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Three-Phase Pulse Train Assisted Sampling for Wideband Signal Reconstruction: A MATLAB-Based Comparative Study

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Abstract: ***This study presents a MATLAB-based framework for wideband signal reconstruction using three pulse trains shifted by 120°. Random binary sequences are converted into pseudo-random binary sequences and interpolated to generate continuous wideband waveforms. Three phase-shifted pulse trains perform multi-branch sampling through peak detection, and the extracted samples are reconstructed and combined to estimate the original signal. The approach is evaluated for pulse density parameters N = 15, 90, and 150 using mean squared error, root mean squared error, maximum error, and correlation coefficient. The results demonstrate that increasing pulse density improves reconstruction fidelity, reduces average reconstruction error, and increases similarity with the original waveform to approximately 98.6%, confirming the effectiveness of the proposed multi-branch sampling architecture.***

Keywords: Wideband Signal Reconstruction; Multi-Branch Sampling; Pulse Train Sampling; Pseudo-Random Binary Sequence; Peak Detection; MATLAB Simulation; Signal Processing

1. Introduction

Wideband signal acquisition requires extremely high sampling rates according to the Nyquist criterion [1]. However, implementing high-speed analog-to-digital converters is often costly and challenging [2], [4]. Alternative architectures employing multiple sampling branches can increase effective sampling density without proportionally increasing hardware complexity.

In this work, a MATLAB-based simulation framework utilizing three pulse trains shifted by 120° is proposed for wideband signal reconstruction. Random binary sequences are converted into PRBS waveforms [3], [7] and sampled through three branches using peak detection. The effect of pulse density parameter N on reconstruction accuracy is investigated using quantitative performance metrics.

2. Methodology

The simulation workflow proceeds as follows: random bits are converted into a PRBS sequence to generate a continuous waveform. Three pulse trains shifted by 120° perform peak detection for sample extraction. Each branch is then reconstructed and recombined, followed by error analysis.

Table 1: Simulation Parameters

Parameters	Values
Bandwidth	5.2 GHz
Sampling Rate	10.8 GS/s
Pulse offset	120°
Pulse density parameter	N = 15, 90, 150
Enhancement	3x

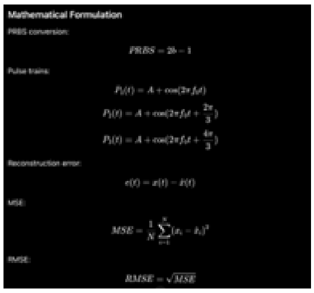

Figure 1: Random bit / PRBS generation

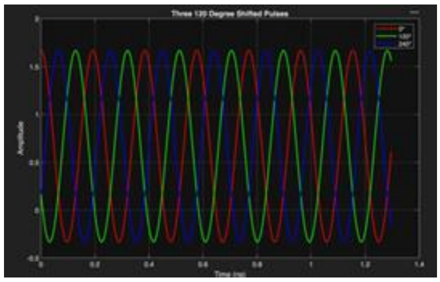

Figure 2: Continuous wideband waveform generation

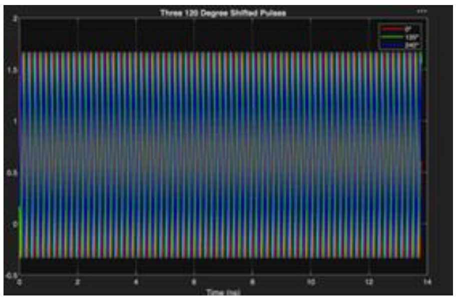

Figure 3: Three 120° phase-shifted pulse trains

2.1 Pulse Trains

Increasing the pulse density parameter N raises the frequency of the pulse trains. A larger N results in denser sampling opportunities and a greater number of extracted peaks across the waveform.

Results: N = 15

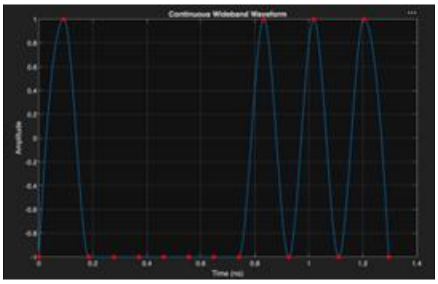

Figure 4: Wideband waveform (N = 15)

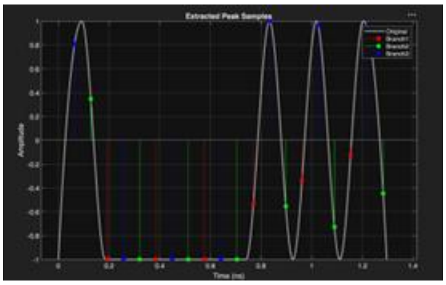

Figure 5: Extracted peaks (N = 15)

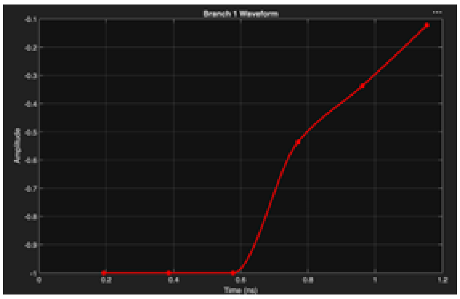

Figure 6: Branch sampling (N = 15)

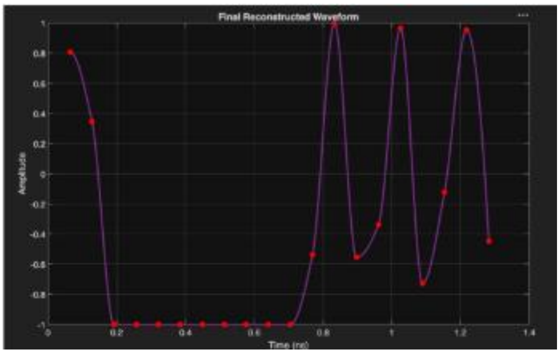

Figure 7: Branches 1–3 extracted samples (N = 15)

For N = 15, only a limited number of samples are obtained from the three branches. Consequently, interpolation artifacts are visible and the reconstructed waveform deviates noticeably from the original signal.

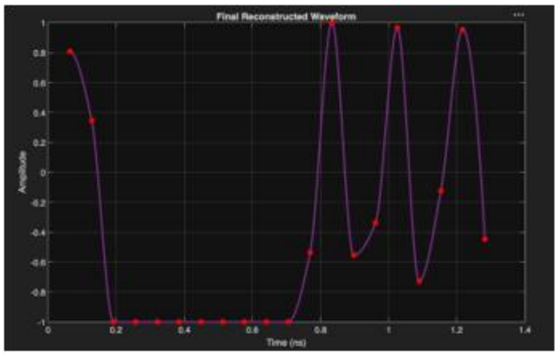

Figure 8: Reconstructed wave (N = 15)

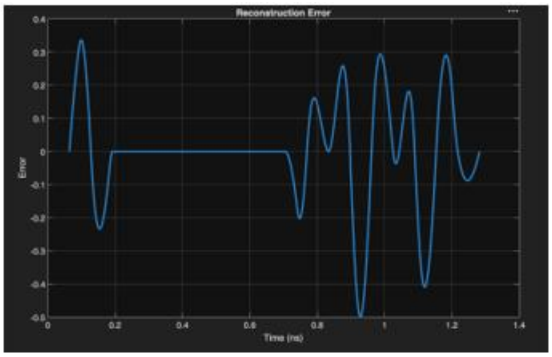

Figure 9: Reconstruction error (N = 15) Results: N = 90

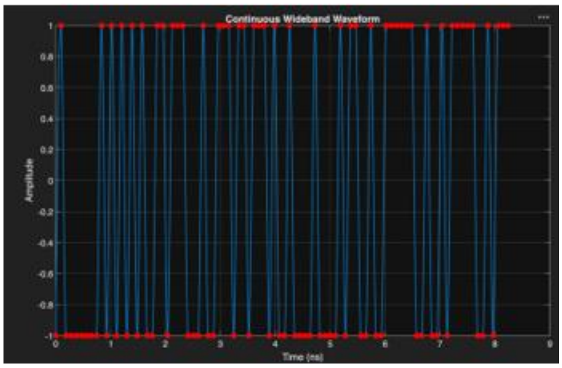

Figure 10: Wideband waveform (N = 90)

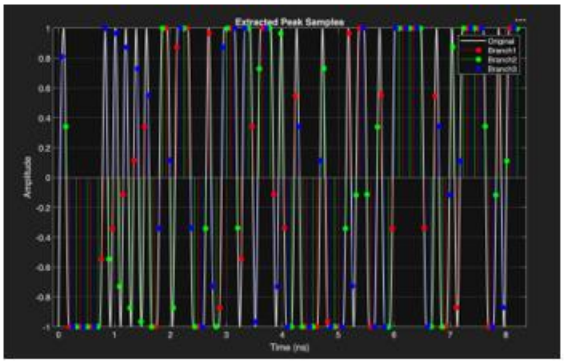

Figure 11: Extracted peaks (N = 90)

Increasing the pulse density to N = 90 improves sampling coverage across the waveform. The reconstructed signal captures the majority of waveform transitions, resulting in lower reconstruction error.

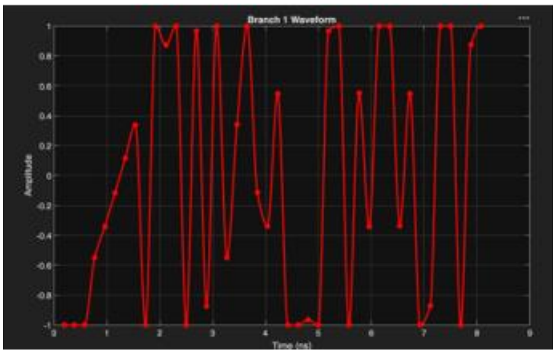

Figure 12: Branch 1 (N = 90)

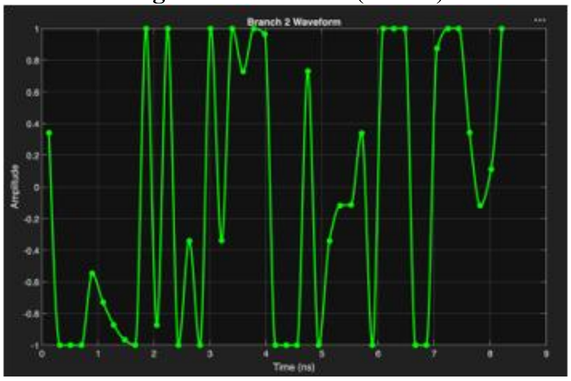

Figure 13: Branch 2 (N = 90)

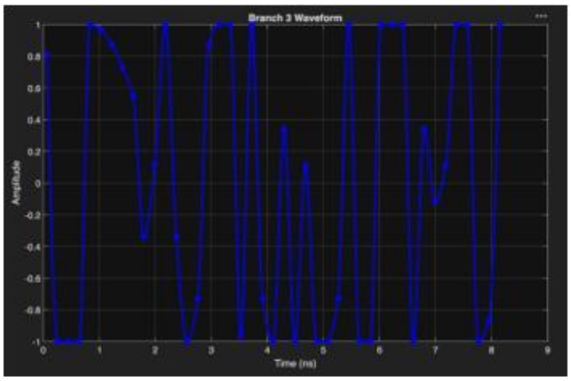

Figure 14: Branch 3 (N = 90)

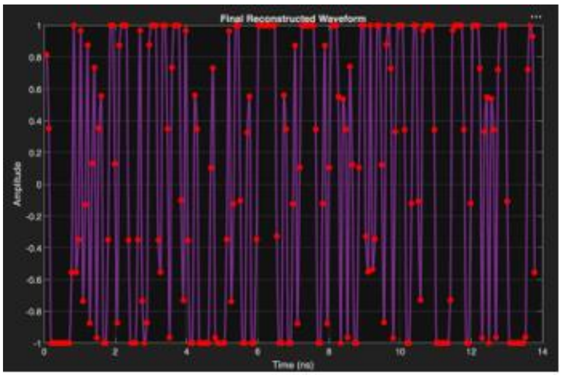

Figure 15: Reconstructed wave (N = 90)

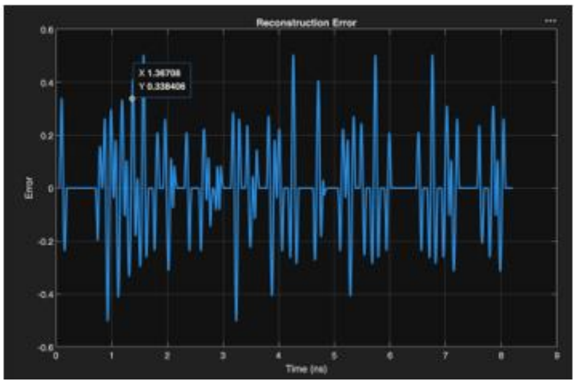

Figure 16: Reconstruction error (N = 90)

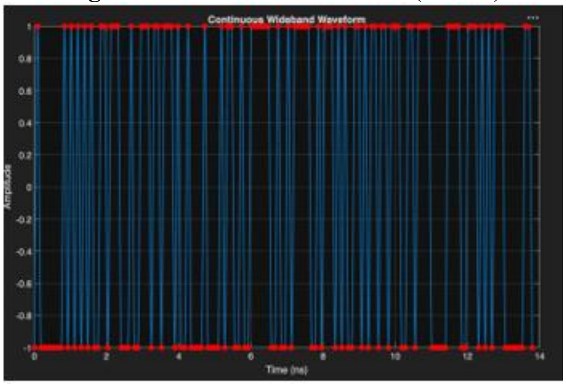

Figure 17: Combined reconstruction (N = 90)

Results: N = 150

For N = 150, dense pulse trains provide sufficient sampling opportunities throughout the signal duration. The reconstructed signal exhibits the closest agreement with the original signal among all investigated cases.

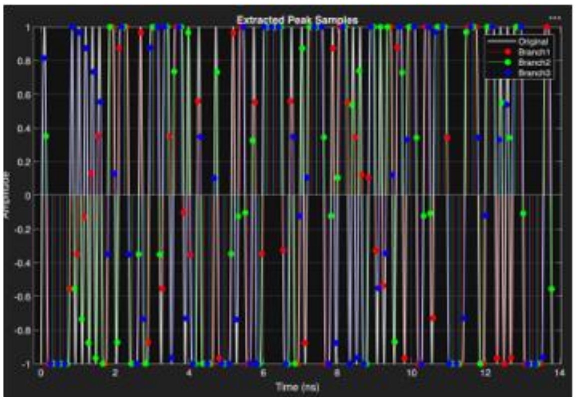

Figure 18: Wideband waveform (N = 150)

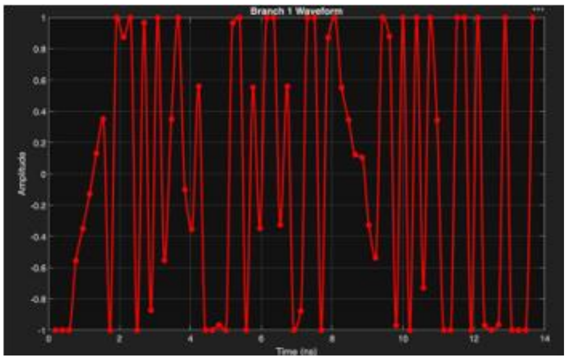

Figure 19: Extracted peaks (N = 150)

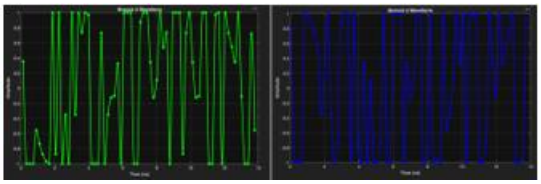

Figure 20: Branches 1–3 (N = 150)

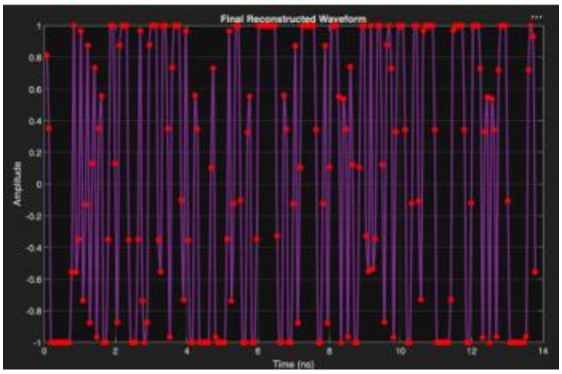

Figure 21: Final reconstructed wave (N = 150)

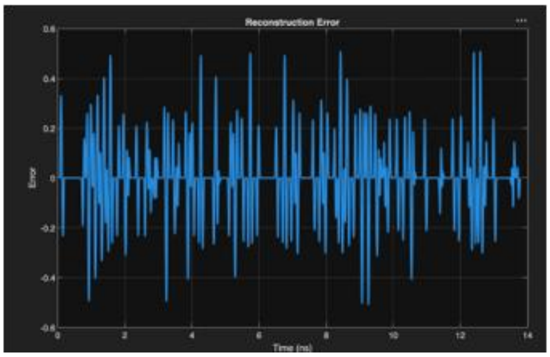

Figure 22: Reconstruction error (N = 150)

3. Original vs. Reconstructed

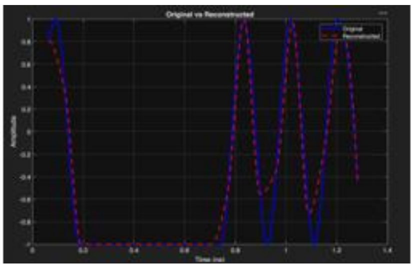

Figure 23: Original vs reconstructed (N = 15)

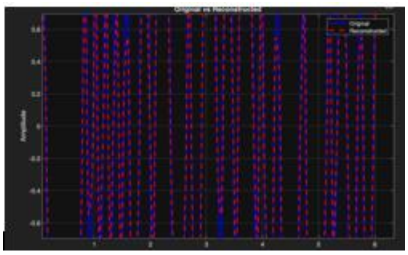

Figure 24: Original vs reconstructed (N = 90)

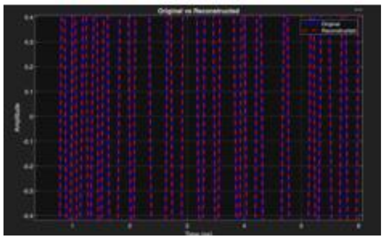

Figure 25: Original vs reconstructed (N = 150)

Reconstruction accuracy significantly improves from N = 15 to N = 90 to N = 150.

4. Implementation Details

To support reproducibility, the key implementation choices are summarized here. The continuous wideband waveform is generated from the PRBS sequence by linear interpolation between successive bit transitions on a uniformly spaced time grid [2], [8], with an oversampling factor that yields a smooth analog-like signal prior to sampling. Each of the three branches applies a local peak-detection criterion in which a sample is extracted at a point whose amplitude exceeds both of its immediate neighbours, evaluated only at the pulse instants defined by the corresponding 120°-shifted pulse train; the pulse density parameter N controls the pulse-train frequency and therefore the number of candidate sampling instants. Branch recombination is performed by mapping the samples extracted from all three branches back onto the common time grid according to their original time indices and merging them into a single non-uniform sample set, which is then interpolated to the full grid to obtain the reconstructed waveform. The simulation uses a total signal duration corresponding to the full PRBS sequence sampled at the rate listed in Table 1, with the sampling interval given by the reciprocal of that rate. The reconstruction is finally compared against the original waveform on the shared time grid using the error metrics reported in the Quantitative Analysis section.

5. Quantitative Analysis

Table 2: Quantitative reconstruction metrics

Metric	N=15	N=90	N=150
MSE	2.344443e- 02	2.294138e- 02	2.195896e- 02
RMSE	1.531157e- 01	1.514641e- 01	1.481855e- 01
Max error	4.993253e- 01	5.034742e- 01	5.091386e- 01
Correlation	0.981187	0.985671	0.986274

The average reconstruction error decreases as N increases. The typical deviation between the original and reconstructed waveforms becomes smaller, reaching approximately 98% similarity with the original waveform.

The results demonstrate that the proposed three-phase pulse-train architecture effectively enhances the available sampling density. Improved reconstruction performance is observed as N increases. However, the maximum error remains relatively unchanged, indicating that interpolation limitations and branch recombination effects continue to influence isolated waveform regions. Therefore, simply increasing pulse density may not completely eliminate reconstruction artifacts.

6. Discussion

The results demonstrate that the proposed three-phase pulse-train architecture effectively enhances the available sampling density. Improved reconstruction performance is observed as N increases. However, the maximum error remains relatively unchanged, indicating that interpolation limitations and branch recombination effects continue to influence isolated waveform regions. Therefore, simply increasing pulse density may not completely eliminate reconstruction artifacts.

7. Conclusion

A MATLAB-based framework for wideband signal reconstruction using three 120° phase-shifted pulse trains was presented. Comparative analysis for N = 15, 90, and 150 showed that higher pulse density improves reconstruction accuracy, reduces average error, and increases correlation with the original waveform. The results confirm the effectiveness of multi-branch pulse-train sampling for enhancing effective sampling density while maintaining manageable system complexity. Future work may focus on adaptive interpolation methods, larger pulse arrays, noise robustness, FPGA implementation, and experimental validation using practical photonic systems.

8. Future Work

- Hardware implementation using FPGA.
- More than three pulse branches.
- Adaptive interpolation methods.
- Noise robustness analysis.
- Experimental validation with real photonic systems.

References

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