SSC10-X-8

Space and Ground Segments Link Performance Verification for Small Satellite TT&C Transponders

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ABSTRACT

Verification of low earth orbit (LEO) satellite communication links is required for evaluation and acceptance purposes. Telemetry and telecommand transponder's bit error rate (BER), which is the main communication link parameter to be evaluated, is required to be verified by measurement rather than by analysis. This paper introduces a novel algorithm for measuring the BER of both space and ground segments. BER could be determined only if a received pattern is compared with a locally generated one. This feature exists for those transponders that utilize direct sequence spread spectrum (DS-SS) technique for purposes of range and range rate measurements, spreading the spectrum, or for security. In this work the space and ground segments' BER verification by measurement is achieved by exploiting the inherent locally generated pseudo random sequences (PRS). The application of this algorithm for measuring the BER of the space segment necessitates sending the information as a telemetry parameter just before the end of the communication session. This algorithm requires measuring BER over a large sample of the received chips due to the randomness of the errors. The high chip rate of the employed PRS (around 0.5MHz) and the period of the communication session (7-10 minutes in average) satisfy this condition. This algorithm is applied for measuring the BER for a digitally implemented coherent MSK DS-SS modem and the results for measuring the BER against E_b/N_o are presented.

INTRODUCTION

Telemetry, tracking and command (TT&C) transponders include three main systems: telecommand system conveys control commands from ground segments' users, in reliable and transparent way, to the controlled devices and processes onboard a space segment (i.e. scientific payload instruments or engineering subsystems)[1].

Telemetry system is responsible of conveying measurements information from different data generating sources located onboard space segment reliably and transparently to ground segment. Typically, data generators are scientific sensors, science housekeeping sensors, engineering sensors and other subsystems onboard a space segment[2].

Tracking system performs the function of range (varying distance between space and ground segments) and range rate (space segment speed) measurements[3] by mathematically manipulating some estimated parameters in the received PRS (which may assume linear or nonlinear codes).

All these systems convey the information between space and ground segments via communication links through digital modems.

Digitally implemented coherent modems are typically used in LEO satellite communication links to convey information between space and ground segments in both directions with minimum BER. Coherent modems provide 3dB improvement in performance of the BER compared to non-coherent modems and allow use of DS-SS to track the satellite by the ground segment due to availability of locally generated carrier and clock references in coherence with the received ones even for low signal to noise ratios (SNR).

Coherent MSK DS-SS is presented in this paper as one of the examples of digitally implemented coherent modems which contains synchronizer for both carrier and clock. The in-phase (I) channel of the MSK modulated signal carries telemetry or telecommand data (spread by I channel PRS's (PRS_I)) while the quadrature (Q) channel carries independently the tracking signal (only Q channel's PRS (PRS_Q) for range and range rate measurements) in downlink and uplink, respectively.

In the following, the need for SNR and BER measurements onboard space segment and in ground segment is first justified. Then a brief description of a digitally implemented coherent MSK DS-SS modem and its performance are shown. A proposed novel simple but efficient technique for measuring BER by exploiting the continuous presence of PRS (DS-SS code) in the Q channel of the MSK modulated signal is then presented.

VERIFICATION OF LEO SATELLITE COMMUNICATION LINKS

In the phase of evaluation and acceptance of LEO space systems, it is required to verify the claimed specs for both space and ground segments independently. One of the important specs to be verified is the BER (which is specified for certain SNR).

Although BER degradation may occur during life time of the space segment (e.g. due to degradation of some of RF blocks in the communication subsystem), current LEO space systems, after lunching, provides no telemetry information about measurement of neither BER nor SNR but rather gives estimation of BER either by incorporating mathematical equations (e.g. if CRC is used) or depending on the designed parameters. Hence, there is a need to the continuous monitoring of BER.

Also, it is required to take control actions (corrective or preventive) onboard space segment, thus correct interpretation of telemetry analysis and narrowing down the possibility of error source is a must.

Providing BER and SNR information by inherently incorporating a block that does these measurements during the development of the communication subsystem, engineering model and flight models is clearly justified.

COHERENT TYPE II MSK DS-SS MODEM

Type II MSK DS-SS Modulator

Typical type II MSK modulated signal consisting of the sum of two quadrature carriers (I channel carrier $\cos(\omega_o t)$ and Q channel carrier $\sin(\omega_o t)$) each is modulated (independently) by baseband data multiplied by weighting functions. The weighting functions (positive half cosines, $|\cos(2\pi t/4T_s)|$, or sines, $|\sin(2\pi t/4T_s)|$, of periods $4T_s$, T_s is the symbol period) do not alter the polarities of the modulating baseband data streams in I or Q channels. This feature is beneficial in the demodulation because there is no more processing needed for proper extraction of the data if compared to alternating sign weighting functions of type I MSK modulation[4].

If PRSs are used to spread the baseband data in each channel, DS-SS modulation results. In this case, the chip rate equals to half the MSK signal symbol rate and the baseband data rate is chosen to be the chip rate divided by certain integer (equal to the processing gain PG). The PRSs (e.g. preferred pairs of Gold codes) have low cross correlation and are aligned so that if one is acquired and tracked correctly the other can be generated depending on the already tracked one.

Coherent Type II MSK DS-SS Demodulator

The coherent type II MSK DS-SS demodulator consists mainly of: demodulator front end (HPF and automatic gain control AGC), synchronizer (including squaring nonlinearity used to generate carrier/clock spectral lines, frequency detector, carrier and clock recovery and phase ambiguities solver) and demodulator. The demodulator block diagram, Fig.1, is only shown for simplicity. Certain patterns of preferred pairs of Gold codes (PRS_I and PRS_Q) are chosen with 31 chip pattern length and generated by two linear feedback shift registers (LFSR).

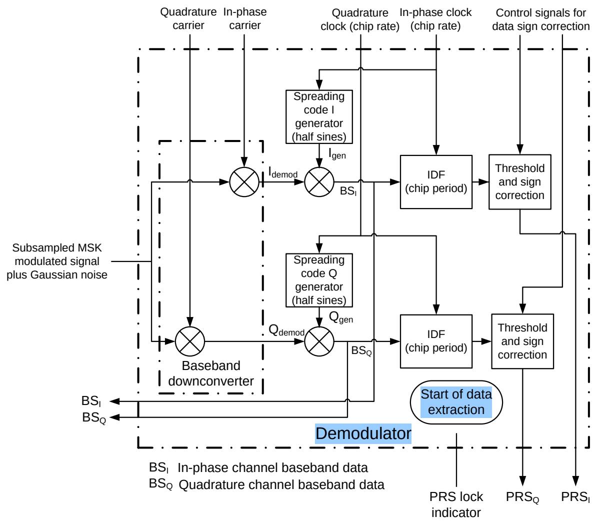

Figure 1: Type II MSK DS-SS Demodulator

BER AND SNR MEASUREMNTS

BER Measurement

While telemetry or telecommand signals (spread by PRS_I), in downlink or uplink respectively, is being conveyed by the I channel of the type II MSK modulated signal, the Q channel contains the tracking signal only, i.e. the PRS_Q. The main idea here is to exploit the presence of the latter signal to continuously provide a measure for BER.

This is done as follows: the estimated logic value (e.g. ‘0’ or ‘1’) of each received chip of PRS_Q (i.e. the output of integrate and dump filter (IDF) and zero threshold limiter) is compared to the coherent locally generated PRS_Q by performing “XOR” operation which yields logic ‘1’ or logic ‘0’ if the inputs are different (chip error occurred) or the same, respectively. The detection of chip error occurrence is counted and accumulated in an accumulator over certain time period (e.g. the communications session period). The accumulated count for the erroneous chips is then divided by the total number of tested chips in this period and the result is the estimated BER, Fig.2.

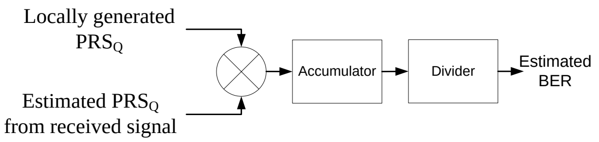

Figure 2: BER Measurement Circuit

SNR Measurement

At the same communication session period, the SNR can be measured as follows. The onboard receiver starts its operation before it can achieve point to point communication (i.e. to receive a signal from the ground segment) due to the geometry of the orbit, thus it receives noise only. The AGC block stabilizes the noise power at the input of the demodulator and the total noise power within the signal bandwidth is measured. Then after the communication link establishment the total signal and noise power could be measured and the average SNR is calculated.

Both the measured BER and SNR for the uplink signal could be encapsulated and sent in a telemetry source packet through all telemetry layers. Fig.3 shows an example for telemetry source packet.

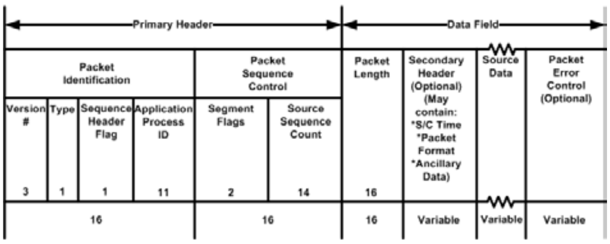

Figure 3: Source Packet (Version 1) Format

FPGA IMPLEMENTATION

The digitally generated type II MSK modulated signal has 1MHz symbol rate (0.5MHz chip rate in the quadrature channels) and apparent nominal carrier frequency located at 5.75MHz, thus the two generated MSK symbols have frequencies f_1 = 5.5MHz and f_2 = 6MHz. The main lobe bandwidth for this signal is (1.5 × 1MHz = 1.5MHz) centered at the apparent carrier.

A 50KHz frequency shift is added to the apparent carrier to simulate the existence of Doppler shift, thus the MSK symbol frequencies become f_{1D} = 5.55MHz and f_{2D} = 6.05MHz and the apparent carrier frequency is located at 5.8MHz with the same main lobe bandwidth for the MSK modulated signal without Doppler shift, Fig.4. The non-smooth spectrum of the type II MSK, Fig.4, with notches separated by 0.5MHz (compared to a smooth spectrum of the type II MSK signal[4]) may be attributed to the existence of the repetitive pattern of the I and Q modulating data streams (i.e. the used preferred pair of m-sequences (Gold code) described later in this paper) rather than a random sequence[4].

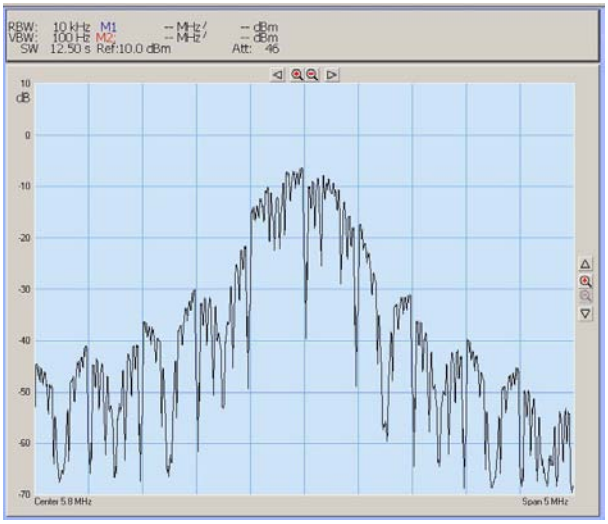

Figure 4: Spectrum of MSK Modulated Signal by I and Q Modulating PRSs

The type II MSK modulated signal is subsampled by an ADC clocked at 5 MHz, where the main lobe is translated in the spectrum and is centered at 0.8MHz (i.e. generated by beating between the sampling frequency and the signal, 5.8 – 5 = 0.8MHz), Fig.5, thus f_{1D} and f_{2D} become f_{1s} = 0.55MHz and f_{2s} = 1.05 MHz. The second alias shown in Fig.5 is due to beating between the second harmonic of the sampling frequency and the signal (10 - 5.8 = 4.2MHz) but attenuated due to the ZOH frequency response of the sampling signal of 5MHz[5].

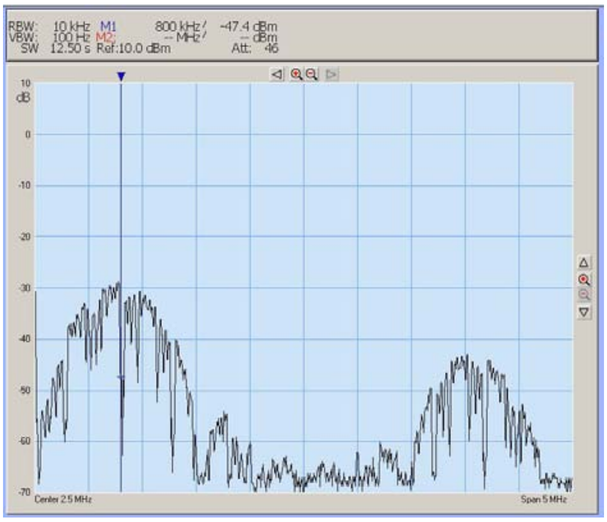

Figure 5: Spectrum of Subsampled MSK Modulated Signal

Fig.6 shows the spectrum of I demodulated baseband signal (i.e. after multiplication by the coherent locally generated I carrier).

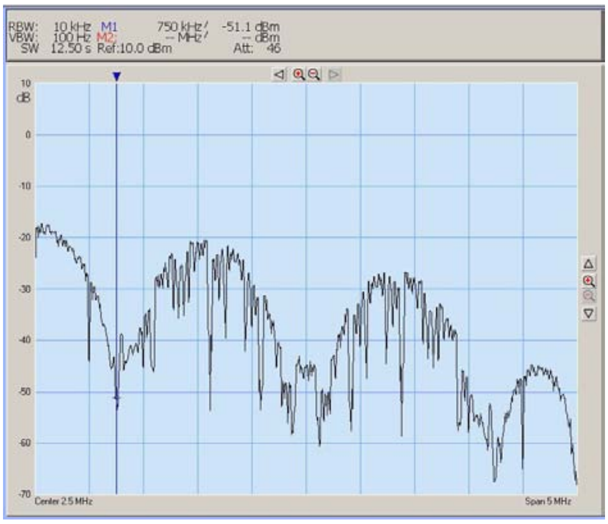

Figure 6: Spectrum of In-Phase Demodulated Baseband Signal

To extract the chips (i.e. from demodulated signal) with minimum probability of error, the signals BS_I and BS_Q, Fig.1, are integrated (in IDFs) over one chip period (this chip correlator corresponds to a correlator implementation of the minimum probability of error receiver for binary signals[6]). The outputs of IDFs are compared with threshold (i.e. zero level) to obtain the binary output data from the demodulator.

Properties of Pairs of m-Sequences with Low Cross-Correlation

The two PRS codes modulating I and Q channels are taken to be a preferred pair of m-sequences (Gold code) of low cross-correlation. These codes are of maximum length, i.e. m-sequences, which are implemented by using LFSRs with 5 stages (maximum length sequence = $2^5 - 1 = 31$). The PRS polynomials for the preferred pair in I and Q channels (PRS_I and PRS_Q) are[6]:

$$g_1(D) = 1 + D^2 + D^5 \qquad (1)$$

$$g_2(D) = 1 + D^2 + D^3 + D^4 + D^5 \qquad (2)$$

The LFSRs' connections are shown in Fig.7.

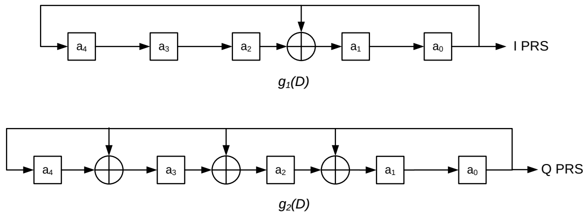

Figure 7: LFSRs to Implement the Preferred Pair of m-Sequences (Gold Code)

These two m-sequences PRSs have three valued cross-correlation spectrum (if the correlation is done with shifts by one chip period over the length of one pattern) and their values are given by[6]:

$$\text{cross-correlation} = \begin{cases} \frac{-1}{N}\,t(n) \\ \frac{-1}{N} \\ \frac{1}{N}[t(n) - 2] \end{cases} \qquad (1)$$

$$\text{, where } t(n) = \begin{cases} 1 + 2^{0.5(n+1)} & \text{for } n \text{ odd} \\ 1 + 2^{0.5(n+2)} & \text{for } n \text{ even} \end{cases}$$

where N is the sequence (pattern) length and n is the number of stages in the LFSRs. The three valued cross-correlation (with n = 5 and N = 31) are: -9/31, -1/31 and 7/31, noting that these values are normalized to the maximum value of the autocorrelation of each of these m-sequences which is equal to 31. It is to be noted that the cross-correlation spectrum will be five valued if the correlation is done with shifts by half chip and the two remaining values are in the middle between the center value and the two outer values, thus their values are: -9/31, -5/31, -1/31, 3/31 and 7/31.

Fig.8 shows the correlation spectrum of PRS code acquisition process. A locally generated coherent clock with the received PRS is generated in the synchronizer, thus the function of the acquisition and tracking of the PRS is accomplished.

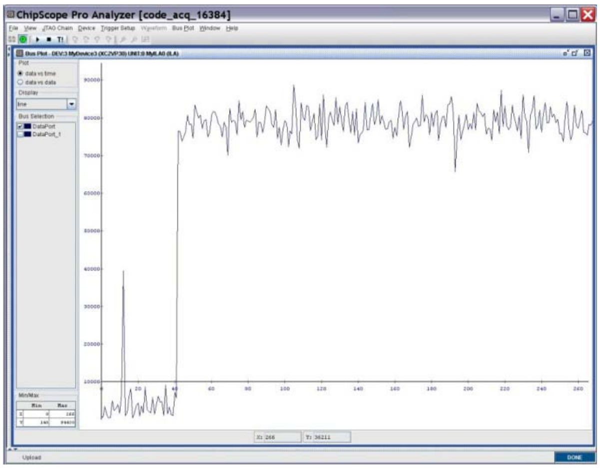

Figure 8: Correlation Spectrum of PRS Code Acquisition

RESULTS AND DISCUSSIONS

Measuring of Symbol Error Probability (SEP)

The errors in the extracted data in either I or the Q channels are equivalent to the SEP. Thus, to measure the SEP, the signs (i.e. zero level threshold) of the extracted chips are compared with those generated locally in the demodulator and the number of erroneous chips is counted. The numbers of compared chips is 10^9 (to account for small number of erroneous chips in case of high SNR) to obtain values for SEP almost equal to those determined theoretically. SEP curve is calculated using different values for E_b/N_o starting from -0.2 dB and ending with 9.8dB with 1dB step, Fig.9. It is to be noted that there is less than 0.3dB difference between the theoretical and the implemented curves for SEP and it is due to implementation loss[7]. It is to be noted that the calculated values for E_b/N_o may be larger by +0.2dB than the value calculated here (due to the different ways in which noise is measured), thus there will be at most 0.5dB difference between the theoretical and the implemented curves for SEP.

Fig.9 shows a good BER performance of the coherent type II MSK DS-SS modem. The stated large chip volume to be tested would not be needed for low SNR links because the error count is large (e.g. for 0dB SNR the BER $\approx 3\times10^{-2}$). The BER for baseband data (rather than for PRS) can be calculated by adding 10 Log(PG) to SNR for the PRS (i.e. dispreading process). Calibration to BER/SNR curve should be done to obtain a reference when verification is required or during self test.

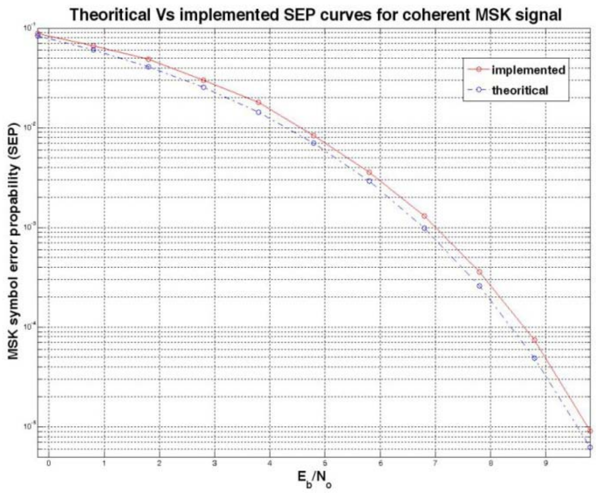

Figure 9: SEP for the Implemented Coherent Type II MSK DS-SS Demodulator

The telemetry information about BER and SNR should be sent just before the end of the communication session with a proper time margin to allow safe acknowledgment. As a redundancy (i.e. due to that fact that the worst instantaneous SNR exist at the start and the end of the communication session), this information could also be stored and sent at the mid of the next session (i.e. nearest geometry distance between space and ground segments, thus the highest SNR unless special radiation pattern is used onboard space segment).

It is to be noted that the added complexity due to BER and SNR measurement is negligible compared to the digitally implemented coherent type II MSK DS-SS modem.

The author suggests including BER and SNR measurements as a telemetry data in CCSDS recommendations and reports.

Acknowledgments

The author wishes to express his deep thanks to Prof. Dr Ayman El-Dessouky, Chairman, and Prof. Dr Salwa Elramly, Telecommunications Group Leader, for their valuable support at NARSS.

References

1. Consultative Committee for Space Data Systems, Telecommand: Summary of Concept and Rationale, CCSDS Secretary, Washington, January 1987.

2. Consultative Committee for Space Data Systems, Telemetry: Summary of Concept and Rationale, CCSDS Secretary, Washington, January 1987.

3. Consultative Committee for Space Data Systems, Radio Metric and Orbit Data, CCSDS Secretary, Washington, January 1987.

4. Maghawry, A. and E. Eldiwany, "FPGA-Based MSK DS-SS Modulator for Digital Satellite Communications," 23rd Annual AIAA/USU Conference on Small Satellites, SSC09-VI-11, August 2009.

5. Smith, J. R., Modern Communication Circuits, McGraw-Hill, 1998.

6. Peterson, R. L. et al., Spread Spectrum Communications, Prentice Hall, 1995.

7. Meyr, H. et al, Digital Communication Receivers: Synchronization, Channel Estimation, and Signal Processing, Volume 2, John Wiley & Sons, 1998.