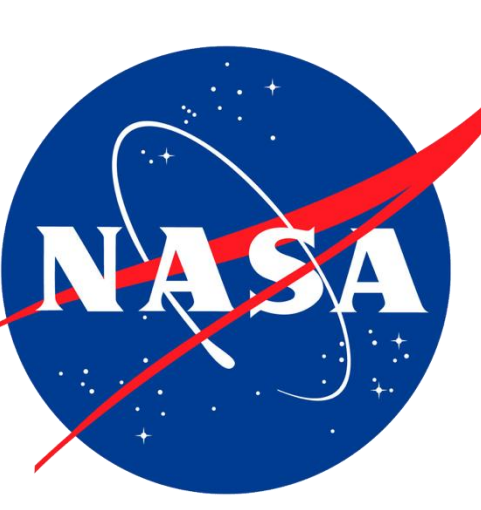


Super-Additive Joint-Detection Optical Receiver for Deep-Space



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Introduction

Demand for space based digital communication capacity has grown rapidly over the last decade, this demand will extend to Lunar and Martian missions. Instrument generated data already exceeds the capacity available on RF/Microwave communication platforms¹. Traditional transceivers operate with electromagnetic radiation with wavelength \sim mm to 10s of meters in length, optical links use \sim μ m scale wavelength. Moving to optical communications offers an increase in bandwidth, reduction in size, weight and power (SWaP) requirements, and has no spectrum regulations². A single spatial-temporal bandwidth limited symbol can be characterized by the mean photon number, n , for the ideal laser operating as a coherent state, $|\alpha\rangle$ then $n = |\alpha|^2$. In the case of photon-starved regime, $n \ll 1$, the Photon Information Efficiency (PIE), $PIE = \frac{C(n)}{n}$. The PIE for classical symbol-by-symbol detection plateaus at 2.88 bits/photon, exceeding this value arises in super-additive communication systems and requires optical joint-detection receivers (O-JDR)³. The design of structured O-JDRs that can achieve super-additivity is needed to increase optical communication rates in deep-space.

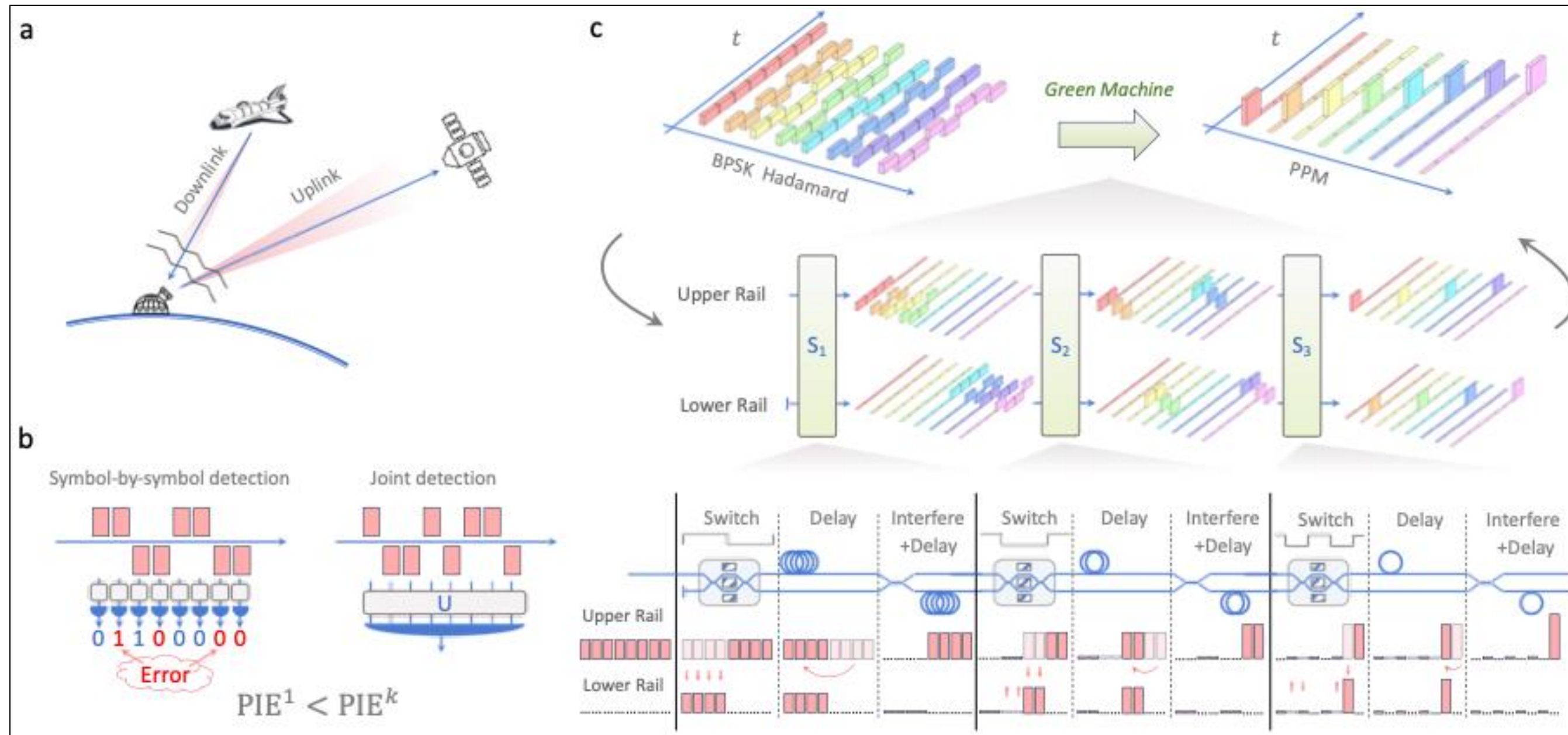


Fig 1. (a) Photon-Starved optical communications predominantly impacts downlink from deep space. (b) Comparison of symbol-by-symbol to joint detection. (c) Visualization of GM3 receiver operation, on top the codebook transformation, in the middle the transformation broken into stages, finally schematic of the overall GM3 operation on a single codeword

Green-Hadamard Transceiver

BPSK modulation of CW source using Hadamard Codebook, \mathcal{C} , is paired with the *Green Machine*⁴ O-JDR to perform unitary transformation of length M codewords, generating PPM codewords prior to photon detection. Each interferometric stage requires passive and active linear optic components. The number of stages matches the bit-size of the codebook, k , and codewords have length $M=2^k$. Photodetection of the transformed codebook induces an M -ary erasure channel with capacity $C_{M-ary} = k(1 - e^{-Mn})/M$

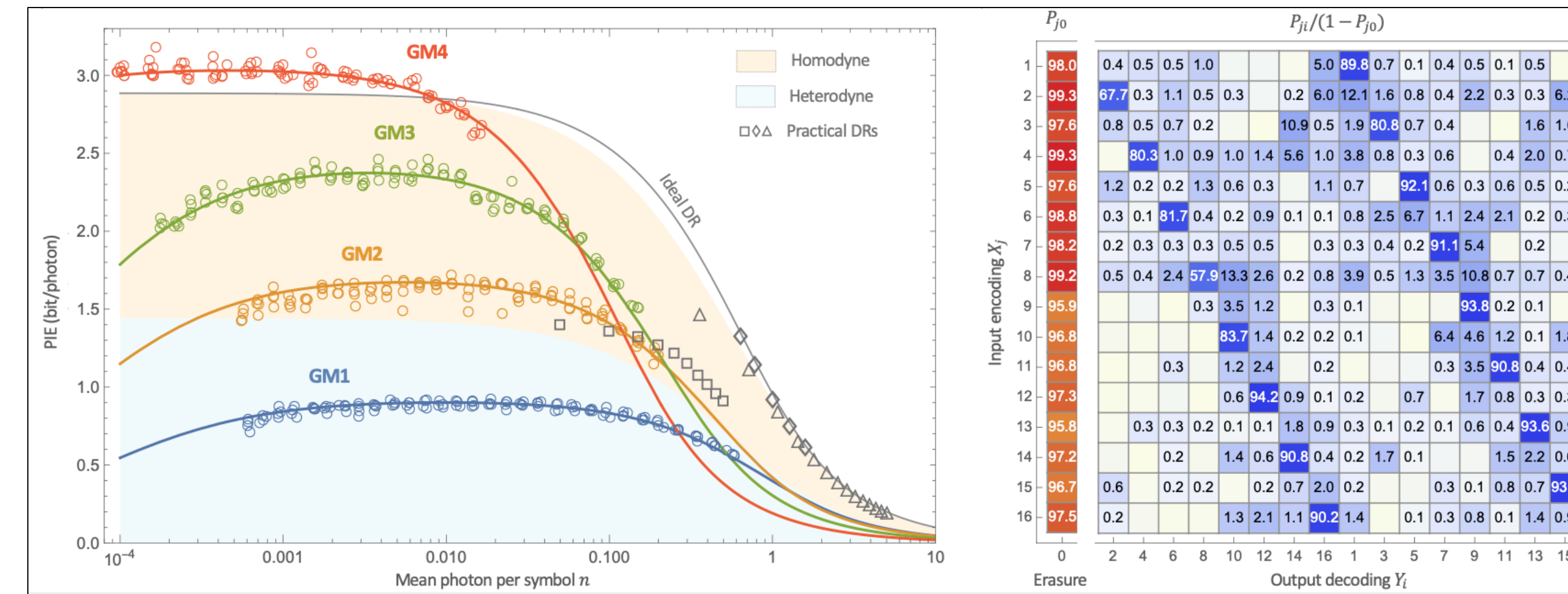


Fig 2. Experimental results of Green-Hadamard Channel. The plot on the left shows the data and fit of the fiber Green Machine receiver of various sizes plotting the PIE for the calculated receiver mean photon number, n . Each circle represents a calculated PIE from a transition probability matrix like the example on the right. The GM4 receiver showed super-additivity, reaching a maximum of 3.15 bits/photon

Experiment

Experimental realization of the Green Machine receiver was done⁵ using fiber optic platform, predominantly using polarization maintaining fiber. A continuous wave 1550nm laser source is used to generate the unmodulated coherent state before the BPSK Hadamard codes are phase modulated using fiber coupled electro-optic modulators, pulse duration was reduced for consecutively larger GM receivers ranging from 80 to 10ns. To emulate the aperture-limited photon-starved regime, a variable optical attenuator introduces loss on the signal. On the receiver side, the incoming codeword train is split using a 2x2 intensity electro-optic modulator acting as a switch between fiber lines, an optical delay line introduces a temporal shift in increments of τ before interference on a balanced fiber coupler. A second optical delay removes the temporal shift before entering the next stage. Photon detection events are time-tagged in respective time bins while repeating each codeword to construct the transition probability matrix.

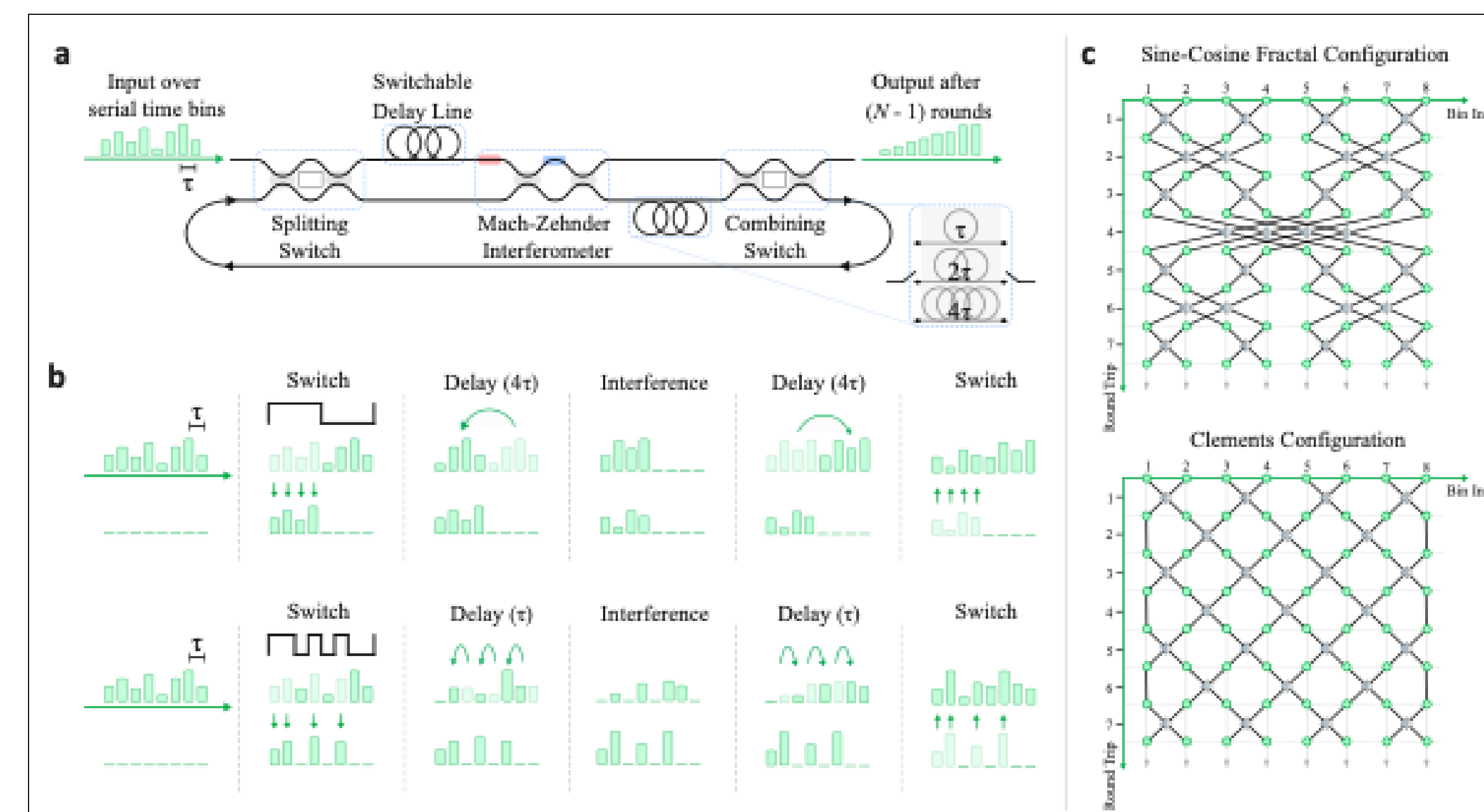


Fig 3. Overview of the reconfigurable Green Machine (a) the overall schematic of the Sine-Cosine Fractal (SCF) single stage reconfigurable GM (b) Visualization of the sequential operations applied for some input temporally encoded signals (c) Interference map for index sequence mapping both the SCF and Clements configurations of the device.

Reconfigurable Green-Machine

The multi-stage Green Machine Receiver showed capability of achieving super-additive communication capacity with a structured O-JDR design, yet it lacks the ability to adapt to codebook size necessary for most realistic mission profiles. A reconfigurable version can be implemented using similar linear optics and fast switching⁶ reconfigured to allow multiple passes of a single interferometric stage and switchable delay lengths, in general any unitary can be decomposed into a series of operations on this design using the Sine-Cosine Fractal decomposition. An alternative reconfigurable structure can be implemented without switchable delay lines but requires the third outer loop delay to be significantly longer than the inner delays, such a system can implement a Clements decomposition for simpler structure at the cost of latency.

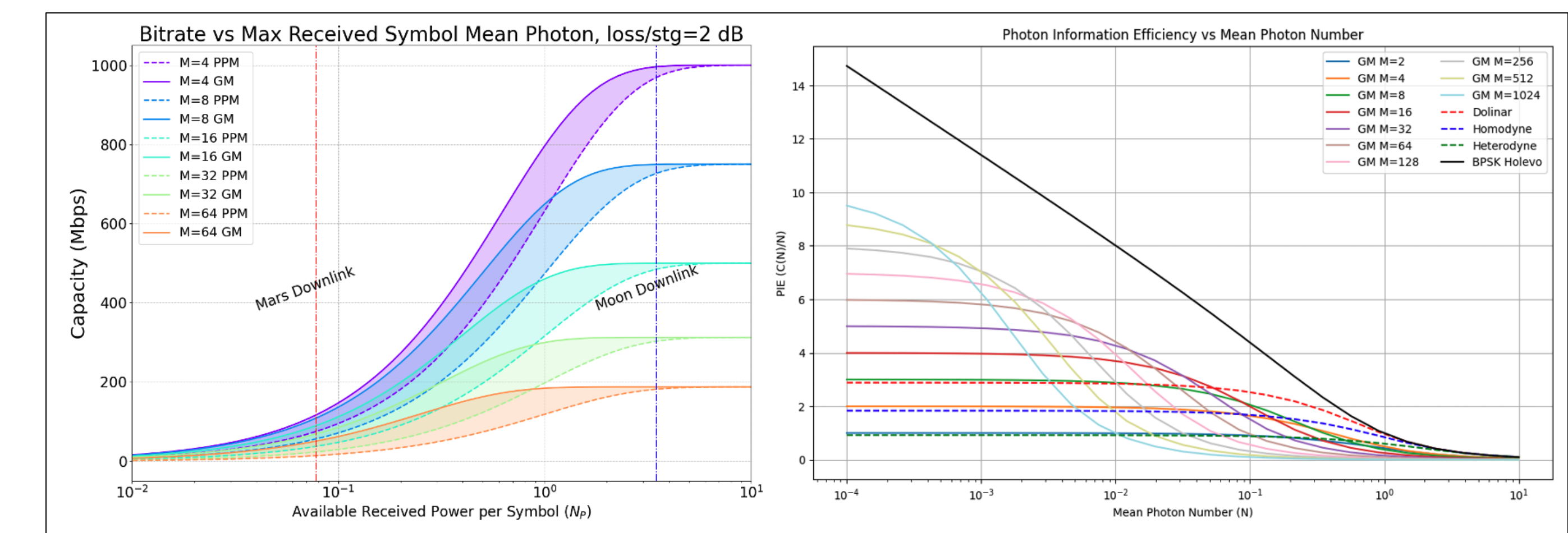


Fig 4. Left a comparison of GM receivers against PPM over maximum pulse powers using realistic mission parameters and showing an advantage of a lossy GM against PPM + Direct Detection. On the right the maximum achievable limits of PIE in the photon starved regime and the achievability gap between the envelope of the GM and the ultimate Holevo Capacity shown with solid black line.

Outlook

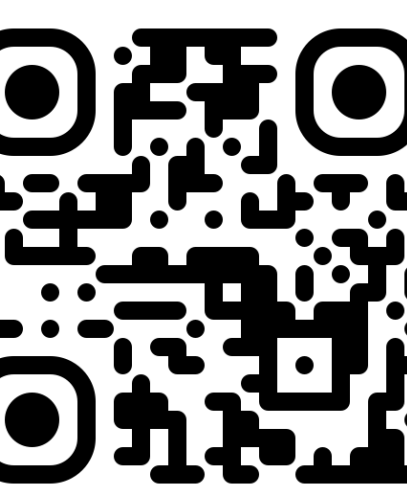
As progress towards Lunar and Martian exploration and sustained colonization continues, O-JDRs stand out as top available options for deep-space communication links. The Green Machine provides a structured and scalable platform able to exceed the power-limited performance of any existing classical transceivers achieving demonstrated super-additive capacity. Improved version will show that with improvements to component level insertion loss, the Green Machine could be deployed for meaningful improvements to communication rates in the near term, with reconfigurable versions allowing for more dynamic mission profiles and potential for distribution of temporally entangled quantum states. Further development of O-JDRs using quantum resources either at the transmit or received end may push the envelope of the GM performance closer to the upper-bound Holevo Capacity.

- H. Hemmati et al. "Deep Space optical communications: Future Perspectives and application," Proc. IEEE 99(11), 2020-2039 (2011)
- W.D. William et al., "RF and optical communications: a comparison of high data rate returns from deep space in the 2020 timeframe," technical report, NASA Glenn Research Center (2007)
- M. Takeoka and S. Guha, Physical Review A(2014).
- S. Guha, Physical Review Letters 106, 240502 (2011)
- C. Cui, J. Postlewaite, B. Saif, L. Fan, S. Guha, Superadditive communication with the green machine as a practical demonstration of nonlocality without entanglement, Nature Communications 2025
- J. Basani, C. Cui, J. Postlewaite, E. Waks, S. Guha, Hardware-Efficient Large-Scale Universal Linear Transformations for Optical Modes in the Synthetic Time Dimension

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