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

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Contents

1	Quantum Mechanics Abstract	1
1.1	Postulates	1
1.1.1	First postulate	1
1.1.2	Second postulate	1
1.1.3	Third postulate	2
1.1.4	Fourth postulate	2
1.1.5	Fifth postulate	2
1.1.6	Sixth postulate	2
1.2	Combining Systems	2
1.2.1	Density operator	3
1.3	Quantized Electromagnetic Field	3
1.3.1	Classical electromagnetic field	3
1.3.2	Quantized electromagnetic field	4
1.3.3	Fock states	5
1.4	QEF States	5
1.4.1	Phase-space description	5
1.4.2	Gaussian states	6
1.4.3	Non-Gaussian states	8
2	Quantum Communication	11
2.1	Quantum Modulation	11
2.1.1	OOK modulation	11
2.1.2	BPSK modulation	11
2.2	Quantum Discriminator	11
	Bibliography	13

Chapter 1

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.

1.1 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].

1.1.1 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.*

1.1.2 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.*

1.1.3 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.

1.1.4 Fourth postulate

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

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

1.1.5 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.

1.1.6 Sixth postulate

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

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

1.2 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.

1.2.1 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.

$$\mathbb{P}(\lambda_i) = \text{tr}\{\Xi \mathcal{P}_i\} \quad (1.1)$$

$$\Xi' = \frac{\mathcal{P}_i \Xi \mathcal{P}_i^\dagger}{\text{tr}\{\mathcal{P}_i \Xi \mathcal{P}_i^\dagger\}} \quad (1.2)$$

$$\Xi(t) = \mathcal{U} \Xi(t_0) \mathcal{U}^\dagger \quad (1.3)$$

1.3 Quantized Electromagnetic Field

Electromagnetic field is the main means of communication for contemporary application. It is important therefor, to give a quantum representation. In this section the representation of quantized electromagnetic field is initially given, so the Fock representation of a state is introduced.

1.3.1 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:

$$\mathbf{e}(\mathbf{r}, t) = \sum_n p_n(t) \mathbf{u}_n(\mathbf{r}) \quad (1.4)$$

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:

$$\mathbf{h}(\mathbf{r}, t) = \sum_n q_n(t) \nabla \times \mathbf{u}_n(\mathbf{r}) \quad (1.5)$$

and

$$p_n(t) = \frac{dq_n(t)}{dt}. \quad (1.6)$$

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

$$H_n = \frac{1}{2}[p_n^2(t) + \omega_n^2 q_n^2(t)]. \quad (1.7)$$

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

$$a_n(t) = \frac{\omega_n q_n(t) + ip_n(t)}{\sqrt{2\hbar\omega_n}} \quad (1.8)$$

and, using 1.8 in 1.7, it is possible to obtain the following expression of the Hamiltonian:

$$H_n = \hbar\omega_n |a_n(t)|^2. \quad (1.9)$$

1.3.2 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]):

$$[\mathbf{Q}_n, \mathbf{P}_m] = i\hbar\delta_{n,m}\mathbf{I} \quad (1.10)$$

$$[\mathbf{Q}_n, \mathbf{Q}_m] = 0 \quad (1.11)$$

$$[\mathbf{P}_n, \mathbf{P}_m] = 0. \quad (1.12)$$

Defining the annihilation operator \mathbf{A}_n as

$$\mathbf{A}_n(t) = \frac{\omega_n \mathbf{Q}_n(t) + i\mathbf{P}_n(t)}{\sqrt{2\hbar\omega_n}} \quad (1.13)$$

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

$$\mathbf{A}_n(t) = \frac{\omega_n \mathbf{Q}_n(t) - i\mathbf{P}_n(t)}{\sqrt{2\hbar\omega_n}} \quad (1.14)$$

it is possible to describe the Hamiltonian of the system as

$$H_n = \hbar\omega_n \mathbf{A}_n^\dagger \mathbf{A}_n. \quad (1.15)$$

1.3.3 Fock states

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

$$\mathbf{N} = \mathbf{A}^\dagger \mathbf{A}. \quad (1.16)$$

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

$$\mathbf{N} |n\rangle = n |n\rangle. \quad (1.17)$$

The Fock state $|n\rangle$ represent the quantum state with exactly n photons. It is important to evidence 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

$$\Xi = \sum_{n,m} c_{n,m} |n\rangle \langle m| \quad (1.18)$$

with

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

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

1.4 QEF States

In this section, some quantum states of electromagnetic field useful for quantum communication are characterized. A brief introduction to another one tool for the description of quantum systems is initially given, so some Gaussian and non-Gaussian states are characterized.

1.4.1 Phase-space description

As seen before, in 1.18, quantum system can be completely described by a density operator Ξ defined in an infinite-dimensional Hilbert space \mathcal{H} . 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:*

$$\chi(\xi, s) = \exp\left\{\frac{s}{2}|\xi|^2\right\} \text{tr}\{\Xi D_\xi\} \quad (1.19)$$

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

$$D_\xi = \exp\{\xi \mathbf{A}^\dagger - \xi^* \mathbf{A}\}. \quad (1.20)$$

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:*

$$W(\alpha, s) = \frac{1}{\pi^2} \int_{\mathbb{R}^2} \chi(\xi, s) e^{\alpha \xi^* - \alpha^* \xi} d\xi^2. \quad (1.21)$$

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

1.4.2 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*

$$W_G(\alpha) = \frac{1}{\pi \sqrt{\det \tilde{\mathbf{C}}_0}} \exp \left\{ -\frac{1}{2} (\tilde{\alpha} - \tilde{\mu})^H \tilde{\mathbf{C}}_0^{-1} (\tilde{\alpha} - \tilde{\mu}) \right\}. \quad (1.22)$$

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

$$\mathbf{A} |\mu\rangle = \mu |\mu\rangle. \quad (1.23)$$

It is possible to obtain a coherent state of parameter μ , from the ground state as

$$|\mu\rangle = \mathbf{D}_\mu |0\rangle. \quad (1.24)$$

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]:

$$W(\alpha) = \frac{2}{\pi} \exp \left\{ -2|\alpha - \mu|^2 \right\}. \quad (1.25)$$

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]:

$$|\mu\rangle = e^{-\frac{|\mu|^2}{2}} \sum_{n=0}^{\infty} \frac{\mu^n}{\sqrt{n!}} |n\rangle. \quad (1.26)$$

Noisy coherent states

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

$$\Xi_{th} = (1-v) \sum_{n=0}^{\infty} v^n |n\rangle \langle n| \quad (1.27)$$

where

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

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

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

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:

$$\Xi_{th}(\mu) = D_\mu^\dagger \Xi_{th} D_\mu. \quad (1.28)$$

The Wigner W-function is given by

$$W_{th}(\alpha) = \frac{1}{\pi(\bar{n} + \frac{1}{2})} \exp \left\{ -\frac{|\alpha - \mu|^2}{\bar{n} + \frac{1}{2}} \right\} \quad (1.29)$$

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

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

The Fock representation is given by

$$\langle n | \Xi_{th}(\mu) | m \rangle = (1-v) e^{-(1-v)|\mu|^2} \sqrt{\frac{n!}{m!}} v^n [(1-v)\mu^*]^{m-n} L_n^{m-n} \left(\frac{-(1-v)^2 |\mu|^2}{v} \right) \quad (1.30)$$

Squeezed states

A squeezed state with amplitude μ and squeezing parameter ζ , is a defined as

$$|\mu, \zeta\rangle = D_\mu S_\zeta |0\rangle \quad (1.31)$$

where S_ζ is the squeezing operator, defined as

$$S_\zeta = \exp \left\{ \frac{1}{2} \left(\zeta (A^\dagger)^2 + \zeta^* A^2 \right) \right\}. \quad (1.32)$$

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 $\zeta = re^{i\phi}$. The Wigner W-function of a squeezed state, unlike that 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, similary to a noisy coherent state, as:

$$\Xi_{th}(\mu, \zeta) = D_\mu S_\zeta \Xi_{th} S_\zeta^\dagger D_\mu^\dagger. \quad (1.33)$$

The Gaussian Wigner 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 [16]

$$\begin{aligned} \langle n | \Xi_{th}(\mu, \zeta) | m \rangle &= \frac{\pi Q(0)}{(n!m!)^{1/2}} \sum_{k=0}^{\min(n,m)} k! \binom{n}{k} \binom{m}{k} \tilde{A}^k \left(\frac{1}{2} \tilde{B} \right)^{(n-k)/2} \\ &\quad \left(\frac{1}{2} \tilde{B}^* \right)^{(m-k)/2} H_{n-k}((2\tilde{B})^{-1/2} \tilde{C}) H_{m-k}((2\tilde{B}^*)^{-1/2} \tilde{C}^*) \end{aligned} \quad (1.34)$$

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

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

1.4.3 Non-Gaussian states

A state that does not meet the definition 6 is a non-Gaussian state. An important class of non-Gaussian states, useful for communications 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:

$$\Xi^{(1)} = \frac{A^\dagger \Xi A}{\text{tr}\{A^\dagger \Xi A\}}. \quad (1.35)$$

The name *photon addition*, despite can be thought, does not mean that the mean photon number of the photon added state is one more then the non-photon added state. In general, its mean number of photon could be the same,

more or less then 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

$$\Xi^{(k)} = \frac{(\mathbf{A}^\dagger)^k \Xi \mathbf{A}^k}{\text{tr}\{(\mathbf{A}^\dagger)^k \Xi \mathbf{A}^k\}}. \quad (1.36)$$

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

$$\Xi^{(k)} = \frac{\tilde{\Xi}^{(k)}}{\text{tr}\{\tilde{\Xi}^{(k)}\}} \quad (1.37)$$

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 2

Quantum Communication

Introduction of chapter [...]

2.1 Quantum Modulation

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

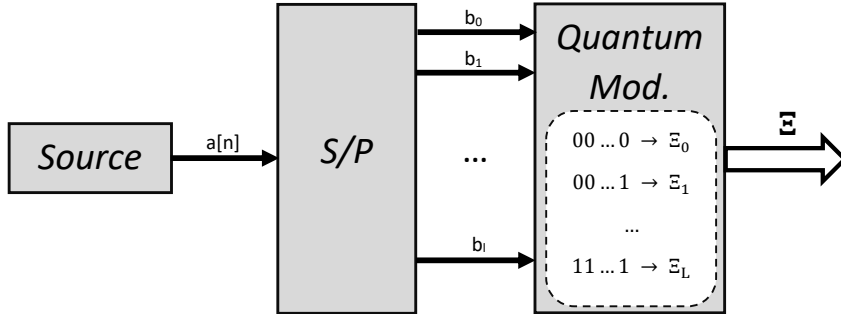


Figure 2.1: Block diagram of a quantum trasmitter.

It is possible to think about the quantum trasmitter as in figure 2.1. The bit source emits a bit sequence, the serial-parallel converter parallelize 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 last associate to every group of bit, one quantum state. The operation of quantum state creation, in real cases, is affected by noise.

The sequence of operation is very closer to a classical trasmitter, the main difference is that the modulator map the bits into quantum states instead of classical modulation. It is, therefore, possible to achieve the equivalent of classical modulation, that it is called quantum modulation, with several states and assess

the impact on performance. In this thesis only the binary will be considered and assessed, in the OOK and BPSK configuration.

2.1.1 OOK modulation

2.1.2 BPSK modulation

2.2 Quantum Discriminator

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