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A Deep-Learning Framework for Reconstructing Ringdown Signals with Data Gaps

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We introduce DenoiseGapFiller (DGF), a deep-learning framework specifically designed to reconstruct gravitational-wave ringdown signals corrupted by data gaps and instrumental noise. DGF employs a dual-branch encoder–decoder architecture: one branch ingests Q-transform time–frequency representations to capture narrow-band quasi-normal mode ridges in time-frequency representation, while the parallel branch uses multi-resolution wavelet embeddings to encode broader temporal context; these are fused via temporal mixing layers and Transformer-style attention. Trained end-to-end on synthetic ringdown waveforms with gaps up to 20% of the segment length and network signal-to-noise ratio(SNR) spanning 1–10, DGF achieves mean waveform mismatches of 0.023 in the low-SNR (1–5) regime and 0.002 in the
high-SNR (5–10) regime. Time-domain residual amplitudes shrink by roughly an order of magnitude, and power spectral density in the 0.01–1 Hz band is suppressed by 1–2 orders of magnitude, restoring the QNM peak around 0.01-0.1 Hz. Phase deviation analysis yields mean peak-phase deviations of -0.47° and -3.71° for low-SNR, with high-SNR case of -0.01° and 0.90°. These results demonstrate that a well designed convolutional time-mixing network can infer damped oscillatory structures directly from limited, corrupted observations, making DGF a promising preprocessing module for precision black hole spectroscopy in next-generation gravitational wave detectors.

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