Parametric Study of the Multibeam Transmitter and Fly-eye Receiver

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ABATRACT

This work aims to study the improvement that has been achieved when replacing the traditional single-element (SE) receivers by imaging (IMG) receivers in line of sight (LOS) links, which can reduce the received ambient light noise, multipath distortion and co-channel interference. Also in non-directed non-LOS, the replacement of diffuse (DIF) transmitters by multi-beam (quasi-diffuse) (QDIF) transmitters has been studied; such replacement leads to reduction in the path loss. This study first based on making validation to a previous approximate and exact analysis to LOS and non-LOS links, and then a parametric study to some parameters has been made to check their effect on the link performance. We quantify the performance of the LOS and NLOS links using two main parameters; the reduction in the required transmitter power and high improvement in the signal to noise ratio (SNR).

Keywords: imaging receiver, non-imaging receiver, diffuse transmitter, quasi-diffuse transmitter, line of sight, signal to noise ratio.

1. INTRODUCTION

The growing demand for high-speed wireless communication in an indoor environment has encouraged the use of optical wireless (OW) or free space optics (FSO) links [1]. Wider bandwidth and inexpensive optoelectronic devices such as light emitting diodes and silicon detectors are the main reasons for using the infrared (IR) spectrum. Furthermore, the motivation for FSO is to eliminate the cost, time and effort of installing fiber optic cable, yet retain the benefit of high data rates for transmission of voice, data, images and video [2]. However, OW has also drawbacks; the performance of FSO networks is affected by fog, absorption, scattering, physical obstructions, building sway/seismic activity and scintillation.

Because of the complexity associated with phase or frequency modulation, and to minimize the path loss current FSO communication systems typically use intensity modulation with direct detection (IM/DD) [3]. In such systems the SNR of a DD receiver is proportional to the square of the received optical power.

Infrared links can be classified according to their directionality and whether or not the link requires a line of sight (LOS). Almost all current IR communication systems employ an SE receiver which consists of an optical concentrator whose output is coupled to a single photodetector. In an SE receiver, the desired signal, ambient light noise, co-channel interference and delayed multipath signal are combined into a single electrical signal [3]. Directed LOS is not affected by multipath propagation, and ambient background light is largely rejected. Thus, the potential data communication rate is limited only by the available power budget. Directed LOS is the most well known link topology, and has been used for many years in low bit rate, simplex remote control applications for domestic electrical equipment, such as televisions and audio equipment [4]. To improve the performance, an angle-diversity receiver has been used instead of SE receiver, which utilizes multiple receiving elements that are pointed in different directions, but it requires a separate optical concentrator for each receiving element, which may be excessively bulk and costly. A more elegant implementation is

Photonics North 2010, edited by Henry P. Schriemer, Rafael N. Kleiman, Proc. of SPIE Vol. 7750, 77502B · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.871387

the imaging angle diversity receiver, it is also called fly eye receiver, which consists of a single IMG optical concentrator (e.g., a lens) that forms an image of the received light on a collection of photodetectors, thereby separating signals that arrive from different directions. They can significantly reduce the effects of ambient light noise, co-channel interference and multipath distortion. An improvement in the power efficiency of DIF links can be achieved by replacing the single wide-beam DIF transmitter, which is pointing to a reflecting surface within a room, with a multi-beam transmitter (QDIF), which consists of multiple narrow beams pointing in different directions

In this paper, we followed the approximated analysis in Ref. [7] for simplicity, and then we follow it with the exact analysis which is used in Ref. [5]. Nearly our results coincides with their counterparts in Ref. [7] and [5]. After that, we make some changes in the parameters which affect the resulting curves, showing how to get higher improvements in the SNR and require less transmitter power in both of LOS and non-LOS links.

2. ANALYSIS OF LOS LINKS

LOS/non-imaging (LOS/NIMG) and LOS/imaging (LOS/IMG) are shown in Fig.1 (a) and (b). In the LOS/NIMG link, SNR is maximized by using a directional receiver, but in the LOS/IMG link, it will be seen that, the SNR can be achieved by using a large receiver acceptance angle.

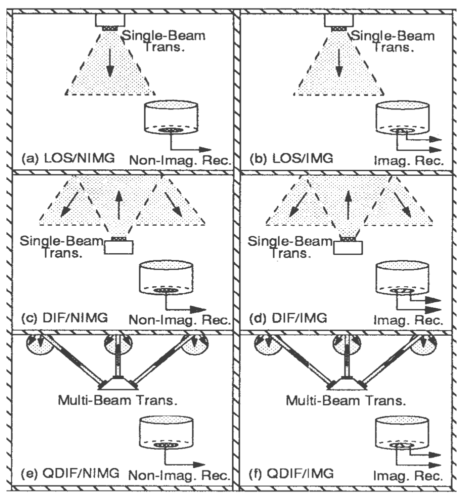


Fig.1. Various configurations of infrared links.

Following the same analysis in Ref. [7], the average electrical SNR of the direct detection receiver is

$$SNR = \frac{(rP_{sig})^2}{\sigma^2{}_T} = \frac{rP_{sig}^2}{2qBI_2P_b} = \alpha\frac{P_{sig}^2}{P_b} \quad (1)$$

where $\alpha = r/2qBI_2$, P_{sig} is the received signal power, r is the detector responsivity and σ_T is the input referred variance noise The bit error rate (BER) is given by BER= Q($\sqrt{SNR}$), so that a SNR of 36 (15.6 dB) is required to achieve 10^{-9} BER. The SNR of the NIMG receiver is [7]

$$SNR_{LOS\,/\,NIMG} = \frac{16\pi\alpha AB_s^2\cos^2\theta_s\sin^4\left(\frac{\theta i}{2}\right)}{B_{bw}\sin^2\theta_a + 4B_{bs}\cos\theta_{bs}\sin^2\left(\frac{\theta_{bsi}}{2}\right)} \quad (2)$$

where B_s is the incident radiance, θ_s is the incident angle of the signal, and distributed uniformly over a small semiangle, θ_i, Strong ambient light, incident at angle θ_{bs} and distributed uniformly over a small semiangle θ_{bsi}, is received with radiance B_{bs}. Weak ambient light, distributed uniformly over the entire acceptance angle θ_a, is received with radiance B_{bw}. The SNR of the IMG receiver assuming that we use only the signal from a single detector pixel is

$$SNR_{LOS/IMG} = \frac{4\pi\alpha A B_s^2 \cos\theta_s \sin^4\left(\frac{\theta_i}{2}\right)}{B_{bw}\sin^2\left(\frac{\theta_{a-px}}{2}\right)} \quad (3)$$

As θ_a is not small, it is necessary to assume a specific angular distribution for the weak ambient radiation; it is assumed Lambertian. $\theta_{a\text{-}px}$ is the acceptance semiangle of a single pixel; it can lie between 0° and θ_a, and is calculated by [7]

$$\theta_{a-px} = 2\sin^{-1}\left(\frac{1}{\sqrt{J}}\sin\left(\frac{\theta_a}{2}\right)\right) \quad (4)$$

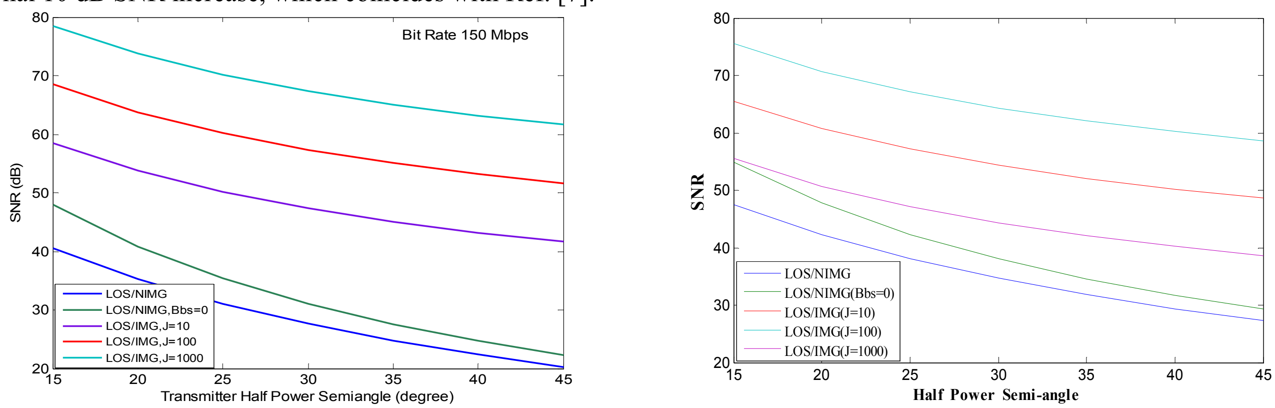
Assuming that both IMG and NIMG concentrators have the same entrance area A, the total ambient power received by the detector in the NIMG receiver is $P_{b,NIMG} = \pi A B_{bw}\sin^2\theta_a + 4\pi A B_{bs}\cos\theta_{bs}\sin^2(\theta_{bsi}/2)$. In the IMG links, the pixel detects only the portion of the weak ambient light that lies within the pixel. The total ambient power detected in this pixel is: $P_{b,IMG} = 4\pi A B_{bw}\cos\theta_s\sin^2(\theta_{a\text{-}px}/2)$.

3. PERFORMANCE EVALUATION

A validation to Ref. [7] has been done, using the following parameter's values, $\theta_s = 0°$, $\theta_{a,NIMG} = \Phi_{1/2}$ will take values from 15° to 45°, $\theta_{a,IMG} = 45°$, A= 9π/4 cm^2, the half-power bandwidth of the used optical bandpass filter = 50 nm, $B_{bw} = 1\times10^{-4}$ W/(cm^2.sr), $B_{bs} = 1\times10^{-3}$ W/(cm^2. sr), $\theta_{bsi} = 10°$ and r = 0.5 A/W.

To study the effect of the bit rate on the SNR, many values of bit rate has been assumed, such as 10, 30, 100 and 150 Mbps. It is observed that, the SNR shows a 10 dB higher performance than 100 Mbps in both LOS/IMG and LOS/NIMG links when working on 10 Mbps, while working on 150 Mbps reduce the SNR by about 2 dB than in 100 Mbps in both links.

Figure 2 represents the SNR as a function of transmitter half power semiangle $\Phi_{1/2}$, at B = 150 and 30 Mbps, the average transmitted power is 100 mW, and the transmitter receiver separation is 3 m. We can observe that, in Fig. 2(a), when $\Phi_{1/2}$ is decreased leading to increase in the received signal power, the SNR is increased. In the case of the IMG receiver, because $\theta_{a,IMG}$ is held constant at 45°, the received ambient power dos not change as $\Phi_{1/2}$ is reduced, so that the SNR increases at a rate similar to the case of the NIMG receiver with $B_{bs} \neq 0$. As compared to the NIMG receiver, the IMG receiver with J = 10 pixels provides about 8 dB SNR improvement. Each tenfold increase in the pixel count provides an additional 10 dB SNR increase, which coincides with Ref. [7].

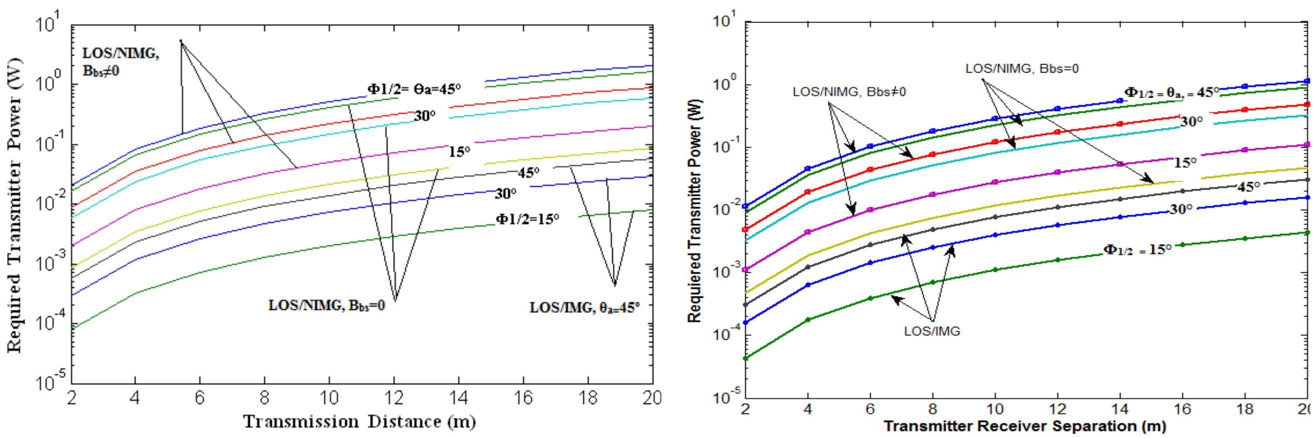


(a) (b)

Fig.2. SNR as a function of transmitter half power semiangle $\Phi_{1/2}$. (a) B =150 Mbps (b) B = 30 Mbps

By examining the NIMG receiver, we get that, it is affected by the strong ambient light source, if it is neglected ($B_{bs} = 0$), as $\theta_{a,NIMG} = \Phi_{1/2}$ decreases, the received ambient power decreases, further enhancing the SNR, but if it is included ($B_{bs} \neq 0$), as $\theta_{a,NIMG} = \Phi_{1/2}$ decreases, the total received ambient power does not decrease as much, so the SNR increases more slowly. As a result, the replacement of the NIMG receiver by an IMG one in the LOS links leads to a good improvement in the SNR which can be increased by using higher number of pixels, but this will increase the receiver complexity too. Figure 2(b) shows that, when the bit rate is reduced to 30 Mbps, the SNR achieves about 6 dB improvement more than at bit rate 100 Mbps as in Ref. [7].

In Fig.3, the average transmitter power required to achieve 10^{-9} BER is presented as a function of the transmitter-receiver separation, for SE and IMG receivers. The IMG receiver is assumed to employ $J = 1000$ pixels. For a given value of $\Phi_{1/2}$, the use of the IMG receiver reduces the required transmitter optical power by about 16 optical dB. Here, $\Phi_{1/2}$ takes values 15°, 30° and 45°, and all other parameters are assigned as in Fig.2. In Fig. 3(a) we get the same results as in Ref.[7], when we reduce the bit rate to 30 Mbps as shown in Fig. 3(b), we observe that, the required transmitter power is reduced by about 10 dB. When trying to check the bit rate effect on the required transmitter power using more values like 10 and 150 Mbps, it is observed that, whenever the bit rate is reduced the required transmitter power is reduced too and vice versa.



(a) (b)

Fig.3. Required transmitter power as a function of the horizontal transmission distance. (a) B = 100 Mbps (b) B = 30 Mbps.

4. ANALYSIS OF NON-LOS LINKS

Here, we will discus the four types of non-LOS links that are shown in Fig.1 (c)-(f). The power efficiency of non-directed non-LOS links can be improved significantly if the diffuse transmitter is replaced by one that emits a number of relatively narrow beams that illuminate a lattice of spots on the ceiling. Each beam should have a divergence angle large enough to make it eye-safe, but small enough that it does not spread excessively when traversing a room [8]. The QDIF transmitter design can be combined with either a SE or IMG receiver to significantly improve the power efficiency of non-directed non-LOS links. DIF/NIMG suffers from high path loss and multipath distortion. Using DIF/IMG link instead of DIF/NIMG one reduces multipath distortion and therefore improve the SNR, but the QDIF link is better; it has a much smaller path loss and affords some immunity to blockage.

Following the analysis in Ref. [7], the received signal power P_{sig} obtained from DIF/NIMG link is calculated as

$$P_{sig,DIF/NIMG} = \frac{A\rho P_{trs} h_1^2 \tan^2\theta_a}{\pi(h_1^2 + d_r^2)2} \tag{5}$$

where P_{trs} is the average transmitted power and the ceiling has a height h and a DIF reflectivity ρ. d_r is the circle radius about the transmitter where the receiver moved throughout to guarantee that at least one spot will lie within the receiver

FOV and hence, one can neglect the effect of multipath distortion. While the signal power received in QDIF/NIMG and QDIF/IMG links is given by [7]

$$P_{sig,QDIF} = \frac{A\rho P_{trs}\tan^2\theta_a}{\pi d_r^2} \quad (6)$$

where M is the number of signal spots on the ceiling, which is assumed to be a Lambertian reflector. Each spot is assumed to occupy an area small enough that it is imaged to a single pixel of the IMG receiver. We note that at large d_r, $P_{sig,QDIF}$ is proportional to d_r^{-2}, by contrast with $P_{sig,DIF/NIMG}$, which is proportional to d_r^{-4}. This difference greatly enhances the SNR of QDIF links over their DIF counterparts.

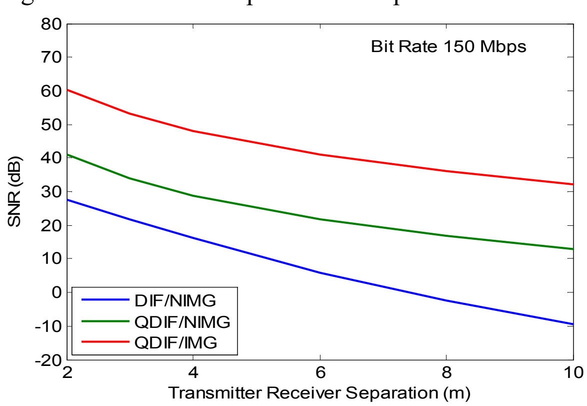
The SNR obtained from the three types of non-LOS links, is given by

$$SNR_{DIF/NIMG} = \frac{\alpha A P_{trs}^2 h^4 \tan^4\theta_a}{\pi^3\left(h^2+d_r^2\right)^4 B_{bw}\sin^2(\theta_a)} \quad (7)$$

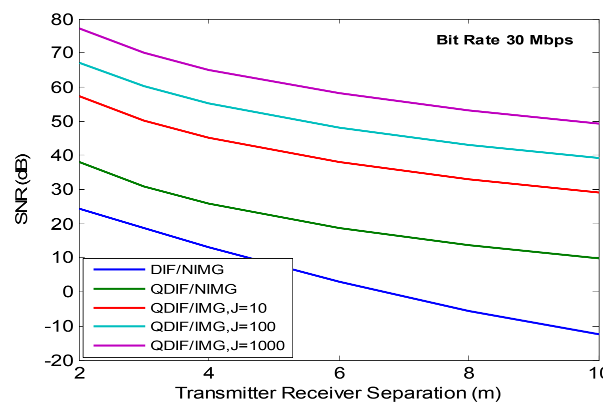
$$SNR_{QDIF/NIMG} = \frac{\alpha A P_{trs}^2 \tan^4\theta_a}{\pi^3 d_r^4 B_{bw}\sin^2(\theta_a)} \quad (8)$$

$$SNR_{QDIF/IMG} = \frac{\alpha A P_{trs}^2 \tan^4\theta_a}{4\pi^3 d_r^4 B_{bw}\sin^2\left(\frac{\theta_{a-px}}{2}\right)} \quad (9)$$

First a validation to Ref. [7] has been done. By taking $\rho = 1$, $h_1 = h_2 = h = 3$ m, M ranges from 1 to 11, and $P_{trs} = 100$ mW, assuming the same ambient lighting configuration, and the same other parameters as in LOS analysis, we can get Fig. 4, which represents the SNR of the three types of non-LOS links, as a function of the transmitter receiver separation. our results is reduced by about 5 dB than in Ref. [7]. In Fig. 4(a), it is observed that, when maximizing the bit rate from 100 to 150 Mbps, the SNR has been decreased by about 1 dB. Figure 4(b) represents the effect of number of pixels on the resulting SNR, and here we are working on 30 Mbps. It is clear that the QDIF/IMG link gives the best SNR, and whenever the number of pixels is increased, the SNR is enhanced. The QDIF/NIMG gives about 13 dB enhancement in the SNR over the DIF/NIMG, while the QDIF/IMG with 10 pixels can enhance the SNR by about 10 dB over the QDIF/NIMG. The use of the QDIF transmitter greatly enhances the SNR at large horizontal distances, where it provides the greatest reduction of path loss compared to the DIF transmitter.



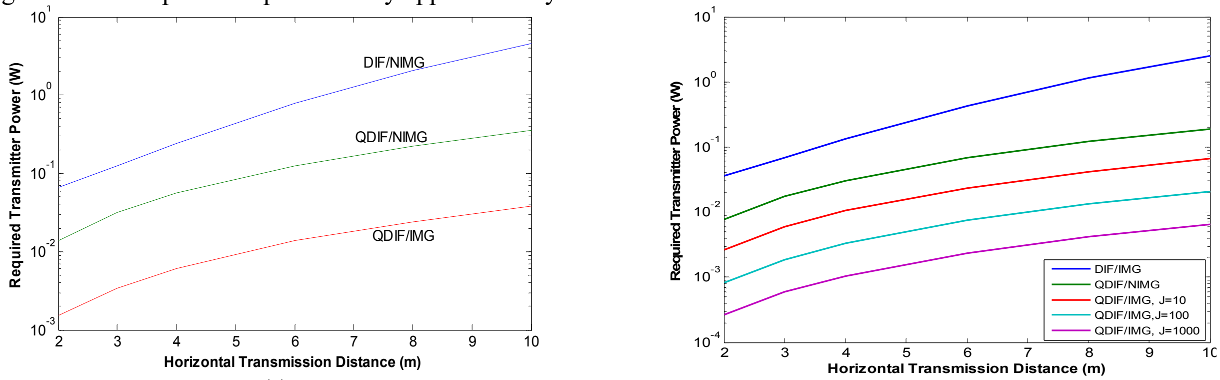
(a)



(b)

Fig.4. SNR of non-LOS links as a function of horizontal transmission distance with, Using (a) B = 150 Mbps (b) B = 30 Mbps.

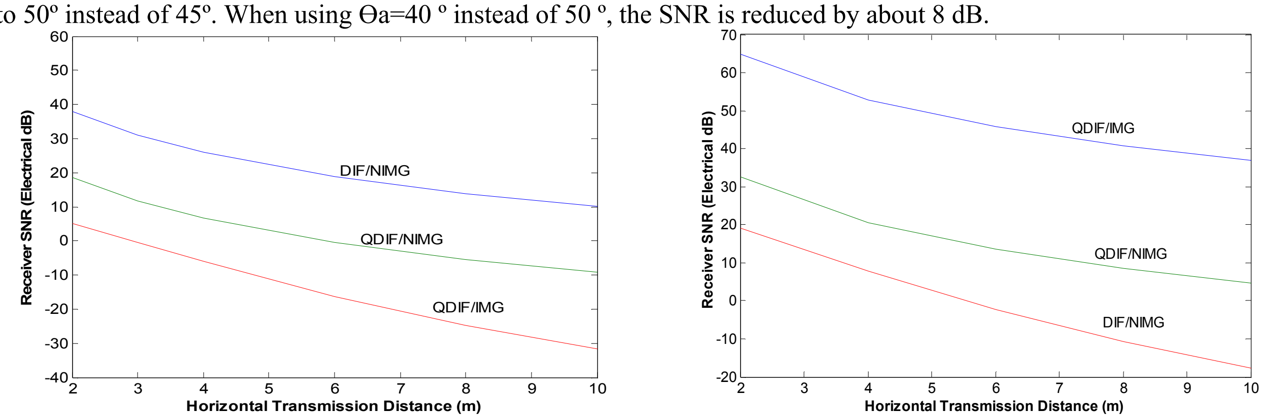
Figure 5 represents the required transmitter Power required for non-LOS links to achieve 10^{-9} BER as a function of the horizontal transmission distance. In Fig. 5(a) our results differ from Ref. [7] by about 5 dB reduction. In Fig. 5(b) it is clear that, the reduction in the bit rate to 30 Mbps leads to reduction in the required transmitter power, also as the number of pixels is increased the required transmitter power is decreased, which is better. The use of the QDIF/NIMG link design reduces the required power by about 8 dB over the DIF/NIMG design, while QDIF/IMG using 10 pixels design reduces the power requirement by approximately 6 dB more.



(a) (b)

Fig.5. Transmitter Power required for non-LOS links to achieve 10^{-9} BER as a function of the horizontal transmission distance Using (a) B = 100 Mbps (b) B = 30 Mbps.

Figure 6(a) shows that when we reduce the value of the diffuse reflectivity from 1 to 0.2, the received SNR is reduced by about 13 dB, when we maximize the diffuse reflectivity to 1.5, the SNR is increased by about 3.5 dB. Figure 6(b) shows a 13 dB enhancement in the SNR of QDIF/IMG link when we maximize the value of the receiver acceptance semiangle to 50º instead of 45º. When using ϴa=40 º instead of 50 º, the SNR is reduced by about 8 dB.



(a) (b)

Fig.6. Electrical SNR of non-LOS links as a function of horizontal transmission distance, all the parameters take the same values as in Fig. 4(a) except in (a) the diffuse reflectivity = 0.2. (b) ϴa = 50°.

5. EXACT ANALYSIS

Following the analysis of P. Djahani et al. [5], we repeat all the previous approximated analysis but without using the simplified assumptions and using detailed numerical analysis to evaluate the link performance.

In the IMG receivers there are two ways to process the resulting electrical signals, namely, select-best (SB) and maximal-ratio combining (MRC). The SB method chooses the pixel in the detector array that has the highest SNR. In MRC, signals from the J pixels are combined using weights equal to $W_i = r.\ P_{IMG,i} / \sigma^2_{T,i}$, $1 \le i \le J$ [5]. The SNR obtained using SB and MRC is given by [5]

$$SNR_{IMG,SB} = \max_i(r\ P_{IMG,i} / \sigma_{tot,i})^2. \quad 1 \le i \le J. \tag{10}$$

$$\mathrm{SNR}_{IMG,MRC} = \sum_{i=1}^{J} \frac{r^2 P^2{}_{IMG,i}}{\sigma^2{}_{tot,i}} \qquad (11)$$

1

Figure 7 represents the SNR of LOS links as a function of transmitter receiver separation *d*; it is clear that the exact analysis gives more reliable and accurate results than the approximated one. Our results differ from what P. Djahani et al. have got by about 3 dB reduction. As shown in Fig. 8, the required transmitter power in LOS/SE and LOS/IMG links has been established using the estimated complementary cumulative distribution function (ccdf), for *d* ranging from 1 to 8 m, the 37-pixel IMG receiver using MRC requires about 6 dB less power than the SE receiver. With SB, the reduction is at least 5.5 dB. When the number of pixels is 1141, the power requirements are decreased by about 12 and 11.6 dB with MRC and SB, respectively.

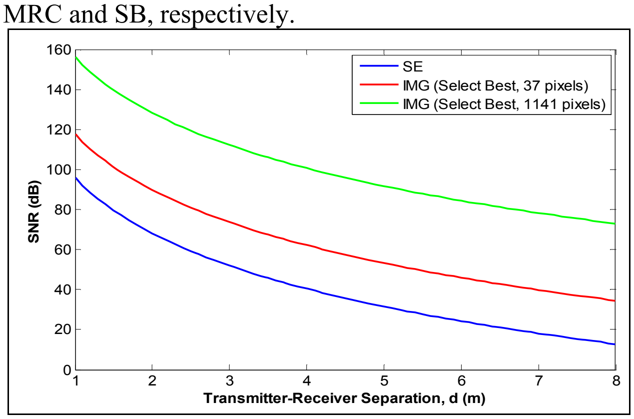


Fig.7. SNR in LOS links as a function of the transmitter-receiver separation distance, the transmitter power = 25 dBm, ψ = 45°, φ = 45°.

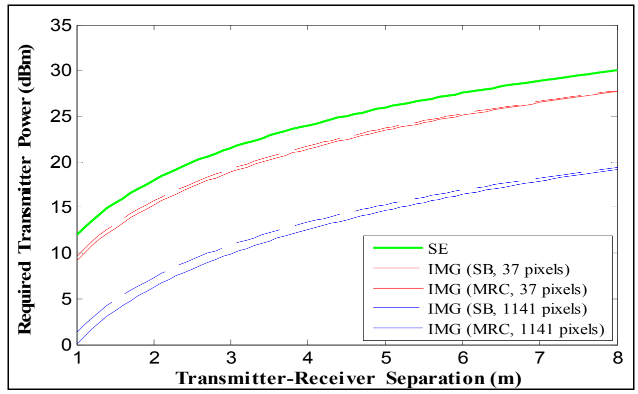


Fig.8. Transmitter power required to achieve a BER not exceeding 10^{-9} with 95% probability in LOS links as a function of the transmitter receiver separation.

In case of non-LOS analysis, two types of QDIF transmitters have been included, referred to as "Type I" and "Type II," and illustrated in Fig. 9(a) and (b), respectively. These configurations minimize the number of spot required per unit area. With a Type I (unshadowed) transmitter, at least one signal spot always lies within the receiver FOV. The Type I transmitter does not provide immunity against blockage of the path between the transmitter and ceiling or between the ceiling and receiver. The Type II (shadowed) transmitter is designed so that at least two signal spots always lie within the receiver FOV, making it possible for the link to operate if a single spot is blocked [5].

Fig.9. Lattice of spots formed on the ceiling by quasi-diffuse transmitters. (a)Type I (b) Type II.

Figure 10 represents the SNR for non-LOS links as a function of the transmitter receiver separation, showing that the QDIF gives higher SNR values for long distances than the DIF one. Type I QDIF/IMG is much better than the QDIF/SE, and than QDIF/IMG Type II. The number of pixels plays an important rule in the resulting SNR, increasing the number of pixels leads to a good improvement in the SNR. By comparing Fig. 10 with Fig. 4(b), we notice that there is a great difference between the approximate and the exact curves, it may be exceed 20 dB, but we have to take into account that in the approximate analysis the number of pixels is differ from the exact one, also here in the exact analysis we use Types I and II. As we suppose, the exact analysis must give more accurate results.

Figure 11 represents the required transmitter power as a function of the horizontal transmission distance. Here, the values are approximately the same as there counterparts in Ref. [5], but the curves are smoother. We can observe that QDIF unshadowed design requires less power than the shadowing one. Also QDIF/IMG with higher number of pixels can reduce the transmitter power requirements. Even in the presence of shadowing, QDIF transmitters and imaging receivers offer significant transmit power reductions over the DIF and SE counterparts.

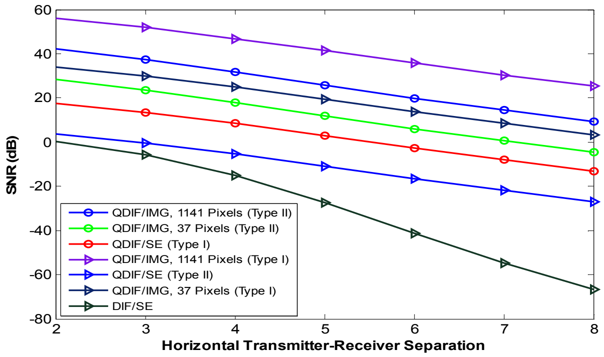


Fig.10. SNR of non-LOS links as a function of transmitter-receiver separation, average transmitter power 25 dBm.

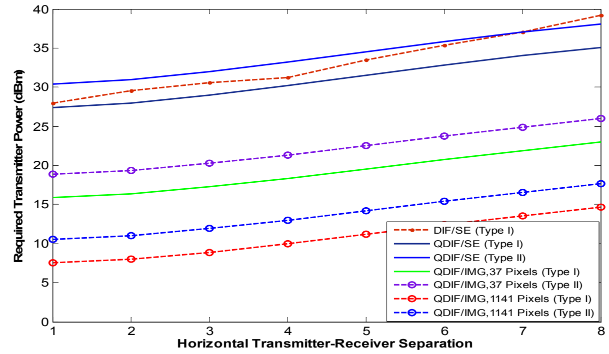


Fig.11. Average transmitter power required to achieve a BER not exceeding 10^{-9} with 95% probability in non-LOS links.

6. CONCLUSION

We follow the two analyses as in Ref. [5] and [7]. We confirmed that the replacement of SE receivers by IMG receivers can reduce the received ambient noise and multipath distortion in both LOS and non-LOS links. This replacement also leads to improvement in the SNR, and reduction in the required transmitter power. In non-LOS links, replacing a DIF transmitter by a QDIF transmitter can also reduce the path loss and the required transmitter power. Combining QDIF transmitters and IMG receivers in non-LOS links can reduce the required transmitter power by tens of decibels. When we made some changes in the LOS and non-LOS link's parameters (in case of approximated analysis) we found that: 1) In LOS and non-LOS links, when increasing the number of pixels in the IMG receivers, the output SNR increases and vice versa. But, one cannot ignore that, as much number of pixels is used, the complexity of the receiver design is increased too and therefore the cost will also increase. 2) The required transmitter power in QDF/IMG links is reduced when using higher number of pixels in the IMG receiver design. 3) When the bit rate is reduced from 100 to 30 Mbps, SNR achieves about 5 dB improvement in both LOS and non-LOS links. Working on 10 and 150 Mbps shows that, whenever the bit rate decreases the SNR value is maximized and the required transmitter power is decreased, and vice versa. 4) The SNR is reduced by about 14 dB when ρ is changed from 1 to 0.2, and I is increased by 3.5 dB when ρ is maximized to 1.5.

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