Transmission system study

1 Introduction

This document describes a simple emission and detection system for coherent states.
We use a constellation based in the states $\{|\alpha\rangle, |i\alpha\rangle, |-\alpha\rangle, |-i\alpha\rangle\}$

One of the main features studied in this system is quantum noise, that is intrinsic to the system. In principle the variance of a coherent state is given by $\Delta X_1 \Delta X_2 = {}^1/_4$.
Therefore, assuming Gaussian shot noise, for each quadrature we want $\text{Var}(X_i) = {}^1/_4$?????
(TENHO DE PROCURAR REFERENCIAS)

This quantum noise is introduced in the photodiodes by the following logic:
We know that a coherent state has an expected number of photons distributed by a Poisson distribution, which has an average number equal to it's variance. Therefore, when the photodiode detects the power of signal, which is proportional to the number of photons, then it's variance must also be proportional to the number of photons.

In fact the last step in detecting the resulting signal introduces an difference between currents, but that only will increase the variance. Assuming the independence between detections, and it's intrinsic noise (PROCURAR MELHOR PALEIO), then:

$$\text{Var}(I_{out}) = \text{Var}(I_1) + \text{Var}(I_2)$$

Therefore, the best result we can achieve will be $\text{Var}(X) = {}^1/_4$???? (PROCURAR PALEIO SOBRE ISTO)

2 Functional Description

The simulation setup is described by diagram in figure 1. We start by generating a state from one of the four available ones.???? Then, the signal is received in a Hybrid Detector??? where the signal is compared with a local oscillator giving four different signals in it's output. Two of those signals are detected by a photodiode which outuput will be the difference of the two photocurrents. The other two signals will be also be detected by another photodiode, which will obtain the other quadrature of the signal.????? (TEM QUE FICAR MELHOR EXPLICADO).

System Blocks	netxpto Blocks
-	MQAM
-	LocalOscillator
-	Hybrid??
-	Photodiode??

3 Required files

Header Files

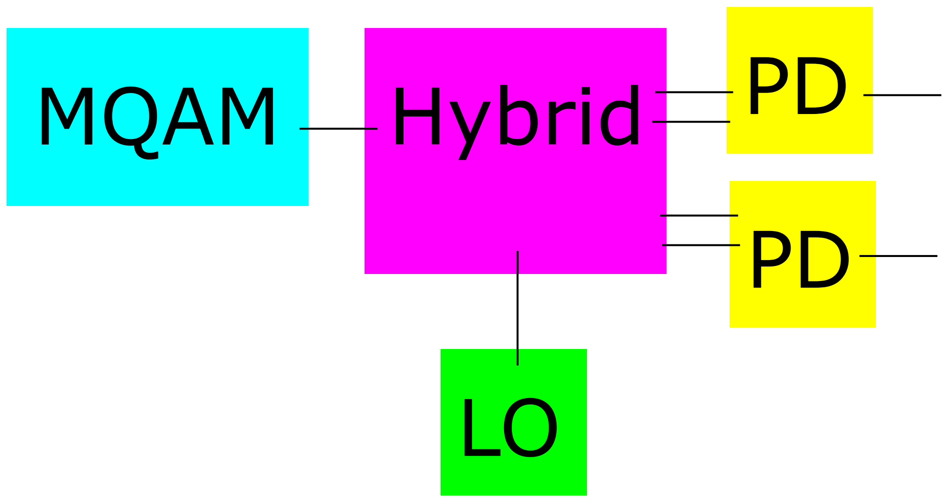

Figure 1: Overview of the optical system being simulated.

File	**Description**
netxpto.h	Generic purpose simulator definitions.
local_oscillator.h	Generates continuous coherent signal.
balanced_beam_splitter.h	Mixes the two input signals into two outputs.
homodyne_reciever.h	Performs coherent detection on the input signal.
sink.h	Closes any unused signals.

Source Files

File	**Description**
netxpto.cpp	Generic purpose simulator definitions.
local_oscillator.cpp	Generates continuous coherent signal.
balanced_beam_splitter.cpp	Mixes the two input signals into two outputs.
homodyne_reciever.cpp	Performs coherent detection on the input signal.
sink.cpp	Closes any unused signals.

4 System Input Parameters

This system takes into account the following input parameters:

System Parameters	**Description**
numberOfBitsGenerated	Gives the number of bits to be simulated
bitPeriod	Sets the time between adjacent bits
samplesPerSymbol	Establishes the number of samples each bit in the string is given
localOscillatorPower_dBm1	Sets the optical power, in units of dBm, of the varied amplitude signal
localOscillatorPower2	Sets the optical power, in units of W, of the constant zero amplitude signal
localOscillatorPhase1	Sets the initial phase of the local oscillator used for reference
localOscillatorPhase2	Sets the initial phase of the local oscillator used for signal
transferMatrix	Sets the transfer matrix of the beam splitter used in the homodyne detector
responsivity	Sets the responsivity of the photodiodes used in the homodyne detector
amplification	Sets the amplification of the trans-impedance amplifier used in the homodyne detector
electricalNoiseAmplitude	Sets the amplitude of the gaussian thermal noise added in the homodyne detector
shotNoise	Chooses if quantum shot noise is used in the simulation

5 Inputs

This system takes no inputs.

6 Outputs

The system outputs the following objects:

- Signals:
  - Local Oscillator Optical Reference; (S_1)
  - Local Oscillator Optical Signal; (S_2)
  - Beam Splitter Outputs; (S_3, S_4)
  - Homodyne Detector Electrical Output; (S_5)

7 Simulation Results

The following results show the dependence of the noise variance with the signal power, expressed in the value of the average photon number per pulse. Experimental results of the characterization of two different balanced homodyne detectors, obtained under the same conditions as the ones stipulated for the simulation, are presented in green and purple points alongside their respective quadratic fits. The thermal noise level is presented as a yellow line. The simulation results are presented as red points.

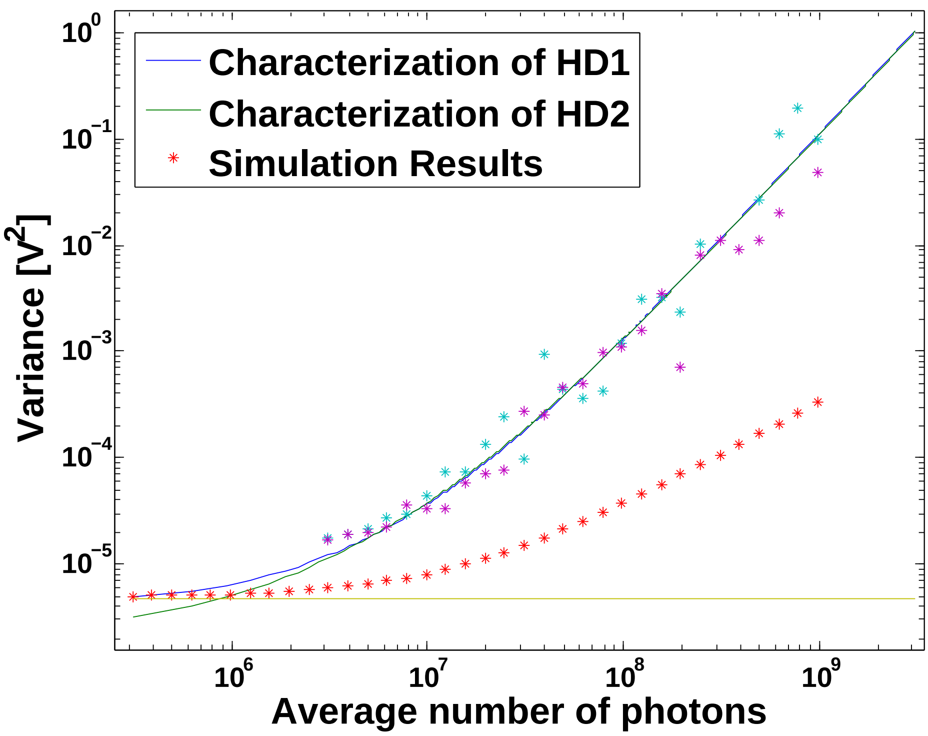

Figure 2: Noise variance in function of signal power.

In Figure 2 one can see that all results tend to the same value of thermal noise, however, simulated and experimental results evolve with different rates with signal power, this is mainly due to the existence of noise sources not considered in the simulation, moreover, setting the quadratic parameter in the experimental fit to 0 results yields the results presented in Figure 3, where the difference between the experimental fits and simulated results can be seen to not be as dramatic as before. The simulation and experimental fits are, respectively:

$$\begin{aligned} y &= p_0 + p_1 x \\ p_0 &= 4.816\times10^{-06} \\ p_1 &= 3.277\times10^{-13} \end{aligned}$$

$$\begin{aligned} y &= p_0 + p_1 x + p_2 x^2 \\ p_0 &= 4.164\times10^{-6} \\ p_1 &= 2.183\times10^{-12} \\ p_2 &= 1.069\times10^{-19} \end{aligned}$$

$$\begin{aligned} y &= p_0 + p_1 x + p_2 x^2 \\ p_0 &= 2.357\times10^{-6} \\ p_1 &= 2.527\times10^{-12} \\ p_2 &= 1.038\times10^{-19} \end{aligned}$$

The linear parameters from the experimental fits are one order of magnitude above the linear parameter from the simulation fit, the reasons for this mismatch are still under study.

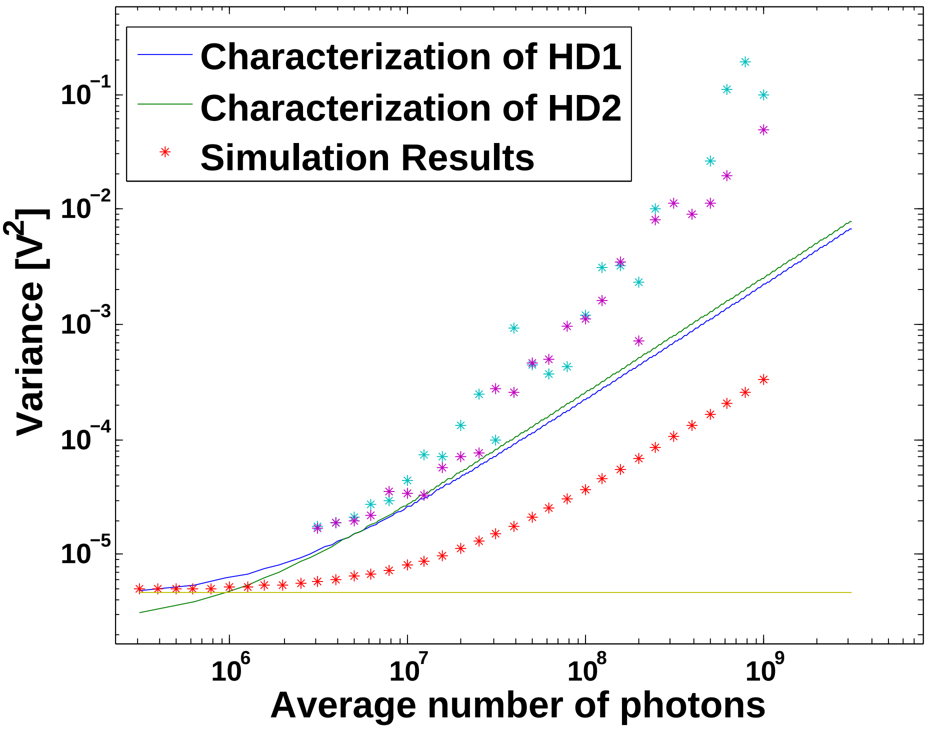

Figure 3: Noise variance in function of signal power with quadratic parameter deactivated.

8 Block Description

8.1 Homodyne Receiver

Homodyne Receiver

Introduction

This super-block compresses the function of the following blocks:

- Photodiode;
- Trans-Impedance Amplifier;

This compression allows for a cleaner code.

Input Parameters

- Responsivity
- Gain
- ElectricalNoiseSpectralDensity
- RollOffFactor
- ImpulseResponseTimeLength
- ImpulseResponseLength
- PassiveFilterMode

Functional Description

The input signals are evaluated by coherent detection and an electrical signal is generated from this evaluation. A diagram of the blocks that constitute this super-block, with the corresponding relations is presented in Figure 4.

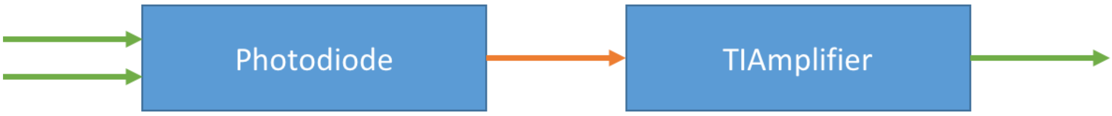

Figure 4: Homodyne Receiver Block Diagram.

Inputs

Number: 2
Type: Complex or Complex_XY (OpticalSignal)

Outputs

Number: 1
Type: Real Signal (ContinuousTimeContinuousAmplitude)

8.2 Local Oscillator

Local Oscillator

Input Parameters

- LocalOscillatorPhase
- LocalOscillatorOpticalPower
- LocalOscillatorOpticalPower_dBm

Functional Description

This blocks outputs a complex signal with a user defined length, phase and power. The phase and optical power are defined by the values of *LocalOscillatorPhase* and *LocalOscillatorOpticalPower* respectively.

Input Signals

Number: 0

Output Signals

Number: 1
Type: Complex or Complex_XY optical signal (ContinuousTimeContinuousAmplitude)

8.3 Beam Splitter

Beam Splitter

Input Parameters

- setTransferMatrix

For simplicity, the input of the transfer Matrix is in the form of a 4x1 array, with the following relation between the array, A, and matrix, M, elements:

$$A = \{ \; \{ \; \alpha, \; \beta, \; \gamma, \; \delta \; \} \; \} \Rightarrow M = \begin{bmatrix} \alpha & \beta \\ \gamma & \delta \end{bmatrix} \tag{1}$$

Functional Description

This block accepts two complex signals and outputs two complex signals built from a mixture of the two inputs according to a pre-determined and user defined transfer matrix.

Input Signals

Number: 2
Type: Complex signal (ContinuousTimeContinuousAmplitude)

Output Signals

Number: 2
Type: Complex signal (ContinuousTimeContinuousAmplitude)

8.4 Photodiode

Photodiode

Input Parameters

- setResponsivity
- useNoise

Functional Description

This block accepts two complex signals and outputs one real signal built from an evaluation of the power of the input signals and their subsequent subtraction. The responsivity is defined by the value of *Responsivity.* This block also adds random gaussian distributed shot noise with an amplitude defined by the power of the inputs. The shot noise is activated by the boolean variable set by the *useNoise* parameter.

Input Signals

Number: 2
Type: Complex signal (ContinuousTimeContinuousAmplitude)

Output Signals

Number: 1
Type: Real signal (ContinuousTimeContinuousAmplitude)

8.5 Amplifier

Ideal Amplifier

Input Parameters

- setGain

Functional Description

This block accepts one time continuous signal and outputs one time continuous signal of the same type built from multiplying the input signals by a predetermined value. The multiplying factor is defined by the values of *Gain*. The input and output signals must be of the same type.

Input Signals

Number: 1
Type: Real, Complex or Complex_XY signal (ContinuousTimeContinuousAmplitude)

Output Signals

Number: 1
Type: Real, Complex or Complex_XY signal (ContinuousTimeContinuousAmplitude)

8.6 Electrical Filter

Pulse Shaper

This blocks applies a time domain, finite impulse response filter to the signal. The filter's transfer function is defined by the vector *impulseResponse*. It allows for passive filter mode operation via a boolean check.

Input Parameters

- filterType
- impulseResponseTimeLength
- rollOfFactor
- usePassiveFilterMode

Functional Description

Input Signals

Number: 1
Type: Sequence of Dirac Delta functions (ContinuousTimeDiscreteAmplitude)

Output Signals

Number: 1
Type: Sequence of impulses modulated by the filter (ContinuousTimeContiousAmplitude)

Suggestions for future improvement

Introduce other types of filters.

9 Known Problems

1. Homodyne Super-Block not functioning