Optical Versus RF Free-Space Signal Transmission: A Comparison of Optical and RF Receivers Based on Noise Equivalent Power and Signal-to-Noise Ratio

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***Abstract*—To compare the power efficiency of free-space signal transmission over an optical carrier with that of signal transmission over an RF carrier, we compare the signal to noise ratio and the noise equivalent power of various optical detection schemes with that of simple antenna reception of an RF signal. We point out that for direct optical detection schemes, the noise equivalent power for optical detection is orders of magnitude larger than for RF signal detection with an antenna, with only coherent optical detection requiring similar power levels at the receiver as RF detection with an antenna and mixer, for the same available bandwidth. This is often ignored in articles in which the relative advantages of optical and RF transmission are discussed. Optical transmission mostly has advantages when very high capacity is required and where the available RF bandwidth is small.**

***Index Terms*—Optical receivers, receiving antennas, noise.**

I. Introduction

In several free-space or guided-wave, analog or digital communication schemes, a choice can be made between doing the entire transmission and reception in the RF domain or using the analog or digital signals to modulate an optical carrier and retrieving the signal after an optical detection scheme. Optical communication allows to transmit signals with much larger bandwidth, implying that simpler modulation formats can in principle be used to obtain a certain data rate, while RF communication has to rely on quadrature amplitude or other complex modulation to reach high data rates. For cases where transmission occurs at very high data rates (or bandwidths) between well-defined points at very long distances, optical fiber communication is usually the more preferred option because of the much lower loss over the transmission channel [1]. When it is impossible (as in satellite communications) or difficult (5G/6G front and back-haul in dense urban areas) to install fiber, both free-space RF and optical communication can be used.

It is however a different matter for lower data rates or shorter distances, as is e.g., the case for communication inside or between buildings, or when larger areas have to be covered. If very large areas have to be covered, as in satellite communication (e.g., for GPS), most communication is necessarily in the RF domain as RF receivers are much more sensitive than optical receivers, especially at low carrier frequencies, and the link availability is much higher for RF than for optical links when considering the attenuation in the atmosphere. However, when distances and area to be covered are not that large, one still has a choice between free-space RF communication and free-space optical communication, provided that the optical link can be assured or limited availability can be managed.

Free-space optical communication can be implemented with collimated beams generated by a laser diode, but it can also take place using diffuse light from LEDs, e.g., for communication in buildings [2], [3]. Collimated optical beams allow a directional communication, but require a line of sight link. In case the transmitter or receiver is mobile, it requires powerful beam steering and localization functions [4].

However, the reception of signals in the RF and optical domain is very different. Optical detection converts the received light intensity into photocurrent and voltage [5], whereas antennas for RF signal reception convert the received electrical field (amplitude and phase) into current and voltage [6]. This difference in the detection scheme implies different signal to noise ratios and different receiver sensitivities, with significant implications for the power budget of the transmission. The signal to noise ratio and sensitivity depend substantially on the specific detection scheme though. In optical communication, one can make use of direct or coherent (e.g., heterodyne) detection, of simple pin-photodiodes or avalanche photodiodes or even of optical pre-amplification.

The purpose of this paper is to highlight the main differences between RF receivers and optical receivers. We compare the signal to noise ratio (SNR) and the noise equivalent power (NEP: signal power that gives a SNR of 1) of antenna reception with the SNR and NEP of the various optical receiver schemes, with direct or coherent detection, with and without electronic pre-amplifier and even with an optical pre-amplifier in front of the optical detector. In particular, we conclude that, under almost all circumstances and assuming the same available bandwidth, optical detection requires elevated received powers compared to RF detection. Only coherent detection with relatively large

Manuscript received July 15, 2021; revised November 9, 2021; accepted November 16, 2021. Date of publication November 19, 2021; date of current version December 6, 2021. *(Corresponding author: Geert Morthier.)*

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/JSTQE.2021.3129250.

Digital Object Identifier 10.1109/JSTQE.2021.3129250

local oscillator power gives a similar noise equivalent power as an antenna with a mixer.

We start with an overview of all the different noise sources that have to be taken into account in the case of antenna reception and optical detection. The main noise sources are thermal noise and shot noise, and in the case of optical pre-amplification, beat noise between the signal and amplified spontaneous emissions. Also the significant difference between the noise figure of an electronic and an optical amplifier is pointed out here.

The second main part of the paper consists of comparisons of Signal to Noise Ratio (SNR) and Noise Equivalent Power (NEP) between the different optical detection schemes and the detection of RF signals with an antenna, assuming equal bandwidth in both cases. For almost all optical detection schemes, we find that the NEP is one to a few tens of dB higher than for direct RF detection, even when including a mixer with a noise figure of 15 dB. The lowest NEP in case of optical detection is obtained for coherent detection with large local oscillator power. The noise equivalent power is then dominated by shot noise and is very close to the noise equivalent power for an antenna followed by a mixer with a noise figure of 15 dB (assuming the same bandwidth).

In a third part, we briefly discuss the required received power levels when different bandwidth for the optical and the RF transmission channel are taken into account. The required signal-to-noise ratio (SNR) is derived from Shannon's capacity limit for different bandwidth of the RF channel. Taking into account a lower bandwidth for the RF transmission channel and the much higher required SNR, it is found that RF transmission can only be competitive with optical transmission if the RF bandwidth is sufficiently high. When coherent optical detection is used (which implies a more complex receiver and larger power consumption), RF transmission and detection can only be competitive when the RF channel bandwidth is very comparable to the bandwidth of the optical transmission system.

II. Overview of Noise Sources in RF and Optical Receivers

A. Thermal Noise

Thermal noise (also called Johnson or Nyquist noise) is present in both RF and optical receivers [8]. In an antenna system for the reception of RF signals, this noise depends on a number of factors: the noise which the antenna picks up from the environment, the noise generated in the resistance of the antenna, the noise due to the losses in the transmission line and the noise due to a load (matching resistor) or input resistance of an amplifying/read out system. These noise sources are all expressed by a power density $p_{N,i}$ which itself is related to an equivalent noise temperature $p_{N,i} = kT_i$, with k the Boltzmann constant and T_i the equivalent noise temperature (which is different for the different noise sources). For a system with bandwidth Δf, each noise contribution can be expressed by the power $P_{N,i} = kT_i\Delta f$. For example, for the noise picked up from the environment:

$$P_A = kT_A\Delta f \tag{1}$$

with T_A the antenna temperature, which is not the physical temperature of the antenna but the temperature of the background radiation picked up by the antenna. For an antenna pointed at the night sky, e.g., T_A is 3 to 5K, while for an antenna pointed towards the horizon during the day it is around 300K. The antenna temperature in general depends on the antenna's effective aperture and on the properties of the radiating bodies in the environment [7]. Here we will assume that the antenna is pointed towards the ground or horizon and that $T_a = 300K$, which is also the temperature we will assume for the optical receivers later. Δf is the bandwidth of the positive frequency part only (i.e., the noise in principle covers a bandwidth Δf on the negative frequency axis and a bandwidth Δf on the positive frequency axis).

If the antenna is not a perfect conductor and has some losses, the noise temperature at the antenna aperture consists of T_A and the temperature T_{AP} due to the physical temperature T_P of the antenna as:

$$T_A + T_{AP} = T_A + T_P\left(\frac{1}{e_A} - 1\right) \tag{2}$$

with e_A the thermal efficiency of the antenna ($e_A \leq 1$). It is 1 for a lossless antenna, for which the supplied power is completely radiated. $e_A < 1$ if some of the supplied RF power is absorbed and converted into heat.

Finally, if the transmission line connecting the antenna to the receiver has conduction loss, its noise contribution at the antenna terminal is:

$$T_L = T_{LP}\left(\frac{1}{e_L} - 1\right)\frac{1}{e_A} \tag{3}$$

With T_{LP} the physical temperature of the transmission line and e_L the thermal efficiency of the line ($e_L = \exp(-2\alpha L)$, with L the length of the line and α the attenuation of the line). The noise temperature T_{AL} at the input of the antenna due to the antenna and the transmission line is thus:

$$T_{AL} = (T_A + T_{AP}) + T_{LP}\left(e^{2\alpha L} - 1\right)\frac{1}{e_A} \tag{4}$$

It is assumed above that RF frequencies f and temperatures T are such that hf/kT<<1. In the remaining part of the paper, we assume very low loss in the antenna and the transmission line ($e_L \approx e_A \approx 1$) and thus $T_{AL} \approx 300K$.

In an optical receiver consisting of a pn or pin photodiode connected to a load resistor R_L, the thermal noise is described by a noise current source Δi_{th} in shunt with the signal current source,

$$\left\langle (\Delta i_{th})^2 \right\rangle = \frac{4kT}{R_L}\Delta f \tag{5}$$

With T the temperature of the resistor and R_L the load resistor connected to the photodiode. It is remarked here that the expression (5) leads to a maximum noise power of $kT\Delta f$ delivered to a resistor matched to the load resistor [8]. In an optical receiver, this impedance matching is however rarely pursued.

B. Shot Noise in Optical Receivers

Shot noise is due to the quantum nature of charge carriers or the discrete nature of the current, which is resulting from the movement of an integer number of carriers. It manifests itself when this quantum nature plays an important role as in the photocurrent generation or when the charge carriers have to overcome certain energy barriers (as in a pn-junction). In resistors/conductors (and therefore antennas) there is no extra generation of shot noise. The inelastic scattering of the electrons in these wires smoothens out any further effect from the discrete nature of the incoming signal, even though the current of course remains composed of a discrete number of charges [9]. In other words, the generation of the current in antennas is itself not taking place in discrete steps. In pn or pin photodiodes where the quantum nature of the current generation is important, shot noise does manifest itself as a noise current Δi_{sh} in shunt with the signal current, with [8], [10]:

$$\left\langle (\Delta i_{sh})^2 \right\rangle = 2qI\Delta f \approx 2qRP_{in}\Delta f \quad (6)$$

with q the elementary charge, R the responsivity of the photodetector (in A/W), P_{in} the total incident power and I the photocurrent. Note that the current consists of the signal current RP_{in} as well as a dark current I_d. For coherent detection, the total incident power includes also the (large) local oscillator power. Good photodiodes (e.g., InGaAs heterojunction pin PDs) can have a dark current well below 1 nA [11]. We will see in Section III that shot noise is only important in the case of coherent detection, but in this case the optical power incident on the photodiode is given by the local oscillator power and is large. The dark current is much lower than the signal current in this scheme.

In addition to pn or pin photodiodes there are also avalanche photodiodes (APDs), in which an internal amplification of the photocurrent is taking place by impact ionization [12]. This avalanche process results in an internal amplification of the signal current with an amplification factor M, but it is itself also subject to extra shot noise, expressed by the excess noise factor F_{ex}:

$$I_{sig} = MRP_{in} \text{ and } \left\langle (\Delta i_{sh})^2 \right\rangle = 2qM^2RP_{in}F_{ex}\Delta f \quad (7)$$

F_{ex} and M depend on the structure of the APD and the used semiconductors. The excess noise factor depends on the hole to electron ionization ratio and the gain and is lowest (close to 2) for very small hole to electron ionization ratio [11]. The signal to noise ratio (SNR) of such photodiodes can be expressed as:

$$\frac{S}{N} = \frac{M^2(RP_{in})^2}{\left(2qM^2F_{ex}RP_{in}\Delta f + \frac{4kT}{R_L}\Delta f\right)} \quad (8)$$

It is emphasized that the shot noise is often negligible relative to the thermal noise, at least at room temperature and for low to moderate received powers. At very low operating temperatures and/or for very high received power levels, shot noise can become dominant. It is clear that an APD gives much better SNR when thermal noise is dominating over shot noise; in that case the signal power increases with a factor M^2, while the noise is hardly affected. Ge and InGaAs have a relatively high ionization ratio and thus a large excess noise factor compared to e.g., Si.

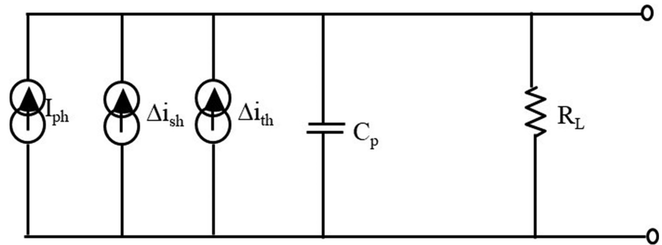

Fig. 1. Equivalent electrical scheme of a photodiode.

An electrical equivalent scheme for a photodiode, under reverse bias, including shot noise and thermal noise is given in Fig. 1. The series resistance of the photodiode has been assumed much smaller than the load resistance. C_p is the parasitic capacitance (depletion or junction capacitance for an isolated PD, plus the pad capacitance).

C. Noise Added by (pre-) Amplifiers

For both antennas and photodetectors connected to an electronic pre-amplifier, the noise generated inside the amplifier(s) is in principle simply described by the noise figure, defined as the ratio of the signal to noise ratio at the amplifier output and the signal to noise ratio at the input when thermal noise and impedance matching are assumed. For an antenna system with amplifier, the noise temperature of the system (at the antenna input) is obtained by adding the noise temperature of the receiver T_r:

$$T_S = (T_A + T_{AP}) + T_{LP}\left(e^{2\alpha L} - 1\right)\frac{1}{e_A} + T_r\frac{1}{e_A e_L} \quad (9)$$

with the receiver temperature T_r being given by:

$$T_r = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1G_2} + \frac{T_4}{G_1G_2G_3} + \cdots \quad (10)$$

with T_n the noise temperature and G_n the gain of the n^{th} amplifying stage. As can be seen from the expression, the receiver noise temperature is often determined by the noise temperature of the first amplifying stage. The receiver temperature can alternatively be expressed as:

$$T_r = T_{AL} \cdot (F_{n,el} - 1) \quad (11)$$

with $F_{n,el}$ the noise figure of the amplifier stage (on a linear scale).

In principle, this noise figure must also include the noise from the mixer. Noise figures of mixers are roughly equal to their conversion loss and can vary between 0 and 15 dB [13]. As RF antenna detection always requires the use of a mixer, we will do calculations in Section III with noise figures of 1 dB and 15 dB. In the following, we will also assume that the noise figure of the mixer also includes the noise figure of any electronic amplifier after the mixer.

For an optical receiver that consists of a photodiode connected to a load resistor followed by a voltage amplifier, the equivalent thermal noise at the input of the receiver is usually simply described by the thermal noise of the load resistor at the input multiplied with the noise figure $F_{n,el}$ of the voltage amplifier. Therefore the thermal noise current at the input of the receiver (including pre-amplifier) can be written as:

$$\left\langle (\Delta i_{th})^2 \right\rangle = \frac{4kT}{R_L} F_{n,el} \Delta f \quad (12)$$

The total current noise at the input of the receiver is:

$$\left\langle (\Delta i)^2 \right\rangle = \left\{ 2qIM^2 F_{ex} \Delta f + \frac{4kT}{R_L} F_{n,el} \Delta f \right\} \quad (13)$$

Furthermore, the electronic amplifiers might also add shot noise if they are based on bipolar transistor technology. In Section III, we have assumed equal noise figure for the electronic amplifier used after an antenna and the voltage amplifier after a resistor loaded photodetector. Although this might not necessarily be the case, one can assume that the noise figures are of the same order of magnitude. Since the NEP's calculated in the next section differ by orders of magnitude, any small difference in noise figure of the electronic amplifiers will not affect the conclusions in the next section.

Expression (13) is mainly valid for resistor-loaded PD's connected to a voltage amplifier. In practice, optical receivers typically consist of a PD followed by a trans-impedance amplifier (TIA). For a good design, the dominant thermal noise is now the thermal noise from the feedback resistor R_F. That feedback resistor can be much larger than the typical load resistor used with a solitary PD or a PD followed by a voltage amplifier. The maximum feedback resistor is given roughly by $2f_T/(2\pi C \Delta f^2)$, with f_T the transition frequency of the used transistor technology [15]. Depending on the transistor technology, this transition frequency can be 100 to several 100's of GHz. The feedback resistor can thus, for a given bandwidth, be a factor $2f_T/\Delta f$ higher than the load resistor used in the voltage amplifier case, reducing the thermal noise considerably.

In the case of optical detectors (or receivers), one can also make use of an optical amplifier as a pre-amplifier in front of the detector. It becomes a bit more complicated to calculate the noise at the output of the detector (or receiver). In addition to amplifying the incoming optical signal, the optical amplifier also generates amplified spontaneous emission (ASE) over a wide spectral range [14]. The optical detector gives a photocurrent which is proportional to the total optical power incident on it. As this total power contains beat terms of signal and ASE frequency components as well as beat terms between different frequency components of the ASE, the noise on the photocurrent is also determined by these beat terms.

In general, all the noise (except the thermal noise) at the output of a photodetector with optical pre-amplifier is expressed as the shot noise multiplied with the noise figure $F_{n,opt}$ of the optical amplifier:

$$\left\langle (\Delta i)^2 \right\rangle = 2qR\,(G-1)\,GP_{in}F_{n,opt}\Delta f \quad (14)$$

With G the amplification of the optical amplifier and P_{in} the optical power incident on the optical amplifier. It is important to remark here that the noise figure of an optical amplifier is defined with respect to the shot noise and not with respect to the thermal noise as for an electrical amplifier. To the noise of (14), one still has to add the thermal noise.

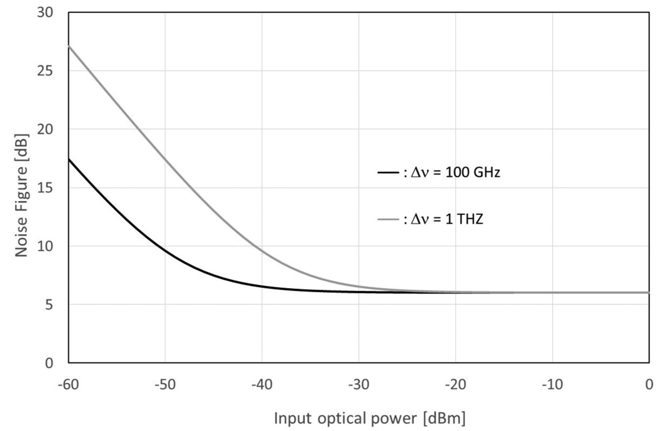

Fig. 2. Noise figure (in dB) of an optical amplifier vs. input optical power for an amplification of 20 dB, an inversion factor n_{sp} of 2 and for 2 different bandwidths $\Delta\nu$ of the ASE: 100 GHz and 1 THz. A wavelength of 1.55 μm (photon energy of 0.8 eV) was assumed also.

The noise figure of an optical amplifier depends strongly on the optical input power, and on the amplification. Fig. 2 shows this noise figure vs. input power for a C-band optical amplifier with an amplification of 20 dB, an inversion factor of 2 and ASE bandwidth of 100 GHz (0.8 nm) and 1 THz (8 nm). At high enough input powers on the optical amplifier the noise figure reduces to $F_{n,opt} = 2n_{sp}$, with n_{sp} the inversion factor (close to 1 for fiber amplifiers and close to 2 for semiconductor optical amplifiers) [14].

III. Comparison of SNR and NEP for Different Receiver Configurations

A. RF Antenna Detection vs. Direct Optical Detection

The signal to noise ratio for detection of RF signals with an antenna can be expressed as:

$$\frac{S}{N} = \frac{P_{sig}}{(kT_s \Delta f F_{n,el})} \quad (15)$$

With P_{sig} the signal power captured by the antenna and T_s the system noise temperature as given by (9). The Noise Equivalent Power (NEP) is thus simply $kT_s\Delta f\ F_{n,el}$ or 40 10^{-19} Δf. $F_{n,el}$ mW (Δf in Hz) for a noise temperature of 300K.

For direct optical detection, we can use expression (8). We consider a pn or pin photodiode without any internal gain (i.e., no APD), connected to an ideal voltage amplifier (i.e., with noise figure one or slightly above one). We can assume that the thermal noise of the load resistor is dominant. The NEP in this case is :

$$NEP = \frac{1}{R}\sqrt{\frac{4kT}{R_L}\Delta f} \quad (16)$$

The responsivity R depends on the used wavelength, but is typically around 1 A/W for wavelengths used in optical fiber communications (O-band and C-band). The choice of the load resistance R_L is determined by the desired bandwidth, which is limited to $1/(2\pi R_L C_p)$ with C_p the parasitic capacitance of

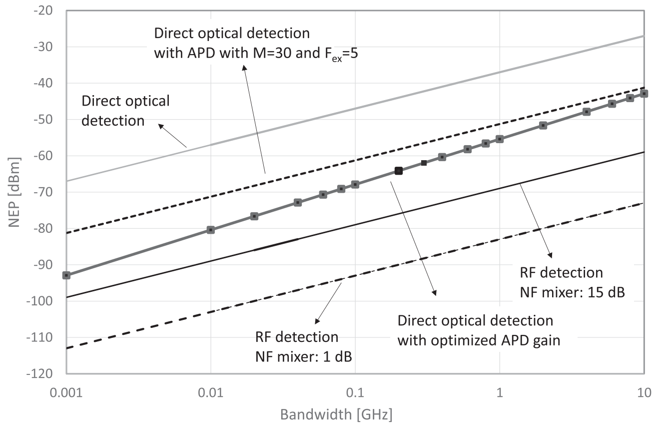

Fig. 3. Noise Equivalent Power for RF detection, for direct optical detection with pn or pin photodetector with responsivitiy 1A/W, and for direct optical detection with APD with R = 1A/W, M = 30 and F_{ex} of 5. The detectors are assumed to be connected to a load resistor, chosen such as to obtain the bandwidth on the x-axis for a capacitance of 0.4 pF. No electronic pre-amplifier is assumed. For RF antenna detection, a mixer with a NF of 1 dB and a mixer with a NF of 15 dB is assumed.

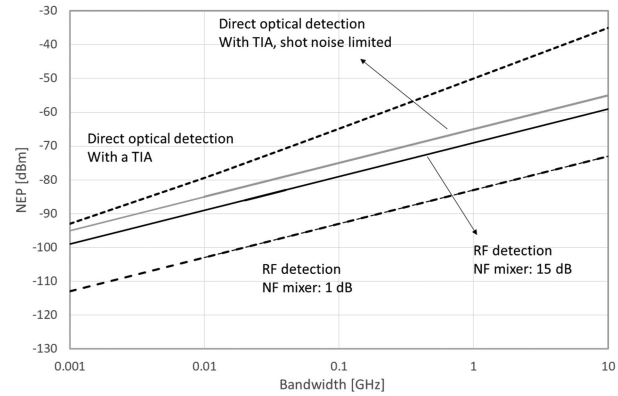

Fig. 4. NEP vs bandwidth for both RF detection (antenna reception) and direct optical detection with a PD followed by a TIA. For RF antenna detection, a mixer with a NF of 1 dB and a mixer with a NF of 15 dB is assumed.

the PD. If we assume a constant typical parasitic capacitance of 0.4 pF and a load resistance given by $R_L = 1/(2\pi\Delta f C_p)$, then a NEP at room temperature of 0.2 μW/GHz is obtained. The parasitic capacitance obviously depends on the specific structure of the photodiode and can for certain photodiodes be an order of magnitude lower.

Fig. 3 compares the NEP for RF and direct optical detection vs. the receiver bandwidth for $C_p = 0.4$pF and for 2 different values of the mixer noise figure, 1 and 15 dB. One can see that even for a mixer NF of 15 dB, the NEP for RF detection is more than 30 dB lower than that for direct optical detection with regular pn or pin photodiode. From the numerical calculations, the influence of shot noise on the NEP was found to be negligible.

When the photodetector is an APD, shot noise may become relatively more important. We find the following expression for the NEP now:

$$NEP = \frac{1}{R}\left\{qF_{ex}\Delta f + \sqrt{\frac{4kT}{M^2 R_L}\Delta f + (qF_{ex}\Delta f)^2}\right\} \tag{17}$$

For several APDs (in particular Ge and InGaAs APDs), the excess noise factor is more or less proportional to the multiplication factor, i.e., $F_{ex} = XM$ with X close to 1 for both Ge and InGaAs APDs. In this case, the multiplication factor can be optimized to give minimal NEP. One finds:

$$M^4 = \frac{4kT}{3R_L(qX\Delta f)^2} \text{ and } NEP = 3^{3/4}\sqrt{qX\Delta f}\sqrt[4]{\frac{4kT\Delta f}{R_L}} \tag{18}$$

This NEP is added in Fig. 3 for the case of a fixed gain M of 30 and a fixed noise excess factor F_{ex} of 5, as well as for the optimum multiplication factor M given by (18) and assuming X = 1. A parasitic capacitance of 0.4 pF was assumed in both cases. The NEP for this APD detection is still largely dominated by the thermal noise. For the case with fixed M = 30 and fixed $F_{ex} = 5$, it is 15 dB (corresponding with M = 30) below the NEP for direct detection with a pn or pin detector. Optimization of M gives mainly lower NEP for lower bandwidths and for bandwidths below 0.1 GHz, the NEP is 20 dB or more below the NEP for direct detection with a pn or pin detector. APDs come however also with a few disadvantages, e.g., they require high (temperature dependent) bias voltage, have lower bandwidth than pin PDs and have a nonlinear response [5].

It is a slightly different matter when the electronic amplifier is a trans-impedance amplifier and the dominant noise is the thermal noise from the feedback resistor R_F (which may not be the case at high frequencies). Fig. 4 compares the NEP of optical detection, using a TIA with the NEP of RF antenna detection. The feedback resistor is determined by $2f_T/(2\pi C\Delta f^2)$ for a capacitance of 0.4 pF and an f_T of 200 GHz. Shot noise is also taken into account. The difference in NEP between RF antenna detection and direct optical detection depends on the bandwidth. At very low bandwidths of 1 MHz, the NEP for direct optical detection with TIA is only 5 dB higher than the NEP for RF antenna detection. At bandwidths of 1 GHz and 10 GHz, that difference has however increased to over 15 dB and 20 dB. Fig. 4 also shows the shot noise limit in case of optical detection with TIA. The NEP at very low bandwidths is very close to the shot noise limit, but it is much higher at bandwidths of 10 GHz. The NEP for optical detection with TIA seems comparable to that of optical detection with an APD connected to a load resistor and an ideal voltage amplifier. TIA's can typically achieve higher bandwidths than APD's though. For an APD connected to the same TIA (not shown in Fig. 4), one finds that the NEP is very close to that determined by shot noise. It is for all bandwidths 7 dB (corresponding with the factor $F_{ex} = 5$) above the shot noise value shown in Fig. 4.

In the following comparisons, we will always assume that the optical receiver consists of a PD followed by a TIA, with the thermal noise being dominated by the feedback resistor.

B. RF vs. Coherent Optical Detection

Coherent optical detection makes use of a local oscillator (a tunable laser diode for example) of which the high power optical

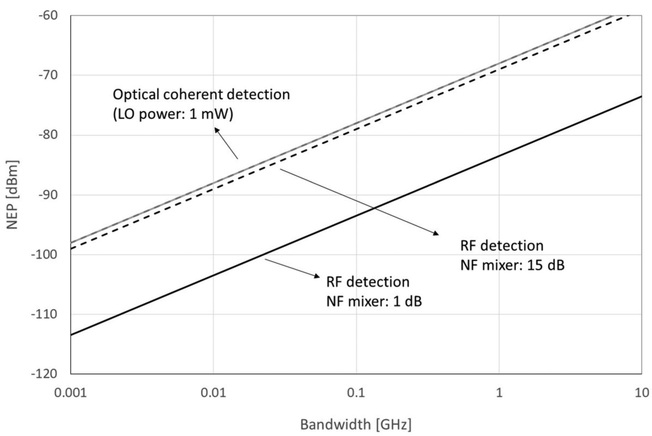

Fig. 5. NEP vs bandwidth for both RF detection (antenna reception with mixer NF of 1 and 15 dB) and coherent optical detection for a LO power of 1 mW.

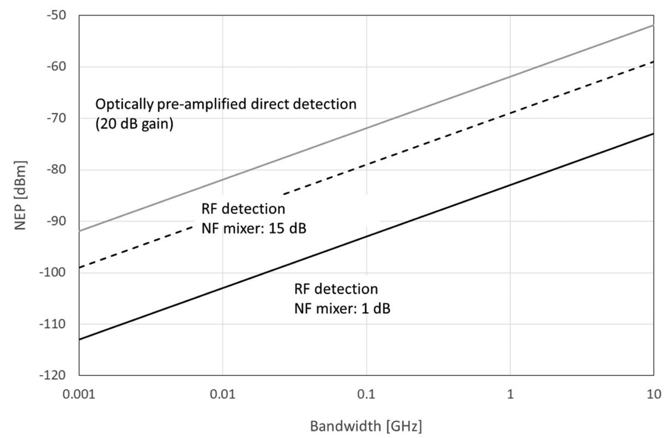

Fig. 6. NEP of optically pre-amplified direct detection (for G = 20 dB, $F_{n,opt}$ = 3 dB) vs. bandwidth, compared to the NEP for RF detection with a mixer NF of 1 and 15 dB.

output is mixed with the incoming optical signal in a photodiode (or pair of photodiodes). The total photocurrent generated by a detector is in this case:

$$I{=}R\left\{P_{LO}+P_{sig}+2\sqrt{P_{LO}P_{sig}}\cos\left[\omega_{IF}t+\phi_s-\phi_{LO}\right]\right\},\quad \text{with } \omega_{IF}=\omega_s-\omega_{LO} \tag{19}$$

As the power from the local oscillator is usually much larger than the signal power, the total noise equivalent power at the input of the amplifier can now be approximated by (assuming a pn or pin PD):

$$\left\langle(\Delta i)^2\right\rangle=\left\{2qRP_{LO}\Delta f+\frac{4kT}{R_F}\Delta f\right\} \tag{20}$$

For heterodyne detection (ω_{IF} nonzero) the signal power is $2R^2P_{LO}P_{sig}$, giving an SNR of:

$$\frac{S}{N}=\frac{2R^2P_{sig}P_{LO}}{\left(2qRP_{LO}\Delta f+\frac{4kT}{R_F}\Delta f\right)} \tag{21}$$

And a NEP of:

$$NEP=\left(q\Delta f+\frac{2kT}{R_FRP_{LO}}\Delta f\right)/R \tag{22}$$

For homodyne detection the signal power (and thus the SNR) is twice as large. For temperatures T close to room temperature, responsivities around 1 A/W, local oscillator powers of 1 mW or more and a load resistance of 100 Ω, the first term in the NEP is dominant and the NEP is determined by shot noise.

Fig. 5 compares the NEP given by (22) with the NEP for antenna reception, again assuming a feedback resistance determined by the bandwidth ($R_F = 2f_T/(2\pi C\Delta f^2)$) and the parasitic capacitance of 0.4 pF. It is seen that the NEP for coherent detection is just a little above that for RF antenna detection with large mixer NF. It is pointed out that this homodyne or heterodyne technique only works when the signal light is coherent itself, i.e., when the transmitter is a laser diode and not an LED.

C. RF vs. Optically Pre-Amplified Detection

For the optically pre-amplified detection we assume that an optical amplifier with noise figure $F_{n,opt}$ and amplification G is placed in front of the photodetector (again followed by a trans impedance amplifier). The SNR vs. input power on the optical amplifier can then be expressed as:

$$\frac{S}{N}=\frac{R^2G^2P_{sig}^2}{\left(2qRG\left(G-1\right)P_{sig}F_{n,opt}\Delta f+\frac{4kT}{R_F}\Delta f\right)} \tag{23}$$

And the NEP is thus given by:

$$NEP=\left(q\Delta fF_{n,opt}+\sqrt{\left(q\Delta fF_{n,opt}\right)^2+\frac{4kT\Delta f}{G^2R_F}}\right)/R \tag{24}$$

For even a medium amplification (20 dB or more, [15]), it was found that the optical amplifier noise is dominant and that the NEP can be approximated by:

$$NEP=2q\Delta fF_{n,opt}/R \tag{25}$$

Fig. 6 compares the NEP vs. bandwidth Δf for the case $F_{n,opt} = 2$, and for an amplification of 20 dB. The NEP is again compared with that for straightforward RF antenna detection of RF signals. One can easily verify that, even for a mixer noise figure of 15 dB, RF detection has about 10 dB lower NEP in the bandwidth range considered in Fig. 6.

The free-space coupling of light into a semiconductor or fiber optical amplifier is usually not very efficient. Coupling losses are easily 3 dB or more. This loss has to be added (in dB) to the NEP power given by (24).

IV. Required Signal to Noise Ratios

We have compared the SNR and NEP of various optical detection schemes with that of RF antenna detection. In reality RF transmission systems have typically much smaller bandwidth than optical transmission systems. To transmit a certain high bitrate, RF systems have to rely on higher order modulation

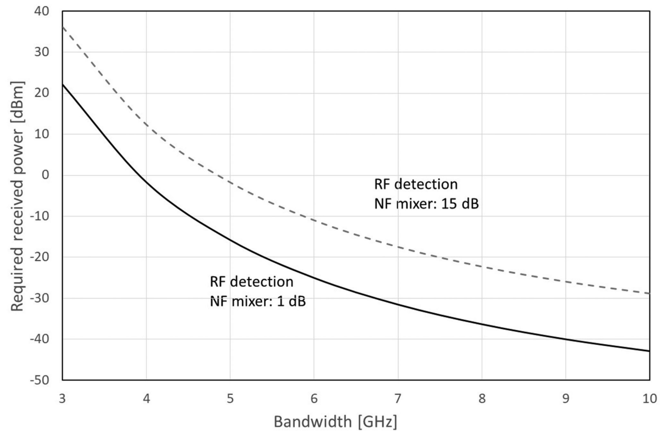

Fig. 7. Required received power vs. channel bandwidth for a 100 Gb/s RF system with a mixer/amplifier noise figure of 1 and 15 dB. This received power has to be compared to the required receiver power of −24.5 dBm for direct optical detection with a 50 GHz TIA-based receiver and with a required receiver power of −58 dBm for a coherent optical detection.

formats which require higher signal to noise ratios (SNR's). How much SNR a certain transmission system for a certain capacity (bitrate) requires can be derived from Shannon's capacity limit expression:

$$C = Blog_2\left(1 + \frac{S}{N}\right) \text{ or } \frac{S}{N} = 2^{(C/B)} - 1 \qquad (26)$$

With B the bandwidth of the channel and C the capacity in bits/s.

As a first example we consider the transmission of 100 Gbit/s. For the optical transmission channel, we assume a bandwidth of 50 GHz. However, for the RF transmission channel, the available bandwidth will be much smaller. Expression (26) readily allows to calculate the required S/N ratios in all cases. For the optical transmission, the required S/N is 3. In case of a receiver with TIA in which thermal noise dominates, the power incident on the optical receiver has to be 1.7 times the NEP. Assuming a bandwidth of 10 GHz for the RF channel (which is a rather high bandwidth for an RF system), a SNR of 30 dB (a factor 1000) is required. For a bandwidth of 50 GHz, direct optical detection with a receiver consisting of a PD and a TIA has a NEP of −24.5 dBm. Thus a received power of −22 dBm would be required. The required received powers for RF transmission, assuming an antenna followed by a mixer with a NF of both 1 and 15 dB, are shown in Fig. 7 vs. the bandwidth. Only for an RF bandwidth of 6 GHz or more does RF transmission give some advantage. When coherent detection with large LO power is used, the optical detection has a NEP at 50 GHz of −51 dBm and only a received power of −48 dBm would be required by Shannon's limit. Not even a mixer with a NF of 0 dB would then make an RF transmission with 10 GHz bandwidth win in terms of required power at the receiver.

We also consider the transmission of 10 Gbit/s signals, now assuming an optical channel (receiver) with a bandwidth of 5 GHz. Again the optical system with direct detection, using a receiver with a TIA in which thermal noise dominates, will require a S/N of 3 and an incident power at the receiver of NEP+2.5 dB. For a bandwidth of 5 GHz, we find a NEP of −39.5 dBm and thus a minimum received power of −37 dBm. For the RF system, we consider bandwidths between 300 MHz and 1 GHz. The required received powers for a certain bandwidth B are 10 dB lower than those given in Fig. 7 for a bandwidth of 10 times B. RF transmission now only has advantages for RF bandwidths equal to or above 0.7 GHz. For coherent optical detection, the NEP scales with bandwidth just as does the NEP for RF detection. The conclusions remain therefore the same as for the 100 Gbit/s case.

The required power levels at the receiver are the minimum power levels that are required by the Shannon limit. In practice, the required power levels to obtain a certain BER are substantially higher. How much power above the Shannon limit is required is typically smaller for optical NRZ transmission than for RF QAM transmission. Something which makes optical transmission even more competitive.

V. Conclusion

We have compared the SNR and NEP of various optical detection schemes and found that for almost all optical detection schemes, the NEP for a given bandwidth is higher by ten to a few tens of dB than for RF antenna detection. The only exception is coherent detection with large local oscillator power. In that case, the NEP is dominated by shot noise. The NEP of coherent optical detection with large LO power is almost equal to the NEP for RF antenna detection when also a mixer/amplifier with a noise figure of 15 dB is included. When a low noise figure of e.g., 1 dB for the mixer/amplifier is assumed, then the NEP for RF antenna detection is about 15 dB below that of coherent detection.

In our comparison, we have assumed identical bandwidths for optical and RF antenna detection. However, the available bandwidth is often smaller for RF transmission than for optical transmission, either because of bandwidth availability or because of bandwidth limitations of transmitter or receiver. When it is taken into account that RF transmission has less available bandwidth, a much higher signal-to-noise ratio is required for the RF transmission of a certain capacity. Taking this into account, the much higher bandwidth of optical transmission systems makes them much more attractive in terms of required received power. From a theoretical point, the RF system should have a bandwidth of at least a tenth of the optical bandwidth to be competitive. In practice, an even higher bandwidth for RF systems may be required to make them competitive.

An important factor in the comparison is the total power consumption, which we didn't discuss here and which might be the subject of a follow-up paper.

Acknowledgment

The authors thanks their colleagues Guy Torfs and Xin Yin for carefull reading of the manuscript and useful comments.

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