A Novel Synchronization Algorithm for Hybrid Inter-Satellite Link Establishment

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Abstract—**This paper presents a new synchronization algorithm proposed to establish an inter-satellite link in a system with two satellites flying in tandem. The complete system is described, including both the master and the companion satellite. The proposed physical layer is a customization of the one from Long Term Evolution (LTE) telecommunications systems, based on the Orthogonal Frequency Division Multiplexing (OFDM) technology with Time Division Duplexing (TDD) approach. The proposed synchronization algorithm uses two preamble-symbols per radio frame. Simulation results for different frequency deviations are provided.**

Keywords-synchronization; OFDM; preamble; frequency offset; inter-satellite link.

I. INTRODUCTION

When it comes to data relay satellites or constellation and formation flying missions, the Inter-Satellite Link (ISL) is a topic that has been intensively discussed [1]. The ISL is needed not only to support the communication function, but also to enable the formation acquisition and formation control through precise relative positioning using inter-satellite metrology consisting in ranging and Line of Sight (LoS) determination. Having to fulfill the complex requirements of both the selected communication system and the navigation module, the ISL is the key in finding the tradeoff between ensuring the data bandwidth and the data transfer quality on the communication path, and providing the accurate measurements and inputs for the navigation algorithms.

The Hybrid Inter-Satellite Link (H-ISL) is the new terminology used for a system which shall be able to ensure relative navigation (range and LoS estimation) between two spacecraft flying in formation, and also data exchange using the communication link. Thus, the H-ISL system architecture involves two spacecraft, namely the master satellite and the companion satellite. Both the quality of the link, measured as Bit Error Rate (BER), and the accuracy of the Navigation (NAV) commends are highly dependent on the synchronization algorithm results in terms of frequency alignment (for the two clock references used on the two satellites) and time synchronization (the correct radio frame start shall be identified by the receiver). On the other hand, the total cost of the system, the power consumption and the physical dimensions are to be considered as well.

Synchronization techniques for Orthogonal Frequency Division Multiplexing (OFDM) waveforms are based on either received signal autocorrelation or cross-correlation of a training symbol with a local replica. The autocorrelation is robust to large carrier frequency offsets (CFO) and exploits some form of redundancy built in the transmitted signal, for example the cyclic prefix (CP) [2] or a training symbol with two identical halves [3]. The main disadvantage of autocorrelation is that timing synchronization is only coarse and a fine-timing estimation stage is also required. On the other hand, cross-correlation techniques [4] provide accurate timing, but are very sensitive to large CFO values. Thus, the common approach is to have a coarse estimation stage for timing and fractional CFO, followed by a fine estimation stage for timing and integer frequency offset (IFO). Based on this approach, a two-stage synchronization algorithm is presented in [5]. Synchronization for downlink (DL) Long Term Evolution (LTE) is proposed in [6]. Coarse timing and fractional CFO is estimated using the CP technique, then fine timing consists in identifying the specific synchronization signals and a frequency-domain estimation of the IFO. The residual offset is also tracked. The method developed in [7] exploits the properties of constant amplitude zero autocorrelation sequences to achieve synchronization. In [8] a cross-correlation based joint timing and frequency synchronization scheme based on Zadoff-Chu (ZC) sequences is presented. The technique also uses a two-stage approach and optimizes the ZC sequence parameter selection based on the shift of the cross-correlation peak to allow for coarse timing and CFO estimation.

In this context, a novel synchronization algorithm for H-ISL scenario has been proposed. It is based on the one used in the LTE communications systems, with customizations specific to spatial radio link. Our approach has the advantage of achieving fine timing synchronization without the need for a coarse stage and frequency-domain IFO estimation is not required.

The rest of this paper is organized as follows. Section II provides the system description, with both the digital part (including the 3 main modules MAC, PHY and NAV) and the analog part (RF daughter board plus additional analog circuits). Section III describes the proposed synchronization algorithm, highlighting the changes made compared with the one used in the LTE communication systems. Section IV provides the obtained results, exemplifying the time alignment and the frequency corrections generated by the algorithm in real-life conditions. The acknowledgement and conclusions close the article.

II. SYSTEM DESCRIPTION

A. *The hardware platform selection*

The NAV requirements in terms of information input and resolution set mainly the system architecture. The master satellite, the one on which the NAV algorithm runs, has 3 antennas, placed in a square triangle pattern, with the master antenna corresponding to the intersection of the catetes. This solution with 3 antennas allows the master satellite to compute the LoS, i.e., the vector from the companion spacecraft transmitter to the master spacecraft receiver. The navigation module takes into account measurements coming from the triplet of antennas. The 3 antennas create 2 perpendicular antenna baselines and provide path differences measurements on the two baselines. For navigation purposes H-ISL shall use two frequency bands, 100-200 MHz apart. The two frequencies allocated for navigation purposes are used as carrier frequencies for data communication as well.

In this context, the hardware platform selection is restricted by these constraints and requirements. Several solutions were studied, the final decision being based on a Xilinx ZCU102 board [9] for the digital part, called motherboard, and Analog Devices FMComms5 [10] for the RF part, named daughter board.

The digital part includes the Zynq UltraScale XCZU9EG [11] SoC, which contains a Quad-Core ARM Cortex A-53 for the Application Processor Unit (APU), a Dual-Core ARM Cortex R5 for the Real Time Processor Unit (RTPU), and a Xilinx's 16nm FinFET+ programmable logic fabric (specific to Xilinx 7 families).

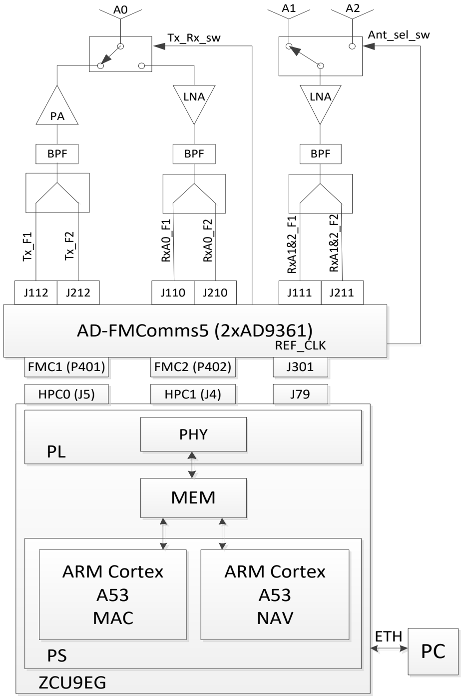

Figure 1. Block scheme of the master satellite.

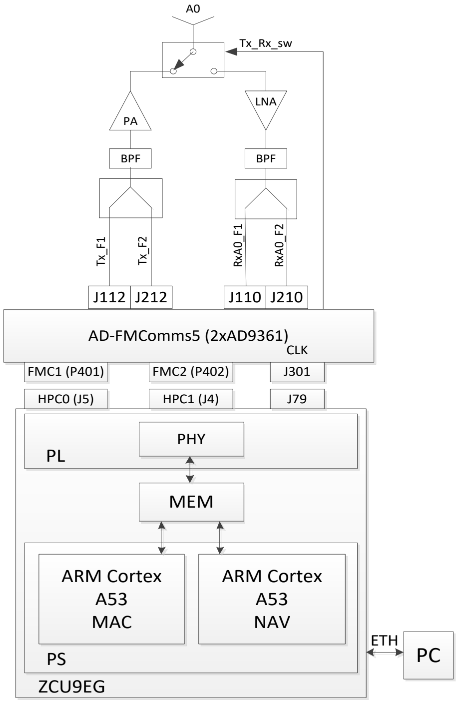

Figure 2. Block scheme of the companion satellite.

This internal structure allows the MAC and NAV modules to run on Processing System (PS), while the PHY is implemented on (Programmable Logic) PL side. The connections between PS and PL is made via AXI interfaces [12], using shared RAMs.

The RF part includes two AD9361 devices [13], each of them supporting 2 × 2 RF transceivers with integrated 12-bit DACs and ADCs.

The connection between the motherboard and the daughter board is made via two FPGA Mezzanine Cards (FMCs) connectors, as depicted in Figure 1 for the master satellite, respectively Figure 2 for the companion satellite. Additionally, in the two above-mentioned figures, one can observe also the extra analog circuitry needed to support the co-existing of the two used frequencies and the duplexing technique.

B. *The PHY parameters*

In order to clearly describe the proposed synchronization algorithm, the PHY parameters should be first presented. The starting point for their values selection was the LTE standard. We consider a TDD duplexing, with radio frames of 10 ms, the DL and uplink (UL) parts being balanced 1:1. The OFDM technology is used, with 1024 sub-carriers spaced at 15 kHz for a channel of 10 MHz.

Normal CP of 72 samples is added to each OFDM symbol of 1024 samples. The resulted sampling frequency is 15.36 MHz. The maximum throughput computation can be done having in mind that the two OFDM symbols on each DL/UL sub-frame are allocated to the preambles used by the synchronization algorithm. The 1096 samples-long OFDM

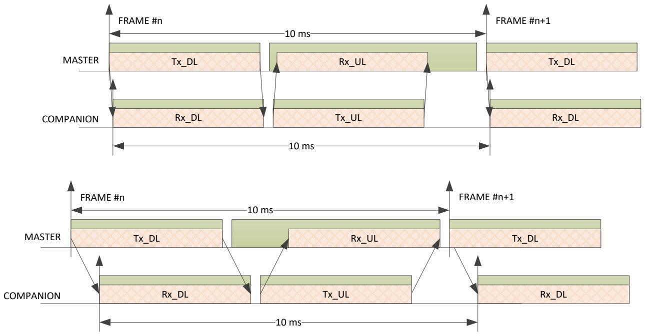

Figure 3. Frame structure for a) short distance between the satelites b) long distance between the satelites

symbol (including the CP) lasts 71.3 us at the indicated sampling frequency, this leading to a targeted number of 64 OFDM symbols per DL/UL. In conclusion, excluding the two symbols for synchronization, a maximum DL/UL throughput of around 2 Mbps can be achieved when BPSK modulation is used, with a channel coding rate of 1/3. The rest of a radio frame is split between the Transmit Time Gap (TTG) and the Receive Time Gap (RTG). Figure 3 depicts the timing expected when the two limit scenarios are considered, i.e, the two satellites being very close to each other, respectively very far.

III. PROPOSED SYNCHRONIZATION ALGORITHM

The first step in establishing the ISL consists in time and frequency synchronization at the companion satellite. Time synchronization is necessary in order to ensure that the receiver window encompasses the entire DL sub-frame and to identify the boundaries of the received OFDM symbols. Frequency synchronization must be performed to eliminate the inter-carrier interference and to prevent loss of sub-carrier orthogonality.

In an Additive White Gaussian Noise (AWGN) channel, the baseband signal received by the companion can be expressed as [2]:

$$y[n]=x[n-n_0]e^{j2\pi n\frac{\Delta f_c}{F_s}}+w[n] \tag{1}$$

where $x[n]$ is the transmitted DL preamble symbol, n_0 is the timing offset in samples, Δf_c is the CFO, F_s is the sampling frequency and $w[n]$ is the AWGN. The training symbol is BPSK-modulated in frequency domain and is constructed as an extension of the Secondary Synchronization Signal (SSS) in LTE.

Firstly, the timing offset must be estimated so that the receiver window can be positioned correctly. To achieve this, the received signal is cross-correlated with a local, time-synchronized replica of the training symbol:

$$R[m]=\sum_{n=0}^{N-1}x^*[n]y[m+n] \tag{2}$$

where N is the Fast Fourier Transform (FFT). The timing offset can by finding the peak of $|R[m]|$:

$$n_0=\arg\max\{|R[m]|\} \tag{3}$$

In practical systems, $R[m]$ is normalized with a factor that depends on the energy of the received signal. Although the cross-correlation provides very accurate timing, it is very sensitive to CFO. For CFO values that are close to or exceed the sub-carrier spacing (15 kHz for LTE signals), the cross-correlation peak can no longer be identified.

In order to overcome this effect, our novel approach consists in performing the cross-correlation between $y[n]$ and a set of training symbols that incorporate certain CFO values untill the cross-correlation peak exceeds a preset threshold. More specifically, at the companion we store seven versions of the training symbol with the following CFOs: 0, ±5, ±10 and ±15 kHz. Moreover, in order to allow for faster computation, the received signal is split into batches of equal length and the cross-correlation theorem is exploited: the spectrum of the batch is multiplied with the spectrum of the complex-conjugated training symbol on a point-to-point basis and then the inverse FFT (IFFT) is computed to obtain the time-domain values.

Our approach ensures fine timing sychronization and allows for joint coarse CFO estimation. The coarse CFO is used to adjust the reference frequency source of the companion satellite. Since there are actually two training symbols in the preamble, the cross-correlation will yield two peaks at n_0 and n_1.

Once timing synchronization has been achieved and the reference frequency has been coarsely adjusted, the remaining, uncorrected frequency offset is estimated using the redundancy of the two training symbols. Let Δf_c^r be the uncorrected offset. The received training symbols in the preamble can be expressed as:

$$y_l[n]=x[n]e^{j2\pi\frac{\Delta f_c^r}{F_s}[n+(l-1)(N+N_{cp})]}+w_l[n] \tag{4}$$

where $l=1,2$ is the symbol index and N_{cp} is the CP length. Δf_c^r can be estimated as follows:

$$\Delta f_c^r=\frac{F_s}{2\pi(N+N_{cp})}angle\left\{\sum_{n=0}^{N-1}y_1^*[n]y_2[n]\right\} \tag{5}$$

Considering the approach presented above, the synchronization steps are detailed in the following paragraphs.

Since the DL preamble is transmitted every radio frame, at the companion 10 ms worth of samples must be processed. This amounts to 153600 samples. The received samples are split into batches of equal length with a 50%

overlap between adjacent batches. The data is processed as follows:

Step 1*: Set the training symbol CFO index i=0 (corresponding to a training symbol with 0 CFO).*

Step 2*: The energy of each batch is computed. Store the minimum energy value (corresponding to noise) in* $b_{\min}$ *and the maximum energy value (corresponding to noise+useful signal) in* $b_{\max}$*. If the ratio* $b_{\max}/b_{\min}>1.5$*, then the preamble is located in the set of the 153600 samples. Proceed to step 3.*

If the energy threshold is not met, the current radio frame is discarded. A new set of 153600 samples is recorded and step 2 is repeated.

Step 3*: Calculate the normalization factor as a weighted difference between* $b_{\max}$ *and* $b_{\min}$ *:*

$$L=\sqrt{\left(b_{\max}-b_{\min}\right)\cdot b_x} \tag{6}$$

where b_x *is the energy of the reference training symbol* $x[n]$*. L is designed such that after normalization, the amplitude of the cross-correlation peak varies only with the CFO.*

Step 4*:The cross-correlation between each batch and* $x_i[n]$ *is calculated (by applying the cross-correlation theorem).*

Step 5*: Find the peak value for each batch and apply the normalization L. If the normalized peak exceeds the fixed threshold* p_{xc}*, then store the peak index.*

Step 6*: If no peaks are identified, increment i and repeat the process starting with step 4. If two peaks have been identified, then adjust the receiver window with the following correction value* c_r *:*

$$c_r=round\left(\frac{n_0+n_1-N-3N_{cp}-2}{2}\right) \tag{7}$$

The correction c_r *is designed such that the receiver window converges towards correct positioning (* c_r *=0) over the course of a few iterations.*

Step 7*: Correct the coarse CFO depending on the current value of i. Proceed to step 8.*

Step 8*: Estimate the uncorrected CFO* Δf_c^r *with (5).*

By strategic selection of p_{xc} it can be ensured that:

- The peaks are always identified before exhausting the set of stored training symbols;
- No undesired peaks (not related to the training symbols) are obtained;
- Δf_c^r is limited to ± 5 kHz.

Once timing synchronization and coarse CFO correction has been achieved, then the values of c_r and i should be 0. Δf_c^r is estimated on every received preamble and the reference frequency is readjusted periodically.

Timing resynchronization is necessary due to oscillator drifts and variations in distance between the satellites or if the ISL is lost. In normal functioning conditions, since the reference frequency is adjusted periodically, only the distance variations would cause significant loss of timing. Considering an inter-satellite relative speed of 1 m/s, at the sampling rate of 15.36 MHz a timing error of one sample would occur approximately every 19.53 seconds. In order to compensate this effect, timing resynchronization is carried out once every 10 seconds or immediately after the radio link is interrupted.

IV. OBTAINED RESULTS

Our first set of results is focused on the effect that the proposed normalization coefficient L has on the amplitude of the cross-correlation peak. To this end, the CFO is set to 0 and the Signal to Noise Ratio (SNR) is varied from 0 to 30 dB. The results, plotted in Figure 4, illustrate that the normalized amplitude of the peak is relatively constant across a wide range of SNR values. Therefore, the use of a fixed threshold p_{xc} regardless of operating SNR is justified.

The second set of results is focused on the performances of the synchronization algorithm. The CFO is set to 18 kHz, the threshold p_{xc} is 0.8 and a delay of 1500 samples is added to the transmitted preamble. Table I shows the effect of adjusting the receiver window; over 3 iterations the correction value c_r converges towards 0 and timing synchronization is achieved.

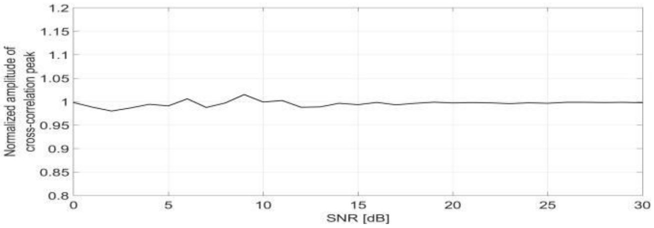

Figure 4. Variation of the normalized peak amplitude vs. SNR

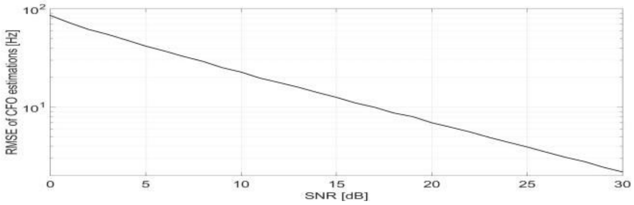

Figure 5. RMSE of CFO estimations vs. SNR in AWGN channel

TABLE I. ADJUSTING THE RECEIVER WINDOW

Iteration	1	2	3
c_r	1226	2394	0

Figure 5 shows the root-mean-square error (RMSE) of the CFO estimations against SNR in an AWGN channel. At 0 dB, the accuracy is approximately 84 Hz.

V. CONCLUSIONS

This paper presented a novel synchronization algorithm proposed to be used in an H-ISL system. The starting point is the model used in the LTE communication systems. The new preamble structure and its positioning in the DL sub-frame, correlated with the new proposed method of computation, provide good results in terms of timing alignment and frequency synchronization. The presented simulation results demonstrate the algorithm performance.

A real test-bench is under preparation and several real test-cases will be executed on the presented setup. The obtained results will be presented in future work.

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