In Situ Confidence Estimation of a Single-Shot Quantum State Identification Measurements

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Energy-efficient communication requires minimizing the rate of errors and optical energy at the receiver. The error rate of a conventional receiver is bounded by its shot-noise limit. Practical quantum measurement can enable below the shot noise limit error rates, a new frontier for low-power optical communications [1-4]. Here we demonstrate the first optical quantum receiver [5,6] that can process arbitrary user data, along with the self-estimation of the measurement confidence for each received symbol [7]. The confidence is based on all *a posteriori* probabilities that the input state is one of M pre-defined states obtained during each act of measurement. We explore various simple forward error correction (FEC) codes based on the received confidence *a posteriory* probability (CAPP) vectors. We report on a quantum measurement-based error-correcting protocol that yields a record low symbol error rate (SER) of $\approx 1(1) \times 10^{-7}$, more than 25 dB below the corresponding classical error limit and requiring energy of just 7.5 photons per bit at the receiver input. We apply the error correction protocols to the raw data obtained for coherent optical pulses with 2 photons (1.49 photons detected due to the receiver system efficiency of 74.5%).

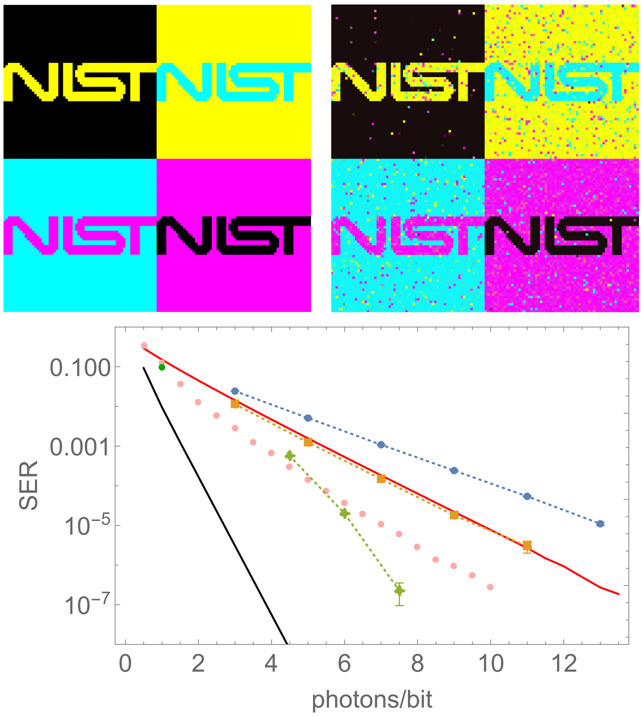

Figure 1: Top left: the original image of 128x128 symbols where 4 primary (CMYK) colors correspond to 4 possible optical states. Top right: the same image where pixels reflect each symbol's accuracy of identification experimentally obtained from a continuous quantum measurement record. The color for each pixel is calculated as a sum of primary colors weighted with CAPP. Bottom: Reducing symbol error rate using naive and quantum-inspired forward error correction protocols. Note that successful error correction protocols use single-shot accuracies obtained from the quantum measurement. The decoded symbol error rate (SER) at 7.5 photons per bit is 25 dB below the classical shot-noise limit

Figure 1 (top right) illustrates experimentally received raw user data (without error correction). However, the experimentally obtained raw SER is not enough to provide reliable communication. The SER can be improved by increasing the optical signal power or by FEC. The first approach was experimentally investigated in [3]; however, here, we show the advantage of using CAPP for FEC, resulting in more than 10 dB improvement in SER (Figure 1).

Figure 1 (bottom) illustrates some FEC strategies. First, naive repetition coding does improve the SER but does so inefficiently. Indeed, the raw received data (green circle) is below the shot-noise limit, but the cumulative energy of the repeating symbols (blue circles) grows faster than the error rate reduction compared to a classical receiver (red line). However, repetition code supplemented with CAPP data (orange squares) yields better error performance for decoded data and remains below the classical limit. More advanced multi-symbol quantum voting methods that also take advantage of shot-to-shot accuracy estimates (CAPPs) reduce symbol error even better (green diamonds). Particularly, we observe SER that is >25 dB lower than the classical homodyne limit for the input states of the same energy. This result shows that the advantage gained by the quantum measurement can be practically used to reduce the input energy requirements, but only when CAPP data is used.

In conclusion, we implemented the first quantum-enabled quantum communication link that can process user-defined data. This effort is also the first demonstration of the experimental measurement of single-shot quantum measurement confidences obtained for a quantum receiver. We survey error correction algorithms and demonstrate significant improvement in error correction using quantum measurement CAPPs. We show the error-corrected SER that is >25 dB below the shot-noise limit of an ideal classical receiver.

References

[1] K Kato, M Osaki, M Sasaki and O Hirota, IEEE Trans. Commun. **47**, 248 (1999)

[2] R L Cook, P J Martin and J M Geremia, Nature **446**, 774 (2007)

[3] F E Becerra, J Fan and A Migdall, Nat. Photon. **9**, 48 (2015)

[4] I A Burenkov, M V Jabir and S V Polyakov, AVS Quantum Sci. **3**, 025301 (2021)

[5] I A Burenkov, M V Jabir, A Battou and S V Polyakov, PRX Quantum **1**, 010308 (2020)

[6] I A Burenkov, O V Tikhonova and S V. Polyakov, Optica **5**, 227 (2018)

[7] I A Burenkov, N F R Annafianto, M V Jabir, M Wayne, A Battou and S V Polyakov, Phys. Rev. Lett. **128**, 040404 (2022)