Shot noise study

1   Introduction

This document describes a model to simulate the experimental results of the characterization of two homodyne receivers.

The average current output for a homodyne receiver, with coherent input signals $S_1 = \sqrt{P_1}e^{i\theta}$ and $S_2 = \sqrt{P_2}e^{i\epsilon}$, is given by:

$$I = \eta\sqrt{P_1 P_2}\cos\Delta\phi, \tag{1}$$

where $\Delta\phi = \theta - \epsilon$ is the phase difference between the two input signals. The current variance introduced by the statistical nature of the photon-number, shot noise, is given by:

$$(\Delta I)^2 = \eta(P_1 + P_2). \tag{2}$$

If only one signal input is used (for example $P_1 \neq 0 \wedge P_2 = 0$), the output will be purely noise and it's amplitude should scale linearly with the signal power. In addition to the shot noise contribution, two other noise sources are commonly present:

- thermal noise, originating from the detectors electronics and which is independent from the power of the applied signal;

- relative intensity noise, originating from instabilities in the power level of the used laser.

The first of these is independent of the laser power while the latter scales with its square.

2   Functional Description

A simplified diagram of the system being simulated is presented in Figures 1. One of the Local Oscillator block is set to a zero amplitude output (0 W), while the other's power is set at different values to allow for a study of the dynamic properties of the system. The two signals are mixed with a Balanced Beam Splitter and are subsequently evaluated with recourse to a Homodyne Receiver.

Both thermal and shot noise were considered for this simulation, the thermal noise amplitude was set to coincide with the value observed in the experimental results.
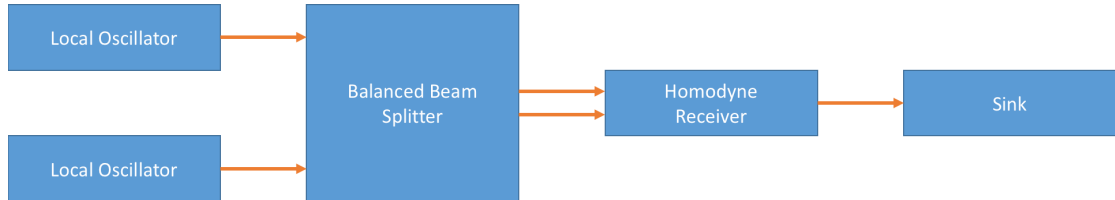

Figure 1: Overview of the optical system being simulated.

System Blocks	netxpto Blocks
Local Oscillator	LocalOscillator
Homodyne Receiver	I_HomodyneReceiver
Balanced Beam Splitter	BalancedBeamSplitter

3 Required files

Header Files

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.
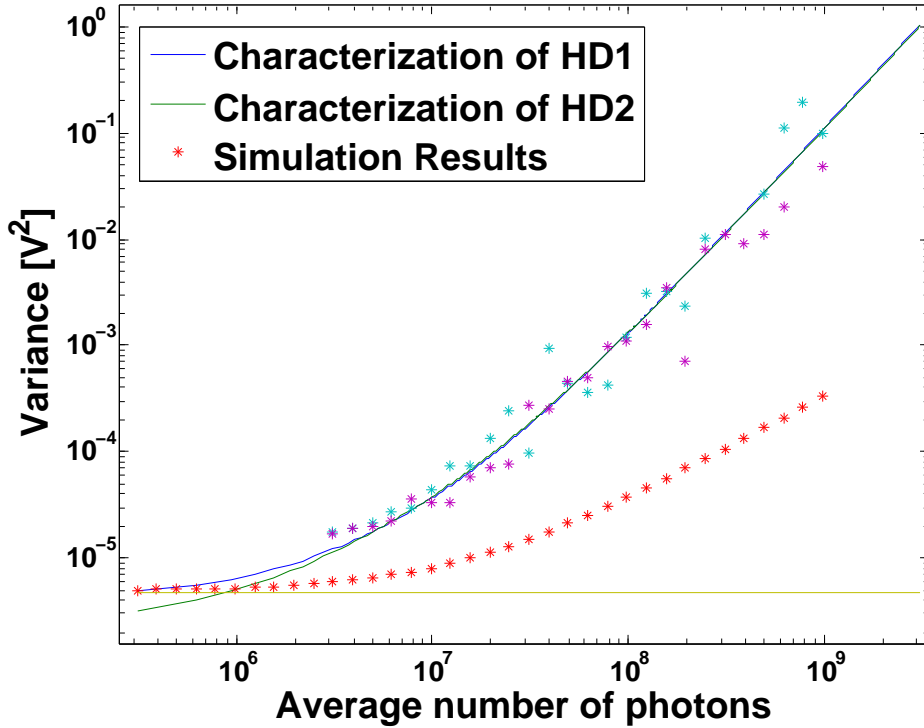

Figure 2: Noise variance in function of signal power.

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:

$$
\begin{array}{rl}
y= & p_0 + p_1 x \\
p_0 = & 4.816 \times 10^{-06} \\
p_1 = & 3.277 \times 10^{-13}
\end{array}
$$

$$
\begin{array}{rl}
y= & p_0 + p_1 x + p_2 x^2 \\
p_0 = & 4.164 \times 10^{-6} \\
p_1 = & 2.183 \times 10^{-12} \\
p_2 = & 1.069 \times 10^{-19}
\end{array}
$$

$$
\begin{array}{rl}
y= & p_0 + p_1 x + p_2 x^2 \\
p_0 = & 2.357 \times 10^{-6} \\
p_1 = & 2.527 \times 10^{-12} \\
p_2 = & 1.038 \times 10^{-19}
\end{array}
$$

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.
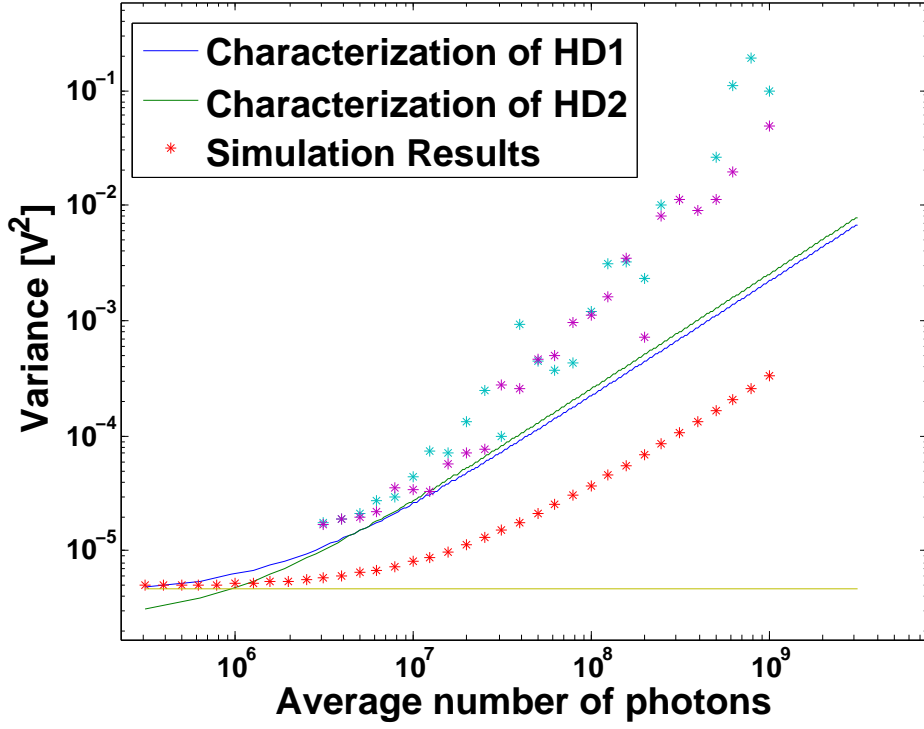

Figure 3: Noise variance in function of signal power with quadratic parameter deactivated.

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:

$$A = \{\ \{\ \alpha,\ \beta,\ \gamma,\ \delta\ \}\ \} \Rightarrow M = \begin{bmatrix} \alpha & \beta \\ \gamma & \delta \end{bmatrix} \tag{3}$$

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