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Optimal Pulsing Schemes for Galileo Pseudolite Signals

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Abstract. Galileo, the European Satellite Navigation System, is currently under development. Even before first satellites of the constellation are launched, Galileo signals will be provided through ground based Navigation Signal Generators for the investigation of signal performance and characteristics. Currently various projects are ongoing to develop these Galileo pseudolites (pseudo satellites). Since pseudolites are part of the Galileo system architecture namely as “Local Elements” it is expected that they will be used together with GNSS for position determination. The main characteristic of pseudolite navigation is the relatively small distance between the signal transmitter and the receiver, compared to the distances from the GNSS satellites to the receiver. This short distance causes the so-called “Near-Far-Problem”. Different attempts have been made in the past to overcome the near-far problem. A possible solution is to pulse the pseudolite transmitter signals, which has been proposed by many researchers and the success of pulsing has also been demonstrated. Basically these studies have been focused on the GPS pseudolites and the proposed pulsing schemes are optimised for the GPS signals (RTCM, RTCA). Due to major differences between the GPS and Galileo signal structures, these pulsing schemes cannot directly be adopted for use in the Galileo pseudolites. Thus new pulsing schemes and patterns have to be found and investigated. This paper summarises and assesses the existing GPS pulse patterns and pulsing techniques. The parameters which characterise a pulsing scheme are discussed and implemented. Simulations based on the Galileo signal structure (codes, chipping rates, cross correlation properties) have been performed and the results will be presented. These simulations form the basis for the proposal of a new optimised pulsing scheme for Galileo pseudolites w.r.t. pulse length, duty cycles and pulse patterns.

Keywords: Galileo, Pseudolites, Near-Far Problem

1 Introduction

Users of satellite navigation systems such as the US-American Global Positioning System (GPS) and the future European Satellite Navigation System Galileo require positioning information at any place on the earth, at any time and during all kinds of weather. Positioning information has become more and more valuable during the past twenty years. Beside the US military many other civilian groups have discovered the advantages of a global satellite navigation system. As the number of different users increases their requirements on the satellite navigation systems rises as well.

One answer to this is the augmentation of the GNSS at both local and wide areas. Tests with additional reference ground stations and geostationary satellites (EGNOS, WAAS) as well as pseudolites, PLs, have already shown significant improvements towards the availability of positioning and navigation services.

PLs are expected to meet the critical requirements of certain high precision applications like aircraft navigation during takeoff and landing where a satellite-only navigation system might not be sufficient.

One of the main constraints with PLs is the problem of the near-far effect which describes the incapability of a common satellite receiver to work with the signals of highly varying power levels. While satellite signals show an almost constant power level due to their far distance to the receiver, PLs can cause a big difference between the minimum and maximum received signal power levels, depending on the PL/receiver distance. However, common receivers are not designed for such a large dynamic range of power levels.

Many techniques have been introduced to overcome the near-far problem such as PL signal pulsing (Cobb 1997), the design of new spreading codes (Ndili 1994), the frequency offsets (Parkinson and Spilker 1996) and the Successive Interference Cancellation (Madhani et al. 2001).

The main reason for pulsing a PL signal is that the reception of the satellite signals is only jammed during the pulses. In an ideal situation the pulses are short enough so that the PL signals do not significantly harm the satellite signals. On the other hand the pulses need to be long enough so that the PL signals can be acquired and tracked.

Pulsing and its combination with other techniques allow the simultaneous reception of both satellite and PL signals within the given dynamic range. Fig. 1 illustrates the basic concept of a pulsing PL.

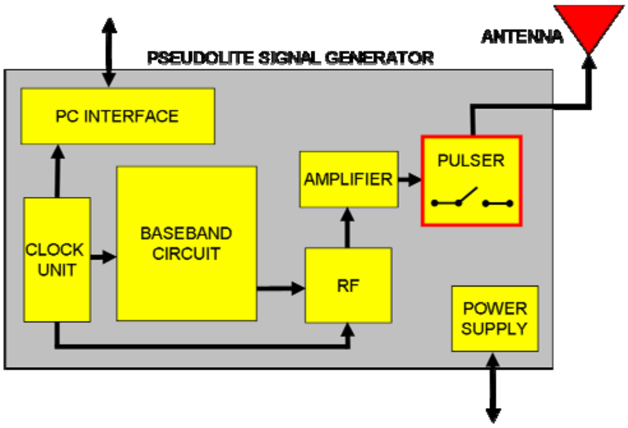

Fig. 1 Pseudolite Signal Generator

Within the above described background several promising investigations on PLs transmitting GPS signals have been done in the past. Two pulsing schemes which mitigate the near-far effect have been developed and will be introduced later.

This study aims to derive a new optimal pulsing scheme which is valid for Galileo PLs.

2 PARAMETERS OF A PL PULSING SCHEME

The following parameters are involved in the design of a PL pulsing scheme. The right implementation of these parameters leads to an optimised pulsing scheme. Due to the different properties of the GPS and Galileo signals (code periods, signal strength, cross correlation properties) the parameters have to be new determined in the case of Galileo.

Spreading code

The design of the spreading code has a major impact on the autocorrelation and cross correlation properties of the signals and therefore influences the tracking performance of the receiver. It should therefore carefully be chosen which code the PL will transmit. The code is defined by its code bit pattern and the chip frequency.

In the case of Galileo PLs, the spreading codes will be given by the Galileo Signal in Space ICD and will belong to the Galileo code family.

Pulse duration

The pulse duration or pulse width is one of the most fundamental parameters as it decides how much of the satellite signal will be blinded. The level of satellite signal interference can directly be related to the pulse duration. The pulse duration can also be expressed by the PL pulsing frequency.

Pulse position

The pulse position basically determines the time slots when the PL is transmitting. A randomised pulse sequence dissolves aliasing effects from an additional frequency and the probability of pulse overlaps is reduced.

The pulse pattern also determines how many pulses occur during one integration time of the receiver. The number of these pulses times the pulse duration expressed in percentage of the integration time delivers the Pulse Duty Cycle (PDC). If the number of pulses per integration time changes, only an averaged PDC can be calculated.

Subsampling problems arise if the pulse repetition time is higher than the integration time. In the worst case, this would mean that the receiver loses lock on the PL signals.

Saturation

There are three possibilities. First, the PL power level is tuned so that no saturation effects occur. Second, the PLs are on the maximum allowable power so that it saturates the receiver all the time. Third, neither of the cases is established. Consequently, the nearby PLs saturate the receiver while the more distant PLs will not.

Setting the receiver to saturation has the advantage that larger signal coverage can be obtained due to the high PL power.

Blanking

A blanking device improves the SNR/SIR of the satellite as well as of the PL and changes therefore the tracking performance of the receiver. This has a direct effect on the optimal pulse duration.

Two constraints of this study are that a PL must not harm a non participating user and should not require many receiver modifications from a participating user. The receiver is therefore considered to be saturated during the received PL pulses and no blanking mechanism is installed. This provides the same conditions for participating and non participating users.

Number of PLs

If the number of the utilised PLs is increased their benefits will increase as well. However, one has to be precautious about the side effects. More PLs cause a higher range of interference on the satellite signals (a receiver is saturated) but also on the other PL signals (pulse collisions). The maximal possible pulse duration decreases as the PDC is divided by the number of the PLs.

A minimum number of four satellites are required for positioning. Each PL can thereby replace a satellite. It has therefore been decided that in this case no more then four PLs on the same local site will be provided.

Signal strength

The number and the location of the PLs characterise the signal coverage (far boundary). The third factor which influences this is the signal strength of each PL. The higher the power level, the wider the area where the PL signal can be received. One has to account for varying signal wave losses dependent on the surrounding environment.

The power level increases or reduces the operational area. This parameter should be implemented when a specific application and its environment are given.

3 PL PULSING SCHEMES FOR GPS

RTCM

In November 1983, a subcommittee of RTCM SC-104 was assigned to recommend a pulsing scheme for the GPS PL signals (Stansell 1986).

The PL signals in this case belong to the C/A-code family which guarantees that only minimal changes to a standard GPS receiver have to be done to receive both the satellite and PL signals simultaneously.

The pulse duration is defined as 1/11 of a code period (1ms). This responds to 90.91µs or 93 code chips per pulse. One pulse occurs per period. However, in each 10th period, two pulses are sent to provide an average duty cycle of 10% (LeMaster 2002). The pulses are supposed to saturate the receiver.

The pulse position is altered within the 11 possible time slots from period to period. These variations are necessary to prevent aliasing effects. After 10 periods (10ms) a complete PL code is transmitted.

The 11 pulse positions also change from one data bit to the other over a 10bit and 200ms interval so that all possible pulse positions are transmitted after 200ms.

RTCA

The Special Committee SC-159 of RTCA proposed a pulsing scheme for the LAAS system in year 2000 (RTCA 2000).

The PL code is in this case generated like a GPS P-code, specifically the P-code for satellite PRN 34, utilising a frequency of 10.23MHz. The code is one week long but in contrast to the code of PRN 34 satellite, the generated code includes a phase delay with respect to the beginning of the GPS week in minutes. The definition of the code phase delay is an integer N, between 1 and 10079 minutes.

The commission proposed 72 out of all the possible delays for PLs. These delays are referred to as PRN 139-210. The generated PL signals are then transmitted in short pulses.

In contrast to the pulsing scheme introduced by the RTCM, the pulse positions of the RTCA are more pseudo-randomly distributed as they are determined by the output of a shift register (Fig. 2). The number of pulses within a given interval is therefore not constant. That means, for example, that more or less than one pulse can occur within the period of 1ms.

A 19-stage feedback shift register (Fig. 2) generates a pseudorandom binary sequence. The shift register is clocked at a rate of 511.500 kHz which is 20 times lower than the chipping rate of the code. The repetition interval of the shift register would be 1.025s. However, the register is short cycled so that one period takes only 1s. Each time a string of exactly six 1s (01111110) appears at the output of the shift register a pulse will be set. The clock frequency of the pulse sequence is consequently seven times lower than the frequency of the shift register and 140 times lower than the chipping rate of the code. Each pulse transmits therefore 140 code chips. This is a constant pulse width which equals approximately 13.685µs.

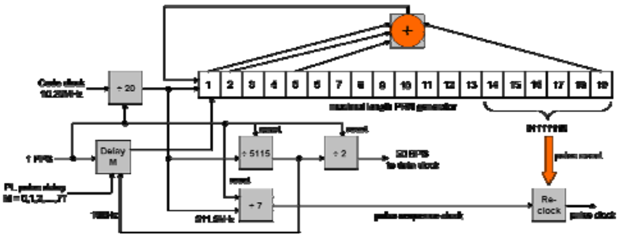

Fig. 2 Pulse Sequence Generator

The number of pulses in one second is 1997. From this, an average PDC can be derived as:

$$PDC = \frac{1997 * 140}{10,230,000} \approx 2.733\% \qquad (1)$$

The suggested pulse pattern causes difficulties for standard receivers. About 12% of the pulses are separated by a gap longer than 1ms and the longest gaps exceed

3ms. A receiver which has not been adjusted to these conditions might lose lock on the signal or might fail to acquire it at all.

Another drawback is that RTCA SC-159 working group 4 comes to the conclusion that the existing GPS certified receivers do not have sufficient design requirements to guarantee that the receivers would be protected from in-band jamming PLs.

All the references to PLs in the RTCA document DO-246C have therefore been removed. However, PLs at the L5 frequency are still an open topic to RTCA.

4 PDC FOR GALILEO PL SIGNALS

There has been previous research on how to derive the optimal PDC for a GPS PL. The idea is to use those considerations but with specific Galileo input parameters.

Signal-to-Interference ratio of a satellite

A PL decreases the average Signal-to-Interference ratio, SIR, of a satellite as the interference power of the PL is added to the interference power of the other GNSS satellites and to the thermal noise:

$$\frac{S}{I_{avg}} = \frac{S}{I+P} \tag{2}$$

where

$S =$ power of satellite signal

$I =$ interference power of other satellites and thermal noise

$P =$ interference power of PL

Based on this, Cobb (1997) has derived an equation which also accounts for the PDC of the PL (Eq. 3).

The greater the PDC, the lower the SIR of a satellite becomes. A low SIR in return makes tracking the satellite signals more difficult. This effect is surveyed in order to define the maximal possible PDC.

It is assumed that a constant number of equally long pulses appear within one period of the code otherwise Equation (1) could change for each period. The duration of a code period equals the integration time of the receiver.

$$\left(\frac{S}{I}\right)_{avg} = 10\log_{10}\left(\frac{s_{typ}(1-d)}{p\cdot d+(1-d)}\right) \tag{3}$$

where

$s_{typ} = 10^{\left(\frac{S}{I}\right)_{typ}\cdot 10^{-1}}$

$\left(\frac{S}{I}\right)_{typ}$ [dB] typical tracked SIR of a satellite

$p = 10^{\left(\frac{P}{I}\right)\cdot 10^{-1}}$

$d =$ duty cycle $0 \le d \le 1$.

Signal-to-Interference ratio of a PL

In an analogue way, as the degradation of a satellite signal caused by a PL is analysed, the degradation of a PL signal caused by other PLs can be investigated. LeMaster (2002) therefore derived Equation (4) from Equation (3). In this case the size of the signal interference depends on two parameters, namely on the PDC and on the number of PLs.

$$\left(\frac{S}{I}\right)_{avg} = 10\log_{10}\left(\frac{s_{\max}\cdot d}{p\cdot(N_{PL}-1)\cdot d+1-(N_{PL}-1)\cdot d}\right) \tag{4}$$

where

$s_{\max} = 10^{\left(\frac{S}{I}\right)_{\max}\cdot 10^{-1}}$

$\left(\frac{S}{I}\right)_{\max}$ [dB] maximum SIR (saturation level)

$N_{PL} =$ number of pseudolites

Simulation results

If the SIR falls below a certain receiver threshold (assumed as 6dB for a standard receiver) a signal cannot be tracked and data cannot be demodulated. The combination of Cobb's and LeMaster's equations defines therefore the maximum and minimum possible PDC. In this way, the size of the duty cycle can be fixed to a certain range. The influence of pulse overlaps is not considered in those calculations.

The input ratios $(S/I)_{typ}$ and (P/I) are derived by taking into account the precorrelation and postcorrelation bandwidths of the Galileo codes (Table 1) (Hein et al. 2002).

Table 1 Correlation Bandwidths

CHANNEL	BW_{pre}	BW_{post}
L1 B	6.138MHz	500Hz
L1 C	6.138MHz	10Hz
E5a-I	24.552MHz	100Hz
E5a-Q	24.552MHz	10Hz
E5b-I	24.552MHz	500Hz
E5b-Q	24.552MHz	10Hz
E6 B	10.23MHz	2000Hz
E6 C	10.23MHz	10Hz

The minimum required satellite signal strength of each of those codes is -158dBW.

In contrast to Cobb (1997), it has been decided that the ratio P/I is influenced by the cross correlation of the worst case instead of an averaged case.

The Galileo cross correlation properties for each channel have been achieved by correlating each possible combination of codes including the Doppler shifts from 0Hz to 6700Hz.

The results of the above described simulations are presented from Fig. 3 to Fig. 10 where each code family at one of the Galileo frequency channels show their own characteristics.

The red line presents the threshold of 6dB. SIRs below this line are not sufficient enough for signal tracking and data demodulation. The green curvature shows the satellite $(S/I)_{avg}$ of Equation (3) while the blue curvatures stand for the PL $(S/I)_{avg}$ of Equation (4) depending on the number of PLs (from one to ten).

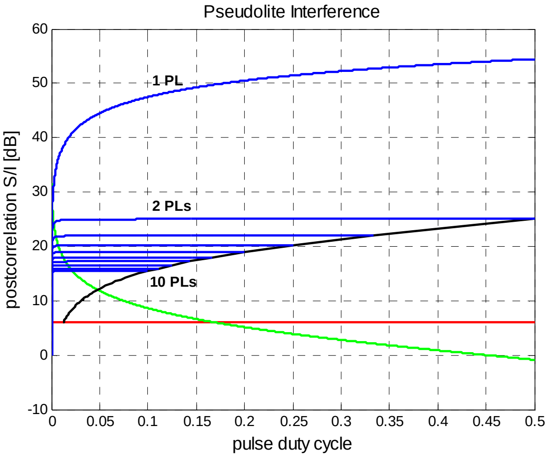

Fig. 3 L1 C (pilot)

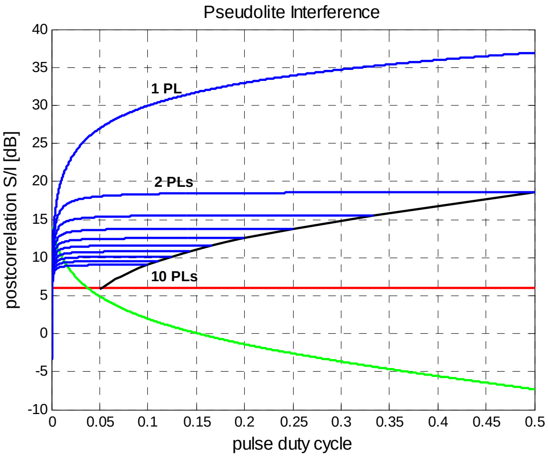

Fig. 4 L1 B (data)

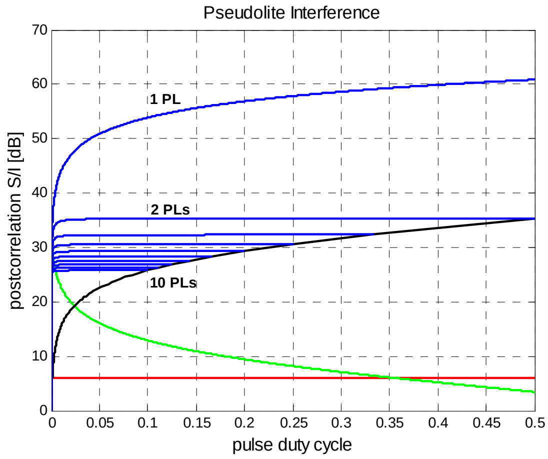

Fig. 5 E5a-Q (pilot)

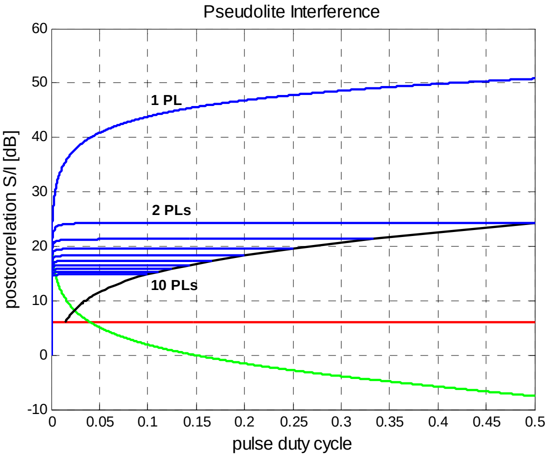

Fig. 6 E5a-I (data)

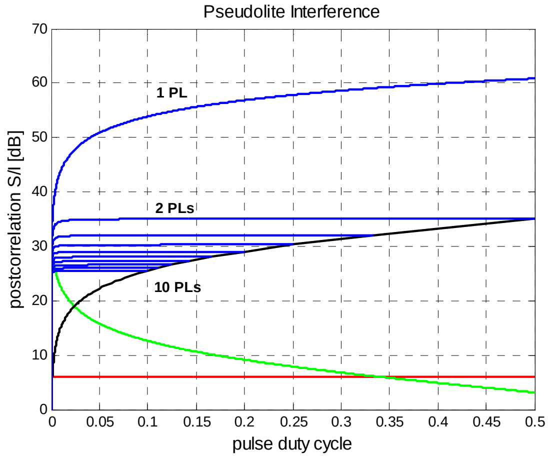

Fig. 7 E5b-Q (pilot)

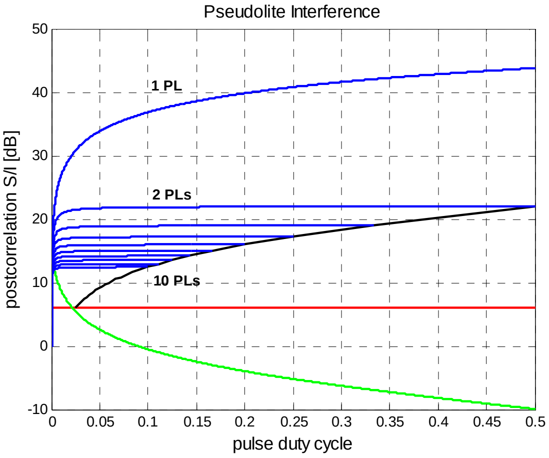

Fig. 8 E5b-I (data)

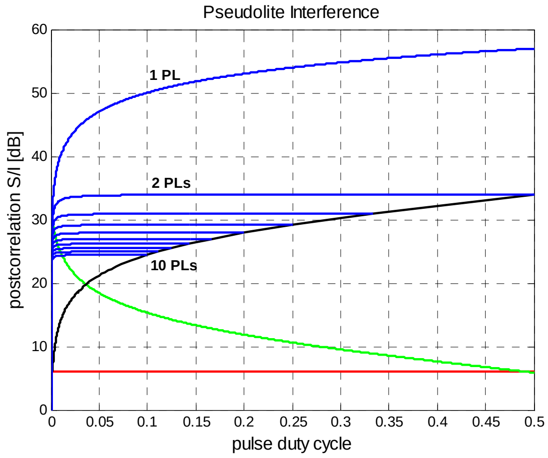

Fig. 9 E6 C (pilot)

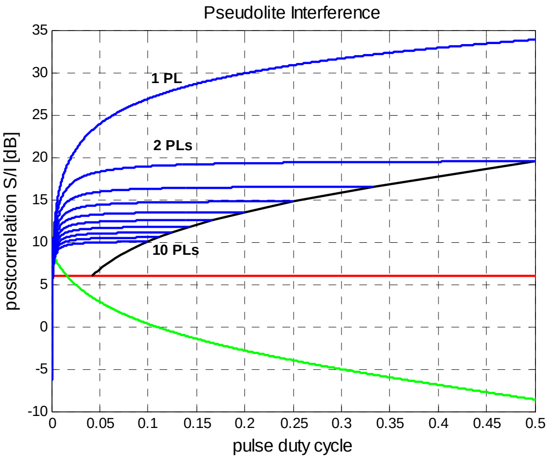

Fig. 10 E6 B (data)

It can be concluded from the blue graphs that only a small percentage of the code (a few chips) is enough to track and demodulate the PL signal. The minimum required PDC is therefore very low.

The maximum allowable PDCs are summarised in Table 2 where it is distinguished between the codes at the pilot channels (L1 C, E5a-Q, E5b-Q, E6 C) and at the data channels (L1 B, E5a-I, E5b-I, E6 B). The percentages are based on the respective code lengths.

Table 2 Allowable PDCs

$\mathbf{PDC_{max}}$	L1	E5a	E5b	E6
pilot	17.06%	35.7%	34.2%	49.3%
data	3.81%	4.14%	2.19%	1.64%

It should be noted that the codes at the pilot channels have higher PDCs than those with data. This can be explained by the fact that the dataless codes are longer and have therefore better cross correlation properties.

As a consequence, the PDCs at the data channels are the driving parameter because even if the maximum PDC of each of those data codes is utilised the maximum PDC at the corresponding pilot channel will never be reached. Thus, only the data channels are considered in the following course.

At this stage, it can be concluded that neither the RTCM nor the RTCA pulsing scheme can directly be adopted to the current task of using four Galileo PLs.

The RTCM pulsing scheme would utilise, for example, for four PLs, a PDC of 4 x 9% = 36% within 1ms which exceeds the maximal possible PDCs that have been derived in Table 2.

The RTCA scheme transmits within 1ms up to 7 pulses which corresponds to 4 x 9.6% = 38.4% and within 20ms up to 53 pulses which corresponds to 4 x 3.6% = 14.4%. Consequently, it can be utilised for some Galileo channels if only one PL is implemented. However, if the number of the PLs increases (up to 4) the maximum PDCs from Table 2 will also be exceeded. A new pulsing pattern is therefore needed.

5 PULSE PATTERN FOR GALILEO PL SIGNALS

The task is to find a pulse pattern which ensures a pseudo-random distribution of the pulse positions in order to avoid aliasing effects. One solution is to generate a binary code utilising a shift register. The output of the shift register can be divided into blocks containing a constant number of code chips. The code chip sequence of each block can than be calculated into a decimal number which defines the pulse position. Fig. 11 illustrates this technique at a 13-stage feedback shift register where seven chips (=7bits) are combined to one block. One is added to the decimal numbers in order to avoid the position 0. In Fig. 11, the positions therefore can go from 1 to 128.

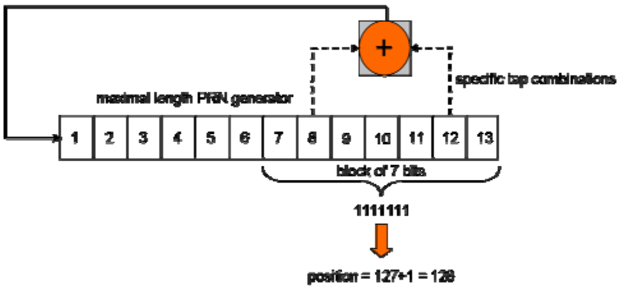

Fig. 11 13-stage shift register

The period of a PL code is divided into, for example 128 (=2^7), slots. Each position defines therefore within which slot the PL transmits its pulse. In such a way one pulse per PL code period can be guaranteed.

If a PL pulses within the same slot of two close periods, the right acquisition of the PL signals is problematic. The receiver can mix up the cross correlation of the high energy PL signals and the autocorrelation of the low energy satellite signals. If the cross correlation peak occurs several times at exactly the same part of the PL code period a receiver might acquire and track on the wrong signal.

In order to avoid this effect, all possible slots will be pulsed before the pulse pattern starts to repeat. That means for the shift register that only those positions are utilised that have not occurred before. Fig. 11 generates therefore a sequence of 128 pulse positions between 1 and 128.

Based on the chipping rate, PDC, and period length of the different Galileo codes the following possible options have been derived and implemented (Table 3).

Table 3 Galileo Codes

Channel	# bits per block	positions per period	# pulses per period	# code periods
L1 B	7	1-128	1	128
	8	1-256	2	128
E5a-I	7	1-128	1	128
	8	1-256	2	128
	9	1-512	5	102
	10	1-1024	10	102
E5b-I	8	1-256	1	256
	9	1-512	2	256
	10	1-1024	5	204
E6 B	8	1-256	1	256

The number of bits defines how many chips of the shift register output (Fig. 13) determine one position. This is directly related to the number of positions or time slots the code period is divided into.

The last column of Table 3 indicates how many code periods are pulsed before the pulse pattern starts from the beginning again.

If the number of slots increases the pulse duration decreases. Thus more pulses are allowed to be transmitted within one PL code period.

It has to be considered that only an integer number of code chips should be transmitted during one pulse slot. In order to realise this, the last slot of all PL code periods contain either more or less chips than the other slots.

It should also be ensured that the number of pulses per period is constant. Residual positions at the end of a pulse pattern period will therefore be ignored.

The question arises how to find the optimal shift register. 727 different registers (158 of stage 13, 242 of stage 14, 166 of stage 15 and 161 of stage 16) have been analysed so far. All the shift registers are defined by primitive polynomials and the roots are linearly dependent.

If a pulse is always transmitted at the same part of the code period a receiver will interpret these pulses as an extra frequency. A pseudorandom pulse pattern has therefore the task to prevent this effect. In other words, the pulsing frequency should change as much as possible that means the spacing between pulses should vary a lot. For that reason, the sum of different spacing between pulse positions has been calculated for all the possible shift registers.

An example of those computations are given by the two histograms of the different spacing where a 14-stage feedback shift register, 128 slots and one pulse per code period are implemented. Fig. 12 represents the results of a shift register with the maximum number of different spacing while Fig. 13 contains the minimum number of different spacing.

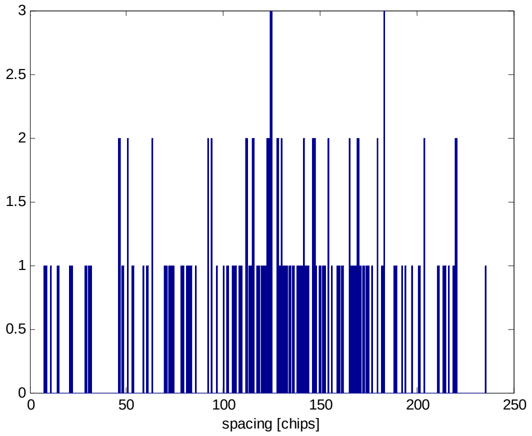

Fig. 12 Histogram (max spacing)

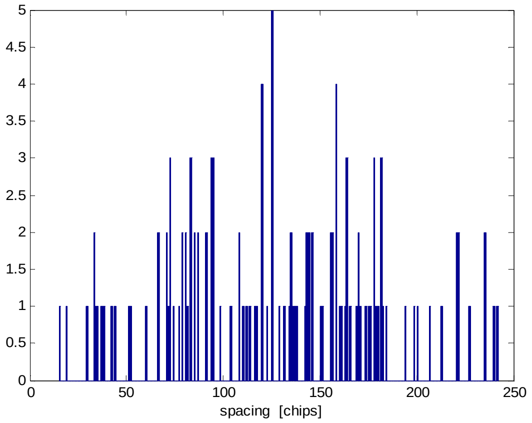

Fig. 13 Histogram (min spacing)

The best shift registers for each Galileo code have been filtered in such a way. However, after this it is still possible that a shift register generates different spacing but the differences between one space to the other are small. The spaces are, for example, quite small in the beginning and start to slowly increase towards the end. In such a case the frequencies would differ but not much.

Thus, the magnitudes of the differences between the spacing are also derived. An example is given by Fig. 14 where again a 14-stage feedback shift register, 128 slots and one pulse per code period are implemented.

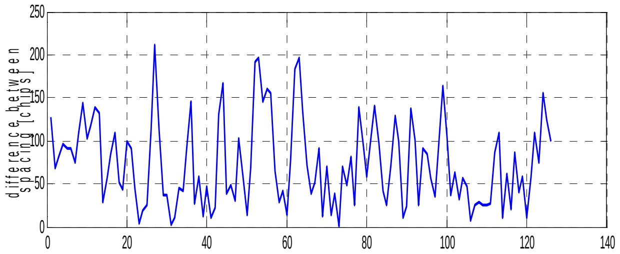

Fig. 14 Differences between spaces [chips]

The combinations of shift register taps which create the most different spaces between pulse positions are selected and out of those, the shift register with the highest magnitude of the differences between the spacing is defined as the optimal one.

This leads finally to one optimal shift register per code and option from Table 3. There is more than one option for each channel, except for E6 B. However, the optimal option for each channel has not been derived yet.

6 CONCLUSIONS AND OUTLOOK

In this study, several aspects of designing the optimal pulsing scheme for pseudolites have been analysed. The range of the possible PDC for each Galileo code family has been derived and a pseudorandom pulse pattern has been found. The choice of an optimal polynomial might be improved in future by investigating more shift registers of even higher stages.

However, the main aspect to be considered is that the research introduced here forms only the basis for finding an optimal Galileo PL pulsing scheme. Further research is required.

The next step will focus on the amount of pulse overlaps assuming the case of four PLs in the same area. Is the receiver performance more affected by a long pulse per PL period or more if several short pulses occur within the same period? The different options (Table 3) need to be simulated so that the best option for each channel can be found.

Another important aspect for investigation is the acquisition of the PL signals. Due to the low PDC in E6 B only a short pulse per period can be realised. Will that pulse, for example, be sufficient for acquisition? Further analyses should be concentrated on the concrete Galileo signals that will be assigned for the Galileo PLs. It will then be possible to determine the amount of code flips within one integration period and to calculate the autocorrelations which characterise the acquisition performance.

Finally, the PL pulsing scheme needs to be tested within a real application where further design aspects will be revealed.

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