Frequency-Bin High-Dimensional Quantum Key Distribution with Multi-Basis Detection

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Quantum key distribution (QKD) promises unconditional security in communication, guaranteed by the fundamental principles of quantum mechanics. High-dimensional encodings enhance noise resilience and increase the information capacity per photon [1,2], but fully exploiting these advantages requires an experimental infrastructure capable of operating reliably across multiple measurement bases. In this work, we present a fully operational platform for high-dimensional QKD (HD-QKD) based on frequency-bin encoding, where projective measurements in superposition bases are implemented via a multi-output quantum pulse gate (mQPG) [3]. The mQPG acts as a programmable time-frequency mode sorter, enabling arbitrary superposition measurements in multiple mutually unbiased bases (MUBs). Using this approach, we demonstrate real-time HD-QKD in dimension $d = 3$, achieving secret key rates of 1.14 bits per sifted photon in the finite-key regime and 1.22 bits asymptotically, with positive key rates sustained up to 22 dB of channel loss (Fig. 1). We implement multi-basis HD-QKD using the complete set of four MUBs in $d = 3$, and extend to all six MUBs in $d = 5$, enabling the investigation of dimensional scaling and multi-basis protocol performance. Our results highlight a practical trade-off between the increased noise tolerance offered by additional bases and the larger implementation errors of high-dimensional superposition measurements. We find that, in the low-loss or finite-key regime, multi-basis implementations can enable positive secret key rates where two-basis protocols fail. Overall, our platform provides a scalable, fiber-compatible architecture for fully frequency-bin-encoded HD-QKD, capable of supporting arbitrary MUBs and adapting the protocol to the channel conditions in the optimal way.

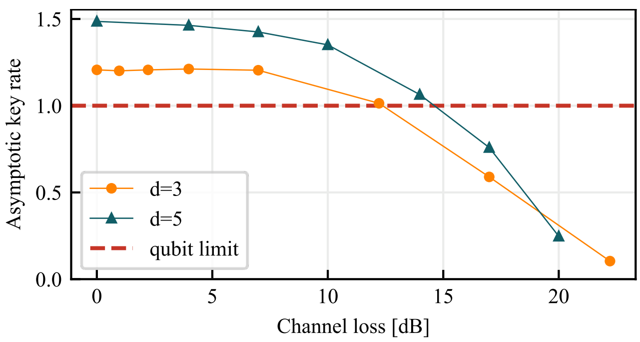

Fig. 1: *Experimental asymptotic secret key rate per sifted photon obtained for a two-basis protocol in d=3 (orange) and d=5 (blue) as a function of optical channel loss. The red dashed line, at 1 bit per photon, represents the maximum achievable key rate for qubits (d=2).*

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References

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