Challenges in Gbps Wireless Optical Transmission

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Abstract. In this paper, the link budget of Gbps wireless infrared indoor communication is analysed. We particularly focus on the receiver sensitivity and identify the most suitable wavelengths range. We show that an optical receiver operating at 1 Gbps will hardly achieve the shot noise limit, which is determined by the received amount of background light. Regarding the link budget, we present two case studies. One deals with (very) short range communication, the other one with a wireless personal area network. We reveal that a network demands for avalanche photodiodes as well as beam steering. This clearly causes major challenges regarding compact and inexpensive components.

Keywords: infrared, communication, eye safety, photodetector, link budget, receiver sensitivity, angle diversity, imaging receiver, non-imaging receiver.

1 Introduction

As a part of the EU Seventh Framework R&D programme (FP7), the hOME Gigabit Access (OMEGA) project aims at bridging the gap between mobile broadband terminals and the wired backbone at home. To provide Gbps connectivity, three main technologies — RF, power line and infrared (IR) — are considered. This paper focuses on IR transmission.

IR radiation exhibits a number of characteristics which qualify it as an appropriate alternative to RF for short range indoor transmission. First of all, IR takes advantage of a completely unregulated and unlicensed spectral range. Since IR radiation does not travel through walls, systems operating in separate rooms do not interfere with each other. For the same reason, the optical medium promises high security against eavesdropping. Furthermore, an IR transmitter does not produce any "electrosmog" in the ideal case.

However, besides these advantages it is known that IR transmission is associated with some real challenges. The most important one is definitely the limited receiver sensitivity. Typically (and even at 1 Gbps), a RF receiver will outperform its IR-counterpart by several tens of decibels. The enormous difference is by far not only a result of detecting the signal coherently or non-coherently. It is a result of the completely different physical mechanisms which underlie the detection [1].

⋆ This work is supported by the European Union Seventh Framework Programme referred as OMEGA [www.ict-omega.eu].

P. Chatzimisios et al. (Eds.): MobiLight 2010, LNICST 45, pp. 484–495, 2010.

For free space optical links (such as those between satellites or between buildings), the limited receiver sensitivity will be (more than) compensated by a very small path loss, since highly directive transmitters and receivers are used. In this case, the link budget profits from the fact that optical radiation can be focused very well leading to huge “antenna gains”.

However, optical indoor communication considered here demands for a reasonable coverage. Even if line-of-sight (LOS) is assumed, it is thus not as straightforward to benefit from a directional gain. To ensure coverage, beam steering needs to be applied. Currently and in the near future, two concepts are realistic and applicable at both the transmitter and the receiver. One uses a mechanical steering of a narrow beam [2]. The other one is based on angle diversity [3], i.e., the solid angle to be covered is divided into a number of sub-sectors, where each sub-sector corresponds to a different transmit/receive angle. In this case, the beam steering is discrete — comparable to switched beam antennas. Two angle diversity approaches can be used. In one case, each laser or photodiode is equipped with its own (possibly non-imaging) optics. These “directional optics” are accordingly aligned, where a certain overlapping is required. In the other case, an array of lasers or photodiodes is combined with an imaging optics — very similar to the sensor-lens combination used in digital cameras.

In this paper, the link budget for non-return-to-zero (NRZ) On-Off Keying (OOK) LOS transmission at a data rate of 1 Gbps is analysed. We will particularly focus on the receiver sensitivity (section 3). It will be shown that silicon photodiodes offer a better receiver sensitivity than photodiodes made of InGaAs or other ternary semiconductors. The primary reason for that is the photodiode capacitance, which is desired to be as small as possible. We will show that the detector will not reach the shot noise limit (determined by the amount of received background light), which makes a good link budget even more challenging. Two case studies presented in section 4 will point out clearly that an optical wireless personal area network (operating at 1 Gbps) demands for beam steering concepts offering large directional gains. This makes the design of compact and lightweight components not easy.

2 Eye Safety

The transmit power is an important link budget parameter. It is ultimatively limited by laser safety constraints. Laser safety is covered by the international standard IEC 60825-1. It is important to note that a new edition of this standard, designated 60825-1:2007 edition 2, has recently been published [4]. In this edition, the measurement condition for diverging sources has been relaxed. The following focuses on the new eye safety constraints.

The classification of any diverging source (with a half-intensity angle larger than a few degrees) can be referred to its on-axis radiant intensity I_0 (in mW/sr). I_0 scaled by 4π (the solid angle of a sphere) is nothing else but the “equivalent isotropic radiated power” (EIRP) which is commonly used for RF link budget analysis. By using I_0, the class 1 limit — “safe under all foreseeable conditions” [4] — to be used here depends only on the apparent source diameter D and on the wavelength λ.

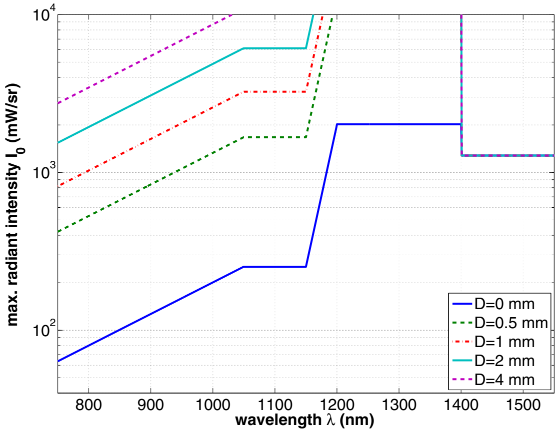


Fig. 1. Permitted on-axis radiant intensity for class 1 sources depending on the source diameter D

The I_0 limits according to edition 2 are shown in Fig. 1. For $\lambda > 1200$ nm, the permitted I_0 can exceed 1000 mW/sr, even for a point source, i.e., $D = 0$ mm. This is in fact a very large value — 1000 mW/sr corresponds to an optical EIRP of 12 W. For $\lambda > 1200$ nm the eye safety will most likely not cause any problem with respect to the system design. Unfortunately, such wavelengths are outside the detection range of inexpensive silicon photodiodes.

At 800 nm, where fast silicon detectors are available (see next section), I_0 is limited to about 80 mW/sr corresponding to an EIRP of 1 W. This is many times more than permitted compared to previous standard editions, but larger values may be still desirable. Especially, if the transmitter shall profit from a large directional gain, an additional diffuser[1] needs to be applied to increase the apparent source size D. Fig. 1 shows that a diffuser diameter of $D = 1$ mm is theoretically sufficient in order to increase I_0 to 1000 mW/sr. Anyway, if each laser of a laser diode array (used for a transmit beam steering) needs to be equipped individually with a diffuser, much technological effort has to be paid to produce compact and lightweight equipment.

3 Receiver Sensitivity — The Major Problem

The receiver sensitivity has a significant impact on the residual system design. Regarding the preamplifier, transimpedance or bootstrap-transimpedance designs are used to obtain a good noise performance altogether with a sufficient bandwidth and a good dynamic range. The noise and sensitivity modelling described in section 3.2 is independent on the preamp design, but the concrete values for the parameters must be assigned very carefully. The photodiode capacitance C_{D} as one very important parameter depends

[1] For $D > 0$, it is assumed that the apparent location of the source corresponds to the physical location of the diffuser.

not only on the photodiode area but also on the photodiode material itself. Inexpensive silicon, which promises a much lower capacitance than InGaAs or other ternary or quaternary semiconductors, can only be used in the 800 nm range but not at 1200 nm and above. This topic will be addressed in section 3.3.

In the opposite to RF receivers, which may be interference limited, IR detectors are generally noise limited. At 1 Gbps, the noise exhibits also a strong f^2 component, i.e., a component whose power spectral density increases with f^2. This makes the design of a power efficient system even more challenging than at lower data rates and bandwidths, respectively. It will be shown that — more expensive — avalanche photodiodes (APDs) are unavoidable in many cases.

3.1 Choosing the Right Modulation Scheme

The receiver sensitivity depends, via the required signal-to-noise ratio, on the modulation scheme as well. The most popular intensity modulation schemes for wireless IR transmission are by far OOK and PPM (Pulse-Position Modulation). Both schemes exhibit only two signal levels making the laser diode driver much easier to build and much more power efficient than a linear driver required for subcarrier modulations or pulse amplitude modulation. The popularity of PPM has primarily two reasons. Firstly, compared to uncoded OOK, it may provide an advantage from the required average optical power point of view. Secondly, PPM has a favourable spectral characteristic, cf. [5].

However, compared to OOK both advantages of PPM are at the expense of an increased bandwidth. This is a serious issue for Gbps transmission, since the speed of the devices is limited, cf. section 3.3. Furthermore, the power advantage of PPM will turn out to be a loss, if the receiver sensitivity is limited primarily by f^2 noise, whose variance increases with the third power of the bandwidth [5,6].

In conclusion, (NRZ) OOK can be seen as a good choice for Gbps operation, although it needs to be combined with a line coding scheme[2] to ensure an appropriate spectral characteristic and DC balance [6,7]. With respect to the following analysis, 8B10B line coding is assumed, which increases the bit rate at the modulator input to 1.25 Gbps. Forward error correction is not considered here. Nevertheless, our analysis reveal that a low redundancy (7%) Reed-Solomon code as used for fiber optics [8] promises an optical 3 dB gain, even if f^2 noise dominates.

3.2 Noise and Sensitivity Modelling

The bit error rate p_b for NRZ-OOK can be expressed as

$$p_\mathrm{b} = \frac{1}{2} \cdot \mathrm{erfc}\sqrt{\frac{\varrho}{2}} \quad \text{with} \quad \varrho = \frac{(d_\mathrm{eucl}/2)^2}{\sigma_n^2},$$

where d_eucl is the eye-opening at the sampling time (assuming no noise) and σ_n^2 is the noise variance. For NRZ-OOK with an average optical receive power P_rx (the peak power is $2P_\mathrm{rx}$), d_eucl is given as

$$d_\mathrm{eucl} = 2P_\mathrm{rx}R_\lambda M,$$

[2] PPM can be regarded as a line coding scheme combined with OOK.

if the receive filter ensures a maximum eye-opening. This leads to

$$\varrho = \frac{(P_{\text{rx}} R_\lambda M)^2}{\sigma_n^2}.$$

Assuming a BJT-based input stage, the noise variance σ_n^2 is given as [9]

$$\sigma_n^2 = \underbrace{\left(\underbrace{2q(P_{\text{bg}} + 2P_{\text{rx}}) R_\lambda M^{2+x_{\text{APD}}}}_{\text{shot noise}} + \underbrace{2qI_{\text{b}} + \frac{4k_B T}{R_L}}_{\text{preamp white noise}} \right) I_2 R_{\text{b}}}_{\text{white noise}} + \underbrace{\left(\frac{2qI_{\text{c}}(2\pi C_{\text{tot}})^2}{S^2} + 4k_B T(R_{\text{bb}} + R_{\text{s}})(2\pi C_{\text{D}})^2 \right) I_3 R_{\text{b}}^3}_{\text{preamp } f^2 \text{ noise}}. \quad (1)$$

Table 1 of the Appendix summarizes the symbol definitions and the parameters used for the analysis. With respect to the electrical receive filter, a 5th order Bessel filter with a 3 dB cut-off frequency of $R_{\text{b}}/2$ is assumed. This filter leads to an eye-opening penalty of 0.5 dB[3], which is additionally considered with respect to d_{eucl}. The preamp's first transistor is assumed to be a state of the art silicon germanium transistor (such as Infineon BFP650) with a very low base spreading resistance. In the following, the photodiode parameters, which have a major impact on the sensitivity, are discussed.

3.3 Photodiode Capacitance and Responsivity

Wireless optical transmission is currently feasible at wavelengths between about 400 nm and 2000 nm. Two candidate bands are of special interest. One at about 800 nm, where Si-based photodiodes can be used. The other one is between about 1300 nm and 1550 nm, where components are readily available from fiber optics. The wavelength determines 3 major parameters contained in Eq. (1): the photodiode responsivity R_λ, the photodiode capacitance C_{D} and the optical power P_{bg} of the received background light. Thus, the wavelength needs to be selected very carefully in order to obtain a satisfactory link budget.

Photodiodes used for Gbps optical indoor transmission need to offer not only a short rise time. They should also exhibit a large area A_{D}, a sufficiently large R_λ as well as a low C_{D}. Unfortunately, all these properties can not be ensured at the same time.

For a given thickness d_i of the i-region, the capacitance of a PIN-photodiode (or APD) can be estimated to

$$C_{\text{D}} = \frac{\varepsilon_0 \varepsilon_r}{d_i} \cdot A_{\text{D}},$$

where ε_r is the relative permittivity of the semiconductor material. Thus, from the capacitance point of view (and also from the R_λ point of view), a large d_i is desirable. However, since the transit time of the carriers increases with d_i as well, the rise time requirements put an upper limit to d_i.

[3] For this filter type, a 3 dB cut-off frequency of $R_{\text{b}}/2$ ensures a good trade-off between the (vertical) eye-opening penalty, the noise power and the data dependent jitter.

Silicon Photodiodes available on the market exhibit a wide variety of spectral characteristics, which mainly depend on the chosen d_i and on the semiconductor process, respectively.

Basic rise time estimations for Si photodiodes show that $d_i = 20\ \mu$m can be seen as a realistic value for Gbps OOK operation: If a reverse voltage of 40 V is assumed, which gives an electrical field of 2 V/μm, the velocity of the (slower) holes is 50 μm/ns [10]. This means that the impulse response is as fast as 0.4 ns.

For a Si PIN-photodiode with $d_i = 20\ \mu$m, the capacitance per area is about 5 pF/mm^2. The thickness determines also the quantum efficiency η and thereby the responsivity R_λ, which is given by

$$R_\lambda = \eta \frac{\lambda}{1.24\ \mu\mathrm{m}} \mathrm{A/W}.$$

For $d_i = 20\ \mu$m and a wavelength of 800 nm, the quantum efficiency (ignoring any reflection losses or carrier recombinations) is still about 0.8, see [11], which gives $R_\lambda = 0.5$ A/W.

InGaAs Photodiodes devices are usually epitaxially grown and it is very difficult to grow devices with the thickness of i-regions available in silicon. Work in [12] details the growth of devices with 5 μm i-regions corresponding to a capacitance of 23.5 pF/mm^2, but these have high leakage. Further optimization work was undertaken with limited success which shows the challenge of fabricating these detectors. Assuming devices with 23.5 pF/mm^2 compared with 5 pF/mm^2 for silicon, there is already an area reduction of a factor 5. “Typical” InGaAs devices are not as good as this, and can easily have capacitances of 60 pF/mm^2, which is 12 times the value of Si devices available on the market.

Similar conclusions can be made for Ge. Although state of the art Germanium on Silicon (Si is used for the substrate) photodiodes provide excellent properties for fiber optic applications, the usage for indoor applications is again restricted by very thin i-layers between only 1 μm to 5 μm.

InGaAs is a direct semiconductor with a sharp edge at the cut-off wavelength. Thus at 1.3 μm, nearly 100% of the photons will be absorbed suggesting $R_{1.3\mu\mathrm{m}} \approx 1$ A/W which is twice as large as $R_{850\mathrm{nm}}$. However, typical values range from about 0.6 A/W to 0.9 A/W [13].

3.4 Received Ambient Light

If ambient light is detected additionally, shot noise will be superimposed to the signal current. The amount of noise depends directly on the optical DC-power P_{bg} of the received ambient light, see Eq. (1). Measurements in [14] prove that sun light, which can be seen as the strongest source for P_{bg}, can be well modelled as a thermal radiator operating at a temperature of 5500 K. According to this model, the background light radiance decreases with increasing wavelengths (for $\lambda > 500$ nm). If the radiance at $\lambda = 800$ nm acts as a reference, the radiance is decreased by a factor 3 for $\lambda = 1300$ nm and a factor 5 for $\lambda = 1550$ nm, respectively.

With respect to wireless IR transmission, the background light induced shot noise is often assumed to be the dominating noise source. This may lead to the premature

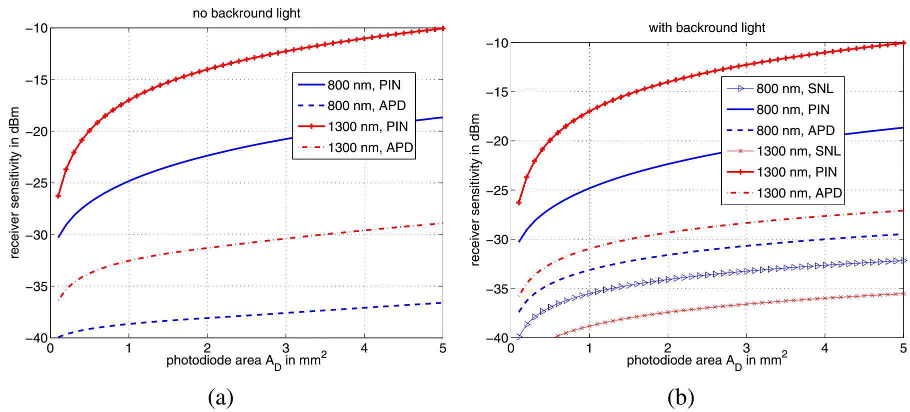


Fig. 2. Receiver sensitivity without (a) and with (b) incorporated background light. Fig. 2(b) shows additionally the shot noise limit "SNL" (only background light induced shot noise).

conclusion that systems operating at 1300 nm and above profit from a better receiver sensitivity. In section 3.6 we show that this is not the case for 1 Gbps transmission.

3.5 Receiver Sensitivity Estimation — No Ambient Light Incorporated

Fig. 2(a) shows the receiver sensitivity, if the photocurrent does not include a background light induced shot noise component, i.e., $P_{\rm bg} = 0$. It can be seen that APD based receivers outperform their PIN-photodiode based counterparts by about 15 dB. An InGaAs receiver operating at 1300 nm — this wavelength is chosen as a representative for the considered second band — does not achieve the sensitivity of the corresponding Si device operating at 800 nm. At a photodiode area of 0.5 mm^2, the gap between Si and InGaAs is about 5 dB for APDs and 7.5 dB for PIN-photodiodes, see Fig. 2(a).

Clearly, RF receivers will offer a much better sensitivity. Even if optical receivers would operate at the corresponding quantum noise limits (10 photons per bit), the sensitivities would be "only" -55 dBm at 800 nm and -57 dBm at 1300 nm, respectively. These values show clearly how challenging it is to provide coverage (in a sense of a wireless personal area network). For RF receivers operating at the same data rate, -70 dBm is surely not unrealistic.

3.6 Receiver Sensitivity Estimation — Ambient Light Incorporated

The ambient light is assumed to be fully diffuse, i.e., its spectral radiance $L_{\lambda,\rm bg}$ is independent of the rotation of the receiver. In this case, for a given detector area $A_{\rm rx}$ and a given (sub-sector) receiver FOV $\Psi_{\rm rx}$ (half-cone angle), the received amount of background light (per sub-sector) is [11]

$$P_{\rm bg} = L_{\lambda,\rm bg} \Delta\lambda A_{\rm rx} \sin^2(\Psi_{\rm rx})\, \pi. \tag{2}$$

In Eq. (2), it is assumed that $L_{\lambda,\rm bg}$ is constant within the transmission band of the optical filter with bandwidth $\Delta\lambda$. $A_{\rm rx}$ is not the photodiode area — it is the effective detection area, which is increased from A_{D} to A_{rx} by means of an (imaging or non-imaging) optical concentrator. The following analysis assume an ideal optical concentrator with a "directional gain" G of

$$G = \frac{A_{\mathrm{rx}}}{A_{\mathrm{D}}} = \frac{n_c^2}{\sin^2(\Psi_{\mathrm{rx}})}.$$

In this case, the amount of received background light is independent on the FOV, since the product of the effective detection area and the solid angle is a constant.

Fig. 2(b) shows the receiver sensitivity, when background light with a spectral radiance $L_{\lambda,\mathrm{bg}} = 0.04$ μW/(mm^2·sr·nm) @ 800 nm is considered[4]. In the case of PIN-photodiodes, no difference can be observed between Fig. 2(a) and Fig. 2(b), since the variance of f^2 noise exceeds the variance of the ambient light induced shot noise by several magnitudes. To demonstrate this, the shot noise limits are also shown[5]. This motivates the usage of APDs, which increase the signal current by a factor M. It can be observed from Fig. 2(b), that APDs indeed outperform PIN-photodiodes, although the shot noise variance increases disproportionately by $M^{2+x_{\mathrm{APD}}}$, where x_{APD} is the excess noise factor. For $A_{\mathrm{D}} = 1$ mm^2, the gap between APDs and PIN-photodiodes is 7.5 dB at 800 nm and 15 dB at 1300 nm.

4 Required Radiant Intensity

Assuming perfect on-axis alignment and a LOS channel, the received signal power is given by

$$P_{\mathrm{rx}} = \frac{I_0}{d_{\mathrm{tx,rx}}^2} \cdot A_{\mathrm{rx}}.$$

Since I_0 multiplied with 4π corresponds to the EIRP of the transmitter, the quotient $I_0/d_{\mathrm{tx,rx}}^2$ is directly the (on-axis) optical irradiance at the receiver.

Fig. 3 shows the required radiant intensity for a 1 m reference distance[6]. Perfect alignment (on-axis operation) is assumed and no link margin is incorporated. As a result of the limited sensitivity offered by PIN-photodiodes, only APDs with 4 different areas A_{D} are considered. As opposed to Fig. 3(a), the influence of ambient light is taken into account for Fig. 3(b). The required I_0 is shown as a function of the (sub-sector) receiver FOV, where an ideal optical concentrator is assumed to be used. The following presents two case studies.

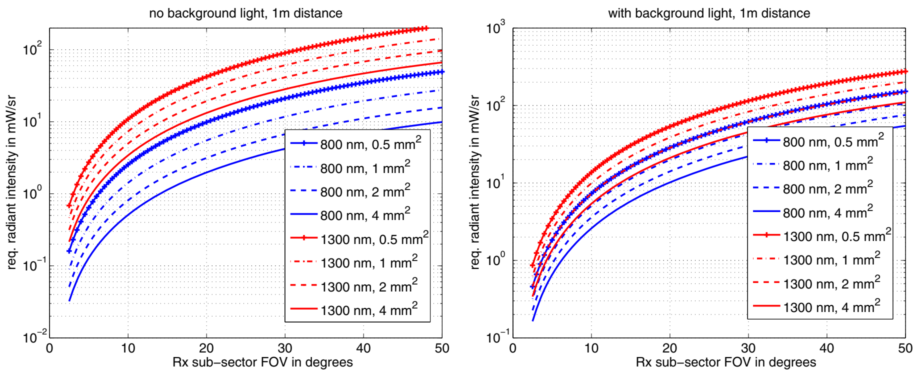
4.1 Case Study I

The first scenario could be treated as a cable replacement between a laptop and a hand-held device, where only a very short distance of 25 cm is assumed. The system FOV is assumed to be 20° and the operation wavelength to be 800 nm. If neither the transmitter nor the receiver uses beam steering, the sub-sector FOV equals the system FOV.

[4] In [15], this value of $L_{\lambda,\mathrm{bg}}$ is denoted as "typical" for bright skylight and $\lambda = 850$ nm.

[5] In this case, the noise variance is reduced to the term $2qP_{\mathrm{bg}}R_\lambda M^2$.

[6] If the distance $d_{\mathrm{tx,rx}}$ is changed by a factor k, I_0 changes by a factor k^2.



(a) (b)

Fig. 3. Required on-axis radiant intensity without (a) and with (b) incorporated background light for a reference distance of 1 m (ideal optical concentrator, no margin)

Assuming an APD area of 1 mm^2, the required radiant intensity for on-axis operation in bright skylight is (20 mW/sr)/$4^2 = 1.25$ mW/sr. Operation at the half-intensity angles increases the required I_0 by a factor 4. If a further 5 dB margin is considered (penalties will surely occur due to a non-ideal concentrator, losses in the optical filter, etc.), the required I_0 needs to be further increased to about 16 mW/sr.

According to Fig. 1, for this value no additional diffuser is required from the eye safety point of view. (If a PIN-photodiode shall be used instead of an APD, the required power increases roughly by 7.5 dB, which gives an I_0 above the point source limit.)

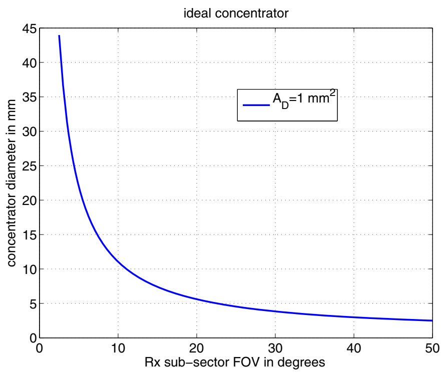
For Fig. 3(b), it is assumed that an ideal concentrator is used. Fig. 4(a) shows that the corresponding diameter of the concentrator aperture is about 6 mm. Assuming an Lambertian transmit characteristic, the total transmit power would be about 8 mW, cf. Fig. 4(b). All these values are really convincing.

4.2 Case Study II

The second example shall be a wireless personal area network with a ceiling mounted base station (BS). The BS and the terminals are assumed to have a system FOV of 45° (half-cone angle). Assuming that the BS is located 3 m above the terminals, the BS defines a cell with a 3 m radius in the horizontal plane of the terminals. The maximum LOS distance $d_{\text{tx,rx}}$ within the cell is therefore $\sqrt{2} \cdot 3$ m.

If both the transmitters and the (opposite) receivers would not use beam steering, the transmission would strongly suffer from multipath dispersion. Therefore, we assume that beam steering is used at least at the receive site. The sub-sector FOV shall be (exemplarily) reduced to 10°.

Supposing again an APD area of 1 mm^2, the required on-axis radiant intensity for $d_{\text{tx,rx}} = \sqrt{2} \cdot 3$ m would be about (5 mW/sr) $\cdot\, 2 \cdot 9 = 90$ mW/sr, cf. Fig. 3(b). If operation at the half-intensity angle altogether with a 5 dB margin is postulated again, the required I_0 will be about 1150 mW/sr. For eye safety reasons, the transmit laser now



(a) (b)

Fig. 4. (a) Detector diameter for $A_{\rm D} = 1$ mm^2 depending on the Rx sub-sector FOV. (b) Required Tx power for $I_0 = 1000$ mW/sr depending on the half-power angle of a Lambertian transmitter.

needs to be equipped with a diffuser. If the transmitter uses only one single transmit element with a system FOV of 45°, the total optical transmit power would be about 2.3 W, see Fig. 4(b). At least for battery powered terminals this value is not acceptable. Therefore, the transmitter has to use beam steering additionally, or the sub-sector FOV of the receiver has to be further reduced.

For a sub-sector FOV of 10°, the diameter of the input aperture of the optics will be at least 11 mm, cf. Fig. 4(a). Supposing an angle diversity concept (and not a mechanical tracking), the diversity order needs to be about 20-25 — depending on the overlapping between the individual beams. This number shows clearly that not each of the 20-25 APDs can be equipped with its own concentrator (each having an 11 mm diameter). The result would be absurdly bulky and heavy. An imaging receiver concept, where an APD array is equipped with a lens, is much more preferable. However, even this receiver is very challenging, since the (wide angle) lens needs to be inexpensive, compact and lightweight. Here solutions similar to the one used in mobile-phone cameras are required. Furthermore, the APD array with a total area of 20-25 mm^2 is surely more expensive than a single 1 mm^2 APD discussed in the previous example. Angle diversity concepts based on imaging optics are also possible at the transmitter, but require the usage of vertical-cavity surface-emitting lasers.

4.3 Demonstrator

Within the OMEGA project, a 1 Gbps IR demonstrator was successfully built. Angle diversity with a diversity order of 3 is used at both the transmitter and the receiver, where the sub-sector half-intensity angles are 5°. The 825 nm transmitter consists of 3 differently aligned lasers, each equipped with a holographic diffuser. The receiver uses 3 differently aligned 0.2 mm^2 silicon APDs, each equipped with a lens offering a gain of 130 (linear scale). Without ambient light, a sensitivity of -35 dBm was achieved. The demonstration clearly shows the possibility of optical indoor transmission at 1 Gbps.

However, it emphasizes also that a compact and lightweight angle diversity concept, which provides a large system FOV as required for networks, is really challenging and rather impossible to built, if only commercial optical and opto-electronical components are used.

5 Conclusion

At 1 Gbps, it is very difficult to achieve a satisfying receiver sensitivity. The main reason is f^2 noise, whose variance increases with the third power of the bandwidth and the second power of the photodiode capacitance. InGaAs photodiodes exhibit a much larger capacitance than well designed silicon photodiodes. Thus at 1 Gbps, the wavelengths range at about 800 nm is still a good choice. By means of two case studies it was shown that a (silicon) PIN-photodiode may be an option — but only for very short distances in the cm-range. For wireless personal area network applications, which demand for coverage, APDs need to be applied. Unfortunately, they are not only more expensive than PIN-photodiodes but also require a high reverse voltage (more than 100 V), which could be disadvantageously from the chip-integration point of view. Wireless optical networks operating at 1 Gbps demand also for beam steering — not only to mitigate multipath dispersion. With the receiver sensitivity in mind (which does not reach the shot noise limit), it is also required to reduce the path loss notably. From the power consumption point of view, beam steering preferably takes place at both the receive and the transmit site. Since the diversity order of angle diversity concepts needs to be large (20-25 in case study II), it is impossible to equip each photodiode with its own optics. The resulting components would be bulky and heavy. Thus APD arrays need to be combined with low cost, compact and lightweight optics as known from mobile phones with digital cameras. Imaging optics known as “Gabor superlenses” could be an interesting option.

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Appendix

Table 1. Parameters used for link budget estimation based on the system presented in [6,7]

bit rate R_{b} in Mbps (8B/10B coded)	1250	
bit error rate p_b	10^{-9}	
photodiode	**Si**	**InGaAs**
wavelength in nm	800	1300
capacitance per area $C_{\mathrm{D}}/A_{\mathrm{D}}$ in pF/mm^2	5	60
responsivity R_λ in A/W	0.5	0.8
APD gain M	optimized between 1 and 100	
excess noise factor x_{APD}	0.3	0.7
radiance of background light $L_{\lambda,\mathrm{bg}}$ in μW/(mm^2·sr·nm)	0.04	0.04/3
optical filter bandwidth $\Delta\lambda$ in nm	10	
refraction index n_c	1.7	
feedback resistance R_{L}	10 kΩ·1 pF/C_{D}	
absolute temperature T in K	330	
collector current I_{c} in mA	optimized between 0.5 and 5	
base current I_{b} in mA	I_{c}/200	
series resistances $R_{\mathrm{S}} + R_{\mathrm{bb}}$ in Ω	10	
total capacitance C_{tot}	$C_{\mathrm{tot}} = C_{\mathrm{D}} + C_{EB} + C_{CB}$	
BJT emitter-base and collector-base capacitance in pF	$C_{EB} = 1.1$ pF, $C_{CB} = 0.25$ pF	
Personick integrals	$I_2 = 0.502$, $I_3 = 0.0843$	