



**Università
degli Studi
di Ferrara**

Università degli Studi di Ferrara

DEPARTMENT OF ENGINEERING

Bachelor's degree in Electronic and Computer Science Engineering

COMMUNICATION NETWORKS

On the Design of Quantum Communication Systems with non-Gaussian States

Candidate:

Federico Forzano

Supervisor:

Chiar.mo Prof. Andrea Conti

Co-Supervisor:

Dott. Ing. Stefano Guerrini

Contents

1	Introduction	1
2	Quantum Mechanics Abstract	3
2.1	Postulates	3
2.1.1	First postulate	3
2.1.2	Second postulate	3
2.1.3	Third postulate	4
2.1.4	Fourth postulate	4
2.1.5	Fifth postulate	4
2.1.6	Sixth postulate	4
2.2	Combining Systems	4
2.2.1	Density operator	5
2.3	Quantized Electromagnetic Field	5
2.3.1	Classical electromagnetic field	5
2.3.2	Quantized electromagnetic field	6
2.3.3	Fock states	7
2.4	QEF States	7
2.4.1	Phase-space description	7
2.4.2	Gaussian states	8
2.4.3	Non-Gaussian states	10
3	Quantum Communication	13
3.1	Quantum Modulation	13
3.1.1	OOK modulation	14
3.1.2	BPSK modulation	14
3.2	Quantum Discriminator	14
3.2.1	Binary quantum state discrimination	15
3.2.2	Optimal discriminator	15
4	Discrimination of Photon Added States	17
4.1	PACS Discrimination	17
4.1.1	Quantum OOK PACS system	17
4.1.2	Quantum BPSK PACS system	18
4.2	PASS Discrimination	20
4.2.1	Squeezed states discrimination	20
4.2.2	PASS discrimination	21
	Bibliography	25

Chapter 1

Introduction

La meccanica quantistica sta aprendo le porte a nuovi modi di comunicare ed elaborare le informazioni. La capacità di comprendere a fondo l'essenza della materia potrà portare, in un futuro molto vicino, a realizzare e progettare tecnologie di prossima generazione con prestazioni notevolmente migliori, in grado di soddisfare le esigenze di un mondo sempre più informatizzato e connesso. Le comunicazioni in tutto ciò rivestiranno un ruolo chiave; studiare ed ottimizzare un sistema di comunicazione efficiente e affidabile risulterà essenziale.

L'obiettivo di questa tesi è quello di analizzare le prestazioni di un optimal binary quantum discriminator in presenza di informazioni codificate con stati quantistici Photon Added. Verranno presentati innanzitutto i principi cardine della meccanica quantistica (capitolo 2), seguiti da una breve rassegna di alcuni strumenti utili ai fini di caratterizzare un sistema di comunicazione basato sull'utilizzo di stati quantistici. Il terzo capitolo riguarderà una rapida presentazione delle modalità comunicazione quantistiche (quantum modulation) e degli aspetti chiave nel riconoscimento dell'informazione (Quantum state discrimination). In questo contesto verrà presentato il discriminatore ottimo per binary systems; ovvero quello che minimizza la distribution error probability (DEP) nel riconoscimento del simbolo trasmesso. Verrà infine analizzato il comportamento di quest'ultimo in presenza di non-Gaussian states di tipo photon added coherent states (PACSs) e photon added squeezed states (PASSs), col fine di ricercare la configurazione ottima di parametri che minimizzi la probabilità d'errore.

Chapter 2

Quantum Mechanics Abstract

In this chapter, a brief overview of quantum mechanics postulates, of the notation and of the essential concept used in this thesis is given. The target of that is to explain to the reader the essential concept, in order to give him the possibility to understand the obtained result.

2.1 Postulates

Like every physics theory, quantum mechanics is built from few essential postulates. In this section are briefly introduced the six Dirac-Von Newman postulates of Quantum Mechanics [1, 2].

2.1.1 First postulate

Postulate 1 (State Representation) *The state of an isolated quantum system is represented by a complex unitary vector in an Hilbert space:*

$$|\psi\rangle \in \mathcal{H}$$

The space of possible states of the system is called state space and it is a separable complex Hilbert space.

Observation *Differently from the classical physics, in quantum mechanics the concept of state of system is introduced. In classical mechanics a system is described by his observables, like position or four-wheeled.*

2.1.2 Second postulate

Postulate 2 (Observables) *Every observables of the system is represented by an Hermitian operator acting on the state space:*

$$\mathcal{M} : \mathcal{H} \rightarrow \mathcal{H}$$

The outcomes of the measurement can only be one of the eigenvalue of the operator \mathcal{M} .

Observation *The possible outcomes of the measurement are real number because \mathcal{M} is self-andjoint.*

2.1.3 Third postulate

Postulate 3 (Born's Rule) *The probability to get the measurement λ_i from the observable \mathcal{M} in the system in state $|\psi\rangle$ is:*

$$\mathbb{P}(\lambda_i) = \langle \psi | \mathcal{P}_i | \psi \rangle$$

where $\langle \psi |$ is the correspondent vector of $|\psi\rangle$ in the dual space of \mathcal{H} and where \mathcal{P}_i is the projection operator of λ_i in the correspondent space.

2.1.4 Fourth postulate

Postulate 4 (Wavefunction Collapse) *The state after measurement of λ_i is $\mathcal{P}_i |\psi\rangle$ (with the necessary normalization):*

$$|\psi'\rangle = \frac{\mathcal{P}_i |\psi\rangle}{\langle \psi | \mathcal{P}_i | \psi \rangle}.$$

2.1.5 Fifth postulate

Postulate 5 (Time Evolution) *The time evolution of an isolated quantum system is given by an unitary operator \mathcal{U} :*

$$|\psi(t)\rangle = \mathcal{U}(t_0, t) |\psi(t_0)\rangle.$$

Observation (Time dependent Shrodinger Equation) *From postulate 5, it is possible to obtain the time dependent Shrodinger Equation:*

$$i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle = H(t) |\psi(t)\rangle$$

where $H(t)$ is the Hemiltonian matrix.

2.1.6 Sixth postulate

Postulate 6 (Composite System) *The state space of a system composed of \mathcal{H}_1 and \mathcal{H}_2 is given by*

$$\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2.$$

2.2 Combining Systems

The last postulate 6 has very important consequences for composite system. It is possible to describe two types of combined systems:

Definition 1 (Product states) *A state $|\psi\rangle \in \mathcal{H}$ with $\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2$ is a pure state if exists $|\psi_1\rangle \in \mathcal{H}_1$ and $|\psi_2\rangle \in \mathcal{H}_2$ such that:*

$$|\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle.$$

A product state represents two states which do not interact; an operation on one of them does not perturb the other.

Definition 2 (Entangled states) *A system that is not in a product state (1), is in an entangled state.*

When a system is in an entangled state it is not possible to characterize the two subsystems with the states vector, although the state vector of the composite system is known.

2.2.1 Density operator

For a more general treatment, the following representation of states is given:

Definition 3 *The state of quantum system is described by a linear operator, called density operator such that:*

$$\Xi : \mathcal{H} \rightarrow \mathcal{H}; \quad \Xi^\dagger = \Xi; \quad \text{tr}\{\Xi\} = 1.$$

According to the definition 3, the postulates 3, 4, 5 can be reformulate as following.

$$\mathbb{P}(\lambda_i) = \text{tr}\{\Xi \mathcal{P}_i\} \quad (2.1)$$

$$\Xi' = \frac{\mathcal{P}_i \Xi \mathcal{P}_i^\dagger}{\text{tr}\{\mathcal{P}_i \Xi \mathcal{P}_i^\dagger\}} \quad (2.2)$$

$$\Xi(t) = \mathcal{U} \Xi(t_0) \mathcal{U}^\dagger \quad (2.3)$$

2.3 Quantized Electromagnetic Field

Electromagnetic field is the main means of communication for contemporary applications, it is important therefor to give its quantum conception. In this section, the representation of quantized electromagnetic field is firstly given, then the Fock's representation of a quantum state is introduced.

2.3.1 Classical electromagnetic field

In a volume $\mathcal{V} \in \mathbb{R}^3$ classical electromagnetic field is determined from Maxwell's equations as a superposition of the cavity modes ([3] quoting [4, 5]). Electric field is given by the well-known expression:

$$\mathbf{e}(\mathbf{r}, t) = - \sum_n p_n(t) \mathbf{u}_n(\mathbf{r}) \quad (2.4)$$

where

$$\mathbf{u}_n(\mathbf{r}) = \mathbf{u}_{n0} e^{i\mathbf{k}_n \cdot \mathbf{r}}$$

and \mathbf{u}_{n0} is determined by the initial condition. The corresponding magnetic field is determined by:

$$\mathbf{h}(\mathbf{r}, t) = \sum_n q_n(t) \nabla \times \mathbf{u}_n(\mathbf{r}) \quad (2.5)$$

and

$$p_n(t) = \frac{dq_n(t)}{dt}. \quad (2.6)$$

The Hamiltonian associated to the n -th mode is given by

$$H_n = \frac{1}{2}[p_n^2(t) + \omega_n^2 q_n^2(t)]. \quad (2.7)$$

Equivalently, it is possible to define the complex variable $a_n(t)$ as

$$a_n(t) = \frac{\omega_n q_n(t) + ip_n(t)}{\sqrt{2\hbar\omega_n}} \quad (2.8)$$

and, using 2.8 in 2.7, it is possible to obtain the following expression of the Hamiltonian:

$$H_n = \hbar\omega_n |a_n(t)|^2. \quad (2.9)$$

2.3.2 Quantized electromagnetic field

The quantization of electromagnetic field is obtained replacing the two quantities $p_n(t)$ and $q_n(t)$ with the Hermitian operators $\mathbf{P}_n(t)$, $\mathbf{Q}_n(t) : \mathcal{H}_n \rightarrow \mathcal{H}_n$ and by imposing the following commutation conditions ([3] quoting [4, 5]):

$$[\mathbf{Q}_n, \mathbf{P}_m] = i\hbar\delta_{n,m}\mathbf{I} \quad (2.10)$$

$$[\mathbf{Q}_n, \mathbf{Q}_m] = 0 \quad (2.11)$$

$$[\mathbf{P}_n, \mathbf{P}_m] = 0. \quad (2.12)$$

Defining the annihilation operator \mathbf{A}_n as

$$\mathbf{A}_n(t) = \frac{\omega_n \mathbf{Q}_n(t) + i\mathbf{P}_n(t)}{\sqrt{2\hbar\omega_n}} \quad (2.13)$$

and the adjoint of \mathbf{A}_n , the creation operator \mathbf{A}_n^\dagger as

$$\mathbf{A}_n(t) = \frac{\omega_n \mathbf{Q}_n(t) - i\mathbf{P}_n(t)}{\sqrt{2\hbar\omega_n}} \quad (2.14)$$

it is possible to describe the Hamiltonian of the system as

$$H_n = \hbar\omega_n \mathbf{A}_n^\dagger \mathbf{A}_n. \quad (2.15)$$

2.3.3 Fock states

In a single mode cavity, it is possible to define the number operator N as

$$N = A^\dagger A. \quad (2.16)$$

Single mode Fock states are the eigenvector of N , i.e the solution of equation:

$$N |n\rangle = n |n\rangle. \quad (2.17)$$

The Fock state $|n\rangle$ represents the quantum state with exactly n photons. It is important to point out that the set of all Fock states forms an orthonormal basis of the Hilbert space \mathcal{H} , so every state Ξ can be expressed as

$$\Xi = \sum_{n,m} c_{n,m} |n\rangle \langle m| \quad (2.18)$$

with

$$c_{n,m} = \langle n | \Xi | m \rangle.$$

Using the representation in Fock basis, it is possible to characterize different types of quantum state of the quantum electromagnetic field. In the following section the states studied are briefly described.

2.4 QEF States

This section characterizes some quantum states of electromagnetic field. These states are helpful for the development of quantum communication and, in a more general way, of quantum networks. It is firstly given a brief introduction to another one tool involved in the description of quantum systems. Secondly, some Gaussian and non-Gaussian states are characterized.

2.4.1 Phase-space description

As seen before in 2.18, a quantum system can be completely described by a density operator Ξ defined in an infinite-dimensional Hilbert space \mathcal{H} , and this operator can be expressed by the Fock representation (3). Sometimes, however, it is convenient to give another representation of state Ξ by means of a complex function introduced by Wigner [6]: the quasi-probability distribution. In this thesis, this representation will be introduced and it will be used to classify the possible states.

Definition 4 (Quantum characteristic function) *The s -order characteristic function $\chi(\xi, s)$, with $\xi, s \in \mathbb{C}$, associated to the quantum state Ξ is defined as:*

$$\chi(\xi, s) = \exp\left\{\frac{s}{2}|\xi|^2\right\} \text{tr}\{\Xi D_\xi\} \quad (2.19)$$

where D_ξ is the displacement operator of parameter ξ , defined as:

$$D_\xi = \exp\{\xi A^\dagger - \xi^* A\}. \quad (2.20)$$

Definition 5 (Quasi-probability distribution) *The s -order quasi-probability distribution $W(\alpha, s)$, with $s \in \mathbb{C}$, associated to the quantum state Ξ is given by:*

$$W(\alpha, s) = \frac{1}{\pi^2} \int_{\mathbb{R}^2} \chi(\xi, s) e^{\alpha \xi^* - \alpha^* \xi} d\xi^2. \quad (2.21)$$

The quasi-probability distribution, for $s = 0$ ($W(\alpha) = W(\alpha, 0)$) is called Wigner W-function.

2.4.2 Gaussian states

With the Wigner W-function $W(\alpha)$, it is possible to define the concept of Gaussian state ([3] quoting [7, 8, 9, 10, 11]).

Definition 6 (Gaussian state) *A quantum state Ξ_G is a Gaussian state if its Wigner W-function $W_G(\alpha)$ is Gaussian, i.e*

$$W_G(\alpha) = \frac{1}{\pi \sqrt{\det \tilde{\mathbf{C}}_0}} \exp \left\{ -\frac{1}{2} (\tilde{\alpha} - \tilde{\mu})^H \tilde{\mathbf{C}}_0^{-1} (\tilde{\alpha} - \tilde{\mu}) \right\}. \quad (2.22)$$

where $\tilde{\mu}$ is the augmented displacement vector, and $\tilde{\mathbf{C}}_0$ is the augmented covariance matrix.

Coherent states

A coherent state is the state of a quantum harmonic oscillator of amplitude μ . It is defined ([3] seen [12, 13]) as the eigenvector $|\mu\rangle$ of \mathbf{A} associated to the eigenvalue μ ; i.e

$$\mathbf{A} |\mu\rangle = \mu |\mu\rangle. \quad (2.23)$$

It is possible to obtain a coherent state of parameter μ , applying the displacement operator to the ground state:

$$|\mu\rangle = \mathbf{D}_\mu |0\rangle. \quad (2.24)$$

As mentioned before, it is possible to characterize a state with the Fock representation and, equivalently, with the Wigner W-function. The last one is given, for a coherent state, by [14]:

$$W(\alpha) = \frac{2}{\pi} \exp \left\{ -2|\alpha - \mu|^2 \right\}. \quad (2.25)$$

It is easy to proof that $W(\alpha)$ is gaussian, with $\tilde{\mu} = [\mu \ \mu^*]^T$ and

$$\tilde{\mathbf{C}}_0 = \frac{1}{2} \mathbf{I}.$$

The Fock representation is given by [15]:

$$|\mu\rangle = e^{-\frac{|\mu|^2}{2}} \sum_{n=0}^{\infty} \frac{\mu^n}{\sqrt{n!}} |n\rangle. \quad (2.26)$$

Noisy coherent states

It is possible to characterize the state of a noisy armonic oscillator introducing the thermal state, i.e the state of an electromagnetic cavity in thermal equilibrium. The Fock representation of the thermal state Ξ_{th} is given by [3]

$$\Xi_{th} = (1-v) \sum_{n=0}^{\infty} v^n |n\rangle \langle n| \quad (2.27)$$

where

$$v = \frac{\bar{n}}{\bar{n} + 1}$$

and \bar{n} is the well-known Plank distribution

$$\bar{n} = \left(\exp \left\{ \frac{\hbar\omega}{k_B T} \right\} - 1 \right)^{-1}.$$

A noisy coherent states $\Xi_{th}(\mu)$ of parameter μ can be obtained by applying the displacement operator D_μ to the thermal state Ξ_{th} , as follow:

$$\Xi_{th}(\mu) = D_\mu^\dagger \Xi_{th} D_\mu. \quad (2.28)$$

The Wigner W-function is given by [14]

$$W_{th}(\alpha) = \frac{1}{\pi(\bar{n} + \frac{1}{2})} \exp \left\{ -\frac{|\alpha - \mu|^2}{\bar{n} + \frac{1}{2}} \right\} \quad (2.29)$$

and it can be proved that it is a Gaussian function with $\check{\mu} = [\mu \ \mu^*]^T$ and

$$\check{C}_0 = \left(\bar{n} + \frac{1}{2} \right) \mathbf{I}.$$

The Fock representation is given by

$$\langle n | \Xi_{th}(\mu) | m \rangle = (1-v) e^{-(1-v)|\mu|^2} \sqrt{\frac{n!}{m!}} v^n [(1-v)\mu^*]^{m-n} L_n^{m-n} \left(\frac{-(1-v)^2 |\mu|^2}{v} \right) \quad (2.30)$$

Squeezed states

A squeezed state with amplitude μ and squeezing parameter ζ , is a defined as [3, 16, 17]

$$|\mu, \zeta\rangle = D_\mu \mathcal{S}_\zeta |0\rangle \quad (2.31)$$

where \mathcal{S}_ζ is the squeezing operator, defined as

$$\mathcal{S}_\zeta = \exp \left\{ \frac{1}{2} \left(\zeta (\mathbf{A}^\dagger)^2 + \zeta^* \mathbf{A}^2 \right) \right\}. \quad (2.32)$$

It can be proven that a squeezed state is a Gaussian state with $\check{\mu} = [\mu \ \mu^*]^T$ and

$$\check{C}_0 = \frac{1}{2} \begin{bmatrix} \cosh(2r) & \sinh(2r)e^{-i\phi} \\ \sinh(2r)e^{-i\phi} & \cosh(2r) \end{bmatrix}$$

with $\zeta = r e^{i\phi}$. The Wigner W-function of a squeezed state, differently from the one of a coherent state, has not a circular symmetry.

Noisy squeezed states

The representation of a noisy squeezed state $\Xi_{th}(\mu, \zeta)$ is obtained, similarly to a noisy coherent state, as:

$$\Xi_{th}(\mu, \zeta) = D_\mu S_\zeta \Xi_{th} S_\zeta^\dagger D_\mu^\dagger. \quad (2.33)$$

The Gaussian Wigner W-function is obtained with $\check{\mu} = [\mu \ \mu^*]^T$ and

$$\check{C}_0 = \left(\bar{n} + \frac{1}{2} \right) \begin{bmatrix} \cosh(2r) & \sinh(2r)e^{-i\phi} \\ \sinh(2r)e^{-i\phi} & \cosh(2r) \end{bmatrix}.$$

The Fock representation is given by [18]

$$\begin{aligned} \langle n | \Xi_{th}(\mu, \zeta) | m \rangle &= \frac{\pi Q(0)}{(n!m!)^{1/2}} \sum_{k=0}^{\min(n,m)} k! \binom{n}{k} \binom{m}{k} \tilde{A}^k \left(\frac{1}{2} \tilde{B} \right)^{(n-k)/2} \\ &\quad \left(\frac{1}{2} \tilde{B}^* \right)^{(m-k)/2} H_{n-k}((2\tilde{B})^{-1/2} \tilde{C}) H_{m-k}((2\tilde{B}^*)^{-1/2} \tilde{C}^*) \end{aligned} \quad (2.34)$$

where H_n is the Hermite polynomial with parameter n ,

$$Q(0) = \frac{1}{\pi} [(1+A)^2 - |B|^2]^{-1/2} \exp \left\{ -\frac{(1+A)|C|^2 + \frac{1}{2}[B(C^*)^2 + B^*C^2]}{(1+A)^2 - |B|^2} \right\},$$

$$\tilde{A} = \frac{A(1+A) - |B|^2}{(1+A)^2 - |B|^2},$$

$$\tilde{B} = \frac{B}{(1+A)^2 - |B|^2},$$

$$\tilde{C} = \frac{(1+A)C + BC^*}{(1+A)^2 - |B|^2};$$

and

$$A = \bar{n} + (2\bar{n} + 1)(\sinh(r))^2, \quad B = -(2\bar{n} + 1)e^{i\phi} \sinh(r) \cosh(r), \quad C = \mu.$$

2.4.3 Non-Gaussian states

A state that does not fulfill the definition 6 is a non-Gaussian state. An important and useful for communications class of non-Gaussian states, are the photon added states, examined in this thesis.

Photon added states

The photon added state $\Xi^{(1)}$, obtained from the quantum state Ξ , is given by:

$$\Xi^{(1)} = \frac{A^\dagger \Xi A}{\text{tr}\{A^\dagger \Xi A\}}. \quad (2.35)$$

The name *photon addition* could lead to believe that the mean photon number of the photon added state is increased by one compared to the previous non photon added state. However, that is incorrect. In general, its mean number of photons

could be the same, more or less than the starting state. Only if $\Xi = |n\rangle\langle n|$, i.e Ξ is the density operator corresponding to the Fock state $|n\rangle$, the result of the photon addition is a state with one more photon.

Logically, the photon added state $\Xi^{(k)}$ (with k photon addition) is given by

$$\Xi^{(k)} = \frac{(\mathbf{A}^\dagger)^k \Xi \mathbf{A}^k}{\text{tr}\{(\mathbf{A}^\dagger)^k \Xi \mathbf{A}^k\}}. \quad (2.36)$$

The Fock representation of a photon added state, can be obtained as:

$$\Xi^{(k)} = \frac{\tilde{\Xi}^{(k)}}{\text{tr}\{\tilde{\Xi}^{(k)}\}} \quad (2.37)$$

and

$$\langle n | \tilde{\Xi}^{(k)} | m \rangle = \begin{cases} \sqrt{\frac{n!m!}{(n-k)!(m-k)!}} \langle n-k | \Xi | m-k \rangle & \text{if } n, m \geq k \\ 0 & \text{otherwise} \end{cases}$$

If Ξ is a noisy coherent state of amplitude μ ($\Xi = \Xi_{th}(\mu)$), the photon added state $\Xi_{th}^{(k)}(\mu)$ is called noisy photon added coherent state (PACS); if Ξ is a noisy squeezed state with amplitude μ and squeezing factor ζ ($\Xi = \Xi_{th}(\mu, \zeta)$), the photon added state $\Xi_{th}^{(k)}(\mu, \zeta)$ is called noisy photon added squeezed state (PASS).

Chapter 3

Quantum Communication

Thanks to quantum mechanics, it will be possible to overcome the limits of classical communication systems. In the last decades the research in this field has led to very interesting results that could significantly improve the performance of communication systems. This chapter gives a brief overview of quantum communication tools: in the first section we present the equivalents of classical modulation for quantum communication systems; in the second section we report the concept of quantum states discriminator (QSD), included when it can be considered optimal.

3.1 Quantum Modulation

As in a classical system, it is possible to define the concept of modulation for a quantum communication system. The transmitted information will be associated to a quantum state of the electromagnetic field, so it can be transmitted on the communication channel.

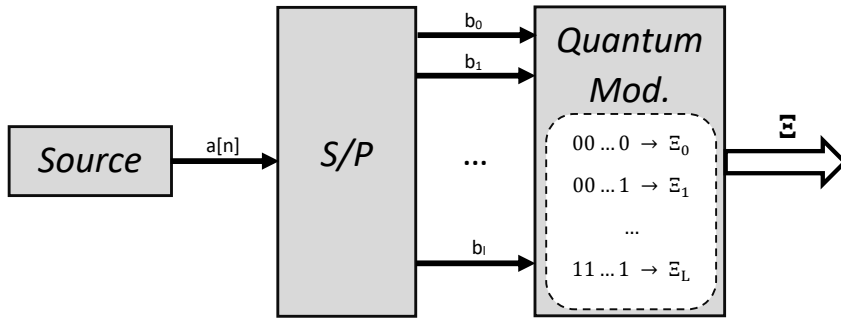


Figure 3.1: Block diagram of a quantum transmitter.

It is possible to think about the quantum transmitter as in figure 3.1. The bit source emits a bit sequence $a[n]$, the serial-parallel converter parallelizes a group of l -bit (where if L is the number of quantum states, $l = \log_2(L)$) and

sends them to the quantum modulator. This latter associates one quantum state to every group of bit. The operation of quantum state creation, in real cases, is affected by noise.

The sequence of operations is very close to a classical transmitter: the main difference is that the modulator maps the bits into quantum states instead of classical modulation. Therefore, it is possible to achieve the quantum equivalent of classical modulation, with several states. After that, the impact on performance can be tested. This thesis only considers and assesses the binary cases, in the OOK and BPSK configuration.

3.1.1 OOK modulation

The OOK (on-off keying) is the most simple possible configuration for a communication system. The quantum implementation of that is realized associating the low-energy state to the ground state $|0\rangle$ and the high-energy state to another state. It is important to consider that the physical realization of these states are not free-noise; this issue will be considered using noisy states 3.1.

$$\Xi_0 = \Xi_{th} \quad (3.1)$$

$$\Xi_1 = \Xi_{th}(\mu)$$

In the equation 3.1, the high-energy state is associated to a coherent state. This configuration has been widely analyzed in [19, 20, 21, 22, 23, 24] but this is not the only possible way. The use of PACS states $\Xi_{th}^{(k)}(\mu)$ is analyzed in [25, 3]; the use of PASS are briefly assessed in the following chapter of this thesis.

3.1.2 BPSK modulation

BPSK quantum systems are implemented using two states with opposite amplitude, like

$$\Xi_0 = \Xi_{th}(-\mu) \quad (3.2)$$

$$\Xi_1 = \Xi_{th}(\mu).$$

There is no guarantee that the use of a BPSK solution in a quantum system will improve its performance. The effect depends on which are the used states. In the next chapter some configuration are assessed.

3.2 Quantum Discriminator

The problem of quantum state discrimination (QSD) is one of the most important aspects of quantum communication. As in classical communication, the ability to distinguish between two or more states in presence of noise can be decisive in order to determine the performance of the communication system. However, differently from the classical situation, the discrimination can be done using a custom-designed quantum discriminator, overcoming the classical physics limits.

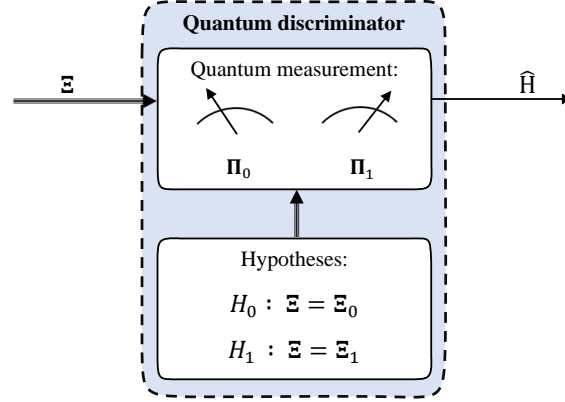


Figure 3.2: Binary quantum state discriminator.

3.2.1 Binary quantum state discrimination

The problem of discrimination between two quantum states is realized, as every measurement process 2, using an operator or a set of operators. If the state of the system is unknown, as shown in figure 3.2, there are two hypotheses about the state Ξ (the problem is easily generalizable for M different states), given by:

$$\begin{aligned} H_0 : \Xi &= \Xi_0 \\ H_1 : \Xi &= \Xi_1 \end{aligned} \quad (3.3)$$

It is necessary a set of two positive-definites operator (POVM)

$$\mathcal{P} = \{\Pi_0, \Pi_1\} \quad (3.4)$$

for the discrimination process, and the probability that the hypothesis H_j is chosen if H_k is the right choose is given by [3]:

$$\mathbb{P}\{H_j|H_k\} = \text{tr}\{\Xi_k \Pi_j\}. \quad (3.5)$$

The distribution error probability (DEP) in the discrimination process, if p_0 and p_1 are respectively the probability of symbols 0 and 1, is so given by

$$P_e = 1 - (p_0 \text{tr}\{\Xi_0 \Pi_0\} + p_1 \text{tr}\{\Xi_1 \Pi_1\}). \quad (3.6)$$

3.2.2 Optimal discriminator

The issue of finding the optimal POVM that minimizes the DEP was exhaustively discuss by Helstrom in [26, 27]. The minimum distribution error probability (MDEP) for a binary communication system is given by the well-known Helstrom bound

$$\check{P}_e = \frac{1}{2} (1 - \|p_1 \Xi_1 - p_0 \Xi_0\|_1), \quad (3.7)$$

where p_0, p_1 are the probability that the states Ξ_0, Ξ_1 are transmitted and the operator $\|\cdot\|_1$ represents the trace norm. The MDEP 3.7 is obtained with the following POVM:

$$\begin{aligned}\check{\Pi}_0 &= \sum_{\substack{i \\ \lambda_i < 0}} |\lambda_i\rangle \langle \lambda_i|, \\ \check{\Pi}_1 &= 1 - \check{\Pi}_0 = \sum_{\substack{i \\ \lambda_i \geq 0}} |\lambda_i\rangle \langle \lambda_i|;\end{aligned}\tag{3.8}$$

where $|\lambda_i\rangle$ is the eigenvector of $p_1\Xi_1 - p_0\Xi_0$ associated to the eigenvalue λ_i . For pure states, i.e $\Xi_0 = |\psi_0\rangle \langle \psi_0|$ and $\Xi_1 = |\psi_1\rangle \langle \psi_1|$, the equation 3.7 begin

$$\check{P}_e = \frac{1}{2} \left(1 - \sqrt{1 - 4p_0p_1|\langle \psi_0 | \psi_1 \rangle|^2} \right).\tag{3.9}$$

It is possible to observe that, for pure states, the MDEP is equal to 0 if $\langle \psi_0 | \psi_1 \rangle$, that is $|\psi_0\rangle$ and $|\psi_1\rangle$ are orthogonal states.

Chapter 4

Discrimination of Photon Added States

This chapter characterizes two systems with different types of photon added state in term of their discrimination MDEP 3.7: a photon added coherent state system (from [25]) and a photon added squeezed state. For each system, we consider the OOK configuration and the BPSK. The use of photon added states, as it will be shown, can improve significantly the performance of the communication.

The analyzed situation does not consider the channel effect on the transmitted information: it has been supposed that the noisy states reach the discriminator as they were created. The channel effects for a PACS system are described in [25].

4.1 PACS Discrimination

The effect of the use of PACS in an OOK communication system was extensively discussed in [25]. In this section the most important result will be reported and a BPSK system will be tested.

4.1.1 Quantum OOK PACS system

The use of PACS in an OOK system can significantly improve the performance. The MDEP, with thermal noise, is given by the Helstrom bound 3.7, where, for an OOK PACS system,

$$\begin{aligned}\Xi_0 &= \Xi_{th} = \Xi_{th}^{(0)}(0) \\ \Xi_1 &= \Xi_{th}^{(k)}(\mu).\end{aligned}\tag{4.1}$$

It is useful, in order to evaluate the performance of the system, to introduce the mean number of photon n_p in a quantum state Ξ , which is given by:

$$n_p = tr\{\Xi \mathbf{A}^\dagger \mathbf{A}\}.\tag{4.2}$$

For a photon added coherent state, the equation 4.2 becomes [25]:

$$n_p(\mu, \bar{n}) = \frac{N_{k+1}(\mu, \bar{n})}{N_k(\mu, \bar{n})} - 1,\tag{4.3}$$

where

$$N_k(\mu, \bar{n}) = \text{tr}\{(\mathbf{A}^\dagger)^k \mathbf{\Xi}_{th}(\mu) \mathbf{A}^k\}. \quad (4.4)$$

It is possible to observe that the minimum of n_p is given by:

$$n_p(0, \bar{n}) = (k+1)(\bar{n}+1) - 1. \quad (4.5)$$

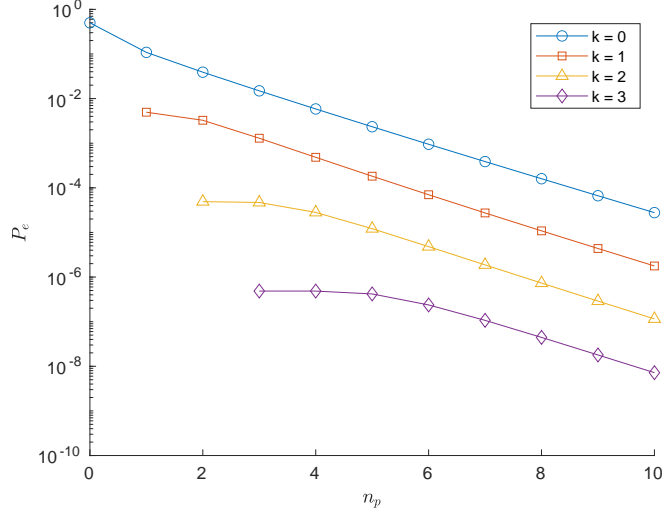


Figure 4.1: MDEP for PACS QOOK with: $k = 0, 1, 2, 3$; $\bar{n} = 10^{-2}$; $p_0 = p_1 = 1/2$

The MDEP of a quantum OOK system with PACS in function of n_p is represented in the figure 4.1, where in the x-axis there are the mean number of photon n_p in the state $\mathbf{\Xi}_1$ (which corresponds to the mean number of photon in the whole system) and in the y-axes there are the MDEP (P_e). The simulation was obtained for equiprobable symbols and mean number of thermal photons $\bar{n} = 10^{-2}$. The argument of the trace norm $\|\cdot\|_1$ in the Helstrom bound 3.7, is an operator in an infinite dimensional Hilbert space; for the simulation, it has been approximated in $N = 30$ dimension. It is possible to observe that the photon addition improves significantly the performance in terms of error probability.

4.1.2 Quantum BPSK PACS system

It can be interesting to assess the effect of photon addition in a quantum BPSK system. The constellation is given, for a PACS BPSK, by:

$$\mathbf{\Xi}_0 = \mathbf{\Xi}_{th} = \mathbf{\Xi}_{th}^{(k)}(-\mu) \quad (4.6)$$

$$\mathbf{\Xi}_1 = \mathbf{\Xi}_{th}^{(k)}(\mu).$$

In absence of noise ($\bar{n} = 0$), the MDEP is given by formula 3.9 where

$$\begin{aligned} |\psi_0\rangle &= |-\mu^{(k)}\rangle, \\ |\psi_1\rangle &= |\mu^{(k)}\rangle. \end{aligned} \quad (4.7)$$

The inner product is given, in closed form, by [25]:

$$\langle -\mu^{(k)} | \mu^{(k)} \rangle = \frac{L_k(|\mu|^2)}{L_k(-|\mu|^2)} e^{-2|\mu|^2}, \quad (4.8)$$

where $L_k(x)$ is the Laguerre polynomial of parameter k , evaluate in x . In figure

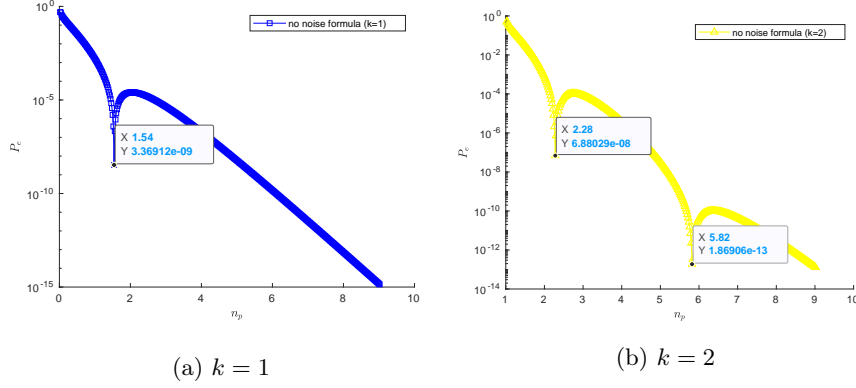


Figure 4.2: MDEP of quantum BPSK in absence of noise, $N = 30$.

4.2 the MDEP in absence of noise, for QBPSK with PACS, is plotted for $k = 1$ and for $k = 2$, in function of n_p , with $N = 30$. It can be noticed that exist k zeros in the MDEP plot, where k is the number of photon additions. The existence of these zeros is not really useful for the design of a quantum communication system because their selectivity factors are too high for a physical implementation. It is, nevertheless, possible to use that in order to evaluate the effect of the thermal noise. In figure 4.3, the sluggish performance due to the thermal noise is clear.

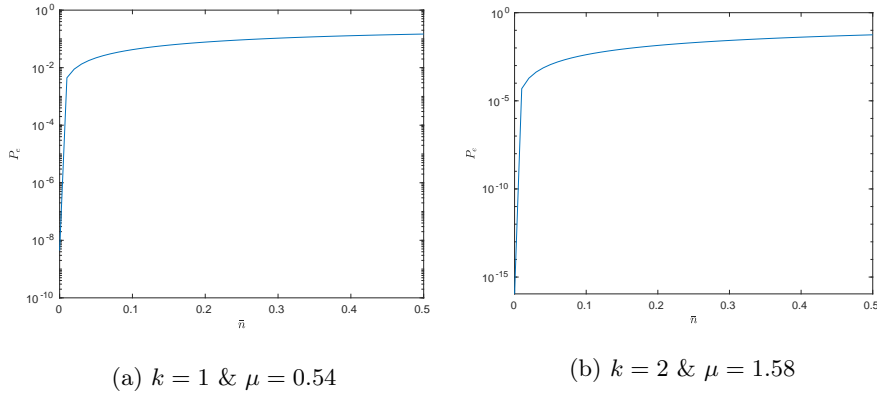


Figure 4.3: Thermal noise effect, in corrispondence of MDEP zeros ($N = 40$).

The plot shows the trend of MDEP, for zeros value of μ , in function of \bar{n} ; the used approximation is $N = 30$. The MDEP in presence of noise is given using the expression 3.7.

The comparison between a quantum OOK system and a quantum BPSK system is given in figure 4.4, in function of the mean energy of the system

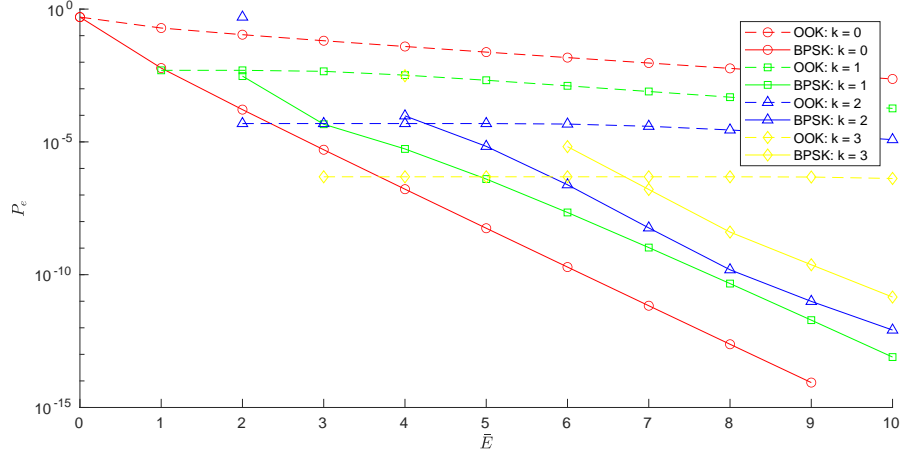


Figure 4.4: BPSK and OOK comparison.
 $N = 45$, $\bar{n} = 10^{-2}$, $p_0 = p_1 = 1/2$

\bar{E} , that is equal to n_p for the OOK system and the sum of the n_p for each state for the BPSK system. The plots are given with $\bar{n} = 10^{-2}$, $N = 45$ and equiprobable symbols. The obtained result is really interesting: the quantum BPSK has a sluggish performance due to the photon addition process. At an equal level of energy \bar{E} , for PACS systems, it is possible to find an OOK configuration that maximizes the performance.

4.2 PASS Discrimination

The use of squeezed states instead of coherent states allows us to overcome the limits of precedent systems. The representation of a noisy squeezed state is given in 2.4.2. This section initially discusses the advantages of using squeezed states without photon addition; then it evaluates the effect of the photon addition in quantum OOK and BPSK systems.

4.2.1 Squeezed states discrimination

At first, we assess the effect of squeezing on the performance in absence of photon addition and thermal noise. As for PACS systems, it can be useful to define the mean number of photon n_p in a squeezed state, which is given by

$$n_p(\mu, r) = |\mu|^2 + (\sinh r)^2; \quad (4.9)$$

where μ is the amplitude of the starter coherent state and the squeezing factor is $\zeta = re^{i\theta}$. The minimum value of n_p is given by $n_p(0, r) = \sinh^2 r$.

For a quantum squeezed states BPSK system, the MDEP, obtained with the Helstrom bound 3.7, is plotted in figure 4.5 in function of \bar{E} , i.e the mean energy of the system (given by the sum of n_p for each state), with: $\theta = \pi$, $N = 30$, equiprobable symbols and $\bar{n} = 0$.

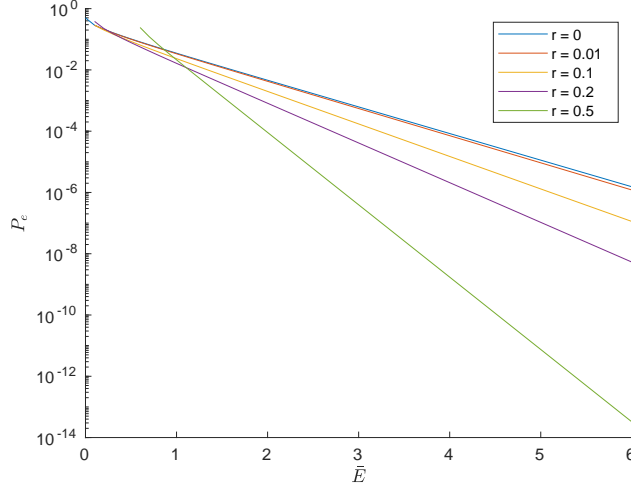


Figure 4.5: MDEP of squeezed state BPSK system. $N = 30$, $\bar{n} = 0$, $\theta = \pi$, $p_0 = p_1 = 1/2$

It can be noticed that the optimal configuration of r depends on the energy in the system. For low energy levels the squeezing has not a positive effect.

4.2.2 PASS discrimination

We are analyzing now the performance of a noisy photon added squeezed state system (PASS) 2.4.3, in OOK and BPSK configuration. The MDEP is found again with the Helstrom bound 3.7. As for the other systems, it is useful to define the mean number of photons n_p for noisy photon added squeezed states, that is given by:

$$n_p(\mu, \zeta, \bar{n}) = \frac{N_{k+1}(\mu, \zeta, \bar{n})}{N_k(\mu, \zeta, \bar{n})} - 1, \quad (4.10)$$

where

$$\begin{aligned} N_k(\mu, \zeta, \bar{n}) &= \text{tr}\{(\mathbf{A}^\dagger)^k \mathbf{\Xi}_{th}(\mu, \zeta) \mathbf{A}^k\} \\ &= \text{tr}\{(\mathbf{A}^\dagger)^k \mathbf{D}_\mu \mathbf{S}_\zeta \mathbf{\Xi}_{th} \mathbf{S}_\zeta^\dagger \mathbf{D}_\mu^\dagger \mathbf{A}^k\}. \end{aligned} \quad (4.11)$$

OOK PASS system

The constellation of a quantum OOK system with noisy PASS, is given by:

$$\begin{aligned} \Xi_0 &= \Xi_{th}^{(0)}(0, 0) \\ \Xi_1 &= \Xi_{th}^{(k)}(\mu, \zeta). \end{aligned} \quad (4.12)$$

In figure 4.6, the MDEP of a quantum OOK noisy PASS system is plotted in function of the mean number of photon n_p in the PASS (that is equivalent to the mean energy in the system). For the simulation are used $N = 30$, $\bar{n} = 10^{-2}$, $\theta = \pi$ and equiprobable symbols. It can be noticed that the photon addition significantly improves the performance of the system, at least for the plotted energy level.

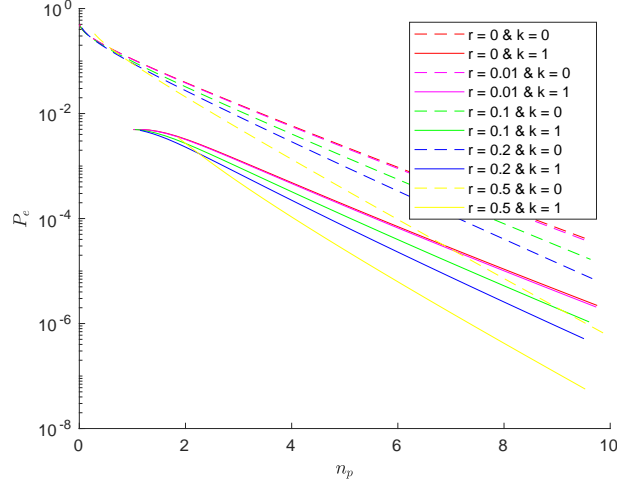


Figure 4.6: MDEP of noisy PASS quantum OOK system.
 $N = 30$, $\bar{n} = 10^{-2}$, $\theta = \pi$ and $p_0 = p_1 = 1/2$.

BPSK PASS system

Similar to the PACS BPSK, the constellation of PASS BPSK is given by:

$$\begin{aligned}\Xi_0 &= \Xi_{th}^{(k)}(-\mu, \zeta) \\ \Xi_1 &= \Xi_{th}^{(k)}(\mu, \zeta).\end{aligned}\tag{4.13}$$

The figure 4.7 shows the effects of the photon addition in a quantum BPSK system, in terms of the mean energy in the system \bar{E} , given by the sum of the mean photon number n_p of Ξ_0 and Ξ_1 . The parameters used for the simulation are $N = 30$, $\bar{n} = 10^{-2}$, $\theta = \pi$ and equiprobable symbols. As in PACS case, it is evident that the photon addition, in a BPSK system, has not the positive effect that has in an OOK system.

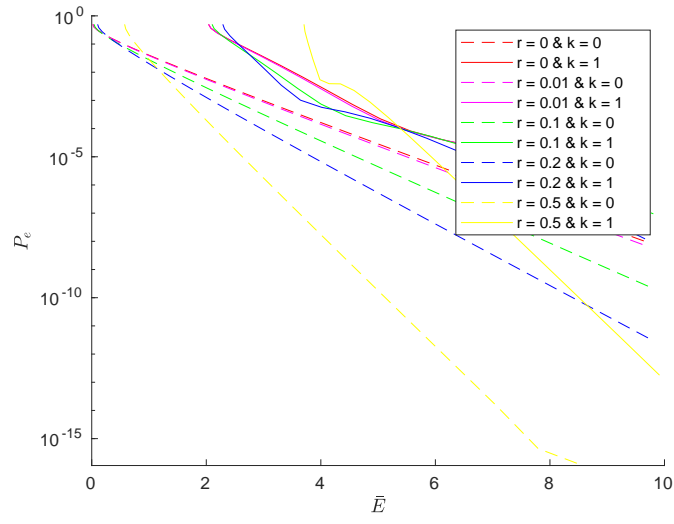


Figure 4.7: MDEP of noisy PASS quantum BPSK system.
 $N = 30$, $\bar{n} = 10^{-2}$, $\theta = \pi$ and $p_0 = p_1 = 1/2$.

Bibliography

- [1] P.A.M. Dirac. *The Principles of Quantum Mechanics*. Oxford University Press, 1981.
- [2] J. Von Neumann. *Mathematical foundations of quantum mechanics*. Princeton University Press, 1995.
- [3] Stefano Guerrini. “Quantum Communications: State Characterization and System Design”. 2021.
- [4] W. H. Louisell. *Quantum Statistical Properties of Radiation*. New York: Wiley, 1973.
- [5] L. Mandel and E. Wolf. *Optical Coherence and Quantum Optics*. New York: Cambridge University Press, 1995.
- [6] E. Wigner. “On the quantum correction for thermodynamic equilibrium”. In: *Phys.Rev.* 40.5 (1932), p. 749.
- [7] S. L. Braunstein and P. van Loock. “Quantum information with continuous variables”. In: *Rev. Mod. Phys.* 77 (June 2005), pp. 513–577.
- [8] S. Olivares A. Ferraro and M. G. A. Paris. *Gaussian States in Continuous Variable Quantum Information*. Napoli, Italy: Biliopolis, 2005.
- [9] C. Weedbrook et al. “Gaussian quantum information”. In: *Rev. Mod. Phys.* 84 (May 2012), pp. 621–669.
- [10] S. Ragy G. Adesso and A. R. Lee. “Continuous variable quantum information: Gaussian states and beyond”. In: *Open Syst. Inf. Dyn.* 21 (2014).
- [11] A. Serafini. *Quantum Continuous Variables: A Primer of Theoretical Methods*. Boca Raton, FL: CRC Press, 2017.
- [12] R. J. Glauber. “The quantum theory of optical coherence”. In: *Phys. Rev.* 130 (June 1963), pp. 2529–2539.
- [13] R. J. Glauber. “Coherent and incoherent states of the radiation field”. In: *Phys. Rev.* 131 (Sept. 1963), pp. 2766–2788.
- [14] C. W. Gardiner and P. Zoller. *Quantum noise*. 3rd. Berlin: Springer-Verlag, 2004.
- [15] J. P. Dowling. *Schrödinger’s Killer App: Race to Build the World’s First Quantum Computer*. Boca Raton, FL: CRC Press, 2013.
- [16] H. P. Yuen. “Two-photon coherent states of the radiation field”. In: *Phys. Rev. A* 13 (June 1976), pp. 2226–2243.
- [17] C. M. Caves. “Quantum-mechanical noise in an interferometer”. In: *Phys. Rev. D* 23 (Apr. 1981), pp. 1693–1708.

- [18] Paulina Marian and Tudor A. Marian. “Squeezed states with thermal noise. I. Photon number statistics”. In: *Phu. Rev. A* 47.5 (May 1993).
- [19] C. W. Helstrom. “Detection theory and quantum mechanics”. In: *Inf. Control* 10.3 (1967), pp. 254–291.
- [20] C. W. Helstrom. “Fundamental limitations on the detectability of electromagnetic signals”. In: *Int. J. Theor. Phys.* 1.1 (May 1968), pp. 37–50.
- [21] R. Yoshitani. “On the detectability limit of coherent optical signals in thermal radiation”. In: *J. Stat. Phys.* 2.4 (Dec. 1970), pp. 347–378.
- [22] M. Takeoka and M. Sasaki. “Discrimination of the binary coherent signal. Gaussian-operation limit and simple non-Gaussian near-optimal receivers”. In: *Phys. Rev. A* 78.022320 (Aug. 2008).
- [23] N. Dalla Pozza and G. Pierobon. “Optimality of square-root measurements in quantum state discrimination”. In: *Phys. Rev. A* 91.042334 (Apr. 2015).
- [24] R. Yuan et al. “Kennedy receiver using threshold detection and optimized displacement under thermal noise”. In: *IEEE Commun. Lett.* 24.6 (June 2020), pp. 1313–1317.
- [25] Stefano Guerrini et al. “Quantum Discrimination of Noisy Photon-Added Coherent States”. In: *IEEE journal* 1.2 (Aug. 2020).
- [26] C. W. Helstrom. *Quantum Detection and Estimation Theory*. Academic Press, New York, 1976.
- [27] C. W. Helstrom. *Probabilistic and Statistical Aspects of Quantum Theory*. North-Holland, Amsterdam, 1979.