Radiation Tolerant Stochastic Fourier-Transformation

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Abstract

When radiation affects electronic equipment, bit errors are caused on the digital level. It is likely to avoid such errors especially on most significant bits (MSB). Stochastic computation (SxC) utilizes bit streams with all bits having the same significance. The information is, e.g., stored in the probability of ones. Single bit flips have less impact compared, e.g., to fix-point representation. Additionally, multiple errors can cancel each other out and reduce the impact of radiation even further.

Using the example of a Fourier-Transformation, the reliability of the calculation for a fixed-point and a stochastic approach are compared.

I. Introduction

The significance of Fourier-Transformation is proved by its numerous applications. Its importance increased through the possibility of implementing it on hardware in the specialized form known as the Fast Fourier-Transform (FFT).

For space applications, radiation is one of the most significant factors to be taken into account, when reliability of electronic equipment is in the focus. Long term usage and large temperature differences are present for electronic devices in satellites as well. On circuit level for terrestrial applications the keyword summing up these effects is PVTA, which is the short form for process variations (P), supply voltage variations (V), temperature (T) and aging (A).

Regardless of the actual effect, bit-flips must be taken into account at the digital or algorithmic level. Within a fixed-point representation, such errors have of course the highest impact on the MSB. On the contrary stochastic computation use bit-streams and store the information in the frequency of logical 1's or the ratio of logical 1's to 0's. This way all bits have the identical significance and the outlined impacts are expected to have less severe effects on the reliable calculation of the exemplarily chosen Fourier transform.

In the following section II both approaches are presented followed by details about the model of the simulation setup. Using that simulation environment the performance of the two setups is analyzed in section III. The spectrums are calculated for different parameter setups to represent different environmental conditions, e.g., caused through a mission duration or profile. In section IV further details about an implementation approach for the SxC setup are given according to the complexity and necessary logical modules. Finally, this work is concluded in section V.

II. Simulation Model

Two setups are compared with each other. On the one hand a double precision scaled fix-point FFT and on the other a stochastic DFT using the two-line bipolar representation. The results of both setups are referred to the MATLAB built-in *fft()* function.

The basics of stochastic computation have been published in [1], among others. Using an unipolar encoding, values in the range of *[0,1]* can be represented. The probability of ones within the overall stream length corresponds to the information. By linking the ratio of 1's and 0's to the overall length a bipolar encoding is set up, extending the representable range to *[-1,1]*. Assuming uncorrelated streams, simple mathematical operations can be performed by logical gates. E.g., a real multiplication is achieved by an AND gate. If the square is needed one stream needs to be delayed to avoid the correlation. For each addition, OR gates are used next to further modules to take care about the overflows, e.g., by scaling. Further details are given in [5]. Nevertheless, the SxC approach offers high system clocks, much parallelism options and, as will be shown in the next section, high reliability without using expensive rad-Hard components.

[2] and [3] showed approaches of a stochastic FFT and DFT introducing an unscaled adder and a stochastic representation using a sign- and magnitude stream. In contrast to those first publications on stochastic DFT/FFT, another encoding form is used here: The two line bipolar representation, which separates between real and imaginary part and for each between the positive and the negative part. The total of 4 streams are portrayed with 1024 bits each. It should be mentioned, that the type of representation as well the usage of a bipolar or unipolar encoding on the one hand defines the range of representable values, and on the other it has a distinct influence on the later on discussed performance. The way how the arithmetic's needs to be implemented, the necessary or used amount of bits and of course the achievable precision of the representation. Implementing an algorithm like the FFT, temporal back-conversions to the decimal domain may be necessary.

The fixed-point (FI) representation is well known and documented. Within this work, the setup works with double precision and thereby utilizes 64 bits per real and imaginary part.

The overall system setup is shown in Figure 2: From an analog time signal, considering out of the superposition of four trigonometric functions, 64 samples are taken and converted to the digital domain using the shown ADC. The input signal is shown in Figure 1.

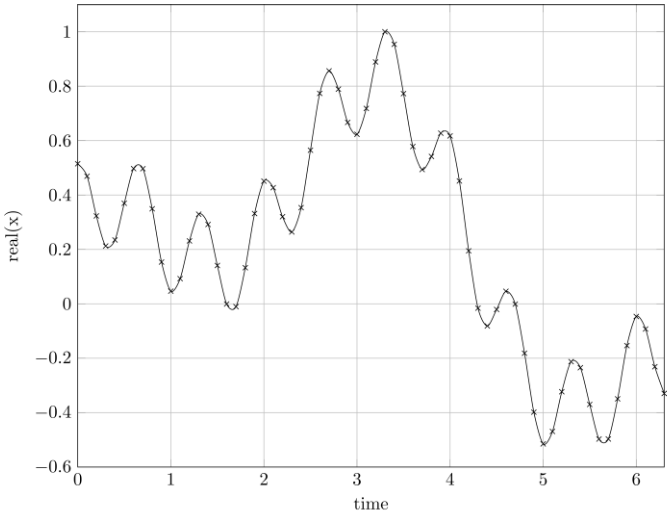

Figure 1: Input Signal

The PVTAR faults are applied to the digital samples of the input signal assumed to be stored within D-FlipFlops (FFs) in the shown N-bit buffer. The twiddle factors are assumed not to be affected.

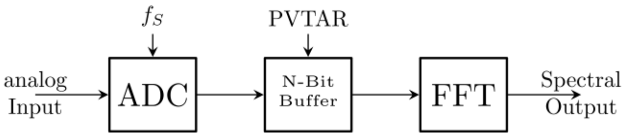

Figure 2: Simulation Setup

The error model, affecting the digital representation, is based on the analog circuit design. In detail, the PVTAR effects are simulated for each transistor in the D-FF circuit separately and summed up to model the FF in total. An error on bit level is injected, if the subsequent logical devices copy a false value compared to the FF input. The error model was published in [4].

III. Performance Analysis

As mentioned in section II the FI approach utilizes 64 bits twice, while the SxC system encodes each sample with four times 1024bits. In the first place, no PVTAR effects shall be present. The FI system is able to show its expected very high accuracy and precision (absolute error in order of 10^{-16}) in Figure 3, while the SxC setup is able to achieve an absolute error (compared to the built-in reference function) in the range of 10^{-3}, which is comparable to the inverse of the length of the bit-stream. Note that for each spectral sample the mean of 100 iterations is calculated. This holds for all following results.

However, both approaches offer very good spectral analysis. The first results match to the expectations, due to the binary representation techniques/encoding of the systems.

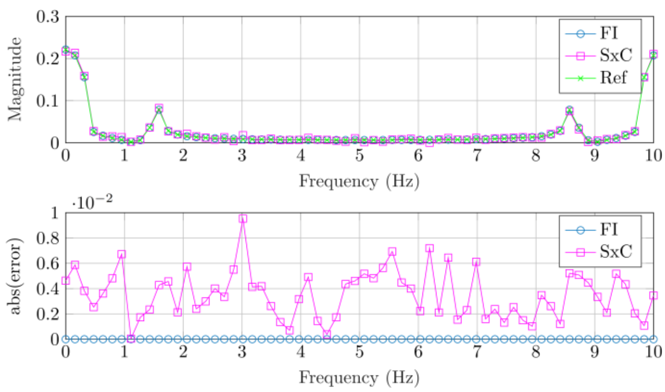

Figure 3: Performance without PVTAR

Next, both systems are analyzed in a more realistic scenario, considering to be used in space. The simulations parameters compromise process variations, a supply voltage of 0.8V, an operational temperature of 60°C, a Linear Energy Transfer (LET) of 500keV/µm and no aging/new devices. The spectrums are calculated according to the input signal given in Figure 1.

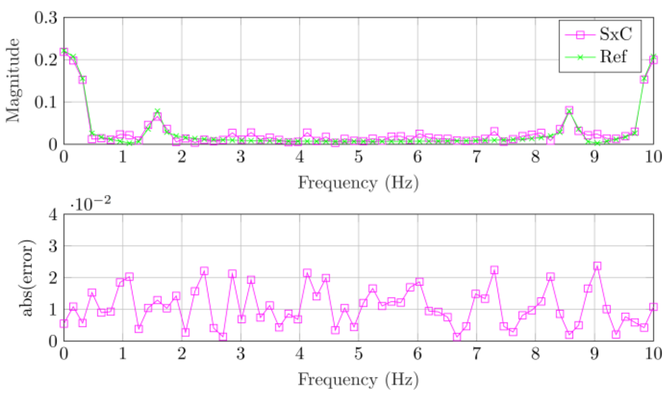

Figure 4: SxC spectrum with reference for P, V=0.8V, T=60°C, R=500keV/µm

In Figure 4, the calculated SxC spectrum is shown next to the reference of the MATLAB built-in function only. As the error for the FI setup increases from the first case (no PVTAR) to the order of ~10^{+300} the visualization is skipped in Figure 4. This means, that the FI approach is unusable within an exemplarily space mission. No reliable FFT can be calculated for the assumed parameter set. Additional radiation hardening techniques or certain devices are obviously necessary for a reliable FI processing. On the other hand, the SxC approach loses, due to the PVTAR impact, roughly one order of the magnitude considering the absolute error. However, a good approximation of the given reference spectrum is still achieved and visualized in Figure 4, even when no certain space qualified devices are assumed. These results motivate to take a closer look on the achievable performances with the SxC encoding type, as well to find a limit for the FI approach.

Figure 5 depicts the FI spectral results for two different cases. The parameters are set as follows: disabled process variations, a supply voltage of 0.9V, a temperature of 20°C and a LET of 150keV/µm (case 1) or 250keV/µm (case 2).

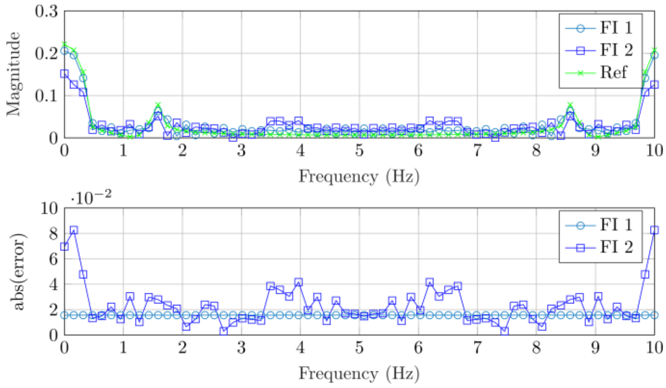

Figure 5: FI spectrums for P=0, V=0.9V, T=20°C, R=150 bzw. 250keV/µm

The moderate temperature and supply voltage enable the evaluation of the sensitivity of the FI approach for mainly radiation impacts. The mean of the absolute error is in the same order for almost both cases, but the precision for the low radiation case suffers from an offset. Therefore, the spectrum is still very accurate to the given reference. Increasing the LET (case 2) is it obvious, that the quality of the calculation decreases. According to the results visualized in Figure 4, it can be concluded that the FI setup has a limited usability with commercial of the shelf (COTS) components.

As the SxC approach already showed significantly more accurate results for higher PVTAR impacts (cmp. Figure 4), these two parameter sets are not to be considered for the SxC implementation. Instead, higher radiation is applied to figure out its upper limit. The simulation parameters are: P=on, V=0.9V, T=120°C, R=750keV/µm. The results are shown in Figure 6.

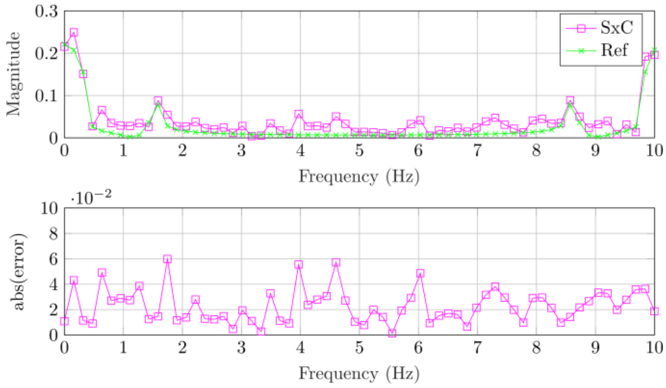

Figure 6: SxC spectrum for P=1, V=0.9V, T=120°C, R=750keV/µm

The mean of the absolute error is in the same order as the first case, discussed and presented next to Figure 4. Out of this, it becomes clear that even a LET of 750keV/µm achieves sufficient results in terms of accuracy and especially precision. However, for occasional uses the upper limit for radiation impact is even further extendable.

IV. SxC Complexity

A. Stochastic arithmetics

In section II, it was pointed out, that the SxC approach offers the usage of logical gates to perform simple arithmetic calculations. In detail, this depends on the representation type, meaning an exemplary multiplication can be performed by a single AND gate in a single line, unipolar representation type, using XNOR's for a bipolar single-line approach and several AND gates for the two line bipolar format.

For SxC-based additions, it needs to be ensured, that no overflow will occur. One possibility to avoid any result out of the limited range, is to introduce an additional scaling. In [2] an alternative approach is presented considering a sign and magnitude stream as well as additional counters.

B. Stochastic DFT

In order to perform the discrete Fourier Transformation (DFT), shown in Equation (1) a bipolar representation offering the in- and outputs with positive and negative signs is usually chosen.

$$X[n] = \sum_{k=0}^{N-1} x[k] \cdot e^{-j\frac{2\pi kn}{N}} \quad \textbf{(1)}$$

Out of equation (1) it becomes clear, that complex values must be handled. Hence, the stochastic representation separates between the real and the imaginary part. For the calculation of the algorithm this needs to be taken into account. The two-line bipolar representation finally uses in total four streams.

The processing of every DFT point, thereby requires 16N multiplications, each one performed by a logic AND gate. As the positive and the negative, as well as the imaginary and the real part, are considered separately the final addition requires a large multiplexer with 16N inputs and four outputs (one for each stream). The control signal of the multiplexer uses arbitrary binary numbers of $\log_2(4N)$ length. The entire scheme of the implemented DFT is given in Figure 7.

Alternatively, the DFT can be set up with scaling free adders (cmp. [2]). This would result in four streams as well (sign + magnitude for real and imaginary part), and a multiplication needs 4N AND's for the magnitude streams and 4N XOR's for the sign streams. Two further additions per multiplication and one N-point sum per real and imaginary part are necessary to complete one complex multiplication in that case. A high sensitivity against overflows is a huge drawback for this way of implementation. The two line bipolar approach, can be expected to give higher accuracy and was therefore the preferred choice.

C. IC-Implementation

A synthesis of the two-line bipolar approach was realized for 65nm CMOS technology using the Cadence Genus Synthesis tool for length from 16 to 256 points. For a 64 point implementation without pipelining, a frequency of 600MHz was achieved using an area of 364µm² and less than 55mW power consumption.

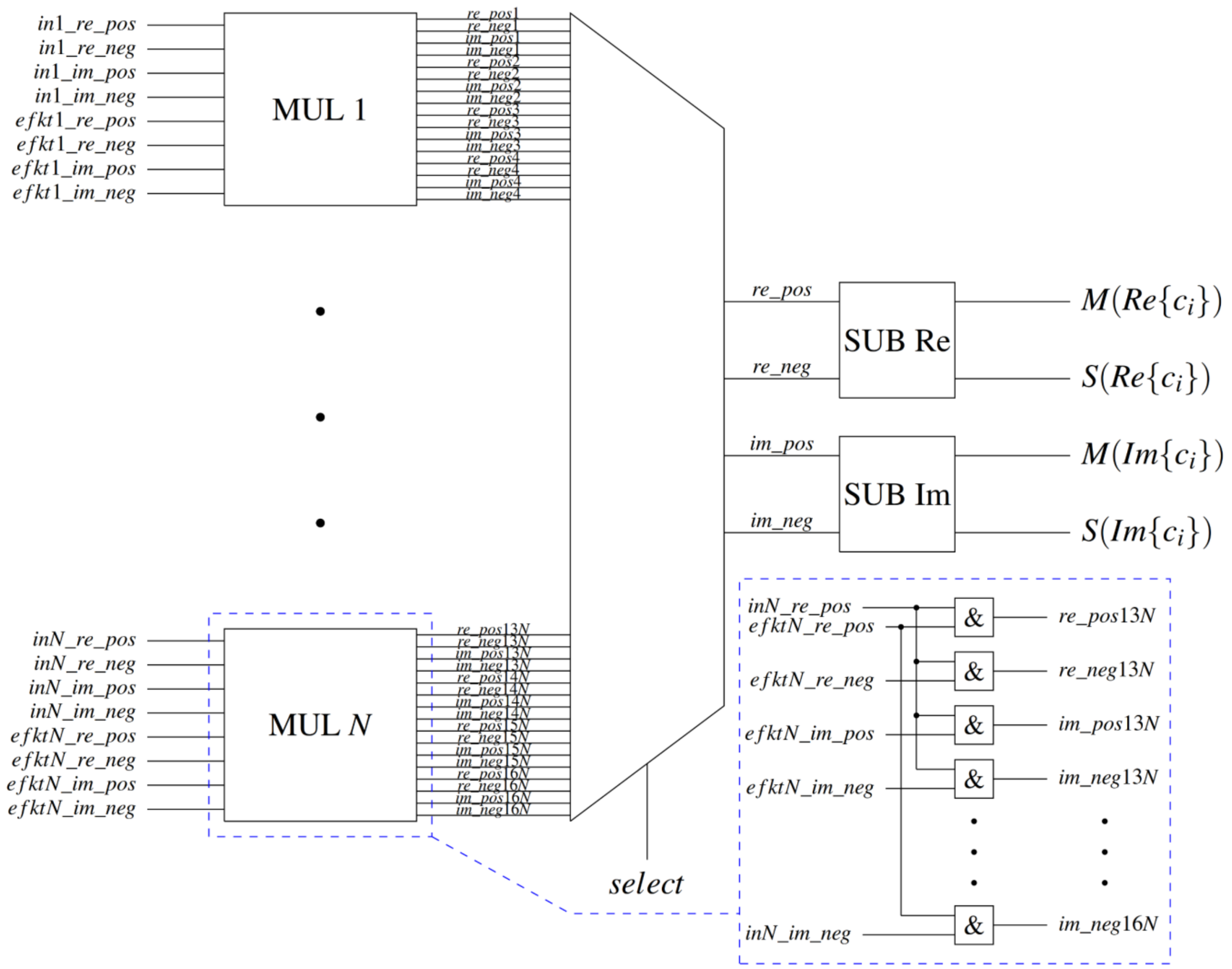

Figure 7: Schematic for two-line bipolar N point DFT, with scaling free adder used for the subtraction.

V. Conclusion

As it was stated in the ECSS-E-ST-10-12 document, “there is no space system in which radiation effects can be neglected.” The effect of radiation is one of the PVTAR effects modeled in this work to simulate its impacts on the digital level. Exemplarily, the well known and in numerous (space) applications used Fourier-Transform, it was shown, that the SxC encoding scheme outperforms the common FI approach according to the precision and accuracy in the presence of multiple bit errors.

The benefits of very high system clocks and parallel computing possibilities compensates more than the drawbacks stemming from the increased number of the overall used bits, or the remaining imprecision for ideal conditions.

All in all, it was discussed, that different stochastic encoding types have its own pros and cons, which needs to be taken into account for developing or adapting an algorithm. The two line bipolar setup emerges good for the presented DFT application but does not need to be the best choice in every case.

Furthermore, the precision of the SxC approach benefits from longer bit streams. Studies on this aspect were presented in [5].

VI. References

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