

Performance simulation of Power over Ethernet on spacecraft buses

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Abstract—This paper presents a waveform level simulation for 100Base-TX Ethernet for performance evaluation on spacecraft power buses. The article starts by explaining the motives behind using Ethernet technology on spacecrafts. Then, the functionality of 100Base-TX is explained. The main focus is the simulation environment which emulates the behaviour of the 100Base-TX signal and its performance analysis with different Signal-to-Noise ratios (SNR). A Spice environment was constructed to simulate Power over Ethernet topologies. The generated Ethernet signals were applied to the Spice model along with simulated DC-DC converter output. The resulting waveform is exported from the spice environment and analysed in MATLAB.

Keywords—Ethernet, 100Base-TX, waveform, simulation, Power Over Ethernet, PLC,

I. INTRODUCTION

Ethernet is a well-known and nowadays a highly preferred technology in the automotive and industrial market besides the commercial use. Recently the space industry also turned its attention towards this technology [1]. Ethernet standards offer different data speeds that can be used with sensors with different data rates. Additionally, by sharing top-layer protocols, software interfaces can be made more straightforward, and data communication interfaces can become more broadly applicable. Furthermore, it opens up the possibility for satellites and other spacecraft to communicate with one another using commercial off-the-shelf (COTS) components. Applications can include satellite constellations, space stations, and launch vehicles [2].

Different aspects of implementing Power Line Communication (PLC) on spacecrafts were assessed several times before. For example, the use of PLC can reduce the mass and volume of the spacecraft, and it can simplify the harness [3]. Furthermore, the feasibility of combining data and power on the same wires was examined [3] [4].

Ethernet, as was previously established, offers a variety of implementations with a range of possible data rates using a variety of signalling technologies. The most relevant set of Ethernet standards for potential spacecraft applications are 10Base-T (commercial 10 Mbps Ethernet), 100Base-TX (commercial 100 Mbps “fast” Ethernet), 100Base-T1 (automotive 100Mbps Ethernet) and 1000Base-T1 (automotive 1000Mbps Ethernet).

Future spacecrafts may use Ethernet as a reliable communication interface. However, signal integrity and electromagnetic interference may have an impact on its performance.

A reliable simulation environment can significantly benefit the design of Ethernet interfaces on spacecraft data

buses by allowing engineers to test and evaluate the performance of the system before it is built and deployed.

Engineers can simulate the behaviour of the Ethernet system under many situations and settings, including various data loads, network configurations, and electromagnetic interference. This enables them to find possible problems and alter the design before the system is created, ultimately saving time and resources.

In this paper, a hybrid numerical waveform level simulation technique will be presented, which can estimate expected performance in the means of Bit Error Rate (BER) in a spacecraft environment, taking the noise and different transmission mediums into account. The simulation uses the Monte Carlo method to generate, transmit and receive data and measure the bit error rate over a long data exchange period. First, random data bits are generated and conditioned according to the 100Base-TX standard, consisting of a 4B/5B encoder, scrambler, NRZI coding and MLT-3 converter [2]. After the digital line coding, the digital bits are resampled to transform the digital stream into sampled “analogue” signals. Then the signals are sent through a numerically modelled transmission medium using time domain convolution [3]. Noise can be added both before and after the transmission medium. BCI test simulation can also be performed [4]. On the receiver side, the original data stream is reconstructed. Finally, the received and actual bits are compared to detect faulty bits and calculate the bit error rate.

II. OVERVIEW OF 100BASE-TX TECHNOLOGY

In this chapter, an overview of 100Base-TX Ethernet will be presented.

100Base-TX uses four unshielded (or sometimes shielded) twisted wires for full duplex communication with a 100 Mbps data rate. One pair of wires is sufficient to assess the communication performance.

Figure 1 shows the theoretical block diagram of a 100Base-TX transmitter, officially called an Active Output Interface (AOI). In this communication protocol, the clock is not transmitted. Instead, the receiver must recover the clock from the received signal. To ensure that clock recovery is always possible, a minimum number of signal edges must be guaranteed. The 4B5B encoder serves this function by ensuring enough edges in the signal. It is done by converting every 4-bit nibble into a 5-bit word. The 5-bit words provide more different bit patterns than just 4-bit words. Therefore, this coding scheme guarantees at least two signal edges per 5-bit word [5].

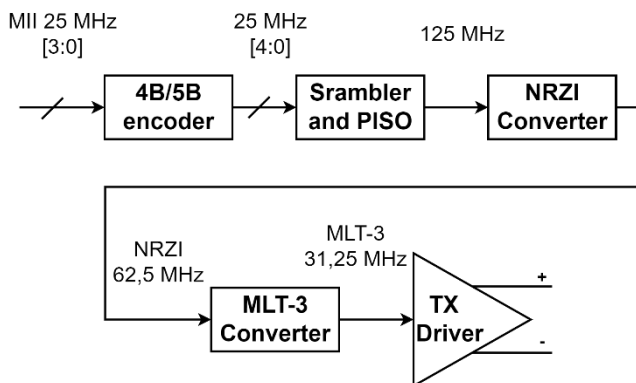


Fig. 1. 100Base-TX PHY transmitter block diagram

To reduce radiated emissions on the unshielded twisted pair (UTP) cable, 100Base-TX requires scrambling. Scrambling and descrambling are implemented with linear-feedback shift registers (LFSR) [5].

Moreover, 100Base-TX uses Multilevel Threshold-3 (MLT3) signalling to transmit data. Three values (+1, 0, -1) are possible to code the signal. Logical ones are represented by a signal edge (Fig. 2). The benefit of the MLT3 transmission is that it reduces the effective bandwidth from 125 MHz to 31.25 MHz.

The TX Driver is a waveform generator whose implementation varies between different PHY manufacturers. The purpose of this circuit is to shape the transmit output pulse. The waveform generator consists of an array of switched current sources to control the shape of the twisted-pair output signal. The reason behind this is to avoid sharp edges when the signal changes. It is achieved by controlling the rise and fall time of the output [6]. The rise and fall times are defined in the ANSI X3.263 standard. The required rise- and the fall time is 4 ± 1 ns.

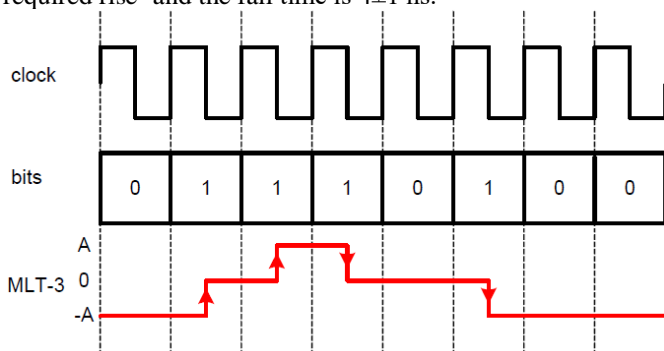


Fig. 2. MLT-3 coding [5]

The receiver, officially called Active Input Interface (AII) side, consists of the same building blocks in reversed order in addition to circuitry, which compensates for the effects of magnetics and long cables. Three additional functions are implemented by the receiver. First, clock information is recovered with the use of a Phased Locked Loop (PLL) or Delay Locked Loop (DLL). The cable, together with the magnetics, define the low frequency response of the channel, which has a high pass characteristic. DC information that the signal carries will be removed by the channel. This effect is called baseline wander, which is compensated by the AII. The receiver uses an adaptive equaliser and baseline wander removal circuitry. The signal is distorted and attenuated by the cable. To mitigate this effect, the transfer function of the

cable is measured by the receiver, and the adaptive filter implements the inverse function of the cable on the signal. The distortion and the attenuation are the functions of the cable length. Thus, the receiver must accurately determine the cable length to avoid over- or under-equalization [7].

III. CONSTRUCTION OF THE SIMULATION ENVIRONMENT

For the simulations, the main goal was to be able to predict the bit-error-rate.

The simulation environment was created by the combination of MATLAB and LTspice. First, the analogue 100Base-TX waveform is produced by a MATLAB script, and the transformer and transmission line model, along with the additive noise, is simulated with LTspice. Then, to create a fully automated simulation, the LTspice model is saved as a netlist file which can be executed in the background through LTspice launched from the command line. The inputs and outputs of the models are defined through spice directives. The MATLAB script runs this command during the simulation at each iteration. After the simulation, the resulting values are loaded into MATLAB again for decoding the signals. Finally, the resulting bitstream is compared with the initial bitstream to calculate the BER. The flowchart of the whole process can be seen on Fig. 3.

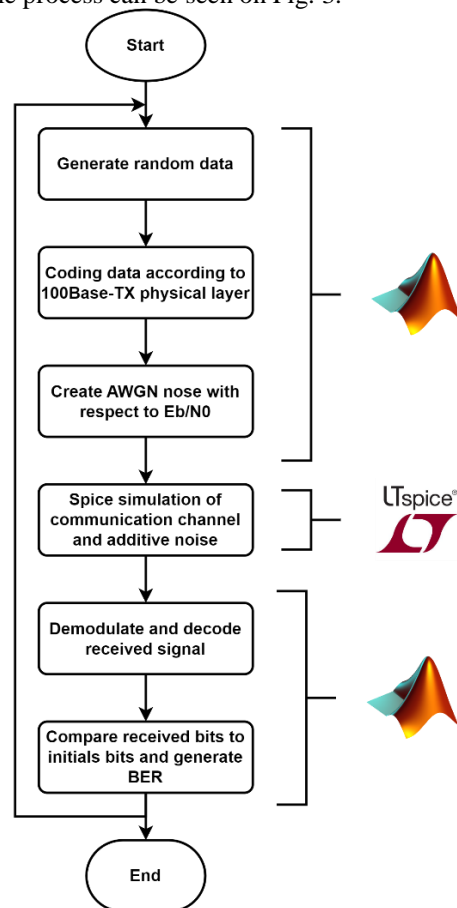


Fig. 3. Flowchart of the whole simulation process

At the beginning, the script creates a random bitstream. The data is then encoded according to the structure of the 100Base-TX transmitter that was mentioned in the previous chapter. Before the MLT-3 conversion, the bitstream is resampled to simulate the analogue behaviour to a NRZ format which is then converted to the standard 100Base-TX

MLT-3 ternary waveform. I choose to represent each data point on 32 samples. A higher sample rate gives more accurate simulations but, with increased computational and memory costs. As it would still need a huge amount of RAM to simulate hundreds of millions of bits in one step, the program simulates a limited number of bits in multiple cycles. Finally, an additional gaussian filter is added to smoothen the edges and to meet the 4 ns rise and fall time requirements. The resulting signal can be seen on figure 4.

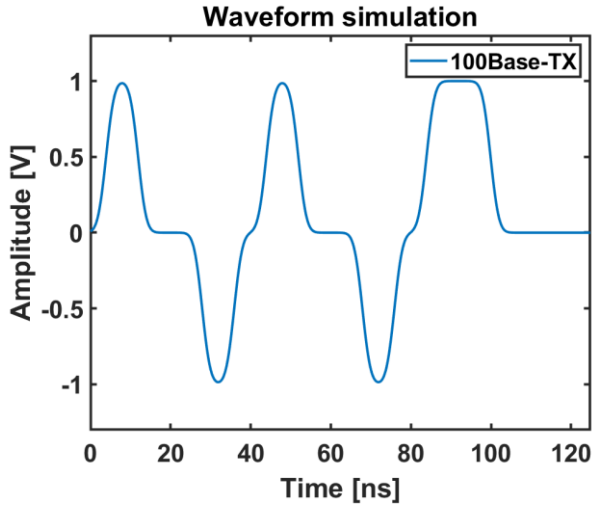


Fig. 4. Simulated 100Base-TX signals.

The simulation is carried out at different E_b/N_0 values. These values are -2dB, 4dB, 8dB, 12dB, 16dB, 20dB and 24dB. To calculate the noise variance for each SNR value the E_b has to be determined first. It can be done with the following equation:

$$E_b = \frac{1}{N \cdot f_{bit}} \sum_{n=1}^N x^2(n) \quad (1)$$

where N is the total number of samples of the signal, and f_{bit} is the bitrate in bits-per-second [8]. With this N_0 can be easily calculated by dividing the E_b by the E_b/N_0 value. Lastly from N_0 the variance σ_n of the noise can be calculated:

$$\sigma_n = \frac{N_0 \cdot f_s}{2} \quad (2)$$

where f_s is the sampling frequency of the signal [8].

To accurately simulate the Ethernet transformers in LTSpice, the SPICE model of the transformers was acquired directly from the manufacturer. The MLT-3 waveform is loaded into the simulation model with the noise. The Ethernet signal is coupled to the primary side of the transformer and the noise is coupled to the centre tap of the secondary coil to simulate common mode noise coming from a power supply possibly a DC-DC converter.

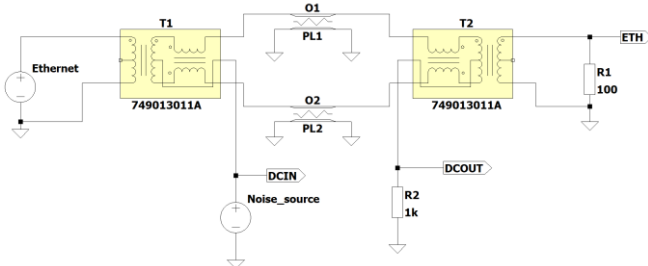


Fig. 5. LTSpice model of PoE channel

IV. RESULTS

The simulation was run with multiple E_b/N_0 values from -4 to 20 dB with a step size of 4 dB. On each level, 20 million bits were generated, coded, modulated, sent through the channel, and then demodulated to get a representative view of the BER. The received signal can be seen on Fig. 6

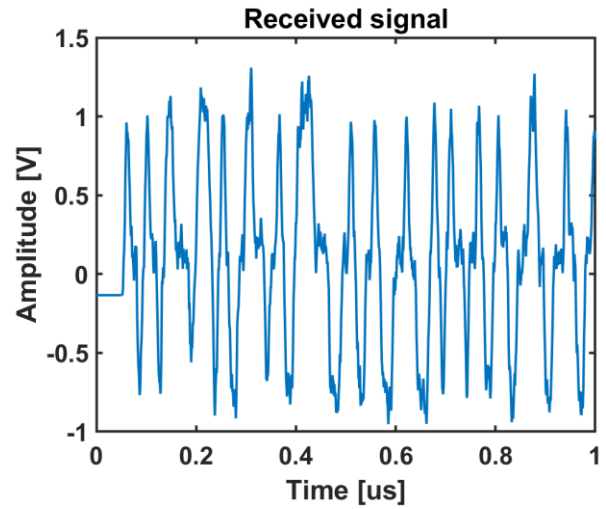


Fig. 6. Received waveform with low noise level

After demodulating and decoding the received signal. The received bits were compared with the original bitstream and the bit-error-rate was calculated and depicted as the function of SNR. This can be seen in Fig. 7. Both BER and SNR are in dB. Since the amplitude of the MLT-3 signal contains the information the protocol is very sensitive to noise compared to other frequencies of phase modulations.

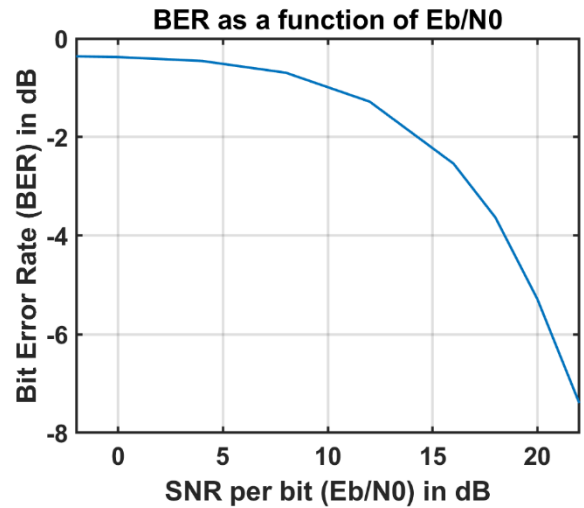


Fig. 7. Resulting BER as the function of the SNR

V. CONCLUSIONS

The created simulation environment can simulate the 100Base-TX signals through a standard twisted wire data connection cable used onboard a spacecraft alongside with the necessary magnetics. With the program, different spacecraft topologies can be simulated. As it was expected Ethernet cannot work properly in a noisy environment, thus it is crucial for PoE applications to ensure that the DC-DC converter does not couple significant noise to the data line of the spacecraft.

The next step is to modify the simulation environment to be able to add real noise measured from an actual DC-DC converter. Also at the current state, the simulation takes a lot of time. It would be beneficial to do the simulations with even greater bit numbers. In the future, the goal is to implement a more efficient simulation which can deal with a great number of bits transferred. To simulate even closer to the physical environment of a satellite a hardware in the loop approach is also considered.

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