# Outage Capacity of Mobile Wireless Optical Link in Indoor Environment

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*Abstract*—In this paper, we investigate the potentiality of a wireless optical communication system in an indoor environment for both line of sight (LOS) and diffuse configurations by taking into account transmitter mobility. Statistical model of the mobile optical channel is defined for each configuration. Our contribution is to determine the outage probability and then the outage capacity considering an On-Off Keying modulation and different data rates. From the results one can obtain the outage probability value which maximizes the outage capacity for the considered indoor mobility scenario. We finally show the LOS performance gain provided by Forward Error Correction (FEC), considering Low-Density Parity-Check (LDPC) codes of different lengths.

*Index Terms*—Indoor Wireless Optical Communications, LOS Links, Diffuse Links, Outage probability, Outage Capacity

## I. INTRODUCTION

Nowadays, wireless optical communications are popular technologies which offer many advantages such as low complexity implementation and high secured transmissions. Infrared (IR) transmissions constitute an interesting alternative solution to radio-frequency (RF) one for many indoor and home applications [1]. Actually, IR systems intrinsically offer several benefits over RF systems due to the absence of multipath fading and robustness to electromagnetic interferences (EMI). Moreover, optical systems permit having an unregulated and quasi-unlimited bandwidth [1,2]. However, IR systems suffer from a high path loss, a reduced coverage area and lower link budget compared to RF systems.

Two kinds of IR systems are generally considered: LOS (Line Of Sight) links and diffuse links [2]. The LOS propagation is the most commonly used scheme. It permits guaranteeing high Signal to Noise Ratio ($SNR$). For IR short range indoor communications, the main drawback is the severe impact on the path loss due to misalignments between transmitter and receiver [1]. On the other side, in diffuse configuration, the light is emitted toward a reflective surface and the detector collects the reflected power from this surface. Diffuse configuration permits obtaining higher coverage area than in the LOS one but this is done at the cost of a reduction of the optical received power (lower $SNR$).

However, for both systems, mobility of transmitter or receiver significantly decreases the performances due to the variations of the distance between transmitter and receiver. In this case, outage probability evaluation permits quantifying attainable data rates and quality of service for the optical com-municating system. Besides, the mobile system potentiality can be well described by analyzing the channel capacity.

The paper is organized as follows: after presenting the state of the art in Section II, the optical transmission system is described in Section III. We then evaluate the outage probability in Section IV in LOS and diffuse configurations using a statistical approach. In Section V, we estimate the outage capacity for both configurations considering the non-stationary channel. In order to illustrate the performance of a FEC, Section VI deals with different LDPC codes in a LOS configuration.

## II. STATE OF THE ART

Capacity of optical channel has been already studied in the case of free space optical transmissions over atmospheric channel subject to scintillation in [5] and [6], respectively, with and without channel side information. Capacities of other outdoor optical channel have been explored, in [7], authors analyse the effect of pointing errors and in [8] and [9], authors determine the capacity considering multiple receivers. However, to the best of our knowledge, capacity of indoor mobile optical channel has not been yet investigated.

Our contribution is to determine the performance of LOS and diffuse configurations considering a statistical model of the mobile indoor optical channel to evaluate the outage probability. From the outage probability analysis, we evaluate the capacity of this channel for both LOS and diffuse configurations. Besides, we illustrate the gain provided by Forward Error Correction (FEC) on the LOS optical transmission by considering different LDPC codes.

## III. SYSTEM DESCRIPTION

We consider an indoor environment and a communication link between a mobile transmitter in the environment and a base station placed on the ceiling.

The transmitter is at $(x_1, y_1, z_1)$ in a room supposed to be free of any obstacles and represented by a box of dimensions (3m,4m,2.5m). The receiver is supposed to be placed on the middle of the ceiling at $(x_2 = 1.5\text{m}, y_2 = 2\text{m}, z_2 = 2.5\text{m})$ and is pointed toward the floor to achieve minimum path losses (see Fig. 1).

Data are sent by using an IR communication system based on Intensity Modulation and Direct Detection (IM/DD). The transmitted signal is thus an optical power which is always

positive and the channel can be modeled by a linear system [1]. The received signal $Y(t)$ can be written as:

$$Y(t) = RX(t) \otimes h(t) + N(t) \qquad (1)$$

where $X(t)$ is the instantaneous optical power, $R$ is the photo-diode responsivity, and $h(t)$ represents the impulse response of the optical channel. $N(t)$ represents the Additive White Gaussian Noise (AWGN) [3].

In the following, we study two IR propagation types: LOS and diffuse ones. For LOS case, the directivity of both optical emitter and receiver does not allow multipath propagation. For diffuse case, delay spread $D$ is typically equal to 10 ns [1] and is supposed to be negligible compared to low rate transmission ($D << 1/R_b$). For higher rates, intersymbol interference can be compensated by an equalization module. Thus the impulse response is only characterized by its static gain $H$ such as: $h(t) = H\delta(t)$. On Off Keying (OOK) modulation is used to transmit symbols over the AWGN channel. At the reception, the electrical $SNR$ is proportional to the square of the received optical power due to photo-diode detection [1]:

$$SNR = \frac{2R^2 P_t^2 H^2}{N_0 R_b} \qquad (2)$$

where $P_t$ is the average transmitted power, $N_0$, the noise power-spectral density and $R_b$ the transmission data rate.

In this study, we have chosen $R = 0.55$ A/W. $N_0$ is determined considering that shot noise is the dominant noise source [2]: $N_0 = 2I_b q$ with mean current $I_b = 200$ $\mu$A and $q = 1.6 \times 10^{-19}$ C thus $N_0 = 6.4 \times 10^{-23}$ W/Hz.

A difference between LOS and diffuse configurations appears in $H$ expression. In a LOS configuration, the static gain $H$ directly depends on the distance $d$ between the transmitter and the receiver and can be evaluated by [1]:

$$H = \frac{A}{\pi d^2} \qquad (3)$$

where $A$ is the photo-detector physical surface. Note that this corresponds to the case where LOS transmitter is perfectly aligned with the receiver.

For the diffuse configuration, the channel gain is obtained using ceiling bounce model [4]. The received power is computed by summing all the contributions of tiny elements of the reflective surface (the floor). The static gain can be thus expressed by:

$$H = \frac{\rho A z_1^2 z_2^2}{\pi^2} \times$$
$$\iint\limits_{plan} \frac{dxdy}{(z_1^2+(x-x_1)^2+(y-y_1)^2)^2(z_2^2+(x-x_2)^2+(y-y_2)^2)^2} \qquad (4)$$

where $\rho$ is the floor reflectivity.

For both LOS and diffuse configurations, we consider a typical physical area $A = 1$ cm$^2$ and $\rho = 0.8$. In order to respect eye safety regulations, $P_t$ have been set to 20 mW for the LOS configuration and to 300 mW for the diffuse one which are the typical allowed transmitted power [10]. The diffuse Field Of View (FOV) of the receiver is set to 70°.

In order to represent the transmitter mobility, as a first approach, we model its location within the room by Gaussian
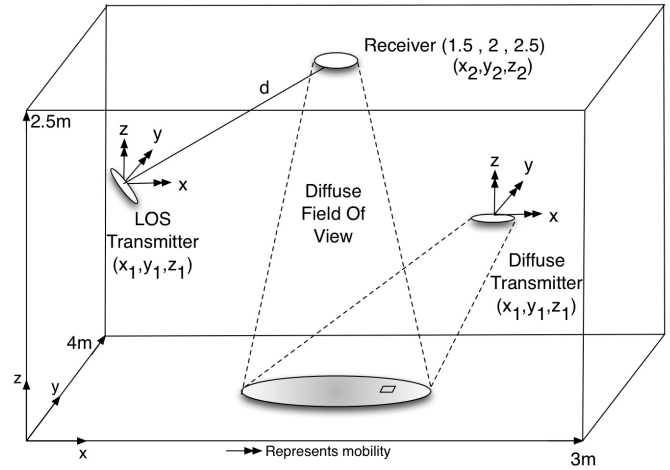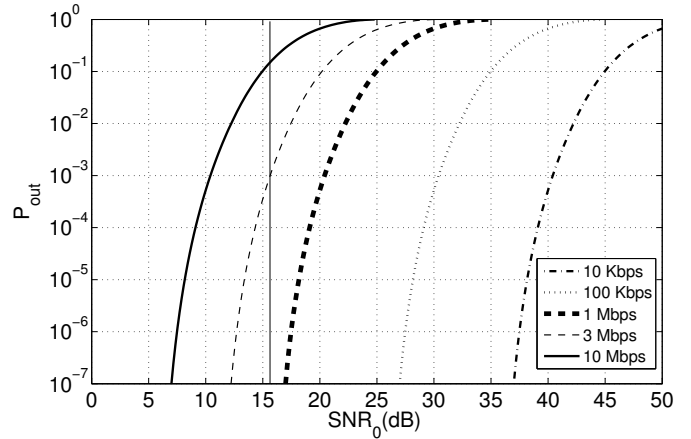


Fig. 1. Room Configuration



Fig. 2. Outage Probability versus $SNR$ in LOS configuration for OOK modulation

distributions in $x$ axis from 0 to 3m, in y axis from 0 to 4m and in $z$ axis from 0 to 1.5m with respectively $\mathcal{N}(1.5, 0.25)$ and $\mathcal{N}(2, 0.36)$ and $\mathcal{N}(1.2, 0.09)$ distributions. The means of the position distributions along $x$ and $y$ axis are chosen equal to the middle of the room, which means that the transmitter presence is more probable in this area (for example for a transmitter placed on a person who moves inside the room). The mean of the distribution in $z$ is chosen equal to 1.2 m and corresponds for example to a transmitter placed at the belt level of a person. The variances of the distributions were defined so that to include 98% of distribution data inside the room.

We can note that by considering mobility, $H$ varies due to the distance variations between the transmitter and the receiver. This is analyzed in the following Sections.

## IV. OUTAGE PROBABILITY

In the context studied, $H$ variations are slow in the bit time even for the lowest considered data rate. Optical channel can
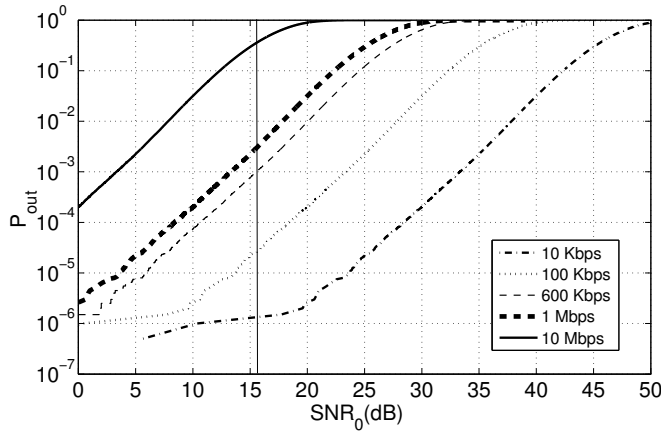
Fig. 3. Outage Probability versus $SNR$ in diffuse configuration for OOK modulation



Fig. 4. Distribution of $SNR$ for $R_b = 1$Mbps

be thus considered as a slow fading channel [1]. Consequently, average BER does not represent a good metric to describe transmission performance. Instead, the outage probability is used to estimate the performance. The outage probability is defined as the probability that the capacity $C$ of the channel does not support the rate $R_0$ of the transmission [11]. Since the capacity is a monotonic function of $SNR$, the outage probability can be expressed as a function of a $SNR$ threshold ($SNR_0$) and corresponds to the probability that the $SNR$ value at a given time drops below $SNR_0$:

$$P_{out} = \Pr[C(SNR) < R_0] = \Pr[SNR < SNR_0] \quad (5)$$

Assuming the mobility scenario we have defined, it is possible to determine the value of the outage capacity for a given $SNR_0$ using Monte Carlo (MC) method. This method is proceeded according to the transmitter position distribution (which has been considered Gaussian and inside the room). For each point, the $SNR$ is computed from (2) and from $H$ expressions (3) or (4) depending on the configuration (LOS or diffuse). The outage probability is equal to the fraction of points whose $SNR$ is below $SNR_0$ among the total number of points.

Figs. 2 and 3 present outage probability $P_{out}$ versus $SNR_0$, estimated with MC method for LOS and diffuse configurations. The results have been plotted for different rates $R_b$.

As expected, we can see that, for both configurations, outage probability increases when the threshold value $SNR_0$ increases. Moreover this performance degradation also depends on the data rate of the transmission and becomes all the more significant as $R_b$ increases. Even if the same behavior can be observed in LOS and diffuse configurations, the outage probability in the LOS configuration is more sensible to $SNR_0$.

For example, in the LOS configuration, if the system requires a $SNR_0$ of 15.6dB (to ensure a $BER$ below $10^{-9}$ when the system is not in outage), and if the targeted outage probability is $10^{-3}$, results reported in Fig. 2 show that the data
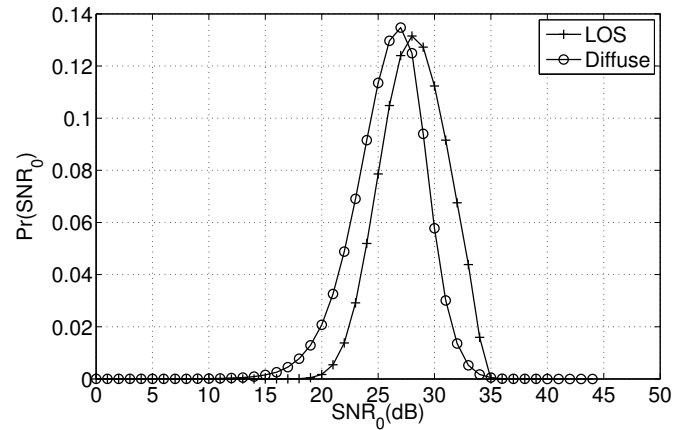
rate has to be chosen below 3 Mbps. In diffuse configuration, if we consider the same outage probability of $10^{-3}$, we observe in Fig. 3 that the rate has to be lower than 600Kbps.

In order to illustrate the performance in both configurations, we now determine the probability density function of the $SNR$ inside the room by deriving $P_{out}$ with respect to $SNR$. SNR distributions are presented in Fig. 4 for both configurations and for the same data rate of 1Mbps.

We can note that the $SNR$ distribution in LOS configuration admits a minimum value $SNR_{min} = 17$dB corresponding to a case where the transmitter is placed on the floor, in a corner ($d = d_{max}$.) Maximum $SNR$ value ($SNR_{max} = 35$dB) is obtained when the transmitter is placed beneath the receiver at a maximum height of 1.5m (due to mobility constraints). In diffuse configuration, the $SNR$ distribution admits a greater spreading than in the LOS case. Moreover, the diffuse case presents a lower average $SNR$ value ($\overline{SNR} = 27.44$dB) compared to LOS one ($\overline{SNR} = 29.5$dB).

These $SNR$ distributions represent the non-stationnarity due to the particular mobility scenario we study for the indoor optical wireless channel in both LOS and diffuse configurations.

## V. OUTAGE CAPACITY

In this paper, we consider a binary input (due to the OOK modulation) and continuous output AWGN channel (due to the noise present over the optical channel).

For stationary channel, the capacity of binary input continuous output AWGN channel does not admit a close form. Thus, this capacity has to be evaluated by using [14]:

$$C(SNR) =$$
$$\sup_{p(x)} \int_{-\infty}^{\infty} \sum_{i=0}^{1} p(y|x_i)p(x_i) \log\left(\frac{p(y|x_i)}{\sum_{k=1}^{n} p(y|x_k)p(x_k)}\right) dy$$
$$(6)$$

where $p(y|x)$ are the conditional probabilities of the received signal and follow Gaussian distributions $\mathcal{N}(RHX, R_bN_0)$. $p(x)$ corresponds to the probability of the symbol $x$. Since the channel is symmetric (6) is maximized when $p(x = 0)$ and
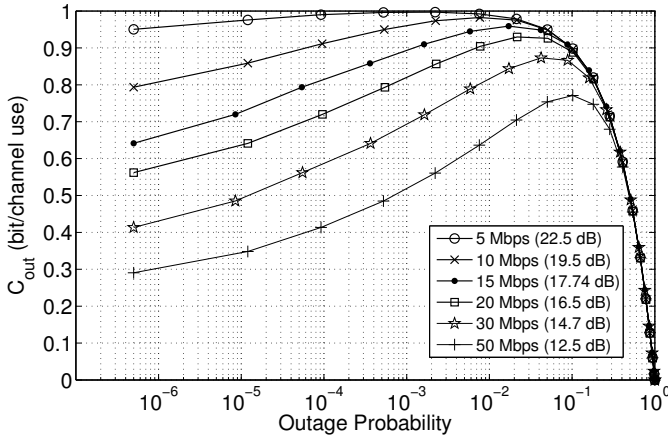
Fig. 5. Capacity of LOS wireless indoor channel for OOK modulation



Fig. 6. Capacity of diffuse wireless indoor channel for OOK modulation

$p(x = 1)$ are equal to 0.5. The capacity is bounded between 0 and 1 due to the binary input.

For non-stationary (flat fading) channel, the capacity depends on the information available at the receiver [11]. In this paper, we assume that the receiver has full and perfect knowledge of the Channel State Information (CSI). This can be obtained by inserting pilot symbols during the transmission. At the receiver, these pilot symbols are used to evaluate instantaneous $SNR$ (or equivalently, instantaneous $H$).

The outage capacity, which well describes the performance of quasi-static channel, is defined as the average information rate that can be received with a given outage probability which increases the information rate. The transmitter fixes a rate *a priori* and sends data over the channel of capacity $C(SNR)$ (see eq. (6)). With a given outage probability, the average information rate correctly received is [11]:

$$C_{out} = (1 - P_{out}(SNR_0))\, C(SNR_0) \qquad (7)$$

Note that $C_{out}$ is proportional to $(1 - P_{out})$ which corresponds to the absence of transmitted information (*i.e.* a null capacity) during outage events.

Figs. 5 and 6 present outage capacity versus outage probability for LOS and diffuse configurations. In both cases, outage capacity is computed with (6) and (7) for different data rates corresponding to different $\overline{SNR}$ reported in parenthesis on the figures. The outage probability has been estimated using previously described MC method.

Outage capacity for both configurations is bounded between 0 and 1 due to the input constraint.

When $P_{out}$ tends to 1, the receiver is always in outage and the maximum information rate that can be transmitted between transmitter and receiver tends to 0 ($C_{out} = 0$). On the other side, when $P_{out}$ tends to zero, $C_{out}$ attempts a minimal value equal to $C(SNR_{min})$ where $SNR_{min}$ is the lower $SNR$ that can be received in the room.

Between these two values of $P_{out}$, there is a given value of the outage probability maximizing the channel capacity. This
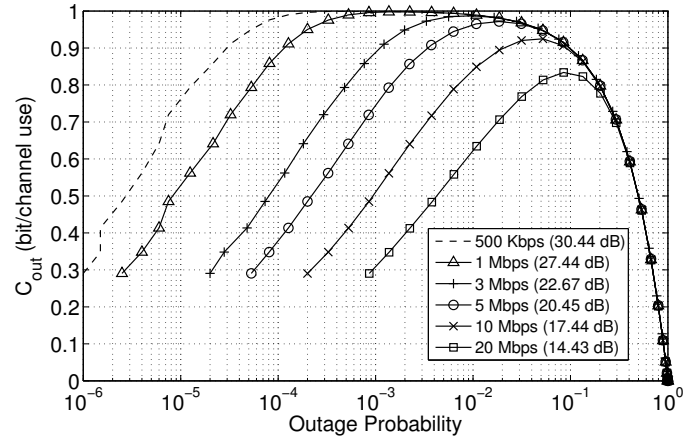
value depends on the data rate *i.e.* $\overline{SNR}$, and increases when data rate or $\overline{SNR}$ decrease.

For LOS configuration, the maximal capacity is obtained for $P_{out}$ belonging in $[10^{-3}, 10^{-1}]$ for data rates between 5 and 50Mbps. Data rates of 5Mbps and 50Mbps corresponds to $\overline{SNR}$ in LOS configuration of 22.5 and 12.5dB. The outage capacity is reduced when $\overline{SNR}$ decreases. For example, the maximal capacity varies from 1 to 0.75 bit/channel use for respectively 5Mbps and 50Mbps. Capacity equal to 1 means that there is no need to use FEC to achieve the maximal information rate. An outage capacity below 1 (*e.g.* $C_{out} = 0.75$) means that using error correction codes (of rate 0.75 in this example), a reliable transmission over the channel can be achieved.

In diffuse configuration same remarks can be done. The outage probability which maximizes the capacity is obtained in the interval $[10^{-3}, 10^{-1}]$ for gross data rate between 500Kbps and 20Mbps (*i.e.* $\overline{SNR}$ of 30.44dB and 14.43dB). The corresponding outage capacity is included in the interval $[1, 0.85]$. To compare the two configurations, we consider a gross data rate of 20Mbps. We can note in Figs. 5 and 6 that the maximal capacity is obtained for $P_{out}$ of $10^{-2}$ in LOS configuration and is equal to 0.9 bit/channel use whereas it is of 0.8 in diffuse one for $P_{out}$ around $10^{-1}$. Consequently, diffuse channel presents lower capacities with higher outage probabilities than the LOS channel.

In the following, we illustrate FEC performance for a given LOS configuration.

## VI. PERFORMANCE EVALUATION OF LDPC CODES

Different LDPC codes will be applied to the LOS channel in order to estimate the gain provided by FEC. A LDPC($N$,$K$) is a linear block code and can be defined by its rate $r = K/N$, where $K$ is the length of information bits and $N$ is the codeword length [12]. The net data rate is thus reduced and can be expressed by $R_a = (K/N) \times R_b$, where $R_b$ is the gross data rate of the transmission. We consider here regular LDPC codes wih a decoding process based on message passing
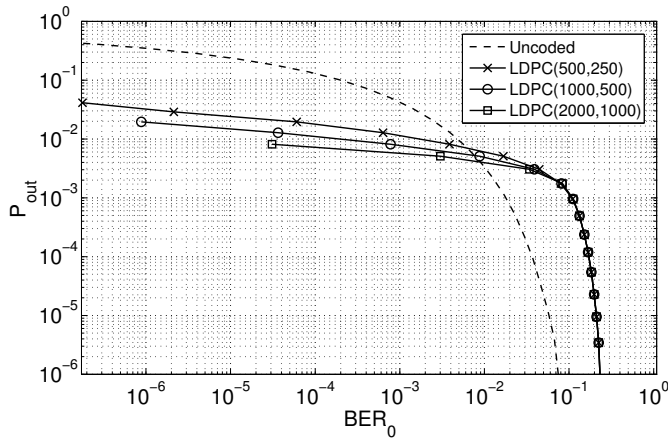
Fig. 7. Performance of LDPC coded transmissions in LOS configuration for OOK modulation and $R_b = 50$ Mbps

algorithm [12]. In order to improve the performance, the decoder uses soft-demodulation followed by the sum-product algorithm [13].

In order to estimate the performance of coded transmission for the two configurations, we introduce a threshold bit error rate $BER_0$. Outage probability can be thus expressed as a function of $BER_0$:

$$P_{out} = \Pr[SNR < SNR_0] = \Pr[BER > BER_0] \quad (8)$$

where $BER = f(SNR)$ is a monotonically decreasing function depending on the error correcting codes and the modulation scheme used. Since close form of this function is only known for uncoded transmission, the estimation of $f(.)$ function for coded transmission over stationary optical channel with OOK modulation and using regular LDPC codes has been done by simulation. We consider a gross data rate of 50Mbps and an outage probability of $10^{-3}$. We can see in Fig. 5, that the LOS channel provides a capacity of 0.5 bit/channel use for this example. We have thus considered LDPC codes of rate 1/2 and of lengths 500, 1000 and 2000.

Fig. 7 presents the performance of coded and uncoded transmissions on the graph $P_{out}$ versus $BER_0$ for LOS configuration.

As expected, we can see that LDPC of rate 1/2 can achieve lower $P_{out}$ than in the uncoded case. Actually, the coded performances approach the capacity bound of $10^{-3}$. Moreover, we can note that the outage probability decreases when the length of the code increases. For example, for a $BER$ of $10^{-6}$, the outage probability varies from $3 \times 10^{-2}$ to $1 \times 10^{-2}$ for respectively $N = 500$ and $N = 1000$, whereas the outage probability in the uncoded case is around $0.5$.

Thus, LDPC codes provide an efficient way to improve the performance of the optical link and permit reducing the outage probability for a given transmission.

## VII. CONCLUSION

In this paper, we have evaluated the performance of LOS and diffuse wireless optical transmissions in indoor environment by considering the mobility of the optical transmitter. For OOK modulation, we have estimated the outage probability of each link configuration using simulations. From the results, one can determine the attainable data rate for a given quality of service. We have then studied the system potentiality by evaluating the outage capacity. In each configuration case, the outage probability that maximizes the capacity for a given data rate has been obtained. We have observed that the diffuse channel presents lower capacities with higher outage probabilities than the LOS one.

The performance gain for LOS case with regular LDPC codes of different lengths has been finally presented. The results have shown that this constitutes an interesting solution to enhance the performance (in terms of outage probability) of a mobile indoor IR transmission.

## REFERENCES

[1] J. M. Kahn and J. R. Barry, "Wireless infrared communications," *Proceedings of the IEEE*, vol. 85, no. 2, pp. 265-298, 1997.

[2] F. R. Gfeller and U. Bapst, "Wireless in-house data communication via diffuse infrared radiation," *Proceedings of the IEEE*, vol. 67, no. 11, pp. 1474-1486, 1979.

[3] H. Park and J. R. Barry, "Modulation analysis for wireless infrared communications," in *ICC ?95 Seattle, Gateway to Globalization, IEEE International Conference on Communications*, vol. 2, pp. 1182-1186, 1995.

[4] J. M. Kahn, W. J. Krause, and J. B. Carruthers, "Experimental characterization of non-directed indoor infrared channels," *IEEE Transactions on Communications*, vol. 43, no. 234, pp. 1613-1623, Apr. 1995.

[5] J. Anguita, I. Djordjevic, M. Neifeld, and B. Vasic, "Shannon capacities and error-correction codes for optical atmospheric turbulent channels," *Journal of Optical Networking*, vol. 4, no. 9, pp. 586-601, 2005.

[6] J. Li and M. Uysal, "Optical wireless communications: system model, capacity and coding," in *Proceedings of IEEE Vehicular Technology Conference, VTC 2003-Fall*, vol. 1, pp. 168-172, 2003.

[7] A. A. Farid and S. Hranilovic, "Outage Capacity Optimization for Free-Space Optical Links With Pointing Errors," Journal of Lightwave Technology, vol. 25, no. 7, pp. 1702-1710, Jul. 2007.

[8] A. Belmonte and J. M. Kahn, "Fundamental limits of diversity coherent reception on atmospheric optical channels," in *2009 Conference Record of the Forty-Third Asilomar Conference on Signals, Systems and Computers*, pp. 1621-1625, 2009.

[9] S. Hranilovic, "On the Design of Bandwidth Efficient Signalling for Indoor Wireless Optical Channels," *International Journal of Communication Systems - Special Issue on Indoor Optical Wireless Communication Systems and Networks*, Wiley Interscience, vol. 18, no. 3, pp.205-228, April 2005.

[10] R. Ramirez-Iniguez and R. J. Green,"Indoor optical wireless communications," *IEE Colloquim on Optical Wireless Communications*, pp. 14/1-14/7, 1999.

[11] A. Goldsmith, *Wireless Communications*. Cambridge University Press, 2005.

[12] S. J. Johnson, *Iterative Error Correction: Turbo, Low-Density Parity-Check and Repeat-Accumulate Codes*, 1st ed. Cambridge University Press, 2009.

[13] D. J. C. MacKay, *Information Theory, Inference and Learning Algorithms*, 1st ed. Cambridge University Press, 2003.

[14] J. Proakis, *Digital Communications*, 4th ed. McGraw-Hill Science/Engineering/Math, 2000.