Maximal Rate of Mobile Wireless Optical Link in Indoor Environment

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***Abstract*—In this paper, we investigate the performance of an indoor wireless optical communication system by taking into account emitter mobility. We consider the two typical optical link configurations, which are Line of Sight (LOS) and diffuse ones. Mobility is described by using Gaussian statistical model of the emitter location. In order to determine the maximal rate, which can be obtained for each configuration, we first determine the outage probability of the link because of emitter mobility. From this, we also estimate the outage capacity, which corresponds to the maximal information rate for a given outage probability value. We analyze the different configuration performance and we point out the trade-off between emitted power and LOS and diffuse schemes constraints (tracking and blocking effect). We finally present the performance of two error control mechanisms, which are Automatic Repeat reQuest (ARQ) and Luby Transform (LT) codes and we compare the obtained rates to the outage capacity. We show that LT codes outperform ARQ mechanism for high outage probability values and provide a robust solution for indoor optical channel when mobility is considered.**

Keywords-Indoor Wireless Optical Communications; Line of Sight Links; Diffuse Links; Outage probability; Outage Capacity; Fountain Codes

I. Introduction

This article constitutes an extended version of [1] and enhances the results about outage capacity of optical links by presenting the performance of Luby Transform (LT) codes and Automatic Repeat reQuest (ARQ). The results permit evaluating the gap between practical error control mechanisms and the bound.

Nowadays, Wireless Optical Communications (WOC) based on Infrared (IR) transmissions are popular indoor technologies, which offer many advantages such as low complexity implementation and high secured transmissions [2]. Besides, WOC are considered as powerful alternative or complementary solutions to radio frequency ones for many indoor and home applications [3], [4]. Actually, IR systems intrinsically offer several benefits over radio frequency systems due to unregulated and quasi-unlimited bandwidth, the absence of multipath fading and the robustness to electromagnetic interferences, which is important in health concerned environments such as hospitals for example [5], [6].

To establish a WOC link, two main transmission configurations are commonly used: Line of Sight (LOS) scheme and diffuse one. Many works have already been published on the LOS and diffuse WOC system design especially considering the wireless optical channel as a stationary one [7]–[12]. The LOS propagation system has been studied for point-to-point communications. Based on a direct propagation, this is the most basic technology and the most commonly investigated one for IR short-range transmissions [7] because guaranteeing high Signal to Noise Ratio (SNR). However, misalignments between emitter and receiver have a strong impact on the path loss and can severely degrade LOS performance. On the contrary, for diffuse configuration, the optical emitter projects wide-beams on reflecting surfaces of the indoor environment and the diffuse reflections are used to establish the link with the receiver. In such a scheme, it is not necessary to ensure a perfect aligned path. This permits obtaining higher coverage area but at the cost of a reduction of the optical received power (lower SNR) [8], [9].

By considering emitter mobility in the indoor environment, the received power for both LOS and diffuse schemes can significantly decrease because of random distance variations between emitter and receiver. In this case, the mobile WOC channel is non-stationary and performance is based on link outage analysis. To guarantee a high Quality of Service (QoS) and an efficient link, it is thus important to assess the impact of mobility in the design of the communicating system. For this purpose, from the outage probability evaluation, we determine the outage capacity of the wireless optical link in the two configurations and we establish the maximal rate that can be achieved by ARQ and LT codes.

In this paper, our first contribution is the determination of the WOC performance for a mobile emitter in a rectangular shaped room where the receiver is fixed and located in the middle of the ceiling. We introduce a statistical model of the non stationary optical channel to evaluate the performance in terms of outage probability for the two configurations LOS and diffuse. Moreover, to establish the maximal data rate that can be achieved we then estimate the channel capacity considering outage events in the case of indoor LOS and diffuse transmissions because of emitter mobility.

In addition, over such non-stationary channel, reliable transmissions cannot be achieved by using a fixed rate code and is classically obtained using Hybrid Automatic Repeat-reQuest (H-ARQ) [13] combining error correcting code and error control mechanism. Another interesting and original method introduced by Luby consists in using fountain codes or LT codes [14], [15] instead of ARQ. A second contribution of the study is to provide the performance of two error control mechanisms, which are ARQ and LT codes for the investigated

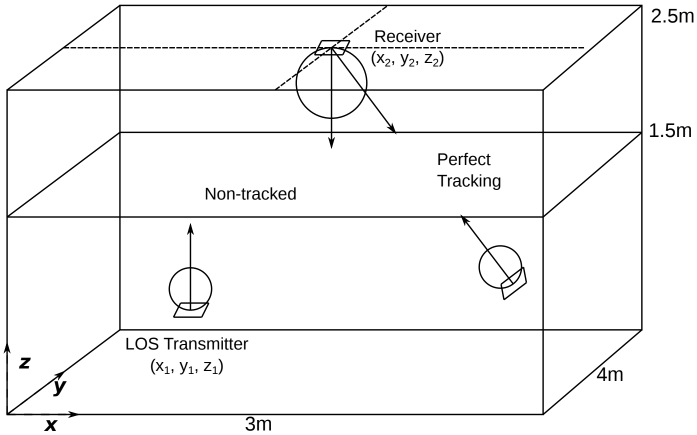

Fig. 1. Room Configuration in LOS case

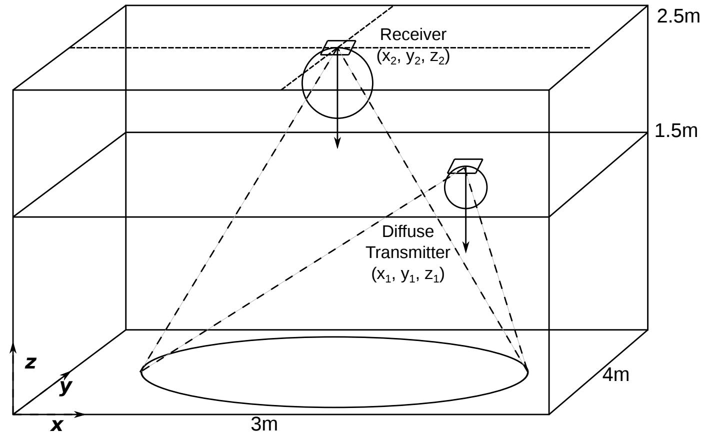

Fig. 2. Room Configuration in diffuse case

mobile WOC. We finally compare the results to the maximal theoretical rate corresponding to outage capacity.

The paper is organized as follows: after presenting related works 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 determine the outage capacity for both configurations considering the non-stationary channel. We finally present ARQ and LT mechanisms in part VI and analyze the attainable rates before concluding.

II. Related Work

Optical channel capacity has already been studied in the case of Free Space Optical (FSO) transmissions over atmospheric channel subject to scintillation effect [16], [17], respectively with and without Channel Side Information (CSI). Capacities of outdoor optical channel have also been explored in [18] where the authors analyze the effect of pointing errors between emitter and receiver. Besides, in [19] and [20], the capacity considering multiple receivers is established. However, to the best of our knowledge, capacity of indoor mobile optical channel has not been yet investigated. Considering a statistical model of the mobile indoor optical channel, our work can be used to determine outage probability and outage capacity for LOS and diffuse transmissions. Since performance of LOS transmission greatly depends on the alignment between the emitter and the receiver, we provide results for a full-tracked and a non-tracked LOS systems.

To estimate system reliability, we also investigate the use of error control mechanism above the physical layer. Recently, it has been shown that LT codes have many advantages over a large range of applications [21]. LT codes use an encoder to produce an infinite packet stream from a finite length message. The LT decoder simply collects the received packets and can decode the message once enough packets have been received. LT codes provide an efficient way to achieve reliable communication for very difficult channels conditions since they do not require feedback channel. Few researchers have applied fountain codes over wireless optical channel [22]–[24]. In [22], authors investigate raptor codes obtained by concatenation of an LT code with an high rate error correcting code such as a Low-Density Parity-Check code (LDPC), in order to improve performance on FSO links affected by scintillation effect and tracking errors. The authors in [23] study the performance of fountain codes to maximize data rate on hybrid RF/FSO links. In [24] we have investigated LT codes performance over indoor mobile wireless optical channel for a fixed data rate.

In this paper, we investigate the maximal data rate that can be achieved by using LT codes and we compare the results to ARQ ones and to outage capacity.

III. System Description

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

A. Studied Scenarios Description

The emitter 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 in the middle of the ceiling at (x_2 = 1.5m, y_2 = 2m, z_2 = 2.5m) and is pointed toward the floor. We consider here an empty room to provide general results and for simplicity.

We define two scenarios in order to investigate the emitter mobility impact on the performance. The first one considers that the emitter is oriented toward the ceiling such as a direct path can be established with the receiver. This corresponds to LOS transmission. Since LOS performance greatly depends on the alignment of both emitter and receiver, we consider two cases. In full-tracked case, both emitter and receiver are perfectly aligned and in non-tracked case the emitter maintains a fixed vertical orientation (see Figure 1).

In the second scenario, the emitter is pointed toward the floor and the transmission is based on reflected paths. This corresponds to diffuse transmission configuration (see Figure 2).

B. Optical Transmission Model

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 and at the reception, the photodetector current is proportional to the received optical signal intensity. Consequently, the WOC link can be modeled by a linear system and the photocurrent $Y(t)$ at the receiver can be written as [7]:

$$Y(t) = RX(t) \otimes h(t) + N(t) \tag{1}$$

where $X(t)$ is the instantaneous optical power, R is the photodiode responsivity, and $h(t)$ represents the impulse response of the optical channel. $N(t)$ represents the additive noise present over the wireless link.

In addition, for LOS case, we consider that 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 [7] 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:

$$h(t) = H\delta(t). \tag{2}$$

On Off Keying (OOK) modulation is used to transmit symbols over the optical channel [25]. At the reception, the electrical SNR is proportional to the received optical power squared due to photo-diode detection [7]:

$$SNR = \frac{2R^2P_t^2H^2}{N_0R_b} \tag{3}$$

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, which can be considered as Gaussian noise [8]: $N_0 = 2I_bq$ with mean current $I_b = 200$ μA and $q = 1.6 \times 10^{-19}$ C thus $N_0 = 6.4 \times 10^{-23}$ W/Hz.

For LOS transmission, the path loss H can be expressed as a function of the distance and the orientation of the emitter and receiver (see Figure 3) [7]:

$$H = \begin{cases} \frac{A}{\pi d}\cos\phi\cos\theta & 0 \leq \theta \leq \theta_c \\ 0 & \theta > \theta_c \end{cases} \tag{4}$$

where A is the photo-detector physical surface, d is the distance between emitter and receiver, and ϕ and θ are the angles of incidence with respect to the emitter and receiver axis respectively. The angle θ_c is the Field Of View (FOV) of the receiver.

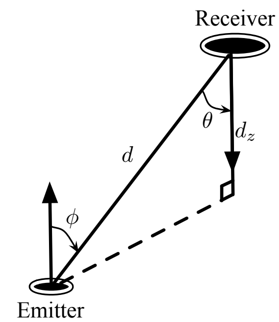

Fig. 3. LOS transmission description

Considering the first LOS scenario, we can thus write the path loss expression corresponding to each case as:

$$H_{ft} = \frac{A}{\pi d^2}\cos\phi\cos\theta = \frac{A}{\pi d^2} \tag{5}$$

$$H_{nt} = \frac{A}{\pi d^2}\cos\phi\cos\theta = \frac{Ad_z^2}{\pi d^4} \tag{6}$$

where H_{ft} and H_{nt} correspond to the static gains of respectively full-tracked and non-tracked cases. and d_z is the vertical distance between emitter and receiver (see Figure 3).

In the second scenario, for the diffuse configuration the channel gain expression is obtained using ceiling bounce model [26]. 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:

$$H = \frac{\rho A z_1^2 z_2^2}{\pi^2} \times \iint\limits_{\substack{\text{reflective} \\ \text{plan included} \\ \text{in FOV}}} \frac{\mathrm{d}x\mathrm{d}y}{\left(z_1^2+(x-x_1)^2+(y-y_1)^2\right)^2\left(z_2^2+(x-x_2)^2+(y-y_2)^2\right)^2} \tag{7}$$

where ρ is the floor reflectivity and is set to 0.8 in this study.

For both LOS and diffuse configurations, we consider in the following that the photodetector has a physical surface $A = 1$ cm^2 and FOV set to 70°. Considering that the optical sources have Lambertian patterns, the optical emitted power P_t is limited to 300 mW in order to respect eye safety regulations [7]. In this study, for LOS cases, we consider two different P_t values 300 mW and 20 mW. The latter corresponds to the typical indoor transmitted power value [27]. For diffuse case, we have set the optical power to 300 mW [27].

In order to represent the emitter mobility, we model its location within the room by Gaussian distributions for simplicity, in x axis from 0 to 3m, in y axis from 0 to 4m and in z axis from 0 to 1.5m. The mobility volume dimensions are represented in Figure 1 and Figure 2. We suppose that

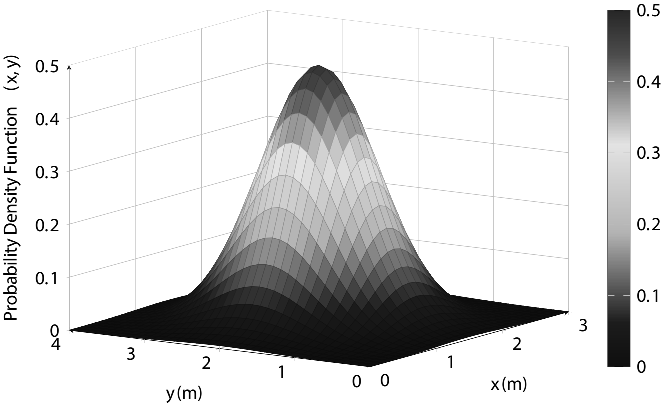

Fig. 4. Probability density function of the emitter location

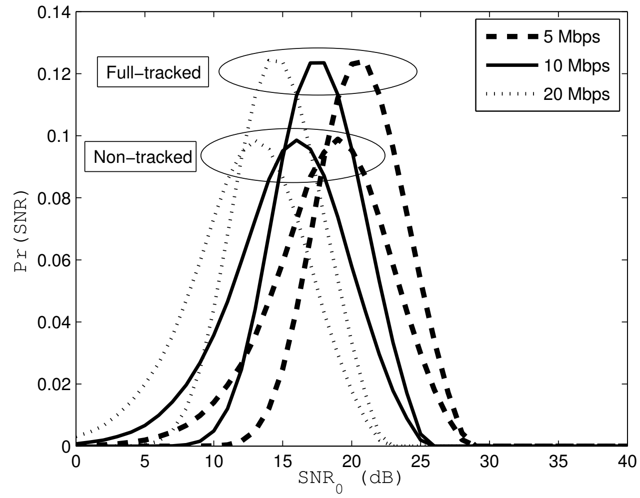

Fig. 5. Distribution of SNR in LOS case for $P_t = 20$ mW

the emitter presence is more probable in the middle of the room. Thus, the means of the position distributions along x and y axis are chosen equal to respectively 1.5 m and 2 m. In addition, the mean of the distribution along z axis is chosen equal to 1.2 m. This corresponds for example to an emitter placed at the belt level of a person. The variances of the x, y, z distributions are defined so that to include 98% of distribution data inside the room. Consequently, the emitter mobility is described along x y z axis by respectively $\mathcal{N}(1.5, 0.25)$ and $\mathcal{N}(2, 0.36)$ and $\mathcal{N}(1.2, 0.09)$ distributions. In addition, the tails of the distributions have been removed to respect the defined dimensions. Figure 4 shows the probability density function (pdf) of the emitter location in two dimensions.

By considering mobility, H varies due to the distance variations between the emitter and the receiver. Note that, taking into account obstacles or another mobility scenario would modify the emitter position pdf, but the analysis presented in the following remains the same.

IV. Outage Probability

In the studied context, H variations are slow compared to bit duration even for the lowest considered data rate. Optical channel can be thus considered as a slow fading channel [7]. Consequently, average Bit Error Rate (BER) does not represent a good metric to describe transmission performance since each transmission experiments a different path loss. 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 [28]. 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:

$$P_{out} = \Pr[C(SNR) < R_0] = \Pr[SNR < SNR_0] \quad (8)$$

Assuming the mobility scenario we have defined, it is possible to determine the value of the outage probability for a given SNR_0 using Monte Carlo (MC) method. This method is proceeded according to the emitter position Gaussian distribution. For each point, the SNR is computed from (3) and from H expressions (5), (6) or (7) depending on the configuration (LOS or diffuse).

SNR distributions for LOS configuration are presented in Figure 5 for full-tracked and non-tracked cases and for different data rates of 5, 10 and 20 Mbps.

We can note that the SNR distribution in LOS configuration admits a minimum value corresponding to a case where the emitter is placed on the floor, in a corner ($d = d_{max}$.) Maximum SNR value is obtained when the emitter is placed beneath the receiver at a maximum height of 1.5m (because of mobility scenario). For example, for full-tracked system and a data rate of 10 Mbps, we can see in Figure 5 that the minimum and maximum SNR values correspond respectively to 5.8 dB and 25.82 dB.

Moreover, if we compare the SNR distributions in full-tracked and non-tracked cases, we observe as expected that, for the same data rates the SNR distributions of non-tracked systems admit lower average values and greater spreading.

Figure 6 presents the SNR distributions for diffuse configuration, with $P_t = 300$ mW and for different data rates.

First, we can see that the SNR distributions of diffuse configuration for the same data rates than previously, admit a greater spreading than in the LOS cases. Moreover, we remark for example that for $R_b = 10$ Mbps, the average SNR value ($\overline{SNR} = 17.4$ dB) is lower than in the full-tracked LOS case ($\overline{SNR} = 19.1$ dB) and is slightly lower than in the non-tracked LOS case ($\overline{SNR} = 17.6$ dB). This shows that diffuse channel is more penalizing than LOS cases in our defined mobility scenario. This is due to the greater distance between emitter and receiver in diffuse configuration than in LOS cases.

These SNR distributions represent the non-stationnarity due to the mobility scenario we study for the indoor optical

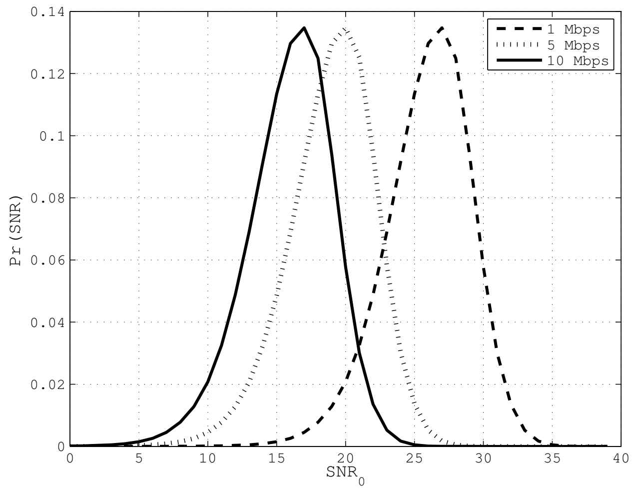

Fig. 6. Distribution of SNR in diffuse case for $P_t = 300$ mW

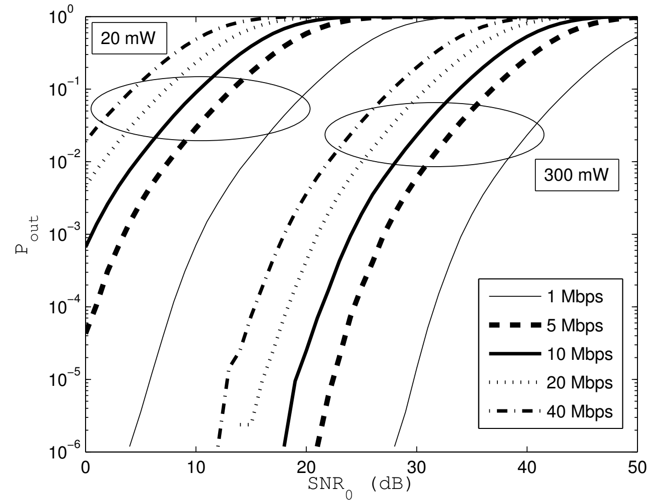

Fig. 8. Outage Probability versus SNR_0 in LOS configuration for non-tracked case

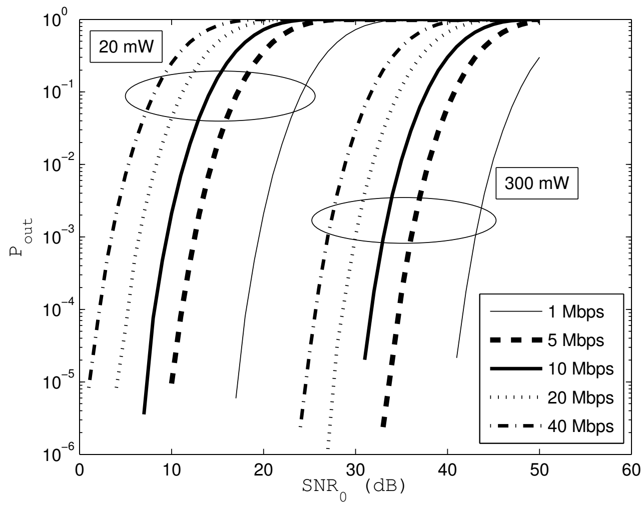

Fig. 7. Outage Probability versus SNR_0 in LOS configuration for full-tracked case

wireless channel in both LOS and diffuse configurations.

From these distributions, we can now estimate the outage probability, which is equal to the fraction of points whose SNR is below the threshold SNR_0.

Figures 7 and 8 present outage probability P_{out} versus SNR_0, estimated with MC method for LOS scenario with full-tracked and non-tracked systems and for two different P_t values of 300 mW and 20 mW. The results have been plotted for different data rates R_b.

As expected, we can see that, for both LOS cases, outage probability increases when the SNR_0 threshold value increases. Moreover, for a given Quality of Service (QoS) *i.e.*, for a given SNR_0, this performance degradation also depends on the data rate of the transmission and becomes more significant when R_b increases. In addition, we can see that for the same SNR_0, the outage probability can be reduced at the cost of an increase of the optical transmitted power. For example if a non-tracked system experiments an outage probability of 10^{-3} at 5 Mbps with $P_t = 20$ mW, the results reported in Figure 8 show that the outage probability can drop below 10^{-6} if the optical power is increased up to 300mW.

Also, if a system with $P_t = 20$ mW requires a SNR_0 of 13.6dB (to ensure a BER below 10^{-6} when the system is not in outage), and if the targeted outage probability is 10^{-3}, the results reported in Figures 7 and 8 show that the data rate has to be chosen below 5 Mbps for full-tracked system and below 1 Mbps for non-tracked system.

As expected, the maximal data rate for a given QoS, is obtained for full-tracked LOS system. However it can be noted that maintaining perfect tracking is a hard task. We now investigate diffuse transmission performance, which does not need tracking system and is intrinsically robust to blocking effect. Figure 9 presents the outage probability as a function of the SNR_0 in diffuse configuration.

As a first remark, we can see that the outage probability variations exhibit the same behavior as in LOS cases. Moreover for a given QoS, the rate that can be achieved by diffuse systems is lower than LOS cases. For example if we consider the same outage probability of 10^{-3} and the same SNR_0 of 13.6 dB as previously, we observe in Figure 9 that the rate of diffuse link has to be lower than 600 Kbps whereas it was of 5 Mbps (respectively 1 Mbps) for full-tracked LOS case (respectively non-tracked LOS). However, diffuse system is more robust than non-tracked LOS case against blocking effect. Besides diffuse systems do not require any tracking device as for full-tracked LOS case, and thus simplify the implementation. Thus there is a trade-off between performance and complexity.

In order to estimate the maximum theoretical rate that can

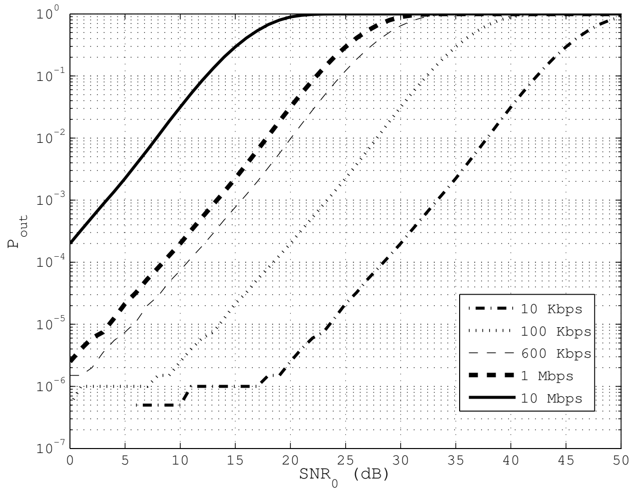

Fig. 9. Outage Probability versus SNR_0 in diffuse configuration

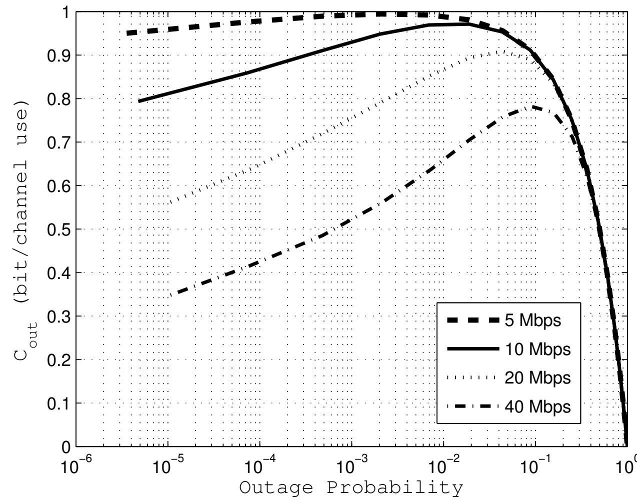

Fig. 10. Capacity of LOS wireless indoor channel for full-tracked system

be achieved in LOS and diffuse configurations when mobility is considered, we now introduce the outage capacity, which provides the maximal information rate for a given outage probability.

V. OUTAGE CAPACITY

We consider a binary input (due to the OOK modulation) and continuous output Additive White Gaussian Noise (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 [29]:

$$C(SNR) = \sup_{p(x)} \int_{-\infty}^{\infty} \sum_{i=0}^{1} p(y|x_i)p(x_i) \log\left(\frac{p(y|x_i)}{\sum_{k=0}^{1} p(y|x_k)p(x_k)}\right) \mathrm{d}y \tag{9}$$

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 binary symbol x. Since the channel is symmetric, equation (9) is maximized when $p(x=0)$ and $p(x=1)$ are equal to 0.5. Moreover, 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 [28]. 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. The emitter fixes a rate *a priori* and sends data over the

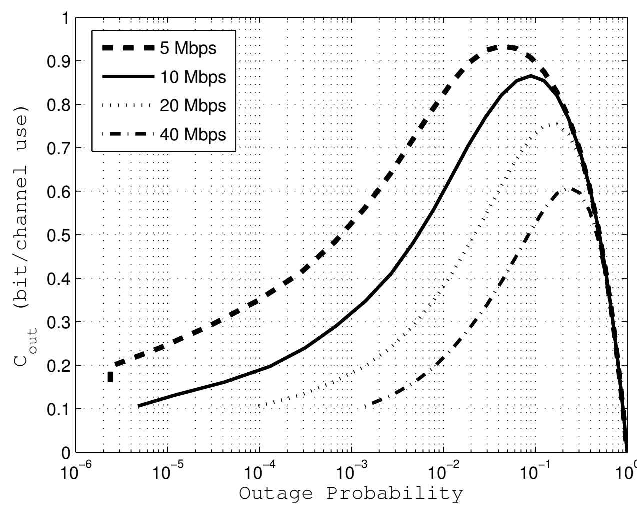

Fig. 11. Capacity of LOS wireless indoor channel for non-tracked system

channel of capacity $C(SNR)$ (see eq. (9)). With a given outage probability, the average information rate correctly received is [28]:

$$C_{out} = (1 - P_{out}(SNR_0))\, C(SNR_0) \tag{10}$$

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.

Figures 10 and 11 present outage capacity versus outage probability for LOS system in full-tracked and non-tracked configurations for a typical emitted power value of 20 mW and different data rate R_b. In both cases, outage capacity is computed with (9) and (10). The outage probability has been estimated using previously described MC method.

We can see that when the outage probability decreases, the

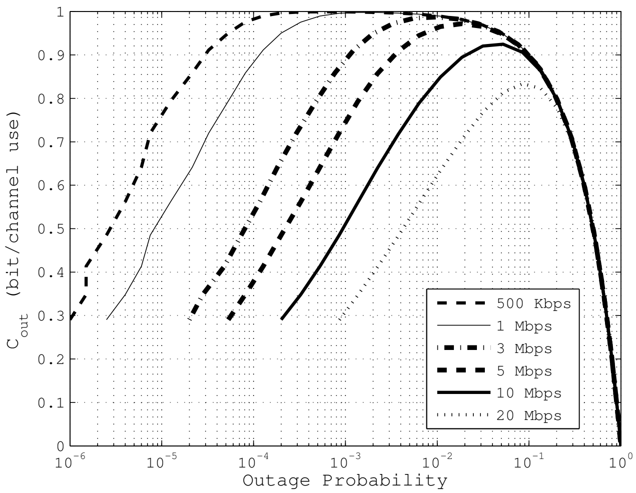

Fig. 12. Capacity of diffuse wireless indoor channel

outage capacity increases and then slowly decreases for very low outage probabilities. Outage capacity below 1 means that, by using Forward Error Correction (FEC) at the physical layer and error control mechanism at the application one, reliable transmission over the channel can be achieved. Capacity equal to 1 means that there is no need to use FEC to achieve the maximal information rate.

When P_{out} tends to 1, the receiver is always in outage and the maximum information rate that can be transmitted between emitter 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}, we can see that there is a given value of the outage probability maximizing the channel capacity. This value depends on the data rate, and increases when data rate decreases. This permits designing an efficient link with maximal achievable rate.

From results reported in Figure 10 and 11 we can see that for LOS configurations, the maximal capacity is obtained for P_{out} belonging in $[5 \times 10^{-2}, 10^{-1}]$ for data rates R_b between 5 and 40 Mbps for both full-tracked and non-tracked cases. Moreover in full-tracked case (respectively in non-tracked case), we can note that the maximal capacity varies from 1 to 0.8 bit/channel use (respectively 0.95 to 0.6 bit/channel use) for data rates between 5Mbps and 40Mbps. Thus, this shows that information rate in full-tracked LOS case is higher than in non-tracked case but at the cost of a complex implementation because of tracking devices.

Figure 12 presents outage capacity versus outage probability for diffuse configuration and with an optical power of $P_t =$ 300 mW. The results have been plotted for different data rate values between 500 kbps and 20 Mbps. The outage probability has been estimated using previously described MC method.

In diffuse configuration same remarks than in LOS cases can be done. The outage probability, which maximizes the capacity is obtained in the interval $[10^{-3}, 10^{-1}]$ for data rates between 500 kbps and 20 Mbps. The corresponding outage capacity is included in the interval $[1, 0.85]$.

To compare the different configurations, we consider a data rate of 20 Mbps. The maximal capacity values and corresponding outage probability ones in full-tracked, non-tracked and diffuse cases are reported in Table I.

As expected we can see that the full-tracked LOS performance outperforms the other ones but at the cost of a more complex implementation. Moreover we can note that non-tracked LOS and diffuse cases permit obtaining quite same information rate even though the optical emitted power in non-tracked case (20 mW) is lower than in the diffuse case (300 mW). This illustrates the trade-off between optical emitted power and robustness to blocking effects that is the main advantage of diffuse systems.

Outage capacity provides the maximal theoretical information rate that we can obtain over the optical channel considering mobility. Unfortunately, real systems operate at a lower rate, which depends among other on the error control mechanism. In the following, we illustrate the performance that can be achieved at the application layer.

VI. Performance of LT Codes

We consider two error control mechanisms: stop-and-wait ARQ [13], which is the simplest technique for short range application, and LT codes [14].

ARQ mechanism uses feedback channel in order to acknowledge each received packet and is penalized by timeouts when packets are lost. Assuming a perfect feedback channel (no loss of acknowledgement), the average information rate that can be achieved by stop-and-wait ARQ can be expressed as a function of the outage probability and the outage capacity:

$$R_{ARQ} = \frac{(1 - P_{out})C(SNR_0)}{(1 - P_{out}) + aP_{out}} \tag{11}$$

where a, the ratio between the ARQ timeout and the transmission time has been set to $a = 5$.

For LT codes, performance is characterized by the code overhead ϵ, which corresponds to the additional information required to decode the received packets. In order to satisfy memory requirements of both emitter and receiver we consider very short length LT codes with $K = 100$. This means that the original message has been divided into $K = 100$ packets.

TABLE I
Performance Comparison for 20 Mbps

Configuration	Power (mW)	P_{out}	$C_{out\ max}$
Full-tracked LOS	20	4×10^{-2}	0.9
Non-tracked LOS	20	2×10^{-1}	0.75
Diffuse	300	10^{-1}	0.81

The key parameter for LT codes is the degree distribution ρ, which is a probability distribution defining the number of blocks combined in a packet.

The code overhead value and the computational cost of the decoding process are linked to the degree distribution and it is important to optimize this value. In order to design an efficient degree distribution for short length LT codes, we define the cost function as the average overhead and we optimize the degree distribution ρ in order to minimize the overhead. Since the cost function is noisy (it can produce different results for the same parameters) and not differentiable, classical optimization methods cannot be applied. We have chosen Differential Evolution method [30], which is based on a genetic algorithm, in order to minimize the cost function. The resulting degree distribution we have obtained is presented in Table II. This corresponds to an average overhead $\epsilon = 23\%$.

Finally, the information rate that can be achieved by LT code depends on the overhead and is equal to:

$$R_{LT} = \frac{1}{1+\epsilon}(1 - P_{out})C(SNR_0). \quad (12)$$

Figure 13 presents the information rate that can be achieved by using ARQ mechanism and LT codes as a function of the outage probability for LOS transmissions considering the different cases (full-tracked and non-tracked cases) and for a data rate R_b of 20 Mbps. Outage capacity we have previously obtained and corresponding to the maximal theoretical information rate is also plotted.

We can see that for low P_{out} values, ARQ mechanism is well suited in all cases. However, for high P_{out} values the information rate obtained with ARQ does not achieve the outage capacity since the transmission is stopped during timeouts. However, LT codes are not an efficient mechanism for low P_{out} values because of code overhead but permit providing an higher rate than ARQ for high P_{out} values. To illustrate the performance, we compare in Table III the information rates obtained by ARQ and LT codes for the optimal outage probability in the two LOS cases *i.e.*, 4×10^{-2} in the full-tracked case and 2×10^{-1} in the non-tracked case.

We can see that for full-tracked case, ARQ mechanism is the best solution since tracking system ensures high QoS. However, for the non-tracked case, it is worth using LT codes due to channel state degradations linked to misalignments.

In addition, from results in Figure 13, we can remark that a non-tracked system designed with LT codes can provide an higher rate than full-tracked case. This means that mechanical complexity can be reduced while maintaining identical rate if LT codes are used instead of ARQ. For example, we consider a full-tracked system using ARQ with an outage probability of 0.1 (see Figure13). The effective data rate is equal to $R_{eff} = R \times R_b = 12.2$ Mbps where R is the information rate. This result is the same as for a non-tracked system with the same P_{out} but using LT codes. This means than LT codes can reduce the mechanical complexity of LOS system while maintaining the achievable rate.

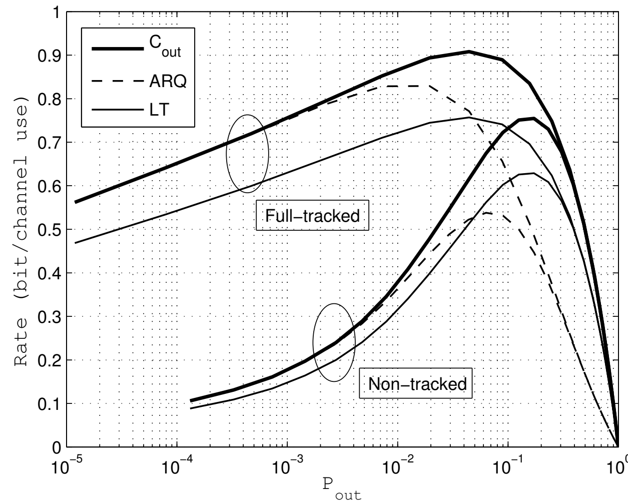

Fig. 13. Information rate of ARQ and LT codes in LOS cases for 20 Mbps

Figure 14 presents the available rate that can be obtained with ARQ and LT codes for the diffuse configuration considering an average transmitted power of 300 mW and different data rates of 5 Mbps, 20 Mbps and 50 Mbps.

The curves present the same behavior as for the LOS configurations. ARQ mechanism constitutes an efficient solution for low P_{out} values but is penalized when the outage probability increases. However, LT codes are well suited for high P_{out} values. Moreover, for P_{out} corresponding to the maximal outage probability, we can see that, as the data rate increases, the performance of LT codes become higher than ARQ. For example, with $R_b = 5$ Mbps and for the optimal P_{out} value, ARQ outperforms LT codes with an information rate of 0.9 bit/channel use compared to 0.81 bit/channel use. On the contrary, for 50 Mbps, LT code performance (0.53 bit/channel) overcomes ARQ one (0.35 bit/channel use).

TABLE II
DEGREE DISTRIBUTION OF LT CODE FOR $K = 100$

$\rho_{[1:5]}$	0.0736	0.4340	0.1875	0.0721	0.0394
$\rho_{[6:10]}$	0.0259	0	0	0	0
$\rho_{[11:15]}$	0	0	0.0125	0.0177	0.0250
$\rho_{[16:20]}$	0.0397	0.0145	0.0148	0	0.0432

TABLE III
ARQ AND LT CODE PERFORMANCE COMPARISON FOR 20 MBPS

Configuration	P_{out}	$Cout\ max$	ARQ	LT Codes
Full-tracked LOS	4×10^{-2}	0.97	0.9	0.8
Non-tracked LOS	2×10^{-1}	0.86	0.63	0.71
Diffuse	10^{-1}	0.84	0.59	0.79

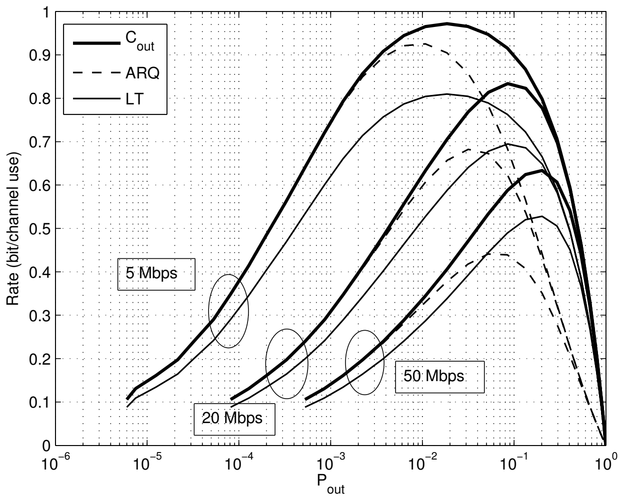

Fig. 14. Information rate of ARQ and LT codes in diffuse configuration for $R_b = 5$, 20 and 50 Mbps

Table III also compares the information rate for the optimal P_{out} of LOS and diffuse configurations for $R_b = 20$ Mbps. We can see that, as in the non-tracked LOS case, LT codes can provide higher rate than ARQ mechanism for diffuse case. Moreover, the gain provided by LT codes for diffuse case is more significant than for non-tracked LOS case. Thus, we have illustrated that LT codes can be a robust error control mechanism especially when channel conditions are degraded.

VII. Conclusion

In this paper, we have investigated the performance of indoor wireless optical channel. Our goal was to determine the maximal rate, which can be obtained by taking into account emitter mobility. For this purpose, we have first studied the outage probability considering two kinds of optical transmissions that is Line Of Sight configuration with full-tracked and non-tracked schemes and diffuse one, which is a more robust solution against blocking effect. From outage analysis, we have then estimated the maximal theoretical rate corresponding to the outage capacity. We have seen that outage capacity can be maximized for high outage probability values. As expected, the best performance has been obtained with full-tracked LOS cases. However this solution requires a complex implementation because of tracking devices. On the other side, we have noted that non-tracked schemes and diffuse one had quite the same performance even though the optical emitted power was different. This has shown the trade-off between emitted power, tracking complexity and robustness to blocking effect.

To complete the theoretical results, performance of ARQ and LT codes has also been investigated and compared to the outage capacity. For LOS and diffuse configurations and considering the optimal outage probability values, we have shown that the maximal rate using LT codes was higher than the rate using ARQ. Besides, we have illustrated that by using LT codes instead of ARQ in LOS configuration, it was possible to achieve the same performance as in full-tracked LOS but without any tracking system. For diffuse configuration, we have shown that the use of LT codes was more efficient than ARQ when channel conditions are degraded because of data rate increase. Thus, LT codes can provide a more robust error control mechanism than ARQ for indoor wireless optical channel especially when mobility and misalignment have a significant impact. Numerous perspectives can be investigated to enhance this work, among which comparison with experimental results and cross-layer design to improve error control mechanism performance.

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