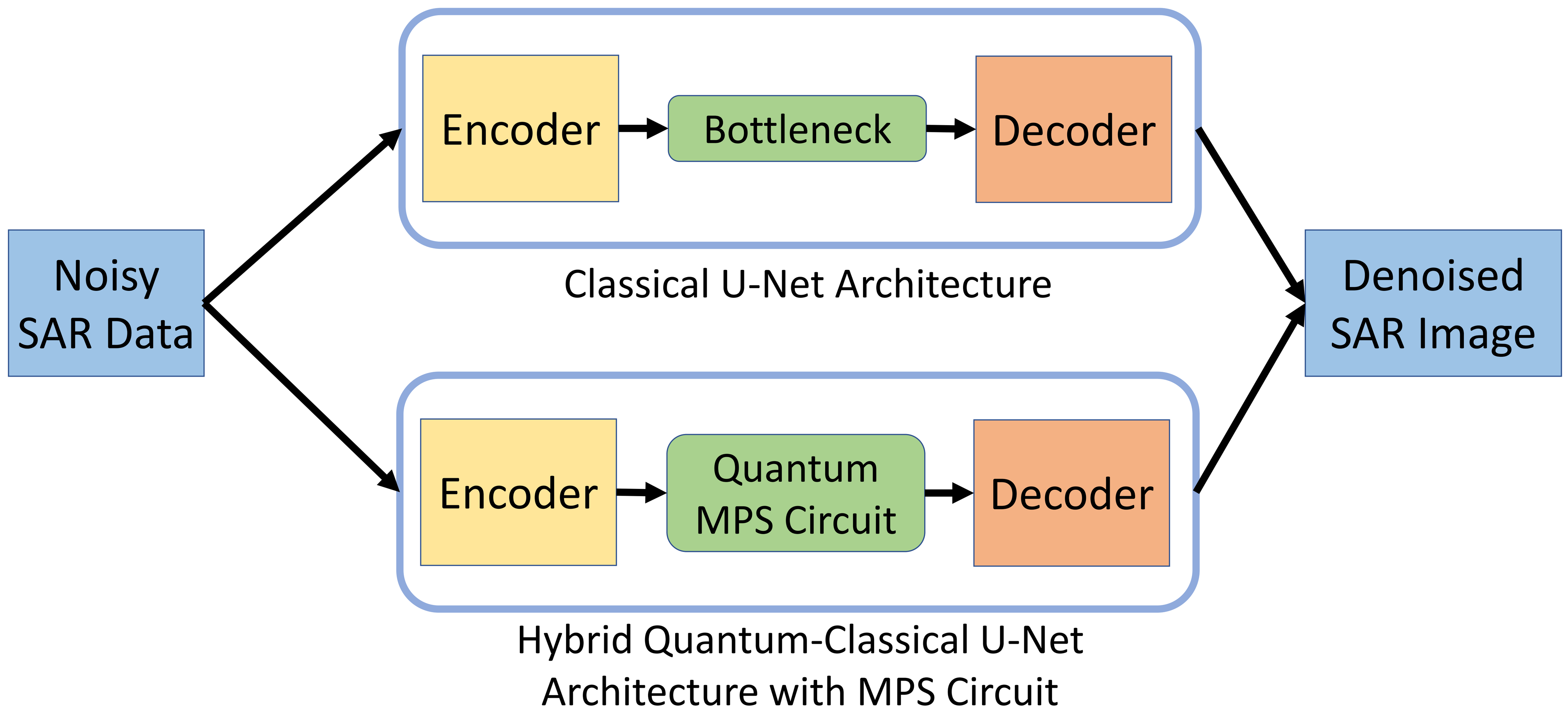
Integrating Quantum-Classical Algorithms with Tensor Networks for Noise Reduction in Synthetic Aperture Radar

Sreejit Dutta, Sigurd Huber, Gerhard Krieger

Deutsches Zentrums für Luft- und Raumfahrt (DLR), Institut für Hochfrequenztechnik und Radarsysteme
*sreejit.dutta@dlr.de



Comparison of a Classical U-Net architecture and our proposed hybrid architecture

Overview

Synthetic Aperture Radar (SAR) imaging is crucial in remote sensing due to its ability to produce high-resolution images regardless of weather conditions or daylight. However, SAR images often suffer from various types of noise, especially speckle noise, which degrades image quality and complicates data analysis. Traditional noise reduction techniques face challenges in balancing noise suppression with the preservation of image details. Recent deep learning approaches, such as U-Net architectures, have made advances in addressing these issues. Simultaneously, quantum computing has emerged as a promising field that can potentially enhance computational methods in image processing.

We propose a hybrid classical-quantum U-Net framework that integrates a quantum circuit in the bottleneck between the encoder and decoder layers of a U-Net for improved noise reduction in SAR images. Embedding a Matrix Product State (MPS) based quantum circuit within the U-Net bottleneck aims to exploit the expressivity and entanglement-preserving capacity of MPS to efficiently represent and transform high-dimensional latent features with fewer parameters. MPS circuits are suited for low-depth implementations on near-term hardware and could make use of structured sparsity and local correlations in SAR data. The non-classical feature transformations could enhance the model's ability to distinguish noise from signal.

Why Speckle Noise is Hard?

Speckle noise in SAR imagery arises from the coherent interference of backscattered signals and is a multiplicative, high-frequency distortion. Unlike additive Gaussian noise, speckle is data-dependent, spatially correlated, and its variance increases with signal intensity. These properties lead to over-smoothing or loss of fine structural details. Furthermore, speckle noise retains spatial patterns that often resemble texture, making it difficult to distinguish from image features.

Quantum Meets U-Net

We integrate a parameterized quantum circuit into the bottleneck of a classical U-Net architecture to enhance its capacity for learning structured transformations in the latent space. After the U-Net encoder compresses spatial features into a lower-dimensional representation, this latent vector is mapped to a quantum state using angle encoding. The quantum circuit, based on a variational Matrix Product State (MPS) ansatz, then processes this quantum state and performs non-linear transformations that classical layers may not easily capture. Upon measurement, the resulting quantum-processed latent representation is returned to the decoder for reconstruction.

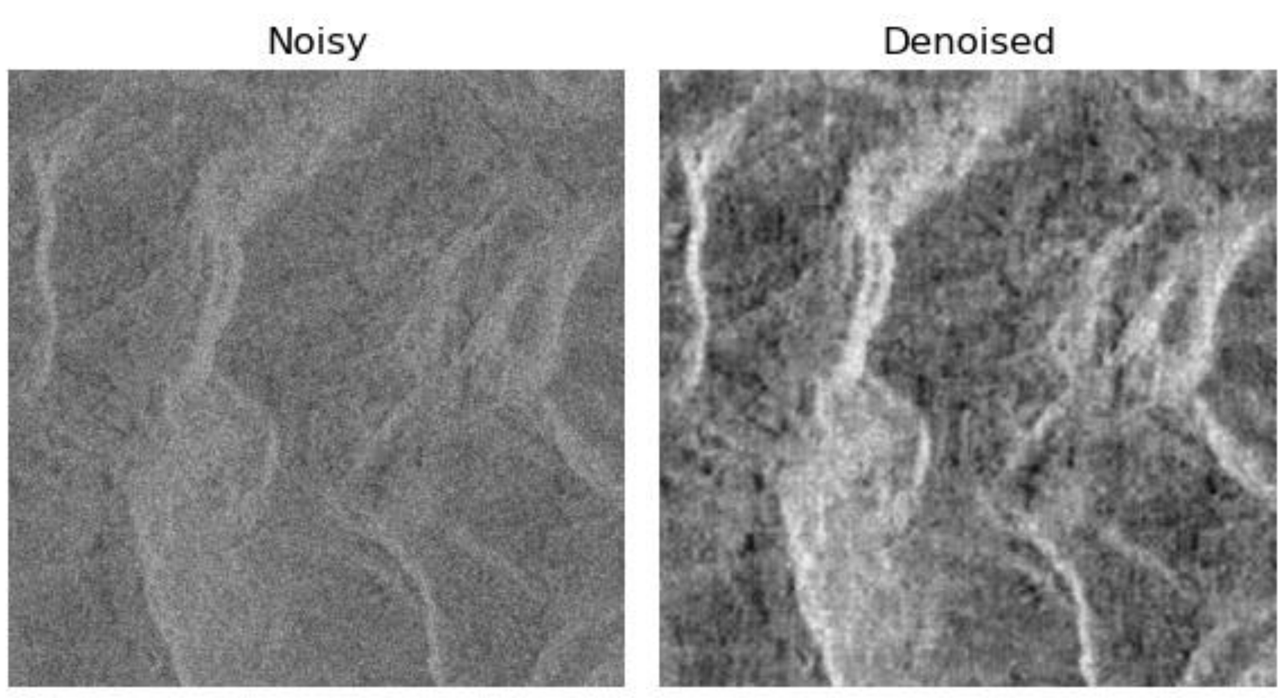
This hybrid approach enables the model to disentangle structured signal content from high-frequency noise—particularly the multiplicative speckle noise inherent in SAR imagery—by learning to project noisy latent features into smoother, more structured representations. The quantum layer effectively acts as a noise-aware filter, which improves the expressive capacity of the network while operating within the resource limits of near-term quantum hardware.

Why MPS?

Matrix Product States (MPS) offer an efficient tensor network representation of quantum states with limited entanglement, making them especially well-suited for near-term quantum computing and structured data transformations. In the context of SAR image denoising, the latent features extracted by the U-Net encoder often exhibit strong local correlations due to spatial continuity and structured noise patterns. MPS circuits capture these correlations with logarithmic parameter scaling, avoiding the exponential complexity of general quantum states. The sequential, low-depth structure of MPS aligns well with hardware-efficient quantum circuit design, allowing scalable implementation with fewer qubits and reduced decoherence. By restricting the Hilbert space to low-entanglement manifolds, MPS filters out high-frequency, unstructured components.

First Insights

We use Sentinel-1 VV GRD imagery over the Munich region and synthetically superimpose multiplicative speckle noise to emulate a low-look SAR acquisition. We then feed these noisy patches directly into a hybrid quantum U-Net architecture. After encoding the compressed feature vector into qubit rotations and applying a small network of entangling gates, the circuit's measurement outcomes are linearly re-embedded into the decoder's feature space, allowing the network to learn classical convolutional filters and quantum-mediated correlations. We train this model using mean squared loss, and evaluate its performance via standard despeckling metrics—SNR improvement, PSNR, and SSIM—on multiple randomly cropped areas.



First Results: On the left we see a Sentinel 1 image with speckle noise, on the right we see the result of our hybrid denoising model. The SNR improvement is 4.78 dB, PSNR is 35.83 dB and the SSIM is 0.872.

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