Quantum phase communication channels in the presence of static and dynamical phase diffusion

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We address quantum communication channels based on phase modulation of coherent states and analyze in details the effects of static and dynamical (stochastic) phase diffusion. We evaluate mutual information for an ideal phase receiver and for a covariant phase-space-based receiver, and compare their performances by varying the number of symbols in the alphabet and/or the overall energy of the channel. Our results show that phase communication channels are generally robust against phase noise, especially for large alphabets in the low energy regime. In the presence of dynamical (non-Markovian) noise the mutual information is preserved by the time correlation of the environment, and when the noise spectra is detuned with respect to the information carrier, revivals of mutual information appear.

I. INTRODUCTION

The transmission of classical information along an ideal bosonic quantum channel is optimized by encoding information onto Fock number states, according to a thermal distribution, and then retrieving this information by the measurement of the number of photons [1,2]. This strategy allows to achieve the ultimate channel capacity, i.e. to maximize the mutual information between the sender and the receiver, given a constraint on the overall energy sent through the channel, thus outperforming other encoding/decoding scheme involving different degrees of freedom of the radiation field, e.g. the amplitude or the phase.

If we take into account the unavoidable noise affecting the information carriers along the channel, the situation becomes more involved and a question arises on whether different coding/encoding schemes may offer better or comparable performances. Indeed, in the presence of a phase insensitive noise, e.g. amplitude damping, also coherent coding has been shown to achieve the ultimate channel capacity [3,4].

In this paper, we address communication channels based on phase encoding [6,8] and analyze in details their performances in the presence of phase diffusion, which represents the most detrimental kind of noise affecting this kind of channel [9,10]. In particular, we will consider communication schemes where the information is encoded by modulating the phase of a coherent signal, which then travels through a phase-diffusing environment before arriving at the receiver station and being detected. We consider two different environment models in which phase noise is either induced by a stationary environment inducing a static noise, or by a fluctuating one.

A schematic diagram of a quantum phase communication channel is depicted in Fig. 1. The sender encodes a finite number $N$ of symbols using $N$ different values of a phase shift $\phi_k$, where $\phi_k < \phi_j$ if $k < j$ and $0 \leq k < N$. We assume a choice of equidistant phase values $\phi_k = 2\pi k/N$. The phase $\phi_k$ is encoded onto a seed state $\rho_0$ of a single-mode radiation field by the unitary phase-shift operation $U(\phi) = \exp(i\phi a^\dagger a)$, $a$ being the annihilation operator, $[a, a^\dagger] = 1$, namely:

$$\rho_0 \rightarrow \rho_k \equiv U(\phi_k)\rho_0 U^\dagger(\phi_k).$$

The signal then propagates along the channel to the receiver station, where it is detected by a suitable measurement scheme in order to retrieve the information it carries. More explicitly: the receiver performs a phase measurement on the output.
The positive operator-valued measure (POVM) \( \Pi \) denoted the value of the resolution function, falling into a bin \( j \), which follows the symmetries of the resolution function, \( f_{\text{r}}(\phi_j) \). The combination of Eqs. 4 and 5 brings to an explicit form of the POVM \( \Pi_j \), given by

\[
\Pi_j = \sum_{n,m=0}^{\infty} A_{n,m} f_{n-m}(j) |n\rangle \langle m| \tag{6}
\]

where the structure of the POVM is determined by the resolution function

\[
f_d(j) = \frac{1}{2\pi} \int_{\phi_j - \Delta}^{\phi_j + \Delta} e^{-i\theta} d\theta = \frac{\sin \Delta}{\pi d} e^{-i\phi_j}, \tag{7}
\]

with the property \( \sum_{j=1}^{N} f_d(j) = \delta_{d,0} \), where \( \delta \) is the Kronecker delta.

The figure of merit to assess the performances of a communication channel is the mutual information between sender and receiver. This quantity measures the amount of information shared by the two parties and can be written as

\[
I = \sum_{k,j=0}^{N-1} p(k,j) \log_2 \frac{p(k,j)}{p(k) p'(j)}
\]

\[
= \sum_{k,j=0}^{N-1} p(j|k) p(k) \log_2 \frac{p(j|k)}{p'(j)}, \tag{8}
\]

where \( p(j|k) \) is the conditional probability of measuring a phase \( \phi_j \) given the input phase \( \phi_k \); \( p(k) \) is the \( a \ priori \) probability distribution of transmitting a \( \phi_k \)-encoded seed state; \( p(k,j) = p(j|k) p(k) \) is the joint probability to send the symbol \( \phi_k \) and obtaining the outcome \( \phi_j \) and, finally, \( p'(j) \equiv p'(\phi_j) \) is the probability of the outcome \( \phi_j \), given by \( p'(j) = \sum_{k=0}^{N-1} p(j|k)p(k) \).

Maximization over the probability \( p(\phi_k) \) leads to the so-called channel capacity, i.e. the maximum information transmitted through the channel per use. In particular, we analyze the case of uniform encoding probability, \( p(k) = N^{-1} \), i.e. the letters have the same probability to be sent through the channel. The conditional probability of an outcome \( \phi \) falling in the bin \( \Xi_j \) given the initial state \( \rho_k \) is

\[
p(\phi \in \Xi_j | \rho_k) \equiv p(j|k) = \text{Tr}[\rho_k \Pi_j]. \tag{9}
\]

Under these conditions, the mutual information reduces to

\[
I = \frac{1}{N} \sum_{k,j=0}^{N-1} \text{Tr}[\rho_k \Pi_j] \log_2 \left\{ \frac{\text{Tr}[\rho_k \Pi_j]}{N^{-1} \sum_{k=0}^{N-1} \text{Tr}[\rho_k \Pi_j]} \right\}. \tag{10}
\]

By using the covariance property of the POVM and its explicit form given in Eq. 6, the conditional probability can be expressed as

\[
p(j|k) = \text{Tr}[\rho_k \Pi_j] = \text{Tr}[\rho_0 \Pi_{j-k}]
\]

\[
= \sum_{n,m=0} A_{n,m} f_{n-m}(j-k) \rho_{n,m}. \tag{11}
\]

Note that \( \sum_{k} p(j|k) = \sum_k \text{Tr}[\rho_k \Pi_j] = 1 \), which follows from the symmetries of the resolution function, \( f_{-d}(j) = \ldots \).
where we introduced the rescale time \( \tau = \Gamma t \). One can easily see that the diagonal elements \( \rho_{n,n} \) are unaffected by the phase noise, thus, energy is conserved, whereas the off-diagonal elements decay away exponentially.

In the rest of our paper we assume that the input seed is a coherent state of the radiation field, namely, \( \rho_0 = |\alpha\rangle \langle \alpha| \) with:

\[
|\alpha\rangle = e^{-|\alpha|^2/2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle ,
\]

Without lack of generality, we assume \( \alpha \) to be real. The density matrix elements associated with the initial coherent state \( \rho_0 \) are

\[
\rho_{n,m} = e^{-\bar{n}/2} \frac{\Gamma(n+m)/\sqrt{n!m!}}{(n+m)!},
\]

where \( \bar{n} \equiv \alpha^2 \) is the average number of photons of the coherent state \( \rho_0 \). Exploiting Eq. (16), we find that the state arriving at the receiver after the propagation through the noisy channel has the following density matrix elements:

\[
\rho_{n,m} \to \rho_{n,m}(t) = e^{-\frac{\tau}{2}(n-m)^2} \rho_{n,m},
\]

which can be used to evaluate the mutual information as written in Eq. (12) once the POVM describing the measurement is given and, thus, the \( f_{n-m}(s) \) are assigned.

The POVM describing the ideal (canonical) measurement is obtained from Eq. (4) with \( A_{n,m} = 1, \forall n,m \). In turn, the probability \( q(s) \) after the phase diffusion process reads:

\[
q_c(s) = \frac{1}{N} \left\{ 1 + 2e^{-\bar{n}} \sum_{n=0}^{\infty} \sum_{d=1}^{\infty} \text{sinc} \left( \frac{\pi d}{N} \right) e^{-\frac{1}{2}d^2\tau} \times \cos \left[ \frac{\pi d}{N} \left( 2s + 1 \right) \frac{\bar{n} + d/2}{\sqrt{n!(n+d)!}} \right] \right\},
\]

where \( \text{sinc}(x) = \sin(x)/x \). The quantum mutual information \( I_Q \) directly follows from Eq. (12).

The probability \( q_Q(s) \) for the \( Q \)-measurement process is obtained using \( A_{n,m} = \Gamma(1 + \frac{d}{2}(n + m))(n!m!)^{-\frac{1}{2}} \):

\[
q_Q(s) = \frac{1}{N} \left\{ 1 + 2e^{-\bar{n}} \sum_{n=0}^{\infty} \sum_{d=1}^{\infty} \text{sinc} \left( \frac{\pi d}{N} \right) e^{-\frac{1}{2}d^2\tau} \times \cos \left[ \frac{\pi d}{N} \left( 2s + 1 \right) \frac{\bar{n} + d/2}{n!(n+d)!} \right] \right\},
\]

The corresponding mutual information \( I_Q \) is again obtained using Eq. (12).

In the upper panels of Fig. 2 we show the mutual information as a function of the rescaled time variable \( \tau \), which plays the role of a noise parameter, for ideal (upper left panel) and \( Q \) (upper right panel) phase-receivers and for different values \( \bar{n} \) of the average number of photons of the seed state. The size of the alphabet is set to \( N = 20 \). As it is apparent from the

The function \( q(s) \) measures the probability of finding a \( 2\pi s/N \) phase difference between the input and output signal, whatsoever value the encoded phase may assume.

The function \( q(s) \) and thus the performances of the communication channel do depend on the measurement performed by the receiver through the matrix \( \{A_{n,m}\} \) and on the seed state via the matrix elements \( \rho_{n,m} = \langle n|\rho_0|m\rangle \). In the following, we will focus on two particular phase measurements: the canonical phase measurement [11–15] and a phase-space-based one, i.e. the marginal phase distribution obtained from the Husimi Q-function [16, 25]. The latter is a feasible phase measurement achievable, e.g., by heterodyne or double-homodyne detection. For the canonical measurement we have \( A_{n,m} = 1 \), whereas for the \( Q \)-measurement \( A_{n,m} = \Gamma[1 + \frac{1}{2}(n + m)](n!m!)^{-\frac{1}{2}} \), \( \Gamma[x] \) being the Euler Gamma function.

III. QUANTUM PHASE COMMUNICATION CHANNELS IN THE PRESENCE OF STATIC PHASE DIFFUSION

In this section we address quantum phase communication channels in the presence of phase diffusion, and start by considering situations where the environmental noise is static. Any phase communication channel is based on the observation that the optical field produced by a laser provides a convenient quantum system for carrying information. In particular, coherence of laser source ensures that a well-defined phase can be attributed to a light mode. Still, the unavoidable presence of noise generates a phase diffusion, which ultimately limits the coherence of the light. The master equation governing the evolution of the light beam in a static phase diffusing environment may be written as [10, 26]:

\[
\frac{d}{dt} \rho = \frac{\Gamma}{2} \mathcal{L}[a^\dagger a] \rho ,
\]

where \( \mathcal{L}[O] = 2O \rho O^\dagger - O^\dagger O \rho - \rho O^\dagger O \) and \( \Gamma \) is the static phase noise factor. An initial state \( \rho(0) \) evolves with time as

\[
\rho(t) = \sum_{n,m=0}^{\infty} e^{-\frac{\tau}{2}(n-m)^2} \rho_{n,m} |n\rangle \langle m| ,
\]
plots, phase diffusion leads to an unavoidable loss of information. The mutual information $I_Q$ for $Q$ receivers shows the same vanishing behavior in time as the ideal one $I_C$, though its value is always slightly smaller. In order to provide a quantitative assessment we show their ratio $I_Q/I_C$ in the lower panel of the same figure, as a function of $\tau$ for different values of $\bar{n}$. The ratio is always below one, thus confirming that $Q$ receivers are not as efficient as the ideal ones. The ratio slightly increases with time, i.e., for long distance channels, and with the energy of the seed signal.

In order to further assess the performances of phase channels we now compare the mutual informations $I_C$ and $I_Q$ with the capacity of a (realistic) coherent channel and with the ultimate quantum capacity of a single-mode channel, which is achieved by the photon number channel

$$C_{PHN} = (\bar{n} + 1) \log_2(\bar{n} + 1) - \bar{n} \log_2 \bar{n},$$

(23)

where information is encoded onto the number of quanta transmitted through the channel according to a thermal distribution, and the decoding stage is performed by photodetection.

At first, let us address noiseless phase channels and consider, for both receivers, the ratio between the corresponding mutual information and the ultimate capacity, i.e., $\gamma_C = I_C/C_{PHN}$ and $\gamma_Q = I_Q/C_{PHN}$. The two quantities are reported in the upper left panel of Fig. 3 as a function of the number of symbols in the phase alphabet, and for different values of the average number of photons $\bar{n}$. The plots reveal that an alphabet of about $N \approx 50$ symbols is enough to reach the asymptotic value of both ratios, and in turn of $I_C$ and $I_Q$. Also, the plots show that the ratio with the ultimate capacity is comparable to that of noiseless coherent channels, with ideal phase receivers slightly outperforming the coherent channel and the $Q$ one being slightly outperformed. Using this size of the alphabet, we have evaluated $\gamma_C$ and $\gamma_Q$ as a function of the average photon number $\bar{n}$. Results are shown in the upper right panel of Fig. 3 confirming that phase channels with ideal receivers performs slightly better than coherent ones, whereas $Q$ receivers lead to slightly worse performances.

Let us now compare phase channel with coherent ones in the presence of noise. In the lower panels of Fig. 3 we show the ratios $\beta_k = I_k/C_{COH}$, $k = C, Q$ between the mutual information of our phase channels and the capacity of the coherent channel as a function of the noise parameters, $\tau$ and $\eta$ of the two channels. Results for different values of the average number of photons $\bar{n}$ are shown. In both cases an energy-dependent threshold on the amount of noise appears, above which phase channels become more effective than coherent ones.

Finally, let us discuss the performances of the two receivers in the relevant quantum regime of low number of photons, $\bar{n} \ll 1$, and large number of letters, $N \gg 1$. As it can be argued from the upper right of Fig. 3 both $I_C$ and $I_Q$ grow linearly with $\bar{n}$ for $\bar{n} \ll 1$, and this resembles the behaviour of both the coherent capacity and the ultimate quantum capacity. This means that, albeit being suboptimal, phase channels offer good performances when low energy should be transmitted through the channel. This finding can be confirmed by expanding the mutual information up to the first order in the average photon number of the seed signal, arriving at the expressions

$$I_{ID} \approx \frac{\bar{n} \sin^2(\bar{n})}{\log 2} e^{-\tau} N \gg 1 \bar{n} e^{-\tau}$$

(24)

for the ideal measurement and

$$I_Q \approx \frac{\pi \bar{n} \sin^2(\bar{n})}{4} e^{-\tau} N \gg 1 \frac{\pi \bar{n} e^{-\tau}}{4 \log 2}$$

(25)

for the $Q$-receiver one, their ratio approaching the limiting value of $\pi/4$. 

![FIG. 2: (Color online) Phase communication channels in the presence of static phase diffusion. The upper panels show the mutual informations for the ideal receiver $I_C$ (left) and the $Q$ one $I_Q$ (right) as a function of the noise parameter $\tau = \Gamma t$ for different values of the average number of photons: from bottom to top, $\bar{n} = 1$ (dashed blue), $\bar{n} = 2$ (dotted orange), and $\bar{n} = 3$ (solid green). We set the alphabet size to $N = 20$. The lower panel shows the ratio $I_Q/I_C$ as a function of $\tau$ for different values of the average number of photons: from bottom to top, $\bar{n} = 1$ (dashed blue), $\bar{n} = 2$ (dotted orange), and $\bar{n} = 3$ (solid green).](image-url)
FIG. 3: (Color online) The upper left panel shows the ratios $\gamma_C$ (symbols joined by solid lines) and $\gamma_Q$ (symbols joined by dotted lines) as a function of the number of symbols in the alphabet for noiseless phase channels ($\eta = 1$). Red circles correspond to $n = 1$, blue squares to $n = 2$ and green triangles to $n = 3$. Solid lines are the ratios $C_{\text{corr}}/C_{\text{PHN}}$ for the same three values of $n$ (from bottom to top) with the same color code. The upper right panel shows the ratios $\gamma_C$ (dotted red), $C_{\text{corr}}/C_{\text{PHN}}$ (solid black) and $\gamma_Q$ (dashed blue) for noiseless channels as a function of $n$ and for a fixed value of $N = 50$. The lower panels show the regions $\beta_C > 1$ and $\beta_Q > 1$, respectively, as functions of $\tau = \Gamma t$ and $\eta$. From left to right we have the regions corresponding to $n = 1, 2, 3$ (green, orange and blue, respectively). When $\beta_k > 1$, the phase channels become more effective than coherent ones. The boundary of each region singles out an energy-dependent threshold on the noise parameters.

IV. DYNAMICAL PHASE DIFFUSION

In many experimental situations, the exchange of information between sender and receiver takes place in noisy environments which cannot be described in terms of a Markovian master equations. In such cases, a full quantum description of the interaction may be inconvenient, as the approximations needed to obtain solvable dynamical equations could preclude the study of interesting features of the dynamics itself. On the other hand, when the exact quantum description is not achievable, it is still possible to model the interaction by classical stochastic fields (CSF), which happen to be reliable models of quantum environments, especially when the noise presents classical features, e.g. a Gaussian noise. Moreover, the use of a CSF also gives the chance to analyze in a simple way the role of the correlation time of the environment, and the influence on the dynamics of the presence of a detuning between the mode playing the role of information carrier and the central (natural) frequency of the environment.

In the following, we consider a generalized phase diffusion model corresponding to the quantum map

$$\rho(\tau) = \int_{-\infty}^{\infty} \frac{d\phi}{2\pi} e^{-\frac{s^2}{2\sigma(\tau)}} U(\phi)\rho(0)U^\dagger(\phi),$$

(26)

where $\sigma(\tau)$ is a time-dependent variance, summarizing the dynamical properties of the environment, and, for convenience, we still use the rescaled time $\tau = \Gamma t$. The static environment of the previous Section is recovered for $\sigma(\tau) = \tau$. The quantum map (26) turns the input state $\rho_k$ into a statistical mixture of states with a time-dependent Gaussian distribution of the phase around the original phase $\phi_k$. The time dependence of $\sigma(\tau)$ is linked to the correlation function of the underlying stochastic noise as follows

$$\sigma(\tau) = \int_0^\tau ds_1 \int_0^\tau ds_2 \cos[\delta(s_1 - s_2)] K(s_1, s_2),$$

(27)

where $K(s_1, s_2)$ is the correlation function of the specific CSF chosen to describe the noise and $\delta = (\omega_0 - \omega)/\Gamma$ is the rescaled detuning between the carrier frequency $\omega_0$ and the central frequency of the environmental spectrum $\omega$. In this paper, we focus on the noise generated by the Ornstein-Uhlenbeck process with a Lorentzian spectrum and correlation function

$$K(\tau_1, \tau_2) = \frac{1}{2\lambda \tau_E^{-1}} \exp[-|\tau_1 - \tau_2|/\tau_E],$$

where $\tau_E$
is the characteristic time of the environment and $\lambda$ is the dynamical phase noise factor, rescaled with $\Gamma$. In this case, $\sigma(\tau)$ is given by

$$
\sigma(\tau) = \frac{\lambda}{[1 + (\delta \tau_E)^2]^{1/2}} \left\{ \tau - \tau_E + (\delta \tau_E)^2(\tau + \tau_E) + \tau_E e^{-\tau/\tau_E} \left[ (1 - (\delta \tau_E)^2) \cos \delta \tau - 2 \delta \tau_E \sin \delta \tau \right] \right\}.
$$

Equation (28) confirms that the quantum map (26) is the solution of the Markovian master equation for a static phase-diffusing environment, upon setting $\lambda = 1$. In this case the environment is characterized by a very short correlation and the stochastic field describes a Markovian interaction. The corresponding dynamics of mutual information approaches that illustrated in Fig. 2.

If the environment shows non-zero correlation time the dynamics of mutual information may be dramatically altered, showing either a different decay rate or the appearance of oscillations. In the following we first analyze the case of a resonant environment with zero detuning $\delta = 0$ and then focus attention to nonresonant situations. In both cases, the probabilities $q_k(s), k = C, Q$ are still given by Eqs. (20) and (21) with the replacement

$$
\exp \left(-\frac{1}{2} d^2 \tau\right) \rightarrow \exp \left[-\frac{1}{2} d^2 \sigma(\tau)\right].
$$

Let us start with the case of a resonant environment ($\delta = 0$). Under such condition, $\sigma(t)$ reduces to

$$
\sigma(\tau) = \lambda \left[ \tau - \tau_E (1 - e^{-\tau/\tau_E}) \right]
$$

and the channel appears to be more robust against the effects of noise, at least for a short time dynamics, compared to the static case. In order to illustrate this feature, in Fig. 4 we show the mutual informations $I_C$ and $I_Q$ as a function of $\tau$ for different values of $\tau_E$. As it is apparent from the plot, the presence of a non-zero correlation time of the environment $\tau_E$ better preserves mutual information against phase diffusion for both ideal and $Q$ receiver. As it happens in the static case the mutual information vanishes with time. However, a time-correlated environment allows a "concave dynamics" of the mutual information, which lasts longer, the higher is the correlation time. This behaviour is due to the transition from linear to quadratic behaviour of $\sigma(\tau)$, see Eq. (30), which may be observed for increasing $\tau_E$. We also show the mutual information for the static case (solid green line) for comparison. In the lower panel of the same Figure we report the ratio $I_Q/I_C$ as a function of $\tau$. Upon comparing this plot with the lower panel of Fig. 2 we conclude that dynamical noise is more detrimental for $Q$ receivers than for ideal ones.

Let us now analyze the effects of detuning between the frequency of the information carrier and the central frequency of the CSF. It is possible to see from the upper panels of Fig. 5 the dynamics of the mutual information is strongly affected by the detuning for both kind of receivers. On the one hand, the detuning contributes to the significative slowdown of the damping of mutual information and, on the other hand, it is responsible for the appearance of revivals of mutual information, which can be interpreted as a sign of a backflow of information caused by the non-Markovian effect of the detuned dynamical map. Yet, the contourplots of mutual information, shown in the lower panels of the same Figure, reveal that the presence of revivals is also related to the correlation time of the environment. In the left panel, we show that for fixed correlation time of the environment $\tau_E = 1$ revivals appear only for particular values of detuning $\delta$. In the right panel, we show that for fixed value of detuning $\delta = 5.5$ revivals appear beyond a threshold value of the correlation time of the environment.
V. CONCLUSIONS

We have analyzed quantum phase communication channels based on phase modulation of coherent states and addressed their performances in presence of static and dynamical phase diffusion by evaluating the mutual information for ideal and realistic phase receivers. In terms of performance, our results show that phase communication channels are robust, especially for large alphabets in the low energy regime, and that their performances are comparable to those of coherent channels in the presence of loss.

In the presence of dynamical (non-Markovian) phase diffusion, phase channels become more robust, the mutual information being preserved by the time correlations of the environment. When the noise spectrum is detuned with respect to the information carrier, revivals of mutual information also appear.

Our results illustrate the potential applications of phase-keyed $M$-ary channels and may be also of interest in other schemes where the information is coded on phase shifts as, for example, in interferometric high-sensitivity measurements.

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