals always have a coherent accumulation number of PRN codes equal to 1 (*U, N=1*).

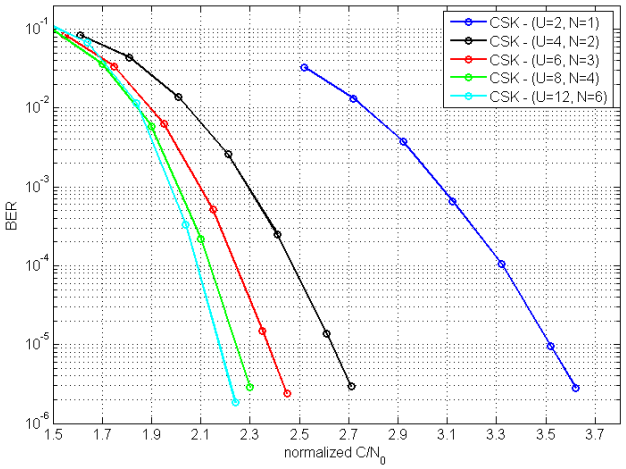


Figure 12: BER vs norm C/N_0 for a different (U,N) configuration of a CSK signal using Classical Decoding method (CD) with mapping A when increasing the bit rate by a factor of 2 w/r to a BPSK signal.

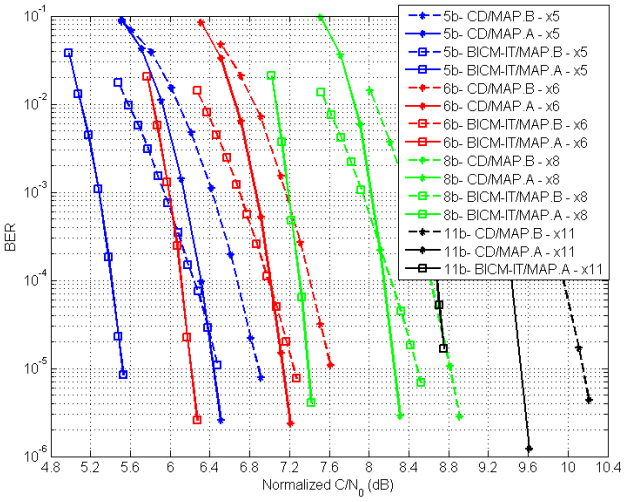


Figure 13: BER vs normalized C/N_0 for CSK signals with increased bit rate with respect to a BPSK signal. CSK signal use Classical Decoding method (CD) and Bit-Interleaved Coded Modulation - Iterative Decoding (BICM-IT) with mapping A and mapping B. All the CSK configurations are defined (U, N=1).

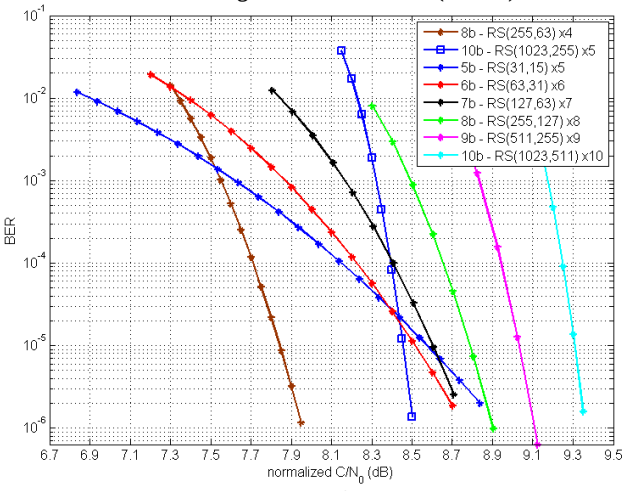


Figure 14: BER vs normalized C/N_0 for CSK signals with increased bit rate with respect to a BPSK signal. CSK signal implement Reed-Solomon (RS) channel codes with code rate equal to 1/2 or 1/4. All the CSK configurations are defined (U, N=1).

Table III: Codeword duration of a CSK signal implementing a LDPC(1200, 600) channel code when increasing the useful bit rate of a reference BPSK signal by a factor of *U/N*.

		Mapping B	*Mapping A*
Bits per CSK symbol, U	**4**	300·N·Ts	1200·N·Ts
	5	240·N·Ts	
	6	200·N·Ts	
	8	150·N·Ts	
	11	≈110·N·Ts	
	12	100·N·Ts	

Table IV: Codeword duration of a CSK signal implementing a Reed-Solomon channel code when increasing the useful bit rate of a reference BPSK signal by a factor of $(U/N) \cdot \frac{r_{code,CSK}}{r_{code,BPSK}}$.

Bits per CSK symbol, U	*Reed-Solomon (2^u-1, 2^{u-1}-1)*
5	31· N·Ts
6	63· N·Ts
7	127· N·Ts
8	255· N·Ts
9	511· N·Ts
10	1023· N·Ts

The number of possible configurations of CSK signals which increase the useful bit rate of a BPSK signal when implementing a RS channel code is very large as expressed in equation (14). In Figure 14, only RS with channel code rates equal to 1/2 or 1/4 are inspected although the optimal channel codes have a code rate equal to 3/4. The reason for this choice is that optimal RS channel codes for a large value of *U* (from 8 bits the RS codes begin to be really interesting) tend to have very large codewords in terms of bits and in terms of duration.

From Figure 13 and Figure 14, it can be observed that a CSK signal implementing a LDPC(1200, 600) channel code and using the BICM-ID and mapping A always outperforms a CSK signal implementing a RS channel code for any number of bits mapped by a CSK symbol, *U*, when the useful bit rate is increased with respect to a BPSK signal. Moreover, when BICM-ID and mapping B are used, it appears that at least *U=9* (equality) or *U=10* bits are required in order to have better demodulation performance (at a BER=10^{-5}) for the RS implementation.

Table IV shows the codeword duration of a CSK signal implementing a Reed-Solomon Channel code increasing the useful bit rate of the reference BPSK signal by the factor expressed in equation (14). From Table IV, it can be seen that the codeword duration of a CSK signal implementing the LDPC (1200,600) and mapping A is longer than the codeword duration of a CSK signal implementing a RS channel code except for 11 or more number of bits mapped by a CSK symbol, *U*. However, the codewords for mapping B are only longer than the codewords for a RS channel code when *U=7* bits. But, remember that at least *U=9* bits are necessary in order to have a CSK signal implementing a RS channel code with a better demodulation performance (BER=10^{-5}) than a CSK signal implementing the LDPC(1200,600) and using BICM-ID with mapping B.

VI. PROPOSED CSK-BASED SIGNALS FOR GNSS

In order to design a signal that is realistically usable for GNSS users, it was decided to take into account a certain number of constraints specific to the GNSS field. These general constraints were derived from the principal conditions of reception and the analysis of the current and future GPS and GALILEO signals:

- The maximum number of bits mapped by a CSK symbol is set to 13 bits ($U_{max} = 13$). This value is determined by the number of chips of the PRN code having the maximum length among all the GPS and GALILEO signals (10230 for GPS L1C and L5) [6].
- A received C/N_0 between 15 and 45 dB-Hz [1]: This constraints provides the maximum and the minimum C/N_0 which a signal can expect to find.
- A limited time to access the codeword. This parameter is important in the GNSS field in order to reduce as much as possible the Time-To-First-Fix (TTFF). The TTFF will condition the choice of the maximum codeword duration. For instance:
  - For Galileo, the time to is 31.63 sec at 95% for E1F and 59.4 sec for E5a [21].
  - For GPS, the time is 35.5 sec at 95% for L1 C/A and 17.6 sec for L1C [21].

VI.A. Specific signal characteristics and constraints

The specific signal characteristics and constraints of the two proposed signal objectives are presented in this section. Table V summarizes the signal characteristics and constraints of a CSK signal keeping the useful bit rate of a reference BPSK signal. Table VI summarizes the signal characteristics and constraints of a CSK signal increasing the useful bit rate of a reference BPSK signal but keeping the same symbol rate.

Table V and Table VI define two types of codewords which divide the proposition of the new CSK modulated into two types:

a) Codeword of 600 invariant bits: Analyzing the defined GPS and GALILEO signals, it is observed that around 600 bits are necessary to carry the satellites ephemeris and clock error correction [22]. Since this information is constant for a period of time, code source mapping B is proposed for this type of signals. The reason is that the coherent accumulation of mapping B code words (one codeword transmitted in parallel) is easier to achieve than for mapping A (U codewords transmitted in parallel). Moreover, only Reed-Solomon codes which have a codeword with about 600 information words are used.

Table V: Signal characteristics and constraints for a CSK signal keeping the useful bit rate of a reference BPSK signal.

	Same Useful Bit Rate	
PRN Symb. Period	1ms to 20ms	
Useful Bit rate	25bps to 500 bps	
Codeword max. Duration	30s	
Codeword number of bits	600 Invariant bits	≥ 600 variant bits
Mapping LDPC (1200,600)	Mapping B	Mapping A
RS code rate	3/4	3/4

Table VI: Signal characteristics and constraints for a CSK signal increasing the useful bit rate of a reference BPSK signal but keeping the same symbol rate.

	Increased Useful Bit Rate	
PRN Symb. Period	1ms to 20ms	
Useful Bit rate	250bps to 5kbps	
Codeword max. Duration	10s	
Codeword number of bits	600 Invariant bits	≥ 600 variant bits
Mapping LDPC (1200,600)	Mapping B	Mapping A
RS code rate	1/4 or 1/2	1/4 or 1/2

Table VII: Considered PRN Code Durations assuming that several identical shifted PRN codes can be repeated to create a CSK symbol

Reference BPSK Symbol Rate	PRN Code Duration		
	Ref. BPSK	CSK with same R_b	CSK with Increased R_b
1 ms	1ms	1 to 16ms (max $T_{S,CSK}$ = 16 ms)	1 to 5ms (max $T_{S,CSK}$ = 5 ms)
4 ms	1 to 4ms	1 to 12ms (max $T_{S,CSK}$ = 56ms)	1 to 24ms (max $T_{S,CSK}$ = 24ms)
10 ms	1 to 10ms	1 to 10ms (max $T_{S,CSK}$ = 120ms)	1 to 20ms (max $T_{S,CSK}$ = 20ms)
20 ms	1 to 20ms	1 to 20ms (max $T_{S,CSK}$ = 240ms)	1 to 20ms (max $T_{S,CSK}$ = 20ms)

b) Codewords of 600 or more variant bits: Information of new applications of services. In this case, the information does not have to be constant and thus mapping A can be used instead of mapping B. The Reed-Solomon channel codes are no longer restricted by the size of codeword information bits.

VI.B. Specific signal characteristics and constraints

Table XI and Table XII show the CSK signal design parameters when the codewords carry 600 invariant bits. Table XI presents the design of a CSK signal keeping the same useful bit rate as a BPSK signal and Table XII presents the design of a CSK signal increasing the useful bit rate as a BPSK signal.

Table XIII and Table XIV show the CSK signal design parameters when the codewords carry 600 or more variant bits. Table XIII presents the design of a CSK signal keeping the same useful bit rate as a BPSK signal and Table XIV presents the design of a CSK signal increasing the useful bit rate as a BPSK signal.

Table XI, Table XII, Table XIII and Table XIV must be interpreted as the choice made by the authors' paper as the most suitable CSK signal design parameters for each one of the analyzed cases. Nevertheless, the reader could design a CSK signal with other parameters which better suits its signal needs. Moreover, these tables do not try to select one pair channel code – decoding method with respect to the other ones. In fact, these tables show that the final choice will be made depending on the signal characteristic or constraint the designer wants to give priority. For example, looking at Table XIV and the case of analysis {reference BPSK symbol equal to 4ms (125bps) and final useful bit rate equal to 500 bps}, the signal choice will be: BICM-ID for demodulation performance priority, RS for codeword duration priority and Classical decoding (CD) for receiver complexity priority.

Finally, the reader must remark that the HDMD method was not included on the tables. The reason is that HDMD provides a worse demodulation performance than BICM-ID but has a higher receiver complexity than CD.

VII. IMPACT OF A CSK MODULATION ON A GNSS RECEIVER

In this section, the constraints that lie in the reception of a CSK signal on a GNSS receiver, compared to the reception of a classical BPSK signal are analyzed.

VII.A. CSK signal model

The proposed CSK signal is assumed to have 2 components: a data component only carrying CSK symbols and a pilot component necessary to synchronize the signal. The option of having a hybrid data component (a part with BPSK symbols and a part with CSK symbols) was shown not to improve the signal acquisition sensitivity in [14] and thus is discarded for this purpose.

The pilot component has a primary PRN code of the same length as the CSK symbols PRN code. Moreover, both PRN codes are synchronized in order to facilitate the synchronization and demodulation of the data component from the pilot component. Additionally, the pilot component should incorporate a secondary code synchronized with the codewords of the data component (as GPS L1C [6]).

Table VII shows the different PRN codes periods depending on the proposed CSK signal option. It was assumed that the duration of a PRN code would not be greater than 24ms, which is close to the maximum usual

values for a GNSS signal (between 1 and 10 ms). Different allocations of power between the data and pilot component are analyzed:

- Data: 25%, Pilot: 75%
- Data: 50%, Pilot: 50%
- Data: 75%, Pilot: 25%

VII.B. Reference BPSK signal model

The reference BPSK signal model used to compare the impact of a CSK modulated signal on a GNSS receiver with a BPSK modulated signal have two components, a BPSK modulated data component and pilot component.

For both components of the BPSK signal, the implemented PRN code has the same length and chipping rate as the components of the CSK modulated signal. For the data component, the only difference is obviously the implemented modulation.

VII.C. Impact of CSK on the Receiver Architecture

The increase of the receiver's complexity when using a CSK modulated signal is found on the demodulator block which is more complex than the demodulator of a BPSK signal as seen in section II-II.C. In this section, the increase of complexity is shown by means of presenting the number of multiplications which should be conducted in a CSK modulator in comparison to a BPSK demodulator.

Two types of demodulators are proposed for a CSK modulated signal, the bank of matched filters (or correlators) and the FFT-based correlator. Moreover, there are two algorithms which can be implemented to apply the FFT-based correlator: the traditional IFT and FT calculation method or the radix-2 Cooley-Tukey FFT algorithm [23].

Table VIII shows the number of multiplications required for the different types of CSK demodulators when a CSK mapping U bits and spanning $N=1$ identical PRN codes is transmitted. Moreover, in order to allow for a fair comparison with a BPSK signal, the number of multiplications required for the traditional BPSK demodulator is shown when U bits are sequentially demodulated. From Table VIII, two conclusions can be extracted. First, for the two values of PRN codes length being analyzed (1023 and 10230), the radix-2 Cooley-Tukey FFT algorithm demodulator always requires the smaller number of multiplications to demodulate a CSK symbol among the 3 proposed CSK demodulators. However, even this modulator requires a larger number of multiplications than the typical BPSK demodulator. Besides, the difference in number of multiplications between the Radix-2 CSK demodulator and the BPSK demodulator is increased when identical PRN codes are coherently accumulated ($N > 1$).

Table VIII: Number of Multiplications for CSK Demodulation for the transmission of *U* bits per CSK symbol when *N=1* PRN codes are coherently accumulated. Number of multiplications for BPSK modulation when *U* bits are sequentially demodulated.

		Number of Multiplications			
		CSK			BPSK
PRN Code Length	U	Radix-2	Traditional IFFT	Bank of Traditional Correlation	Correlator
1023	6	11264	71680	65472	6138
	8	11264	268288	261888	8184
10230	6	245760	1179648	654720	61380
	8	245760	4325376	2618880	81840
	10	245760	16908288	10475520	102300
	12	245760	67239936	41902080	2004600

Finally, when considering using the FFT-based correlator, one has to keep in mind that it creates constraints on the sampling frequency. Indeed, once the receiver is synchronized with the incoming signal, it is important that all the correlator outputs are synchronized with actual PRN code shifts. This means that the samples of the correlation function fall exactly on multiples of a chip. This means that the sampling frequency needs to be a multiple of the chipping rate, which is known to be non-optimal for synchronization purpose [24], especially when the Doppler frequency is close to 0 Hz. For reducing the computational burden, the same constraint actually applies to traditional correlation computation since typical hardware receiver generate local replicas of the PRN code based on shifts that are multiples of the sampling time. However, it seems easier to release this constraint on hardware receiver using traditional correlators than for hardware receiver using FFT-based correlators.

VII.D. Impact of CSK on Acquisition

In this subsection, a comparison between the joint data/pilot acquisition method (only applicable to BPSK signals) and the pilot-only acquisition method (applicable to both modulations) is made in order to inspect the degradation on the acquisition sensitivity introduced by a CSK modulation. Both methods have the same frequency and code delay uncertainty [2], and use the same acquisition detector: the standard single dwell acquisition technique described in [25].

Erreur ! Source du renvoi introuvable. shows the signal characteristics and acquisition parameters of this analysis. Table IX and Table X show the acquisition threshold (total signal C/N_0) for the joint data/pilot acquisition method and for the pilot-only acquisition method with different data/pilot power share. From these tables, it can be see that the pilot-only acquisition method needs to have 75% of the power allocated to the pilot component in order to have the same acquisition performance as the joint data/pilot acquisition method. If only 50% of the power is allocated, there is a degradation of acquisition sensitivity of 2 dB.

Table IX: Acquisition Thresholds (Total Data+Pilot C/N_0 of the Signal) for Different Data/Pilot Power Share, Coherent Integration Time and Non-Coherent Summations for a Targeted False Alarm Probability equal to the Inverse of the PRN Length (1023 Chips) and a Targeted Detection Probability of 90%

Coherent Integration time (ms)	Dwell Time on 1 acquisition bin (ms)	Acquisition Technique (dB-Hz)		
		Pilot- or Data-only with 75%	Pilot- or Data-only with 50%	Data+Pilot
1	10	34.65	36.4	34.4
	50	30.25	32	30.2
	100	28.45	30.2	28.5
	500	24.6	26.3	24.7
5	10	32.75	34.5	32.2
	50	27.65	29.4	27.5
	100	25.75	27.5	25.6
	500	21.45	23.2	21.5
10	10	32.05	33.8	31.5
	50	26.75	28.5	26.4
	100	24.65	26.4	24.4
	500	20.25	22	20.2

Table X: Acquisition Thresholds (Total Data+Pilot C/N_0 of the Signal) for Different Data/Pilot Power Share, Coherent Integration Time and Non-Coherent Summations for a Targeted False Alarm Probability equal to the Inverse of the PRN Length (10230 Chips) and a Targeted Detection Probability of 90%

Coherent Integration time (ms)	Dwell Time on 1 acquisition bin (ms)	Acquisition Technique (dB-Hz)		
		Pilot- or Data-only with 75%	Pilot- or Data-only with 50%	Data+Pilot
1	10	35.25	37	35.2
	50	30.95	32.7	30.9
	100	29.15	30.9	29.1
	500	25.15	26.9	25.3
5	10	33.65	35.4	33.1
	50	28.45	30.2	28.2
	100	26.45	28.2	26.3
	500	22.15	23.9	22.2
10	10	33.05	34.8	32.4
	50	27.65	29.4	27.2
	100	25.45	27.2	25.2
	500	20.95	22.7	20.9

Therefore, it can be concluded that for acquisition purposes, the BPSK data demodulation seems more appropriate as it enables the possibility of a joint data/pilot acquisition. However, in case a 75%/25% pilot/data power split is used, BPSK and CSK signals would have similar performances.

VII.E. Impact of CSK on carrier phase tracking

For the carrier phase tracking process, the main difference between the joint pilot/data carrier phase tracking method and the pilot-only carrier phase method is the type of discriminators of the PLL which can be implemented [2].

For a pilot-only carrier phase tracking method, the implemented discriminators are generally either the four-quadrant arctangent (Atan2) or the quadrature-phase correlator output (Q) [26]. The advantages of these discriminators are the appearance of stable points every 2π and a wider linear region. For the data component carrier phase tracking, the implemented discriminators are the Product discriminator (P) and the arctangent discriminator (Atan), which compared to the pilot discriminators, have the following disadvantages: narrower linearity region (more sensitive to large tracking errors) and stability points every π (demodulated data could be sign-reversed).

Therefore, [26] show that although the joint data/pilot method can use all the available signal power [27] and for the pilot-only method the data component power is lost, the pilot-only method provides better carrier phase tracking performance in poor environments: indeed the data component discriminators start providing erroneous outputs due to its reduced linear region while the pilot component's discriminator actually performs correctly. In this situation, the combination of the discriminator outputs will provide erroneous values. This can lead to cycle slips or loss of lock, while the tracking based on the pilot component only would have performed correctly.

Therefore, it can be concluded that there is no degradation of carrier phase tracking performance between a CSK signal and a BPSK signal since the BPSK will probably track the signal carrier phase using a pilot-only method. Finally, it has to be reminded that CSK modulation allows a non-coherent demodulation whereas a BPSK demodulation does not.

VII.F. Impact of CSK on carrier frequency tracking

Carrier frequency tracking is typically done using a Frequency Lock Loop (FLL). Typical FLL discriminators are based on the measure of the carrier phase variation during one coherent correlation. As a consequence, it systematically uses correlator outputs of the current and previous integration intervals. As a consequence, FLL discriminators are always sensitive to data bit transitions. It is possible to create FLL discriminators that are insensitive to data bit transition, but this is in general detrimental to the performance of the FLL (lower sensitivity, more susceptibility to high frequency errors) [26].

Another important feature of the FLL discriminator is its linearity region that will define the FLL pull-in range. This pull-in range is inversely proportional to the coherent integration time. It is thus in general desirable to have the possibility to use short coherent integration for the transition from acquisition to tracking when the frequency uncertainty is high, and then to use long coherent integration in order to have more accurate frequency tracking [26].

Therefore, it can be concluded that it is better to use only the pilot component to track the carrier frequency of the signal since this components provides a larger integration time that can be conducted over more than one relatively short PRN code, and since this component does not carry data.

In conclusion, there is no degradation of the carrier frequency tracking performance when a CSK modulated signal is used instead of a BPSK modulated signal.

VII.G. Impact of CSK on code delay tracking

As opposite to a joint pilot/data carrier phase tracking method, a joint pilot/data code delay tracking method can implement the same discriminators on the data component as on the pilot component. The reason is that the mostly used discriminators are non-coherent, thus removing the BPSK data [26].

However, the use of the same discriminator on both components implies that the correlator outputs of the data and pilot components have to be output at the same time, and thus that the coherent correlation duration is the same on both components. Therefore, although the discriminators are non-coherent, the coherent integration must still be restricted over a data symbol.

Moreover, the code delay tracking process admits longer coherent integration than the carrier phase tracking process. And it is well known that long coherent integrations improve the code tracking jitter, filter more slowly varying multipath and interference and potentially enables the use of the secondary code properties [26].

Therefore, although a joint/data code delay tracking method can use the same discriminator for both components and can use the entire signal power, an only-pilot code delay tracking method will provide better performance [26] since it could implement longer coherent integrations.

VIII. CONCLUSIONS

This paper has further analyzed the introduction of a CSK modulation on a GNSS signal than pervious works [13][14] and has clearly highlighted the advantages of such modulation:

- the non-coherent demodulation,
- the possibility to increase the bit rate without modifying the symbol rate, chip rate or PRN codes properties and
- the flexibility of dynamically changing the signal bit rate.

Moreover, the drawbacks have been identified: the necessity of introducing a pilot channel to synchronize the signal since the synchronization process cannot be conducted on the data channel and the increase of the complexity of the receiver demodulator block.

Afterwards, this paper has proposed different options of pair channel codes – decoding methods and has evaluated them with a proposed methodology for designing CSK modulated signals which pursue two opposite objectives: keeping the same useful bit rate as a reference BPSK signal and increasing the useful bit rate with respect to a reference BPSK signal while keeping the same symbol rate. This paper has shown the trade-off between demodulation performance, receiver complexity and codeword duration of the different pairs.

Moreover, the analysis of the two previous CSK designed signals and all the determined particular signals characteristics could be combined in a dynamic signal which could change its useful bit rate from low (ephemeris, clock error corrections) to high (new services) and thus be better adapted to the nature of its broadcasted information.

Finally, the analysis of the impact of a CSK modulated signal on a GNSS receiver has shown that although a FFT-based demodulator (radix-2) reduces the complexity of the receiver, this kind of receiver raises an issue with the required sampling frequency: a FFT-demodulator requires a sampling frequency proportional to the chipping rate whereas this kind of sampling frequency has shown to be detrimental for the tracking block.

Moreover, this paper has shown that there is no acquisition performance degradation if at least 75% of the power is allocated to the pilot channel, and that there should not be carrier or code delay tracking performance degradation since pilot-only tracking methods outperform joint pilot/data methods.

IX. FUTURE WORK

On-going work is centered on determining the demodulation performance of a CSK signal in a urban environment (mobile channel). The demodulation performance is being analyzed for the four pairs “channel codes –decoding methods” presented in this paper and for a non-coherent demodulation.

Besides, future work will analyze the limitations on the number of bits mapped by a CSK symbol, U, of a CSK modulation and will inspect the best CSK configurations (U, N) for a urban environment since the long symbols can be undesired due to the fading of these types of environments.

Finally, the concern about the frequency sampling for a FFT-based type of demodulator will be addressed.

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(U,N)
Codeword Duration
C/N0 required at the data component in order to obtain a BER= 10^{-5}

BPSK symbol duration	Codeword Duration
C/N0 required at the data component in order to obtain a BER= 10^{-5}	

Table XI: CSK modulated Signals with the same useful bit rate as a BPSK reference signal. The codewords contain 600 invariant bits.

		Map. B		Optimal Reed Solomon RS(127,91) – 637bits	BPSK LDPC (1200, 600)
		CD	BICM-ID		
Reference BPSK Symbol Duration	1 ms (500bps)	(12,12)	(6,6)	(7,7)	(1,1)
		1.2s	1.2s	1.28s	1.2s
		29.75 dB-Hz	29.45 dB-Hz	29.7 dB-Hz	29.1 dB-Hz
	4 ms (125bps)	(12,12)	(6,6)	(7,7)	(1,1)
		4.8s	4.8s	5.1s	4.8s
		23.75 dB-Hz	23.45 dB-Hz	23.7 dB-Hz	23.1 dB-Hz
	10 ms (50bps)	(12,12)	(6,6)	(7,7)	(1,1)
		12s	12s	12.75s	12s
		19.75dB-Hz	19.45 dB-Hz	19.7 dB-Hz	19.1 dB-Hz
	20 ms (25bps)	(12,12)	(6,6)	(7,7)	(1,1)
		24s	24s	25.5s	24s
		16.75dB-Hz	16.45 dB-Hz	16.7 dB-Hz	16.1 dB-Hz

Table XII: CSK modulated signals with increased useful bit rate with respect a BPSK reference signal but keeping the original symbol rate. The codewords contain 600 invariant bits.

				Useful Data Rate (bps)				
				250	500	1000	2000	5000
Reference BPSK Symbol Duration	1 ms (500 bps)	Map. B	CD	*No 1)	*No 1)	(8,4)	(8,2)	(10,1)
						600ms	300ms	120ms
						32.8 dB-Hz	35.8 dB-Hz	39.8 dB-Hz
			BICM-ID			(8, 4)	(8,2)	(10,1)
						600ms	300ms	120ms
						32.45 dB-Hz	35.45 dB-Hz	39.45 dB-Hz
		Reed Solomon	RS(255,63) 504 bits			(8,2)	(8,1)	***No 3)
						510ms	255ms	
						34.8 dB-Hz	37.8 dB-Hz	
			RS(255,127) 1016b			(8,4)	(8,2)	
						1.02s	510ms	
						32.8 dB-Hz	35.8 dB-Hz	
	4 ms (125 bps)	Map. B	CD	(12,6)	(12,3)	(8,1)	**No 2)	**No 2)
				2.4s	1.2s	600ms		
				26.8 dB-Hz	29.8 dB-Hz	32.8 dB-Hz		
			BICM-ID	(6,3)	(8,2)	(8,1)		
				2.4s	1.2s	600ms		
				26.45 dB-Hz	29.45dB-Hz	32.45 dB-Hz		
		Reed Solomon	RS(255,63) 504 bits	(8,2)	(8,1)	***No 3)		
				2.04s	1.02s			
				28.8 dB-Hz	31.8 dB-Hz			
			RS(255,127) 1016 bits	(8,4)	(8,2)	(8,1)		
				4.08s	2.04s	1.02s		
				26.8 dBHz	29.8 dB-Hz	32.8 dB-Hz		
	10 ms (50 bps)	Map. B	CD	(10,2)	(10,1)	**No 2)	**No 2)	**No 2)
				2.4s	1.2s			
				26.75 dB-Hz	29.75 dB-Hz			
			BICM-ID	(5,1)	(10,1)			
				2.4s	1.2s			
				26.5 dB-Hz	29.45 dB-Hz			
		Reed Solomon		***No 3)	***No 3)			
	20 ms (25 bps)	Map. B	CD	(10,1)	***No 3)	***No 3)	***No 3)	***No 3)
				2.4s				
				26.75 dB-Hz				
			BICM-ID	(10,1)				
				2.4s				
				26.45 dB-Hz				
		Reed Solomon		**No 2)				
Equivalent BPSK with LDPC (1200, 600)				2ms 2.4s	1ms 1.2s	0.5ms 600ms	0.25ms 300ms	0.1ms 120ms
				26.1 dB-Hz	29.1 dB-Hz	32.1 dB-Hz	35.1 dB-Hz	39.1 dB-Hz

*No 1) → The desired R_b requires a slower reference BPSK symbol period

**No 2) → Impossible to reach the desired R_b with the reference BPSK symbol period and $U_{max} = 13$.

***No 3) → Impossible to reach the desired R_b with the reference BPSK symbol period, $U_{max} = 13$ and RS codeword information bits.

(U,N) and k if necessary
Codeword Duration
C/N0 required at the data component in order to obtain a BER= 10^{-5}

BPSK symbol duration	Codeword Duration
C/N0 required at the data component in order to obtain a BER= 10^{-5}	

Table XIII: CSK modulated Signals with the same useful bit rate as a BPSK reference signal. The codewords contain 600 or more variant bits.

Reference BPSK Symbol Duration		Map. A		Optimal Reed Solomon		BPSK LDPC (1200, 600)
		CD	BICM-ID			
1 ms (500bps)		(12,12)	(6,6)	(10,10) – k=7990		(1,1)
		14.4s	7.2s	15.98s		1.2s
		29.1 dB-Hz	28.45 dB-Hz	28.6 dB-Hz		29.1 dB-Hz
4 ms (125bps)		(6,6)	(6,6)	(8,8) – k=1528	(9,9) – k=3519	(1,1)
		28.8s	28.8s	12.21s	28.2s	4.8s
		23.3 dB-Hz	22.45 dB-Hz	23.2 dB-Hz	22.8 dB-Hz	23.1 dB-Hz
10 ms (50bps)		(2,2)	(2,2)	(7,7) – k=637	(8,8) – k=1528	(1,1)
		28.s	28s	5.23s	30.55s	12s
		20.5 dBHz	---	19.7 dB-Hz	19.2 dB-Hz	19.1 dB-Hz
20 ms (25bps)		****No 4)	****No 4)	(6,6) – k=270	(7,7) – k=637	(1,1)
				10.46s	25.50s	24s
				23.35 dB-Hz	16.7 dB-Hz	16.1 dB-Hz

Table XIV: CSK modulated signals with increased useful bit rate with respect a BPSK reference signal but keeping the original symbol rate. The codewords contain 600 or more variant bits.

Reference BPSK Symbol Duration				Useful Data Rate (bps)				
				250	500	1000	2000	5000
1 ms (500 bps)	Map. A	CD		*No 1)	*No 1)	(8,4)	(8,2)	(10,1)
						4.8s	2.4s	1.2s
						32.3 dB-Hz	35.3 dB-Hz	39.2 dB-Hz
		BICM-ID				(6,3)	(8,2)	(10,1)
						3.6s	2.4s	1.2s
						31.45 dB-Hz	34.4 dB-Hz	38.4 dB-Hz
	Reed Solomon U=10b - RS(1023,511) or U=8b - RS(255,123)					(10,5) – k=5110	(8,2) – k=1016	(10,1) – k=5110
						5.115s	510ms	1.023s
						32.3 dB-Hz	35.6 dB-Hz	39.3 dB-Hz
4 ms (125 bps)	Map. A	CD		(6,3)	(12,3)	(8,1)	**No 2)	**No 2)
				14.4s	14.4s	4.8s		
				26.4 dB-Hz	29.1 dB-Hz	32.25 dB-Hz		
		BICM-ID		(6,3)	(8,2)	(8,1)		
				14.4s	9.6s	4.8s		
				25.45 dB-Hz	28.45 dB-Hz	31.45 dB-Hz		
	Reed Solomon U=8b - RS(255,123)			(8,4) – k=1016	(8,2) – k=1016	(8,1) – k=1016		
				4.08s	2.04s	1.02s		
				26.8 dB-Hz	29.8 dB-Hz	32.8 dB-Hz		
10 ms (50 bps)	Map. A	CD		(10,2)	(10,1)	**No 2)	**No 2)	**No 2)
				24s	12s			
				26.2 dB-Hz	29.2 dB-Hz			
		BICM-ID		(5,1)	(10,2)			
				12s	12s			
				25.55 dB-Hz	28.4 dB-Hz			
	Reed Solomon U=10b - RS(1023,511) or U=5b - RS(31,15)			(5,1) – k=75	(10,1) – k=5110			
				310ms	10.23s			
				28.6 dB-Hz	29.2 dB-Hz			
20 ms (25 bps)	Map. A	CD		(10,1)	***No 3)	***No 3)	***No 3)	***No 3)
				24s				
				26.2 dB-Hz				
		BICM-ID		(10,1)				
				24s				
				25.4 dB-Hz				
	Reed Solomon U=10b - RS(1023,511)			(10,1) – k = 5110				
				20.46s				
				26.3 dB-Hz				
Equivalent BPSK with LDPC (1200, 600)				2ms 2.4s	1ms 1.2s	0.5ms 600ms	0.25ms 300ms	0.1ms 120ms
				26.1 dB-Hz	29.1 dB-Hz	32.1 dB-Hz	35.1 dB-Hz	39.1 dB-Hz

*No 1) → The desired R_b requires a slower reference BPSK symbol period
**No 2) → Impossible to reach the desired R_b with the reference BPSK symbol period and $U_{max} = 13$.
***No 3) → Configuration not interesting from the codeword duration / demodulation performance point of view.
****No 4) → Codeword duration exceeds the imposed maximum duration.