Outage Probability in Mobile Indoor Optical Wireless Communication Environment

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***Abstract*-- In this paper, we study an Optical Wireless Communication system for indoor healthcare monitoring application, taking into account the impact of indoor environment. We consider a diffuse link between an emitter placed on a mobile monitored patient and a base station located on the ceiling considering a one-bounce model. Thanks to Ray Propagation Simulator (RaPSor) developed at the Xlim-SIC laboratory, wall, floor and ceiling reflections are taken into account so that the system is more accurately designed, even for low data rates. This is of main concern for healthcare application because it is important to evaluate the required emitter power, related to the power autonomy of monitoring system.**

Index Terms — Optical Wireless Communication, Indoor propagation modeling, outage probability

I. Introduction

Optical Wireless Communications (OWC) constitutes a solution for many indoor and outdoor applications because of the unlicensed large optical bandwidth and the fact that it is highly secure [1-5]. Besides, OWC technology is particularly suitable for indoor environments sensible to electromagnetic interferences such as hospitals [6] and appears as an alternative and complementary solution to Radio Frequency (RF) one.

Two optical transmission configurations are commonly investigated: Line Of Sight (LOS) and diffuse. The LOS configuration requires direct visibility and perfect alignment between the emitter and the receiver. On the opposite, diffuse configurations do not need any visibility or alignment constraints, which is very important when considering mobility. Thus, with a diffuse configuration the received signal is collected from different paths reflected on room walls. We study in this paper an OWC transmission scheme for hospitalized patient monitoring. The emitter is coupled with physiological sensors and placed on the patient. The base station is considered to be located in the middle of the patient room ceiling. As we suppose that the patient can move within the room, we focus on a diffuse configuration and we consider that the emitter is pointed toward the floor. In diffuse configurations, the most commonly used channel model is the ceiling bounce one, taking into account one reflection plane (the ceiling, the floor or a wall) and a single reflection. Thanks to this model, we have previously established the performance of the mobile wireless optical monitoring application considering the floor as the single reflective plane [6]. In this paper, our contribution consists in evaluating the performance by taking into account more than a single reflection, on more than a single surface plane (reflections over floor, walls and ceiling) and for different reflectivity values. The paper is organized as follows: section II introduces the indoor OWC system, the simulation tool and the mobility scenario. Then, section III analyzes the performances. At last, section IV concludes this paper.

Several configurations are proposed for link design. These configurations are classified according to their directivity and line-of-sight (LOS). A link is referred to as directed if the receiver and the transmitter have a narrow radiation pattern and field-of-view (FOV), respectively. In a no directed link, the transmitter has a broad radiation pattern and the receiver uses a large FOV. An LOS/non-LOS classification depends on whether or not an unobstructed path between a transmitter and a receiver exists.

Directed LOS link reduces path loss at the expense of disabling receiver mobility. The link can easily be lost if obstructed by an object. To solve this problem, no directed non-LOS link (also known as diffuse) is used, where the optical power is projected onto a reflecting surface, chosen to be accessible to most receiver locations. The link does not require transmitter/receiver alignment, and thus provides robustness against link loss due to blockage. This configuration, however, suffers from a high path loss due to the absence of a direct path and data-rate limitation caused by reflections. This latter limitation results from multi-path temporal dispersion caused by different paths (including reflections off of walls and ceiling) the signal takes to travel to a receiver.

The indoor optical wireless systems use light sources and photo-detectors which are cheaper than RF or wire-line systems, easy to implement, and free from interference from the other parts of the building. As the infrared does not pass through walls, it makes it easier to make cell-based secure networks by reusing the same wavelength in different rooms of an office building.

II. Related Work

A. Indoor Optical Wireless Communication configuration

We consider a room of dimensions (3m×4m×2.5m) corresponding to a typical hospital room size. In this environment, we study the transmission between an emitter located at (*x*k, *yk*, *zk*), and placed on a patient moving within the room, and a receiver placed in the middle of the ceiling at (*x*R=1.5m, *yR*=2m, *zR*=2.5m). The link is ensured by an OWC based on Infrared (IR) technology using Intensity Modulation/Direct Detection (IM/DD). Moreover, we consider the simplest modulation scheme for optical transmission which is the On-Off Keying (OOK) one. Considering the classical data rates for healthcare monitoring (lower than 1 Mbps) [7], we suppose in this study that the optical channel is a slow-flat fading one and that it is mainly characterized by its static gain *H*. The electrical Signal to Noise Ratio (SNR) at the receiver is directly linked to the *H* value, for a transmission data rate *Rb* as:

"FORMULA"

$$SNR = \frac{2P_t^2 R^2 H^2}{N_0 R_b} \qquad (1)$$

Where *R* is the photodiode responsivity, *Pt* the average transmitted power, *N0* the noise spectral density power. In this study, we have chosen *R* = 0.55A/W which corresponds to the typical value of the photo detector responsivity in IR range [1]. *N*0 is determined considering that the shot noise is the dominant noise source: *N0* = 2*Ibq* = 6.4 × 10-23 W/Hz with mean current *Ib* = 200μA and *q* = 1.6 × 10-19C. Considering that the transmission is based on a diffuse configuration, the total received power is the sum of all contributing reflected signals. However, the most basic used model is the one bounce one, neglecting multipath distortion and bounce over walls.

"EQUATION"

$$H_{Diff} = \frac{\rho_{floor} A z_k^2 z_R^2}{\pi^2} \times \iint_{floor} \frac{dxdy}{(z_k^2 + (x-x_k)^2 + (y-y_k)^2)^2 (z_R^2 + (x-x_R)^2 + (y-y_R)^2)^2} \qquad (2)$$

Where *ρfloor* is the floor reflectivity and *A* is the photo-detector physical surface.

The double integral is numerically computed over the part of the floor included in the receiver's Field Of View. Then, to take into account the reflections over room walls and ceiling, and to produce a more accurate simulation, we use in this study a ray-tracing simulator described in the next paragraph.

INTENSITY MODULATION/DIRECT DETECTION CHANNELS-

The no directed, infrared channel using intensity modulation with direct detection is depicted in Fig. 1. It comprises an infrared emitter as the transmitter and a large-area photo detector as the receiver. The input signal $X(t)$ is the instantaneous optical power of the emitter, and the output of the channel $Y(t)$ is the instantaneous current in the receiving photo detector, which is the product of the photo detector responsivity r and the integral over the photo detector surface of the instantaneous optical power at each location. The signal propagates to the receiver through a room with reflective surfaces. The channel can be modeled as a baseband linear system, with input power $X(t)$ output current $Y(t)$ and an impulse response $h(t)$ which is fixed for a certain physical configuration of receiver, reflectors, and transmitter [1]. The impulse response is quasistatic due to the high signaling rates, high-order diversity of the large-area receiver, and the low speeds at which indoor objects move.

On-off keying (OOK)-

It is the simplest form of amplitude-shift keying (ASK) modulation that represents digital data as the presence or absence of a carrier wave. In its simplest form, the presence of a carrier for a specific duration represents a binary one, while its absence for the same duration represents a binary zero. Some more sophisticated schemes vary these durations to convey additional information. It is analogous to unipolar encoding line code.

On-off keying is most commonly used to transmit Morse code over radio frequencies (referred to as CW (continuous wave) operation), although in principle any digital encoding scheme may be used. OOK has been used in the ISM bands to transfer data between computers, for example.OOK is more spectrally efficient than frequency-shift keying, but more sensitive to noise. In addition to RF carrier waves, OOK is also used in optical communication systems (e.g. IrDA).In aviation, some possibly unmanned airports have equipment that let pilots key their VHF radio a number of times in order to request an Automatic Terminal Information Service broadcast, or turn on runway lights.

III. PROPOSED MECHANISM

A RaPSor Simulator

RaPSor (Ray Propagation Simulator) is a ray-based simulator [8] developed at the Xlim Laboratory of the Poitiers University. It offers the possibility to simulate the propagation of a wave according to several physical configurations from the hypothesis of high frequency approximation. On the base of historical works on radio wave propagation [9], researches have been performed on optical propagation. Different simulation methods can be implemented such as source image one for the determination of specular ray trajectory in the case of radio wave consideration. According to optical communications, the diffusive properties of obstacles have induced the implementation of alternative techniques such as a classical ray launching associated to Monte Carlo algorithm. RaPSor is used in the next section to compute the diffuse impulse responses of the considered optical wireless channel, for each emitter and receiver position according to mobility scenarios, and using a Monte Carlo algorithm. For each simulation, a maximum reflection order of 3 has been used and all the reflective planes (floor, walls and ceiling) have been considered as perfect diffuse surfaces.

***B**. Emitter mobility*

In order to represent the patient mobility, we define a scenario where the emitter moves following a Random Way Point (RWP) mobility model [10] within a volume limited to a height of 1.5m (assuming the emitter is located at the belt of a patient). In addition, we consider in this first approach that the communication link is free of any obstacle or shadowing. The mobility is thus defined by a set of points obtained from the RWP probability density function (pdf). This set is a RaPSor input parameter, so as the output corresponds to an impulse response set, one for each input position. From these impulse responses, we can compute *H* values, by summing all components of the impulse response. Results obtained from RaPSor can be used to evaluate the impact of ISI depending on the transmission data rate (not investigated in this paper).

IV. IMPLEMENTATION

A. Outage probability definition

Since we consider a mobile patient within the room, moving slowly compared to the data rate, the performances can be evaluated with the outage probability, defined as the probability that the link is not ensured, *i.e.* that the SNR value drops below a threshold SNR0. This can be expressed by:

$$Pout = \Pr(SNR \leq SNR0)$$

From the set of simulated H values, we can numerically determine H pdf and thus from (1) the SNR pdf. Then, by integrating over the later, the outage probability is computed.

In the following, we investigate the performances in term of outage probability, comparing the basic simulation results considering only a single reflection on the floor to those obtained using RaPSor, *i.e.* considering at most three reflections on walls, ceiling and floor.

We have reported in Figure 1 the outage probability as a SNR0 function for different configurations: the line without marker corresponds to the single reflection case without (withoutconsidering any reflections on neither the walls nor the ceiling), while the other ones are obtained for different wall reflectivity values (denoted by $\rho wall$). The floor reflectivity (denoted by $\rho floor$) and the ceiling one are set to 0.8 as in previous studies [6]. The results are obtained for a data rate *Rb*= 500kbps which is an upper bound of required data rates in healthcare context [7]. In each configuration, the emitted power is set to 70mW, which is the minimal value required to reach a 10-3 *Pout* for a 10-9 BER0 (corresponding to SNR0=15.6dB). First, we can observe that the performances are largely enhanced when reflections on walls are taken into account, even for small wall reflectivity values. Actually, in all cases the outage probability is lower than 10-4 for the expected performance (BER0 of 10-9), so the link is always maintained for the studied mobility scenario. In addition, one can notice that the performances are growing with the high reflectivity. These results are related to the fact that the emitter positions corresponding to the lowest SNR values have a strong impact on the outage probability. These positions are the ones located near the room borders which are the most distant from the receiver. However, because of their proximity from the walls, multiple reflections cannot be neglected and these contributions are all the more significant as the wall reflectivity is high. Thus, we can conclude that the outage probability will be overestimated using the ceiling bounce model with only one reflection on the floor, even for low data rates and without considering ISI.

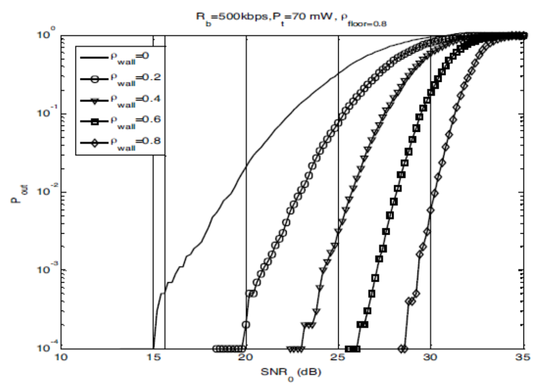

Figure 1. Impact of walls on the outage probability performances

Similar results have been obtained with the other floor reflectivity values. This means that taking into account the reflections over walls optimizes the system design, either by increasing the data rates (not investigated in our context) or by lowering the emitted power. This last point is of main concern in the context of a mobile communication. Actually, as the transmitter is placed on the patient and continuously communicates with the receiver, it is important to optimize the emitter power in order to have high power autonomy.

C. Emitted power analysis

To evaluate the power gain provided by this more accurate transmission model, first without considering any wall reflection, we have determined the minimal required emitted power Pt0 in order to achieve a 10-3 Pout for a 10-9 BER0 at a 500kbps data rate as a floor reflectivity function. The minimal power Pt0 obtained for $\rho floor$.

Equal to 0.8 (resp. 0.6, 0.4 and 0.2) is 70mW (resp. 90mW, 130mW and 260mW). This means that without considering any wall reflection, the value of the floor reflectivity has a strong impact on the emitted power value. Actually, the required power is all the more important as the floor reflectivity is low (the reflected contributions are less important). However, it always respects eye safety constraints (300mW [5]). Then, using RaPSor and for each configuration (*ρfloor* and *ρwall* varying from 0.2 to 0.8), we have searched the minimal required power Ptmin in order to achieve the same performance.

In all cases the ceiling reflectivity is set to 0.8. The results (ratio Ptmin over Pt0) are reported in Figure 2 as a function of *ρwall*. Notice that all the Ptmin results are obtained for Rb=500 kbps. However, since the SNR (1) depends on a Pt2/Rb ratio, using another Rb value leads to new Ptmin and Pt0 ones, but for the same ratio Ptmin/Pt0. Thus, Figure 2 is valid whatever the data rate is. Now focusing on Figure 2, first it can be noticed that all the curves have the same behavior and, since we have plotted the power ratio, they are in the same range. Thus, from these curves it can be determined an optimal required value of emitted power from a given minimal required power obtained without considering wall reflections. For example, with respect to a null *ρwall*, the required power is 50% lower with a 0.3 *ρwall*, and is 80% lower for a 0.8 *ρwal*. Considering *ρfloor* =0.8, this corresponds to an optimal power of 35mW for *ρwall* =0.3 and of 15mW for *ρwall* =0.8. Thus, our study permits designing the system more precisely. Actually, the required emitter power can be decreased, which corresponds to an increase of the monitoring system autonomy. Moreover, thanks to our study, one can assess the required power with only the knowledge of the one issued from results obtained without considering wall reflections (Pt0). In addition, thanks to the impulse response obtained from RaPSor, it is possible to evaluate the ISI impact.

In fact, because of the room dimensions, the impulse response length is limited in time so that the ISI has no impact for data rates lower than 17Mbps that is our investigated scenario. For higher data rates, we have verified from simulation results that ISI impact is all the more important as the wall reflectivity is high.

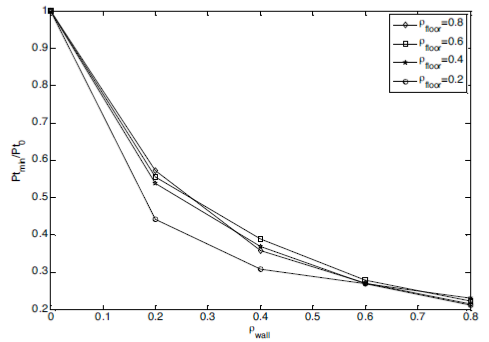

Figure 2. Ratio of power required to ensure a $P_{out}=10^{-3}$ for $BER_0=10^{-9}$

V. CONCLUSION

We have investigated in this paper the impact of an indoor environment on the outage probability in the context of indoor mobile OWC for healthcare monitoring in a hospital. For this purpose, we have developed a ray-based simulator, which permits taking into account wall, floor and ceiling reflections in the case of diffuse transmissions. From our analysis, we have pointed out that considering an emitter mobility scenario; the classical ceiling bounce model clearly overestimates the outage performance. By using our simulator, we have shown the need to take into account higher reflection orders and all reflective planes, even for low data rates. This permits a more accurate design of the OWC based monitoring system that is of main concern especially for power autonomy considerations.

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