High Dynamic Range Multi-channel modulo ADCs for Synthetic Aperture Radar

Wenyi Yan, Lu Gan and Shaoqing Hu
Dept. of Electrical and Electronic Engineering
Brunel University, London, UK
wenyi.yan@brunel.ac.uk, lu.gan@bruenl.ac.uk and shaoqing.hu@brunel.ac.uk

***Abstract*—The accuracy of Synthetic Aperture Radar (SAR) imaging is a critical performance metric that can be significantly impacted by the limited dynamic range of Analog-to-Digital Converters (ADCs) used in the sampling of SAR raw data. The saturation effect caused by the threshold of conventional ADCs can lead to clipped SAR raw data and reduced image quality. This paper proposes a novel solution using multi-channel modulo ADCs to improve SAR imaging performance. The proposed system is designed to recover signals with a higher dynamic range than conventional ADCs, even in noisy environments. Simulation results demonstrate that the proposed system provides improved noise immunity and increased signal dynamic range compared to conventional ADCs.**

***Index Terms*—Analog-to-digital converters (ADCs), modulo samplers, Chinese remainder theorem, Synthetic Aperture Radar(SAR).**

I. Introduction

Synthetic Aperture Radar (SAR) is widely used for ground surveillance, earth observation, and other applications due to its high-resolution imaging capabilities in both range and azimuth directions [1–3]. The SAR system functions by transmitting pulses and collecting the coherent sum of back-scattered signals at the radar antenna [4]. However, the accuracy of SAR imaging can be severely impacted by the limited dynamic range of Analog-to-Digital Converters (ADCs) used in SAR raw data sampling. This limitation results in ADC saturation when the signal exceeds the ADCs threshold, leading to clipped SAR raw data. This issue reduces the accuracy of the resulting image and impacts the statistical characteristics of the SAR raw data.

Current approaches employed to tackle the dynamic range issue of ADCs in SAR systems include i) Establishing a statistical and theoretical model of the raw data to compensate for the lost signal [5] ii) Incorporating an Automatic Gain Control (AGC) module that can effectively regulate SAR raw data within the range of the ADC [6]. However, the signal compensation method has limitations in terms of radiometric accuracy, while adding an AGC module increases hardware costs. To address this issue, recent studies have proposed the use of modulo ADCs, which fold the input signal within the ADCs threshold and use a recovery algorithm to reconstruct the original signal from modulo samples, effectively increasing the dynamic range of the ADCs [7]. Single-channel modulo ADCs sampling systems often require a high sampling rate for reliable signal recovery, which can be challenging and expensive to implement [7, 8]. In contrast, multi-channel modulo ADCs sampling systems based on the Chinese Remainder Theorem (CRT) recovery algorithm can achieve accuracy under certain noise situations and require a lower sampling rate [9, 10]. Therefore, this paper proposes the application of a multi-channel modulo ADCs sampling system to address the dynamic range problem in SAR systems. The rest of this paper is organized as follows: Section II provides a brief introduction to the multi-channel modulo ADCs system, Section III presents simulation results on SAR imaging, and the paper concludes in Section IV.

II. Proposed system

A. Modulo Samples

Modulo ADCs fold the input signal to keep it within the ADC threshold, as different from traditional ADCs. For an input signal $x \in \mathbb{R}$ and modulo ADC threshold $\Delta > 0$, the modulo operation is defined as [7]:

$$\langle x \rangle_\Delta = x \ mod \ \Delta \triangleq x - \Delta \lceil \frac{x}{\Delta} \rfloor \in \left[-\frac{\Delta}{2}, \frac{\Delta}{2} \right), \qquad (1)$$

where $\lceil \cdot \rfloor$ is the rounding operation that returns the closest integer. Eq. (1) represents a centered modulo operation, which calculates the remainder of x divided by Δ.

B. Multi-channel Sampling system

Here, we consider the application of an L-channel modulo-ADC-based sampling system, where the threshold of the l-th modulo ADC is denoted by Δ_l with $\Delta_l \leq \Delta_{max}$. For a complex-valued SAR signal $g(t) = g_r(t) + jg_i(t)$, its real part $g_r(t)$ and the imaginary part $g_i(t)$ are processed separately and sampled at a rate of F_s each. The signal is reconstructed using a robust Chinese remainder theorem (CRT)-based algorithm developed in [10]. The proposed multi-channel sampling system effectively addresses the impact of noise due to the noise-resistance characteristic of the robust CRT, as demonstrated in Section III. After recovering the signal from modulo samples, the algorithm developed in [11, 12] is utilized to generate the SAR images.

III. Simulations

In this section, we present a comparison of the following sampling systems (a) traditional ADCs without saturation (raw data); (b) traditional systems with ADC clipping and

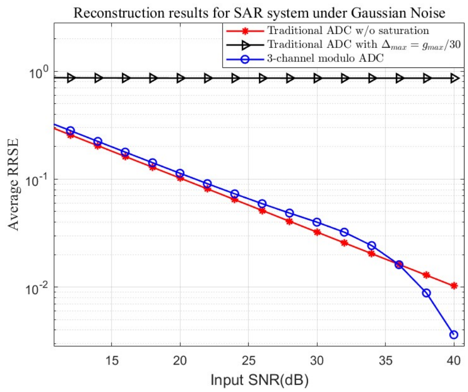

Fig. 1: Simulation results of different sampling systems for SAR imaging under Gaussian noise.

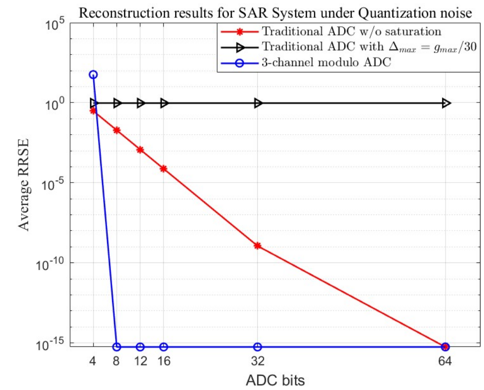

Fig. 2: Simulation results of different sampling systems for SAR imaging under quantization noise.

(c) the proposed multi-channel modulo ADCs for the SAR system, while considering the influence of Gaussian noise and quantization noise. The raw data used in this experiment has been sourced from [12], where each value is quantized with 64 bits and define g_{max} as $g_{max} = max\{\|g_r(t)\|_\infty, \|g_i(t)\|_\infty\}$. We assess the performance of a traditional clipping ADC with a threshold of $\Delta_{max} = g_{max}/30$ against a 3-channel modulo-ADC system with $\Delta_1 = 6.5\tau$, $\Delta_2 = 6\tau$, and $\Delta_3 = 5.5\tau$ with $\tau = g_{max}/195$. Notably, Δ_1 in the modulo-ADC system has the same Δ_{max} as the traditional ADC system.

A. Gaussian Noise

The simulation results in Figure 1 show the effect of adding Gaussian noise to the SAR sampling system. The input signal-to-noise ratio (SNR) varies from 10 dB to 40 dB with a step size of 2 dB. The root relative square error (RRSE) is used to measure the reconstruction error between SAR raw data and reconstruction values. One can observe that traditional ADC systems fail when g_{max} is much higher than the ADC threshold. In contrast, our proposed modulo ADC system offers comparable performance to that of the traditional ADC system when the ADC threshold is only about 1/30th of the traditional ADC. The simulation results confirm that the proposed multi-channel modulo ADC sampling system can enhance the dynamic range and thereby improve the radiometric accuracy of SAR images with limited ADC dynamic range.

B. Quantization Noise

Figure 2 shows the average RRSE results obtained from the SAR system using different numbers of ADC bits for each sample (in each channel), ranging from 4 to 64. Figure 3 displays the reconstructed SAR images. It is noteworthy that our proposed 3-channel modulo ADC system achieves faithful signal recovery with only 8 bits per sample per channel, resulting in a total of 24 bits per sample. Both the average RRSE and the visual quality are comparable to those of traditional ADC systems that use 32 bits per sample without any clipping. These findings demonstrate that multi-channel modulo ADC systems are memory-efficient, as they can achieve excellent performance with a much smaller ADC dynamic range and fewer bits per sample.

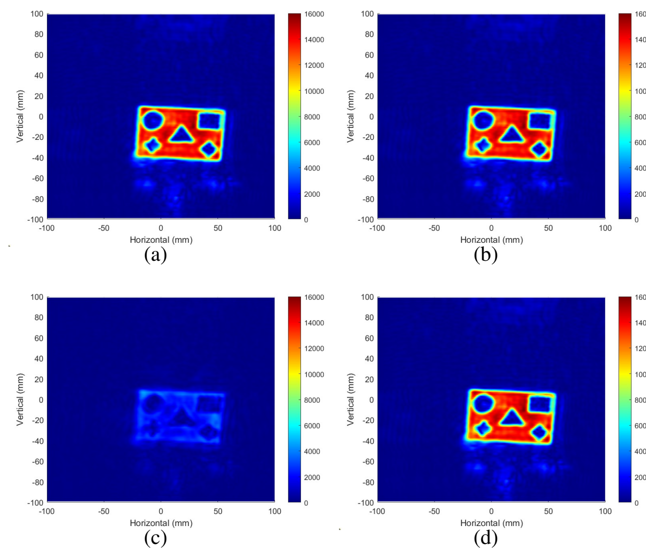

Fig. 3: Recovered SAR images: (a) Ground truth. (b) Results with 32-bits/sample of traditional ADC without saturation. (c) Results with 32-bits/sample of traditional ADC with $\Delta_{max} = g_{max}/30$. (d) Reconstruction results using a 3-channel sampling system with 24 bits/sample and $\Delta_{max} = g_{max}/30$.

IV. Conclusion

This paper proposes a multi-channel modulo ADCs sampling system for SAR imaging, which can increase the dynamic range of ADC and thus improve radiometric accuracy. The experimental results demonstrate that the proposed system exhibits noise resistance in Gaussian and quantization noise models. In the future, we plan to conduct practical hardware experiments and consider other noise models in the SAR system, e.g., multiplicative noises.

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