

Quantum-processing-assisted classical communication

Kelly Werker Smith,^{1,2,*} Don Boroson³, Saikat Guha⁴, and Johannes Borregaard¹

¹*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*

²*Harvard Quantum Initiative, Harvard University, Cambridge, Massachusetts 02138, USA*

³*Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts 02421, USA*

⁴*Department of Electrical and Computer Engineering, University of Maryland, College Park, Maryland 20742, USA*

 (Received 27 June 2025; revised 14 January 2026; accepted 23 February 2026; published 15 April 2026)

We describe a general quantum receiver protocol that maps laser-light-modulated classical communications signals into quantum processors for decoding with quantum logic gates. The quantum gates enable joint quantum measurements over a code word to achieve the quantum limit of communication capacity. Our receiver design requires qubit resources that only logarithmically increase with the size of the code word and accommodates practically relevant coherent-state modulation containing multiple photons per pulse. Focusing on classical-quantum polar codes, we outline the necessary quality of quantum operations and code-word lengths to demonstrate a quantum-processing-enhanced communication rate surpassing that of any known classical optical receiver-decoder pair. Specifically, we show that a small quantum receiver of four qubits with operational errors of approximately 0.2% can already provide a 5% gain in the communication rate in the weak-signal limit. Additionally, we outline a possible hardware implementation of the receiver where efficient spin-photon interfaces such as cavity-coupled diamond color centers or atomic qubits are used to input the received photonic signal to a small-scale quantum processor for decoding. Our results outline a promising route for potential quantum advantage in classical communication with near-term, small-scale quantum computers.

DOI: [10.1103/wp82-718s](https://doi.org/10.1103/wp82-718s)

I. INTRODUCTION

The ability to reliably transfer information over long distances is critical for a broad range of technologies ranging from the high-speed Internet to the Global Positioning System. Optical-frequency laser-light-modulated communication affords far higher rates compared with its radio-frequency counterpart due to its greater spectral bandwidth and smaller diffraction spread. Nonetheless, optical communication is fraught with the need for precise pointing, acquisition, and tracking, and with losses associated with absorption, scattering, and turbulence in propagation through the atmosphere. However, free-space optical satellite-to-satellite and deep-space links over a vacuum are unfettered from the aforesaid limitations, making laser communication a very promising technology for high-rate links. Laser communication has therefore been

pursued for missions such as the NASA–MIT Lincoln Laboratory Lunar Laser Communication Demonstration program [1].

For the above-mentioned long-range free-space optical communication settings, stringent limitations on the transmitted power and on the aperture sizes of the transmitter-receiver telescopes severely restrict the achievable communication rate. Achieving the bandwidth limit imposed by the hardware constraints is a nontrivial task that involves careful optimization of the modulation format, error-correcting codes, and receiver designs, along with efficient decoding algorithms that are capable of countering the effects of transmission loss and operational errors [2,3].

The maximum rate of information transfer is characterized by the channel capacity, which is the maximum number of bits that can be reliably communicated per use of the communication channel. The fundamental limit for classical information transfer is the Holevo bound [4–6], which provides an upper bound for the channel capacity. In particular, the Holevo bound exceeds the Shannon capacity associated with specific optical communication receivers [7]. In these cases, the Shannon capacity ignores the quantum mechanical properties of the communication channel

*Contact author: kwsmith@fas.harvard.edu

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and receiver measurement. This suggests that transmitter-receiver codesigns have to adopt a quantum mechanical description of the encoding and decoding of information to reach ultimate communication rates.

Past work strongly suggests the necessity of entanglement within receivers [8] to achieve information rates approaching the Holevo bound in the weak-signal limit, where the rate of received photons is small. This can be understood from the observation that collective measurements over multiple code-word symbols can result in a superadditive gain over individual symbol detection [9]. For strongly attenuated signals, only a few photons are received across many symbols and the collective measurements become projections onto entangled photonic subspaces. Recently, superadditivity in this weak-signal regime has been demonstrated with trapped ions [10] and optical interferometers [11], but none of the demonstrated designs has any guarantees of reaching the Holevo bound for larger, more practically relevant, code sizes. For example, the Lunar Laser Communication Demonstration used a code-word length of 15 120 bits [12,13].

Classical-quantum polar codes are known to asymptotically approach the Holevo bound for the pure-loss optical channel, with the aid of an entangling quantum successive cancellation (SC) decoder [14]. However, the practical implementation of the required measurements, performance evaluation in the nonasymptotic limit, and robustness regarding operational errors in the quantum decoding hardware have so far not been carefully addressed. Therefore, it is unknown whether practically feasible receivers can be realized for finite-size codes.

In this work, we develop a general framework for mapping photonic states used for optical communications to quantum processors for subsequent decoding with quantum logic gates. We achieve this using photonic-to-binary conversion techniques [15,16], which we extend to the practically relevant multiple-photon regime. Once the received state is loaded into a processor, quantum gates can be used to implement the specific measurements of the decoder in a programmable way. To illustrate our framework, we design a concrete quantum receiver capable of performing SC decoding of classical-quantum polar codes with qubit resources that only logarithmically increase with the code-word length.

Our design consists of a photon-to-qubit transducer, which maps the photonic amplitude information into a small-scale, fault-tolerant quantum processor through state injection (see Fig. 1). The transducer can be implemented with atomic or atomlike qubits strongly coupled to optical cavities, in a manner similar to recent experimental demonstrations of quantum-assisted nonlocal interferometry [17]. We quantitatively investigate the performance of the receiver for finite code-word lengths in the presence of realistic imperfections such as quantum gate noise. We show that a superadditive rate increase of 5% over

any known classical receiver can be demonstrated with modest-sized quantum processors of four qubits, with qubit error rates of a few permille in the weak-signal limit where each symbol contains an average of approximately 0.001 photons. Compared with previous designs of quantum-processor-assisted optical communication systems [18], our design targets practically relevant codes with rigorous guarantees of achieving the Holevo bound in the asymptotic limit, does not require any optical-to-microwave transduction, and has known decoding circuits.

Our analysis suggests that small-scale quantum-error-corrected devices could be used to demonstrate an advantage over classical techniques in optical communications. While further development is needed to make quantum-enhanced classical communications of practical use, our work opens up several promising new directions for future research in this field.

II. RECEIVER DESIGN

As shown schematically in Fig. 1, we model the communication channel as a pure-loss optical channel, which forms a building block for modeling optical communications over diffraction-limited free-space links [19]. This modeling choice is motivated by the space-based free-space communication scenarios of primary interest in this work, where diffraction and finite aperture sizes dominate. In such settings, phase noise accumulated during propagation is negligible compared with photon loss, and modeling the channel as pure loss is a justified approximation [19,20]. We focus on the encoding of classical information in quantum polar codes following the approach in Ref. [21], but our receiver design is generally applicable to any encoding across multiple optical pulses in the limit where the probability of simultaneous arrival of multiple photons is negligible.

A. Signal encoding

The classical information bits are first translated into multibit classical code words of the polar code. Polar coding exploits *channel polarization* to ensure that all the channels are either near useless (bad) or near perfect (good). We can then send our information bits through the good channels and fix the bits input to the bad channels to some value known by both the sender and the receiver (so-called frozen bits). For more details on polar codes, we refer the reader to Ref. [22]. The code words are then encoded bit-by-bit into the phases of individual optical pulses with use of the binary phase shift keying (BPSK) protocol. We model this as encoding bit 0 (1) as an optical coherent state $|\alpha\rangle$ ($|- \alpha\rangle$). The mean photon number of the state is given by $\bar{n} = \alpha^2$. We can take α to be real for the BPSK alphabet without loss of generality [21]. The encoding happens sequentially such that an N -bit-long code word is encoded into a temporal sequence of

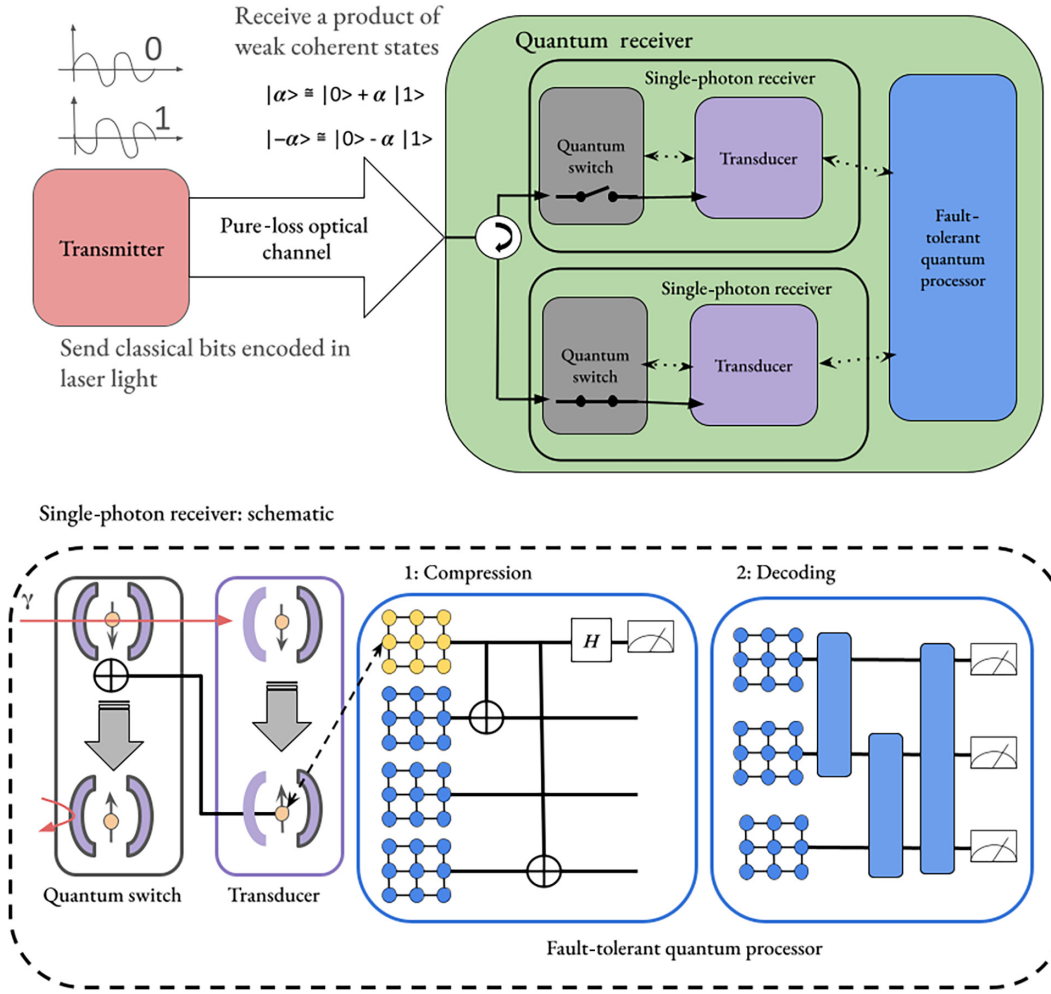


FIG. 1. Top: Full communication setup including the transmitter, channel, and quantum receiver. The receiver, which is the focus of this work, has a modular design to accommodate multiple photon inputs. In each time bin, the signal is routed to the quantum switches, which will transmit (reflect) the signal if the corresponding memory bank in the quantum processor is empty (full). Bottom: A photon (γ) arriving in the first time bin is directed to the transducer qubit. A CNOT gate between the transducer qubit and the quantum switch qubit flips the switch from transmission to reflection. The state of the transducer qubit is mapped to a logical control qubit, and a series of logical CNOT gates flip the processor qubits to encode the photon arrival bin and phase information (the compression step). Next, the control qubit is decoupled from the target qubits with a measurement in the X basis. Finally, gates and measurements are performed on the remaining target qubits to decode the received classical bit string (the decoding step).

N consecutive coherent states. The ratio K/N between the number of information bits K and the length of the code words N is referred to as the “code rate.”

As an illustrative example, we consider $N = 4$ and $K = 2$. With two frozen bits, the information bits can take on the values 00, 01, 10, and 11, and our corresponding polar-coded code words $c = c_1 c_2 c_3 c_4$ are 0000, 1111, 1010, and 0101, respectively [22]. The encoded states are thus of the form $|\psi_c\rangle = \bigotimes_{i=1}^4 |(-1)^{c_i} \alpha\rangle$, with coherent state $|\alpha\rangle = e^{-\frac{1}{2}|\alpha|^2} \sum_{j=0}^{\infty} (\alpha^j / \sqrt{j!}) |j\rangle = e^{-\frac{1}{2}|\alpha|^2} [|0\rangle + \alpha|1\rangle + (\alpha^2/\sqrt{2})|2\rangle + \dots]$. Here and in what follows, $|0\rangle$ and $|1\rangle$ denote the Fock number state, not the classical binary digit. In particular, each digit in a ket represents a time bin, and the numeral is the number

of photons in that time bin. $|\psi_c\rangle$ can be expanded in the weak-field limit as $|\psi_c\rangle \approx e^{-\frac{1}{2}|\alpha|^2} [|0000\rangle + \alpha |\psi_c^{(1)}\rangle + \alpha^2 |\psi_c^{(2)}\rangle + \frac{1}{\sqrt{2}} \alpha^2 |\psi_c'^{(2)}\rangle + O(\alpha^3)]$, where

$$|\psi_c^{(1)}\rangle = (-1)^{c_1} |1000\rangle + (-1)^{c_2} |0100\rangle + (-1)^{c_3} |0010\rangle + (-1)^{c_4} |0001\rangle, \quad (1)$$

$$|\psi_c^{(2)}\rangle = [(-1)^{c_1+c_2} |1100\rangle + (-1)^{c_1+c_3} |1010\rangle + (-1)^{c_1+c_4} |1001\rangle + (-1)^{c_2+c_3} |0110\rangle + (-1)^{c_2+c_4} |0101\rangle + (-1)^{c_3+c_4} |0011\rangle], \quad (2)$$

$$|\psi_c'^{(2)}\rangle = [|2000\rangle + |0200\rangle + |0020\rangle + |0002\rangle]. \quad (3)$$

We expand in the weak-field limit since this a regime where quantum, collective decoding receivers could be beneficial over a classical counterpart. However, the regime for quantum assistance is not demarcated by a sharp line because there are many trade-offs to be considered in the design of practical communication systems. For example, to achieve a particular average power efficiency, the designer could adjust the output power of the transmitter amplifier, the area of the transmit telescope, or the area of the receive telescope. In addition, there might be constraints on bandwidth, peak power, or cost. While the Holevo limit is the ultimate capacity limit, practical systems might meet the desired receiver specifications operating below the Holevo limit, where classical techniques can reach the required rates. Further discussion of the utility of collective decoding versus classical techniques can be found in Refs. [20,23,24]

B. Qubit mapping

The first task of the receiver is to map the photonic state into a quantum processor. The mapping is facilitated by a *transducer* qubit. The transduction from photonic to matter-based encoding can be implemented through a stimulated Raman adiabatic passage as theoretically described in Refs. [25–27] and experimentally demonstrated with cavity-coupled single atoms in Refs. [28,29]. In these schemes, the cavity-coupled transducer qubit is encoded in two stable ground levels of a three-level spin system. The qubit is initially prepared in ground state $|\downarrow\rangle$, which is coupled to an excited state through a cavity-enhanced optical transition. The absorption of a photon excites the spin system, and a control laser pulse adiabatically transfers the population through the excited state to the other ground state $|\uparrow\rangle$. This amounts to the transformation $|1\rangle|\downarrow\rangle \rightarrow |0\rangle|\uparrow\rangle$, which corresponds to the coherent absorption of the photon into the transducer qubit. Through careful design of the incoming photonic pulses and laser control fields, near unit efficiency can be achieved [25,26].

The state of the transducer qubit is then transferred to a logical qubit in the quantum processor through qubit injection [30–33]. At the abstract level, this requires the ability to perform qubit stabilizer measurements between the transducer qubit and a subset of the physical qubits of the logical code. Depending on the specific hardware implementation, this can be achieved in several ways. For atomic-based systems, the possibility to physically transfer atoms between a cavity region and a processing region [34,35] would allow direct injection of the transducer qubit. For solid-state hardware [17], preshared entanglement stored in nearby nuclear spin qubits could be used to teleport the information into the processor, which could consist of the same hardware [36] or different hardware [37].

Once the state of the transducer qubit has been transferred to a logical qubit in the quantum processor, the processor records the photon arrival bin and phase information using the binary encoding approach outlined in Refs. [15,16]. Specifically, the logical qubit that stores the transducer state serves as a control qubit for a series of logical controlled-NOT (CNOT) gates. The vacuum component ($|0000\rangle$) and the single-photon component ($|\psi_c^{(1)}\rangle$) of $|\psi_c\rangle$ can be mapped to the processor by changing the target qubits of these logical CNOT gates depending on the time bin (the “compression” step in Fig. 1). For a code word of length $N = 4$, $\lceil \log_2(4 + 1) \rceil = 3$ logical qubits are required, while for a code word of length N , $\lceil \log_2(N + 1) \rceil$ logical qubits would be required [15,16]. This is an exponential reduction in qubit resources compared with a unary encoding approach, where there is a qubit for each time bin.

However, there are a couple of caveats. First, the logical control qubit has to be decoupled from the rest of the qubit register to complete the mapping. As outlined in Refs. [15,16], this can be done by a final X -basis measurement, projecting onto the states $|\pm\rangle = (|0\rangle \pm |1\rangle)/\sqrt{2}$ following the CNOT encoding sequence of each time bin. Depending on the measurement result, $x_i \in \{0, 1\}$, a phase correction should be applied to the qubit state. These corrections can be recorded and applied later in the classical decoding of the information.

Second, and more problematic, the protocol allows only for the mapping of the vacuum and single-photon components of $|\psi_c\rangle$ since the two-photon terms would lead to errors in the binary encoding of the time-bin information. We solve this issue by adopting a modular design where the receiver consists of multiple logarithmically sized single-photon subreceivers (see Fig. 1). The key element of our multiple-photon receiver is the addition of a qubit switch, which routes the incoming photons between the single-photon qubit registers. The switch can be implemented with use of a second cavity-coupled spin system that controls the input field to the transducer qubit. In particular, if only one of the spin states has a cavity-resonant optical transition and the cavity is a balanced two-sided cavity, then the cavity-qubit system will be reflecting (transmitting) if the qubit is in the coupled (uncoupled) state [38]. Without loss of generality, we can assume that if the switch qubit is in state $|\downarrow\rangle$ ($|\uparrow\rangle$), the photon is transmitted through (reflected from) the cavity.

The quantum switches are initialized in $|\downarrow\rangle$ such that an incident photon is transmitted to the corresponding single-photon receiver. The incoming photons will always be routed from the first to the last switch-register module regardless of the time bin. The single-photon receiver protocol as described above proceeds within each register with the addition of an extra CNOT gate between the switch qubit and the transducer qubit before state injection. The transducer qubit is the control and the switch qubit is

the target of the CNOT gate. If a photon was absorbed by the transducer qubit in that time bin, the CNOT gate will change the qubit switch from transmissive to reflective. This ensures that when one photon is stored in a quantum register module, any subsequent photons will be stored in the next registers. The CNOT interaction between the transducer qubit and the switch qubit can be implemented in a similar way as the injection of the transducer qubit into the processor via either direct or entanglement-assisted gates depending on the hardware implementation.

Using k modules, our receiver is thus able to map k photons into $k \log_2(N + 1)$ logical qubits. The number of physical qubits required per logical qubit depends on the error rate and code used. For example, quantum low-density parity check codes have been designed that can achieve a physical-to-logical ratio of approximately 10:1 [39]. For the transducer and quantum switch, one physical qubit is required for the transducer and one physical qubit is required for the switch, with one transducer and one switch per single-photon receiver.

Note that our scheme as described so far cannot accommodate multiple photons arriving in the same time bin since our qubit switch can interact only with a single photon at a time. In other words, we are able to map all leading terms of $|\psi_c\rangle$ except the $|\psi_c^2\rangle$ term, which is similar to the unary approach. However, in the weak-signal limit, the probability of simultaneously arriving photons is suppressed by a factor of $1/N$ compared with the probability of two photons arriving in different time bins ensuring that such error is suppressed as the code-word length increases. In general, for fixed $k \ll N$, terms with simultaneously arriving photons are suppressed with N relative to the single photon per time bin terms.

For strong signals, the use of spatial splitting can separate simultaneously arriving photons. This breaks the received signal up into multiple channels that are each in the weak-signal limit discussed above. The states incident on the receiver can be separated with the use of 50:50 beam splitters. To split the input into m spatial modes, $m - 1$ beam splitters are required. Each output mode would be routed to a single-photon receiver, requiring m single-photon receivers. This approach comes at the cost of more qubits and more complicated decoding, as the projectors and measurements must now be determined across multiple receivers.

Our receiver provides a logarithmic scaling for the number of qubits with N , as opposed to the linear scaling of a unary encoding. The scaling factor will depend linearly on the number of expected photons received (k) and the number of physical qubits per logical qubit. The scaling difference with the unary encoding is particularly important in the weak-field regime, where the mean photon number per time bin is low such that only a few received photons are expected over the entire code word. Considering a code word of length N , and an expected mean

photon number per time bin at the receiver of α^2 , our receiver would require $N\alpha^2 \log_2(N + 1)$ qubits, while the unary encoding receiver would always require N qubits. The values of α received for a practical system depend on trade-offs with peak power, band width, aperture size, and cost as mentioned in Sec. II A. If a system is designed such that $N \sim 100$ and $\alpha^2 \sim 0.01$, our receiver offers an order of magnitude reduction of the qubit resources. However, in other regimes, the unary encoding might be more favorable.

C. Successive cancellation decoding

Once the photonic states are mapped to the quantum processor, quantum gates can be used to decode the stored information (see the “decoding” step in Fig. 1). Finding the optimal decoding strategy is, in general, a nontrivial task. Yet for polar codes, it was shown in Ref. [14] that quantum successive cancellation decoding can saturate the Holevo bound in the asymptotic limit. It is not known how to implement such a decoding with direct photon detection. However, once the photonic state is mapped into qubit registers, quantum logic operations can be used to perform the decoding. We show a general procedure for implementing this decoder with quantum logic following the photonic-to-qubit mapping in our quantum receiver. We detail the decoding scheme for $N = 4$ and $N = 8$. While the procedure for decoding higher N is the same, we note that there is no general formulation for the polar code construction for arbitrary N . This is because the polarizing transformation is not stepwise and isotropic [40] with the channels it acts on. However, efficient constructions for good classical polar codes for higher N have been devised [41], and are likely to be generalizable for quantum polar codes.

The general idea behind the SC decoding is to perform successive joint measurements on the processor qubits. Each measurement decodes a single bit, and the next measurement is conditioned on the results of the preceding ones. Each bit decision eliminates half of the (remaining) code words. The measurements are, in general, projections onto multiqubit entangled states. We provide the specific projections for $N = 4$ and $N = 8$ in the Supplemental Material [42]. The general decoding circuit and decision tree for $N = 4$ are shown in Figs. 2 and 3, respectively.

As an illustrative example, we consider the decoding of the specific code word of 0001 ($N = 4$). For simplicity, we restrict ourselves to the vacuum and single-photon subspace, where the initial qubit state can be expressed as [with normalization factor $1/(1 + 4\alpha^2)$]:

$$|\uparrow\uparrow\uparrow\rangle - \alpha[|\downarrow\uparrow\uparrow\rangle + |\downarrow\downarrow\uparrow\rangle + |\downarrow\downarrow\downarrow\rangle + |\downarrow\uparrow\downarrow\rangle]. \quad (4)$$

The two controlled Hadamard gates (see Fig. 2) transform the state to

$$|\uparrow\uparrow\uparrow\rangle - 2\alpha|\downarrow\uparrow\uparrow\rangle. \quad (5)$$

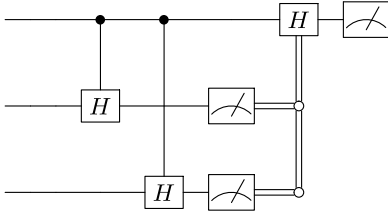


FIG. 2. Decoding circuit for $N = 4$. The double wires with open circles represent classical control conditioned on a measurement outcome of 0. H denotes a Hadamard gate.

The second and third qubits are now measured in the Z basis, with both measurements yielding the outcome “ $|\uparrow\rangle$.” Following the decision tree, an H gate is then applied to the first qubit, resulting in the state

$$\left(\frac{1}{\sqrt{2}} - \sqrt{2}\alpha\right)|\uparrow\rangle + \left(\frac{1}{\sqrt{2}} + \sqrt{2}\alpha\right)|\downarrow\rangle. \quad (6)$$

The probability of measuring “ $|\downarrow\rangle$ ” and correctly decoding 0001 is therefore $(2\alpha^2 + 2\alpha + 0.5)/(4\alpha^2 + 1)$. Notably, if the outcome “ $|\uparrow\rangle$ ” is obtained, the decoding is unsuccessful: the receiver decides that 0000 was sent rather than 0001. As the length of the code word increases, the decision error probability becomes very small, as shown in Ref. [21]. To maximize the communication rate, code words are assigned according to the relative likelihood (the input distribution) of the input strings. In practical scenarios, the code words might encode symbols, for example, letters in the English language. Since “e” is the most frequent letter in English, the code word with the smallest decision error would be assigned to “e.” To calculate the

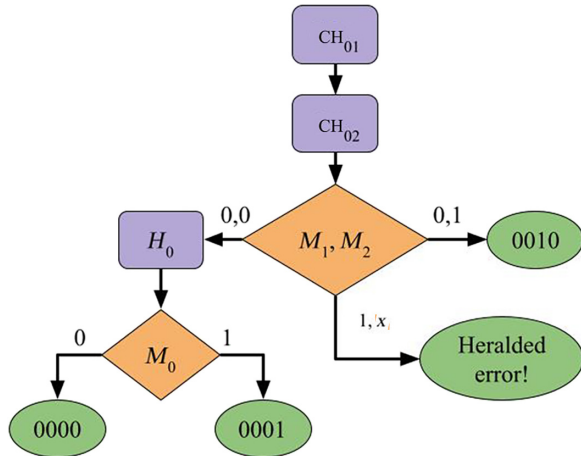


FIG. 3. A decision tree to decode the message for $N = 4$. M_i represents a measurement of qubit i in the Z basis. The binary labels denote measurement outcomes. CH_{ij} is a controlled Hadamard gate with qubit i as the control and qubit j as the target. H_i is a Hadamard gate on qubit i . “0” corresponds to outcome “ $|\uparrow\rangle$ ” and “1” corresponds to outcome “ $|\downarrow\rangle$ ”.

TABLE I. Decoding table for $N = 4$ and $K = 2$. The optimal distribution has only three code words with nonzero input probability. The optimal distribution is given in the Supplemental Material [42]. “0” corresponds to outcome “ $|\uparrow\rangle$ ” and “1” corresponds to outcome “ $|\downarrow\rangle$ ”.

Qubit 0	Qubit 1	Qubit 2	Decision
0	0	0	0000
1	0	0	0001
0, 1	0	1	0010
0, 1	1	0, 1	Error

maximum achievable rate, or capacity, it is necessary to optimize over the input distribution of code words. We refer the reader to Sec. III and the Supplemental Material [42] for further details on this optimization. Table I provides a decoding table that can be used to decide on the transmitted message given the measurement results.

The depth of the circuit for the compression step scales as approximately $N \log_2 N$. In the decoding step, there are approximately $\log_2 N$ input qubits. An arbitrary q qubit unitary can be implemented by a circuit depth of $O(4^q)$ [43], which in our case with $q = \log_2 N$ is $O(N^2)$. Even if the decoding requires processing and measuring out each qubit individually, the depth is upper bounded by approximately $N^2 \log_2 N$ in the worst case. Overall, the processing circuit scales as $O(N^2 \log_2 N)$ in the worst case.

III. RECEIVER PERFORMANCE

From the classical-quantum polar code construction in Ref. [14], we determined the SC decoding projectors for $N = 2$, $N = 4$, $N = 8$, and code rates of $\frac{1}{2}$. From these projectors, we calculated the photon information efficiency (PIE) for the code and receiver scheme. PIE, in bits per photon, is the average number of bits of information that can be reliably transmitted in each photon and is calculated by dividing the channel information rate [44] by the mean photon number of the received pulse. We focus on small code lengths and the weak-signal limit ($\alpha \ll 1$) to investigate the onset and robustness of superadditivity.

The projectors used in the performance analysis are designed for the vacuum and single-photon subspace. Nonetheless, we do include the multiple-photon contributions, assuming that they lead to noninformative measurement outcomes corresponding to a uniform guess probability of the input message. While this design of the quantum receiver is suboptimal, we do not expect any significant degradation of the performance in the weak-field limit (because the probability of higher photon number events is relatively small), while it significantly relaxes the quantum resources for near-term demonstrations.

A. Performance without errors

The PIE for polar codes compared with the best known classical symbol-by-symbol detection with a Dolinar

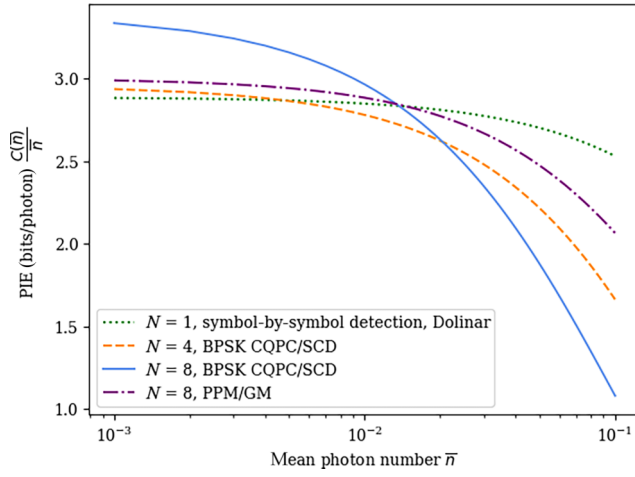


FIG. 4. PIE vs mean photon number for: BPSK classical-quantum polar codes (CQPCs) with a successive cancellation decoder (SCD), symbol-by-symbol detection with a Dolinar receiver, and pulse position modulation (PPM) with a Green Machine (GM).

receiver [45] and a joint-detection Green Machine receiver [11] is plotted versus the mean photon number $\bar{n}$ per time bin in Fig. 4. Already at $N = 4$, we see the onset of superadditivity, where our quantum receiver outperforms the Dolinar receiver for $\bar{n} \lesssim 0.4\%$. Furthermore, at $N = 8$, our quantum receiver surpasses the best performance of the Green Machine receiver for a comparable 8-ary pulse position modulation (PPM) encoding [11] for $\bar{n} \lesssim 1\%$. This shows that even for finite-length code words, our quantum receiver is able to surpass the performance of the best known classical decoders in the weak-field limit. As the code-word length increases, larger gains are expected, but quantifying this requires the identification of larger polar codes, which is beyond the scope of this work. However, we note that Ref. [14] shows that the ultimate Holevo limit is achievable in the asymptotic limit of infinitely long code words and the SC decoder.

B. Performance with errors

Our receiver design has two distinct elements: the photon-to-qubit transducer and the quantum processor. Notably, the former acts on the physical qubit level, where errors from imperfect photon absorption, switch operation, and injection directly degrade the information received from the photonic signal. On the other hand, the latter involves processing the information fault-tolerantly through encoded logical qubits.

To investigate the potential for demonstrations of quantum-processing-enhanced classical communication with near-term quantum hardware, we conceptually distinguish between the physical error rate in the transduction step and the logical error rate of the processor. In our numerical investigations, we perform an optimization of

both the input distribution and α to find the maximum number of bits per photon for a given error rate [46].

It is sufficient for the purposes of this analysis to consider an input pure state $\rho = |\psi\rangle\langle\psi|$, with $|\psi\rangle \in \{\text{polar code words}\}$, because the pure-loss optical channel with BPSK has pure state outputs [14]. The model of the transmission channel as a pure-loss optical channel is an acceptable approximation since photon loss, for instance, from diffraction in free-space propagation, is the dominant source of error for the transmission settings relevant to this work [19,20], as mentioned in Sec. II.

1. Transducer errors

Before the input state is mapped to a fault-tolerant quantum processor, there can be unprotected errors at the physical level in the transducer step. These errors can come from imperfect photon absorption, state injection, and switch operation. The error rates of each of these will depend on the quality of the spin-cavity interfaces [25,26,38], the quality of the CNOT operations between the transducer qubit and the switch qubit, and general state preparation errors and measurement errors. Detailed error modeling of each of these elements can be performed for specific hardware implementations, but to obtain a general estimate of the required error level for demonstrating quantum advantage, we model the effect of these errors as a general depolarizing noise on the injected state in the processor.

By directly injecting the input photonic state into an error-corrected matter qubit, the subsequent time-bin encoding procedure and final decoupling measurement are performed at the level of matter qubits rather than photons, and are protected by the error-correcting code. As such, photonic loss can occur only before absorption or during the physical absorption process itself. Loss before absorption is indistinguishable from transmission loss and acts to reduce the signal amplitude, while loss during absorption manifests itself as spontaneous emission. Treating this process as depolarizing noise provides a conservative lower bound on the receiver performance. The noise model can be modified to account for the biases of specific hardware platforms.

The effects of transducer errors on the PIE are plotted in Fig. 5(a). We see that for physical depolarizing probabilities of up to 0.3%, superadditivity is present. Additionally, as N increases from 4 to 8, we see a change in scaling, with a more rapid decrease in the PIE. Nonetheless, the superadditive gain still increases for a fixed depolarizing probability, showing that as the code-word length increases, higher error rates can be tolerated while maintaining a quantum advantage. A qualitative explanation is that the capacity increases superadditively with the code-word length N , whereas the effective depolarizing error rate of the transduction step grows only approximately

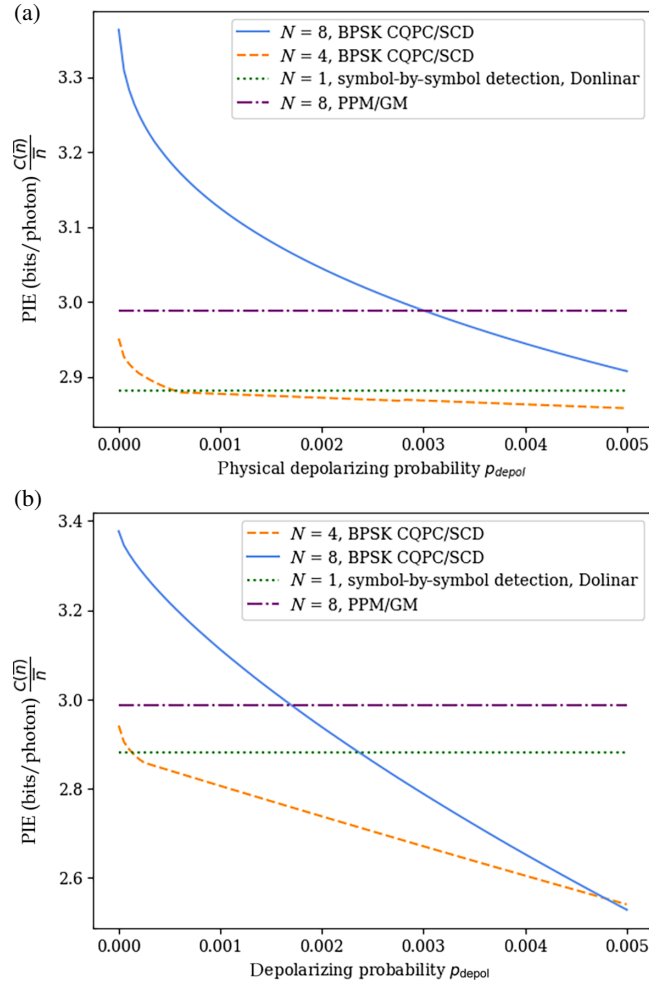


FIG. 5. Receiver performance with (a) transducer errors and (b) gate errors in the compression and decoding steps. The dotted green line denotes the PIE with ideal symbol-by-symbol detection. In (a), we modeled the errors with depolarizing noise at the physical level on the input photonic state. In (b), we used a total depolarizing channel (unbiased Pauli channel) at the logical level for all interactions. CQPC, classical-quantum polar code; GM, Green Machine; SCD, successive-cancellation decoding.

linearly. This occurs because each time bin in the code word, irrespective of whether it contains a photon, undergoes a physical transduction operation, leading to a linear scaling of the effective error rate with N , provided that the per-operation error remains much less than $1/N$.

2. Logical errors

We model the logical quantum gate errors as general Pauli noise channels acting at the logical level on each qubit participating in the gate operation. The encoding and decoding circuit with errors for $N = 4$ is modeled as depicted in Fig. 6. Errors in the compression step are represented by the block labeled “ $\mathcal{E}$.” The faulty binary encoding is modeled as a two-qubit Pauli noise channel on

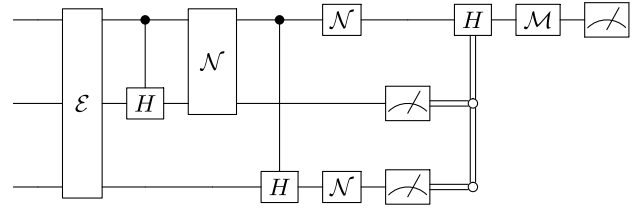


FIG. 6. The $N = 4$ decoding circuit with errors. The faulty photon-to-qubit mapping in the compression step is represented by the block labeled “ $\mathcal{E}$ ” and includes errors in the time-bin binary encoding interactions and in the photon decoupling. Each two-qubit gate in the decoding step is followed by a two-qubit Pauli noise channel ($\mathcal{N}$ block), while single-qubit gates are followed by a single-qubit Pauli noise channel ($\mathcal{M}$ block).

the control qubit that stores the photon arrival information and the target processor qubit after each CNOT interaction. Meanwhile, errors in the photon decoupling operation are modeled with single-qubit Pauli noise channels before the measurement. Further details on the error modeling in the compression step are given in the Supplemental Material [42].

In the decoding step, each two-qubit gate is followed by a two-qubit Pauli noise channel ($\mathcal{N}$ block), while single-qubit gates are followed by a single-qubit Pauli noise channel ($\mathcal{M}$ block). In Fig. 5(b), we plot the performance considering that each error channel consists of independent single-qubit depolarizing channels with error probability p_{depol} . Results for some heuristic correlated error channels are presented in the Supplemental Material [42], but we found little variation in the performance under the different error models. We show the results for unbiased Pauli noise channels as a conservative lower bound on the receiver performance, but the model can be modified to account for biased noise depending on the hardware implementation.

Superadditivity is no longer achieved once errors exceed the permille level for the noise model considered here, but similarly to the transducer errors, we observe that the performance still increases with N for a fixed error probability, which we assign to the interplay between the superadditive gain and the roughly linear increase in overall error probability with N .

Performing a numerical simulation with transduction and logical errors, we find that a quantum receiver with four logical qubits and a physical error in the transducer step of approximately 0.3% or with quantum gate errors of approximately 0.2% can provide a 5% gain in communication rate in the weak-signal limit. Experimentally achieved error rates for spin-photon cavity systems are at the percent level and have clear paths to improve performance [47–49]. Additionally, physical qubit-gate errors below 0.1% have been demonstrated with trapped-ion processors [50], indicating that first demonstrations of quantum advantage might not require logical encoding.

IV. CONCLUSION AND OUTLOOK

In conclusion, we have designed and analyzed a receiver that makes an entangling measurement over multiple modulated laser-light pulses and achieves superadditive communication capacity better than, to our knowledge, any known classical receiver, and is, in principle, capable of attaining the Holevo limit of capacity, using the quantum polar code and a quantum processor. Our receiver protocol provides a general framework in which the multiphoton manifold of coherent-state-modulated optical communications can be mapped effectively to matter qubits. Quantum gates are then performed on the matter qubits to decode the received message. To our knowledge, this is the first superadditive-capacity receiver design with a subexponential scaling in the number of its operations with code-word size [51], and to concretely address how to transfer coherent optical signals into matter qubits in order to utilize a discrete variable paradigm of quantum information processing [52].

Our receiver consists of two stages: a physical transduction stage and a logical processing stage. We have outlined how the transducer can be implemented with efficient spin-photon interfaces such as atoms and solid-state defect systems in optical cavities. Through optically mediated quantum teleportation, the transferred information can then be injected into a quantum processor based on either the same platform or a different platform, offering significant flexibility in the design of the receiver. Our error analysis indicates that error rates below 0.3% in the transduction step or gate errors below 0.2% in the quantum processing will be required for first demonstrations of superadditivity, which is within reach of near-term hardware.

We have established an efficient quantum receiver architecture and provided a quantitative characterization of how realistic operational noise impacts superadditivity in quantum-assisted classical communications. Further research is needed to make quantum-assisted classical communications of practical use, and our work points to several fruitful directions to be addressed. To extend this work, we note that the gate errors in the quantum receiver effectively create a “super channel” on top of the pure-loss bosonic channel originally considered for classical-quantum polar coding [21]. The Holevo-Schumacher-Westmoreland theorem implies that Holevo-bound-achieving codes for this noisy channel can be realized with use of a random-code construction [53,54] or with use of the general polar-coding technique applied to mixed-state modulation symbols [21], which would be interesting to pursue.

In addition, our decoder, in general, requires non-Clifford gates. While work has been done on the efficacy of non-Clifford states and gates on the *quantum* capacity of particular quantum channels [55], the necessity and sufficiency of non-Clifford operations at the receiver for

a classical-quantum channel remains, to our knowledge, unexplored. This line of inquiry builds on similar questions raised in terms of the role of non-Gaussian operations in the continuous-variable setting, for all-photon designs of Holevo-capacity-achieving receivers [56].

Another unsolved problem of paramount practical importance is how the optical communication capacity, in the low mean photon flux regime ($\bar{n} \ll 1$), scales with the code block length N over which the quantum joint-detection receiver acts. Even for the BPSK modulation alphabet of mean received photon number $\bar{n}$ per mode considered in this paper, we know the capacity expressions only for $C_1(\bar{n}) = 1 - h_2([1 - \sqrt{e^{-4\bar{n}}}] / 2)$ and $C_\infty(\bar{n}) = h_2([1 - e^{-2\bar{n}}] / 2)$, corresponding to $N = 1$ (symbol-by-symbol receiver measurement, Dolinar receiver being optimum) and $N = \infty$ (Holevo limit), respectively. Quantifying the optimal increase of $C_N(\bar{n})$ with N (for relatively small values of N) and achieving C_N with an appropriate code and a generalization of our proposed receiver design is an important future research direction.

Finally, we note that the photon-to-quantum-processor map that forms the core of our receiver design can be applied to various other use cases of photonic quantum information processing at the quantum limit, such as squeezed-light-enhanced parameter estimation [57], object classification using a quantum-radar transmitter [58], and quantum-assisted reading from a classical optical memory [51].

ACKNOWLEDGMENTS

We thank Wastu Wisesa Ginanjar for assistance in the early stages of the project and Babak Saif and Nickholas Gutierrez for useful discussions. J.B. acknowledges support from the AWS Quantum Discovery Fund at the Harvard Quantum Initiative. S.G. acknowledges NASA for funding support. K.W.S. acknowledges support from the Natural Sciences and Engineering Research Council of Canada through a PGS D fellowship.

This material is based upon work supported by the Under Secretary of Defense for Research and Engineering under Air Force Contract No. FA8702-15-D-0001 or Contract No. FA8702-25-D-B002. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Under Secretary of Defense for Research and Engineering.

DATA AVAILABILITY

The data that support the findings of this article are available from the authors upon request.

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