Optically preamplified receiver with low quantum limit

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An optically preamplified receiver configuration resulting in a very low quantum limit is presented.

Introduction: Optical amplifiers are proven to efficiently enhance the receiver sensitivity of optical communication systems. In optical communications, it is common practice to compare the system’s ultimate sensitivity in terms of the quantum limit. The (standard) quantum limit is defined as the average number of photons per bit in the optical signal needed to achieve a bit error probability of 10⁻⁴ assuming ideal detection conditions, which for a preamplified receiver means that a large amplifier gain is assumed. In this letter, we present an optically preamplified OOK/DD receiver scheme with a very low quantum limit, which is predicted to outperform previously studied configurations.

System model: The schematic diagram of the studied receiver is illustrated in Fig. 1. The preamplifier is an EDFA (erbium-doped fibre amplifier) which is modelled as a linear optical field amplifier with gain G and AWG (additive white Gaussian) noise n(t) representing the ASE (amplified spontaneous emission) noise. The spectral parameter of n(t) is given by $N_f = n_p (G - 1) W$, where $n_p$ is the amplifier spontaneous emission factor, $h$ is Planck’s constant, and $v$ is the optical frequency. An optical filter f(t) is used to limit the effect of ASE on the system performance, and in the case of WDM (wavelength division multiplexing) systems, to select the desired channel. The incoming signal is a binary sequence of rectangular pulses S(t). At the output of the filter f(t), the signal is denoted by Y(t) and the resultant coloured Gaussian noise by $X(t)$. With the above notation, the incident optical field on the photodetector becomes: $B(t) = Y(t) + X(t)$. The optical filter is a finite-time integrator over the bit duration time $[0, T]$, the impulse response $r(t)$ of which is given by

$$r(t) = \begin{cases} \frac{1}{T} & 0 \leq t \leq T \\ 0 & \text{otherwise} \end{cases}$$

The postdetection filter is assumed to be an integrate-and-dump filter. The integration interval T is chosen to be $T = dt/2$, $T + dt/2$. The parameter d is selected so as to yield the lowest bit-error probability.

Performance analysis: For the performance analysis we need a complete statistical description of the receiver decision variable. The moment generating function (MGF) provides us with such statistical information. The MGF for the receiver decision variable Z is given by $M_Z(s) = M_E(e^s - 1)$, where A is the so-called Poisson parameter [1]. For an integrate-and-dump postdetection filter $\Lambda = \frac{1}{T} \int_0^T Y(t) + X(t) dt$. Based on the MGF for the decision variable Z, error probabilities are expediently computed by the so-called saddlepoint approximation [2, 3].

The general mathematical form for the MGF of $\Lambda, M_\Lambda(s) = E(e^{s\Lambda})$, is well known, e.g. [2], and can be represented as

$$M_\Lambda(s) = |D(s)|^{-1} \exp(F(s))$$

where $F(s)$ and $D(s)$ are found by solving the so-called Fredholm integral equations, e.g. [2, 4]. For the present case we have

$$F(s) = mG[h_2 H_2(\gamma_1) + h_2 H_2(\gamma_2)]$$

with $H_2(s) = \frac{\alpha}{\beta \cos^2\beta} [\sin 2\beta s - \sin 2\beta s]$

where $\gamma_1 = 2 \alpha d - 4, \gamma_2 = 2 \alpha d / 2 - 2$.

References


where $m$ is the number of received photons in an optical pulse for a transmitted symbol 'one'. The parameter $a^2 = n_d(G - 1)$, $\beta = \sqrt{2(G - 1)}$, and $x = (1 - d^2)$. The Fredholm determinant is given by $D(x) = \cos(2\pi x d)$.

Present observed bit $D(x)$ where $x$ is the number of received photons in an optical pulse for a transmitted bit. Hence the bit sequence of interest is presented in Fig. 2. We observe that the lowest quantum limit is $b_0$, the value of knowledge, the lowest reported theoretical quantum limit is $b_1$. The situation is the case when the optical signal is assumed to pass the optical filter undistorted and that for a receiver with an optical matched filter optimised (yielding the lowest error probability), the number of photons is $16.2$.

Fig. 2 shows the result of the Gaussian approximation for the quantum limit against integration interval $d^2$. We observe that for this receiver configuration only a single past and one succeeding bit (with respect to the present observed bit $b_0$) produce intersymbol interference on the present transmitted bit. Hence the bit sequence of interest is $b_1, b_0, b_1$.

A plot of the quantum limit against the integration interval $dT$ is presented in Fig. 2. We observe that the lowest quantum limit is $16.2$ photon/bit for a factor $d = 0.12$ and a value of $G = 20\text{dB}$. If the value of $G$ is large and the integration interval $dT$ is made small and optimised (yielding the lowest error probability), the proposed receiver scheme has a lower quantum limit compared to the previously studied configurations for instance, to the author's knowledge, the lowest reported theoretical quantum limit is $38.4$ for a receiver with an optical matched filter $[3, 5]$. The matched filter situation is the case when the optical signal is assumed to pass the optical filter undistorted and that $X(t)$ is Gaussian band-limited (ideal bandpass filter assumed).

Summary: We have shown that if the optical filter is a finite-time integrator and the postdetection filter an integrator over a small interval centred around the end of each bit interval then a quantum limit of $16.2$ photon/bit can be achieved. Although a finite-time integrator optical filter (corresponding to a filter with a sinc shaped transfer function) is probably difficult to realise, the presented receiver configuration outperforms previously studied schemes. An interesting question, open for study, is which value constitutes the ultimate theoretical lowest quantum limit for optically preamplified OOK/DD receivers.

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References


OTDM applications of dispersion-imbalanced fibre loop mirror


Improvement of the signal quality from 10Gbit/s OTDM system are demonstrated for the first time by means of nonlinear switching in a dispersion-imbalanced fibre loop mirror (DILM).

The nonlinear transformation of optical pulses in fibre interferometers has long been of interest for the purposes of high-capacity data transmission. Recently, a novel approach has been applied to the generation of high-quality optical pulses from simple, directly-modulated sources in a compact fibre device based on self-switching in a dispersion-imbalanced fibre loop mirror (DILM) [1, 2]. High quality femtosecond and picosecond pulse generation have been demonstrated from an ordinary gain-switched laser diode, with pedestal extinction ratio $>20\text{dB}$ in the output signal, this figure being limited by the resolution of the apparatus used at the time.

In this Letter, we describe an application of the above method for pulse quality improvement in conjunction with an electroabsorption modulator (EAM). Furthermore, the same method is implemented for interchannel crosstalk suppression in an $80\text{Gbit/s}$ OTDM system. A high quality femtosecond and picosecond pulse generation has been demonstrated from an ordinary gain-switched laser diode, with pedestal extinction ratio $>20\text{dB}$ in the output signal, this figure being limited by the resolution of the apparatus used at the time.

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Fig. 2 shows the result of the Gaussian approximation for the quantum limit (dotted line). The minimum value is $24.8$ photon/bit for an integration interval $d = 0.12$.