Development of an opensource, openhardware, software-defined radio platform for two-way satellite time and frequency transfer

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***Abstract*—We describe an opensource, openhardware experimental Software-Defined Radio setup for prototyping various digital communication over microwave links with a geostationary satellite for assessing the impact of the various parameters on a Two-Way Satellite Time and Frequency Transfer link. Results consistent with the proprietary SATRE modem are demonstrated, including sub-ns resolution on ranging and two-way measurements. The emitted signal structure and impact of code length are assessed, and the signal acquisition and processing are described.**

***Index Terms*—SDR, TWSTFT**

I. Introduction

Two-Way Satellite Time and Frequency Transfer (TWSTFT) is currently used for the computation of the Coordinated Universal Time (UTC) by direct comparison between atomic clocks disseminated worldwide. The classical means of spectrum spreading by introducing a pseudo-random noise (PRN) binary sequence modulating, using binary phase shift keying (BPSK), of a carrier is used to transfer time information, with the PRN generator being clocked by the reference frequency and triggered by a one pulse per second (1-PPS) signal.

While the historical development of the TWSTFT modem, initially the academic project of MITREX then the SATRE instrument sold by TimeTech GmbH, goes back to the 1980s, hardly any published reference [1]–[3] justifies the selected PRN pattern and the technological limitations at the time that might have driven some of the scientific decision whose relevance to current computational power might be questionable.

With the advent of Software-Defined Radio (SDR) solution, as demonstrated for the computation of UTC in [4], prototyping various codes, code lengths, or modulation schemes has become a matter of reprogramming a Field Programmable Gate Array (FPGA) matrix of logic gates, while recording the raw IQ stream of received signal allows for prototyping multiple processing algorithms on a given dataset. This technology has become available for the development of a TWSTFT prototyping framework thanks to

1) large storage capacity despite the datarates involved with SDR: at a sampling rate of 5 MHz and two channels recorded as 16-bit integer complex values, a datarate of 2.4 Gbytes/minute is produced
2) large FPGA capacity on opensource and openhardware SDR platforms allowing to add PRN generation next to the data handling logic
3) efficient FPGA programming frameworks for efficient prototyping of novel modulation schemes and PRN sequences, in our case the Python-derived Amaranth framework.

In this abstract, we address the technical implementation of an SDR emitter complying with satellite service provider requirements, emitting the standard 70 MHz Intermediate Frequency (IF) signal feeding the upconverter of the Very Small Aperture Terminal (VSAT) transmitter (14 GHz) solely relying on an FPGA and output bandpass filter. We follow with the implementation of an SDR receiver relying on a dual channel radiofrequency frontend, either as Ettus Research B210 (at LNE-LTFB) with the AD9361 providing the local oscillator and variable gain amplifiers, or the Ettus Research X310 (at LNE-SYRTE). Finally, the signal processing steps for computing the relevant link indicators such as frequency translation offset of the downlink frequency introduced by the satellite transponder, Signal to Noise Ratio (SNR) and most relevant time delay in ranging and two-way transfer are discussed. We conclude with a link demonstration between LNE-SYRTE in Paris and LNE-LTFB in Besançon [5].

II. Emitter: coding scheme

The emitted signal is synthesized by an FPGA clocked by the metrological 10 MHz and 1-PPS references, the only means with discrete logic to meet the stringent requirements of aligning the PRN code with the reference frequency and time signals. The design is portable to any FPGA fitted with a PLL fast enough to define the 70 MHz IF carrier BPSK modulated: in the case of the Zynq processor fitted on the Zedboard or the Spartan6 and Kintex7 FPGA fitted on B210 and X310 respectively, a core clock of 280 MHz is selected as an integer multiplication of the reference 10 MHz readily divided to generate the 70 MHz IF and the four states of the QPSK modulation.

While SDR provides a generic and flexible radiofrequency interface, emission is plagued by spurious spectral components

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produced by the digital synthesis: here. the 70 MHz is produced as a square wave as a General Purpose Input/Output (GPIO) interface of the FPGA associated with numerous overtones and unwanted spectral components. Dedicated 70 MHz Surface Acoustic Wave (SAW) filters are selected as C-TECH 321823 or SAWTEK 851547 for keeping the signal within the 4-MHz wide currently allocated satellite transponder band and reject by over 50 dB out-of-band spectral components. The high losses of these filters does not impact the link budget since the digital GPIO voltages must be attenuated anyway to match the SATRE modem output power (typically -20 dBm range) feeding the VSAT upconverter.

III. Receiver: signal processing

On the receiver side, a single board or laptop computer fetches samples from a dual channel SDR receiver, with one channel acting as reference through a loopback link from the emitter and the second channel connected to the VSAT downconverter.

Unlike the closed Costas loop classically used for real time frequency tracking of the BPSK signal, in the context of SDR post-processing the identification of the frequency offset between nominal carrier frequency and received signal frequency is achieved by squaring to cancel BPSK spectrum spreading and identifying the spectral component at twice the frequency offset. A numerically controlled oscillator compensates for the frequency offset before correlating with the local copy of the code. A classical improvement on the time resolution of the correlation peak is brought by parabolic fitting, improving the delay resolution by a factor equal to the SNR on the correlation peak.

Under such considerations, the tradeoff lies between selecting a short PRN code leading to lower Pulse Compression Ratio (PCR) SNR improvement during the correlation but allowing for averaging multiple successive delay estimates, or a long code with fewer estimates for averaging but improved PCR. In order to avoid the ranging and two-way transfer uncertainty related to a short Pulse Repetition Interval (PRI) induced by a short code, a PRN length of at least the two-way trip of 270 ms is selected, and 1-s long code appears as best suited to avoid introducing additional coding schemes for determining the correlation peak associated with the 1-PPS of the beginning of the second.

IV. Results

Correlating the 2.5 Mchips-long PRN code sampled at 5 MS/s introduces artefacts as the satellite is moving at a rate of a few nanoseconds/s depending on the orbital parameters. For example at a rate of 3.2 ns/s and a sampling period of 200 ns, correlation peak position fluctuations of a few nanoseconds are observed every 62.5 s (Fig. 1), inducing unwanted excessive standard deviations on the measurements sessions lasting 180 s. This session duration is derived from the 8 GB broadband Random Access Memory (RAM) used for storing the datastream on the single board Raspberry Pi4 computer used in the current implementation.

This issue is solved by oversampling the received signal: since computing the correlation is most efficiently achieved by computing the Fourier transform of the code (pre-processing) and the received signal whose complex conjugate is multiplied with the former prior to inverse Fourier transform, efficient oversampling is implemented by zero-padding the Fourier transform product prior to the inverse Fourier transform. Such a procedure cancels the unwanted delay fluctuations and provides typical sub-ns standard deviation on the measured ranging or two-way delays over 3-min. sessions as determined by the available broadband storage resources (Fig. 2).

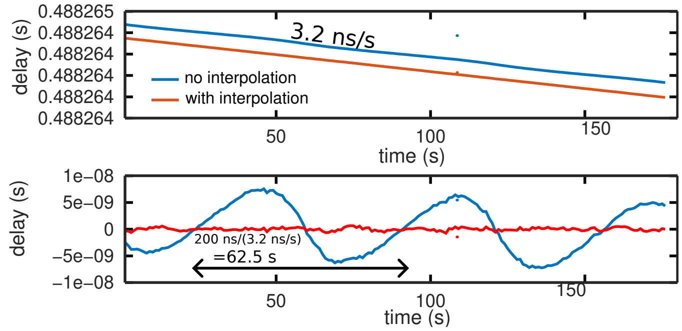

Fig. 1. Top: ranging delay over a 3-min. session, and bottom after removal of the parabolic trend. Top without oversampling (5 MS/s), bottom at 15 MS/s by interpolating using zero-padding prior to inverse Fourier transform when computing the correlation in the Fourier domain.

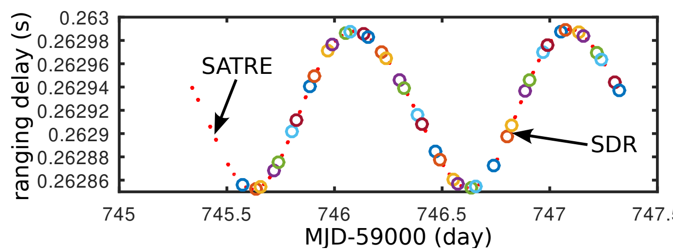

Fig. 2. Ranging measurement over 36 h using the SDR setup (circles) during odd UTC hours and the SATRE modem (dots) during the even UTC hours.

V. Conclusion

We have demonstrated a functional SDR-based TWSTFT framework for analyzing the various parameters of the digital communication. All software for reproducing the proposed setup is available at https://github.com/oscimp/amaranth_twstft

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