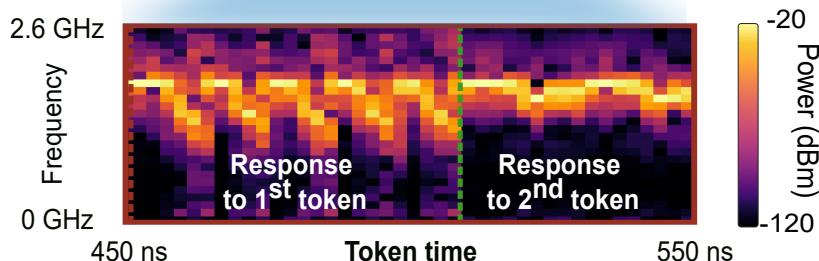
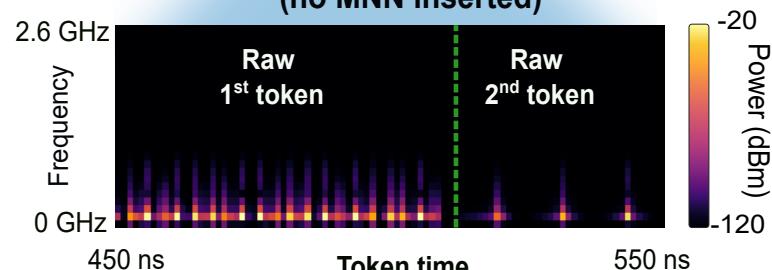
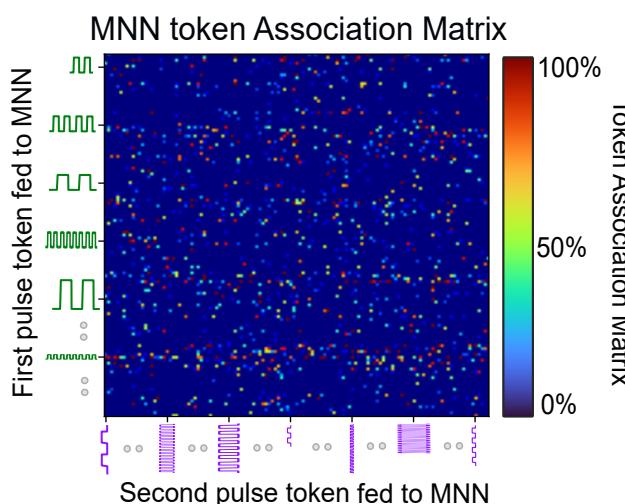


a**With MNN****a.i****Example MNN response spectrogram**

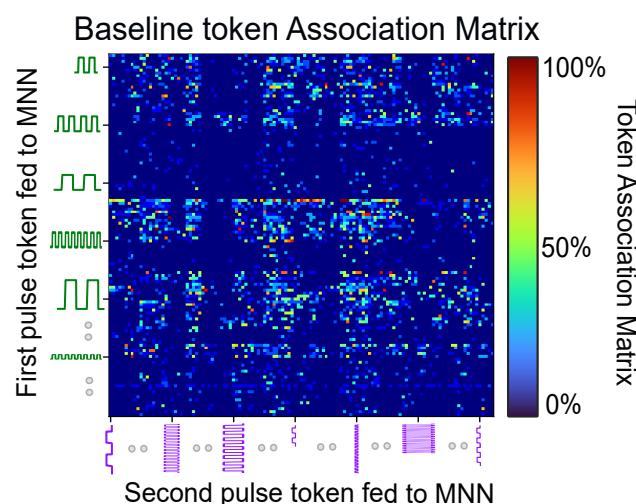
- Instantaneous broadband modulation & feature extraction

b**Baseline (Without MNN)****b.i****Example spectrogram for baseline (no MNN inserted)**

- No wideband modulation, no feature expansion

a.ii

- Clear token relationships extracted

b.ii

- Unclear / smudgy token relationships extracted

Extended Data Figure 3. Effect of MNN-based feature expansion on token relationships. **a.**, RF pulse-train tokens are injected into the MNN, whose nonlinear dynamics expand each token's spectrum over several gigahertz (followed by mixer-based downconversion to baseband for measurement; circuitry not shown). **a.i**, Example spectrogram showing that different tokens generate distinct broadband signatures within a ~100 ns window. **a.ii**, Token Association Matrix derived from a linear classifier applied to these spectrograms, revealing clear and separable token-to-token relationships. **b.**, The same tokens are directly observed using identical measurement bandwidth, without feature expansion. **b.i**, Raw spectrograms remain narrowband and visually similar across different tokens. **b.ii**, The resulting association matrix shows weak, blurred structure, indicating that tokens lack discriminable spectral features without MNN processing.