Diffuse indoor IR communications with MIMO utilizing Photon Density Waves

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Multi-path environment for indoor wireless reduces the bandwidth for diffuse IR communications due to inter-symbol interference. This effect can be mitigated by quasi-diffuse multi-spot IR wireless techniques at the expense of more complicated systems. In the present report, we propose an alternative mitigation method based on using Photon Density Waves (PDW). PDW can be generated by a variety of methods by either modulation or beating of IR signals. We describe how PDW can lead to data rate enhancements by using multiple-input multiple-output (MIMO) methods. We explain the operation of PDW based indoor IR communications with MIMO by simulations based on ray tracing in indoor environments.

Introduction

Optical wireless provides a practical basis for many communication applications and provides solutions for environments where wired links or Radio Frequency (RF) wireless may not give the best implementation. For wide applicability, a wireless link should be compact, consume little power, and be easy to align, yet robust against background noise and interference from the other users. As a transmission medium for indoor wireless communications, infrared has several advantages over radio, such as an enormous unregulated bandwidth for high bit rates and absence of interference between links operating in rooms separated by walls. Furthermore infrared components are usually inexpensive and consume little power.

Optical wireless communication technologies are mostly implemented by using Infra-Red (IR) radiation [1]. However, in some recent studies, we observe that there is growing interest to use visible radiation from Light Emitting Diodes (LED) developed originally for lighting applications [2]. In this way the optical wireless technologies can be made as ubiquitous as the lighting infrastructure in our environments, opening up huge marketing potential especially for indoor applications. In order to reach this goal in an efficient and reliable manner, however, we have to deal with the inter-symbol interference (ISI) originating from multi-path environment for diffuse indoor wireless to reach the intrinsic bandwidth of optical communications.

In a recent paper [3], we had addressed one of the most promising candidates for high-speed in-house IR wireless communications, called, Multi-Spot Diffusing Configuration (MSDC) [4]. MSDC is actually a quasi-diffuse configuration using multi-beam transmitters emitting nearly collimated beams and an array of detectors with each one having a narrow Field-Of-View (FOV). In our previous work [3], we had seen that, although MSDC has the potential to provide data rates of several 100 Mbps, it requires careful alignment of optical beams and spots in order to reach these rates.

The goal of this paper is to explore an alternative ISI mitigation method based on using Photon Density Waves (PDW) in conjunction with Multiple-Input Multiple-Output (MIMO) method, which is commonly employed in multi-path RF wireless communications [5]. PDW can be generated by a variety of methods by either modulation or beating of optical signals [6]. We describe how PDW can lead to data rate enhancements by using MIMO methods. Our goal is to find out if high data rates are possible with this approach without the system complications needed in the case of MSDC. Before we get into the details of our work with PDW, we point out that MIMO operation for optical wireless is also possible with the MSDC as has been shown in recent studies [4].

Diffuse IR channel model

The geometry of the IR channel considered in this report is shown schematically in Figure 1 in the form of a room. In this figure, we define a pair of transmitters (T) and receivers (R) and assume that their optical beams couple primarily via the ceiling, since this is the best reflecting surface available in most common rooms. In this report, we model the beams and the FOV of the transmitters and detectors using a generalized Lambertian pattern [7]. This pattern is defined by $[(n+1)\,\mathrm{Cos}^{n}(\alpha)]/2\pi$, where α is the angle from directivity vector of the transmitter/detector and n is an integer for setting the narrowness of the beam/FOV. The angle between the reflecting surface and the light incidence direction is also taken into account by another cosine term. The patterns of optical light incident on the ceiling and their detected portions are calculated using this expression and assuming a uniform reflectivity function for the ceiling surface. Note that, changing these assumptions to more realistic beam/FOV forms and reflectivity functions are not expected to change the main qualitative conclusions of this report for the data-rate optimizations.

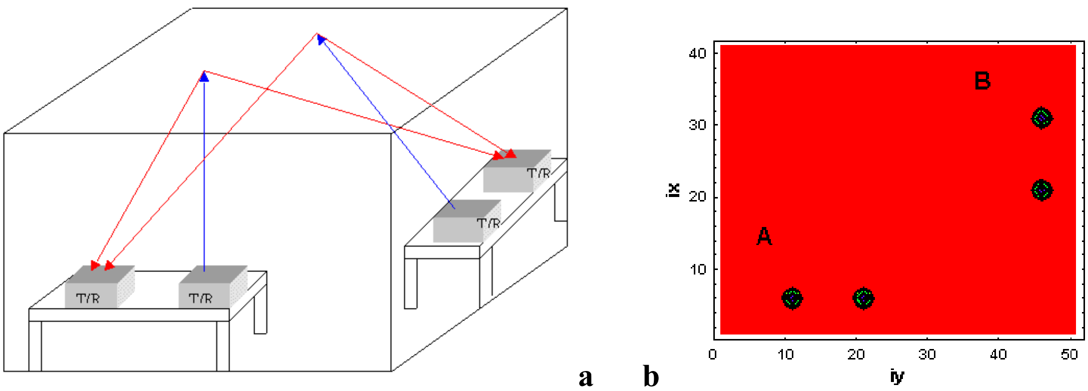

Fig. 1: *(a) gives the sketch of a room for the IR channel model. The transmitters (T) and receivers (R) interact via the ceiling only. Figure (b) on the right indicates the positions of two specific sets (A and B) transmitter/receiver pairs on the floor of a 4x5 meter room (axes are in dm). Set A T/Rs are 1 and 3 (left to right) and Set B are 2 and 4 (top to bottom).*

For the rest of this report, we assume that we have an optical channel defined between a pair of transmitter/receivers (T/R) indicated as A and B in Figure 1b. This figure shows the positions of these transmitters and detectors in the horizontal floor of a 4x5 meter room. All of the communications and channel responses are defined between the T/R pairs of the sets A and B. Figure 2 shows the patterns of illumination on the ceiling detected by set B acting as a receiver set, when set A is acting as transmitter. The directivity patterns of the transmitters and receivers are chosen arbitrarily for Fig.2a.

Fig.2b shows the total impulse response of the room IR channel under these assumptions [3], with the individual contributions between different T/R pair are shown with lighter colored curves under the total response. The light output power of the sources in this report is taken to be unity for all cases. A direct observation from Fig.2b is that the individual contributions to the impulse response are narrower in time, by about a factor of 3, as compared to the total impulse response shown by the thick envelope curve. This is clear from the set of plots shown in Fig.3, where the total channel matrix response (3a) and individual channel responses (3b) are shown.

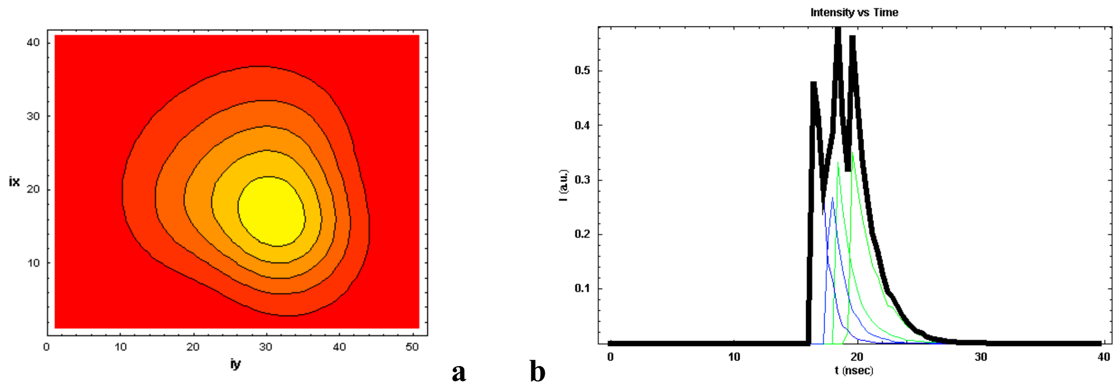

Fig. 2. *(a) indicates the detected IR light pattern by set B when set A transmits. (b) is the impulse response for this case in (intensity vs time-nsec)*

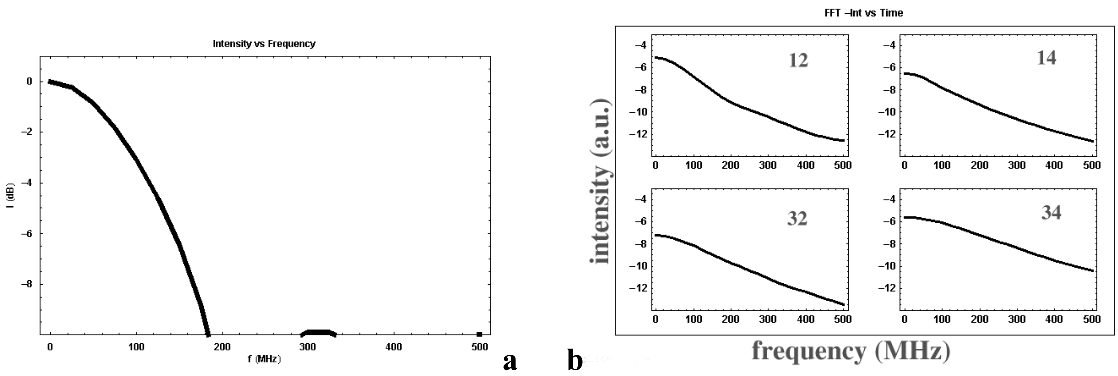

Fig. 3. *Plots in (a) and (b) above indicate the spectrum of the total and individual channel matrices respectively. These plots are given in (intensity vs frequency- MHz). Note that the individual channel matrices have larger 3dB bandwidths that the total channel matrix.*

IR channel with PDW

The photon density waves are basically amplitude modulated light beams with a modulation function in the form of exp[i (w_{pdw} t – k_{pdw} r)]. The benefits of PDW for IR channel communication are two fold. The first is that due to faster multipath fading for PDWs, the contributions of the multipath to the channel matrices becomes less. The second is that, by changing the frequency of the PDW, one can tailor the correlations between the channel matrix elements. The latter implies that the utilization of MIMO can be made more effective by changing the PDW frequency. The appearance of an example PDW pattern for the in-phase and quadrature-phase components are shown in

Figure 4 showing a richer distribution than constant illumination (Fig.2). This means that the PDW enhances scattering depending on the geometry of the indoor environment and the light beam properties, such as divergence angle and FOV.

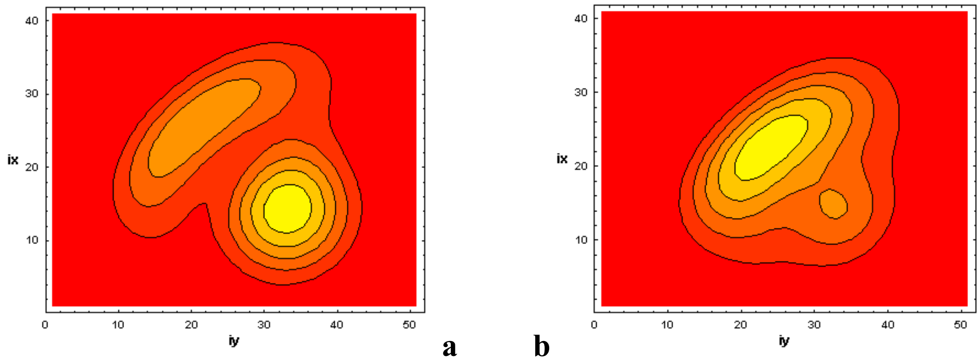

Fig. 4. *(a) and (b) show the detected IR light pattern by set B when set A transmits a PDW beam with 150 MHz, for in- and quadrature- phase components (other parameters as in Fig.2).*

Discussion and conclusions

As observed clearly in Fig2 and 3, the bandwidths of the individual components of channel matrices are nearly 3 times wider than the total channel matrix. From the Shannon capacity formula, C = W log[1 + S/NW], where W is the bandwidth, the data rate of the individual channels can be nearly three times higher. PDW introduces two more advantages to this situation. The first is that by changing the frequency of the PDW the correlations in matrix components decreases and the decoupling of the channel matrix to its components can be more effective. We have confirmed this in our simulations by changing the frequency and the light beam parameters, such as the divergence angle width and exit angles. The second advantage of PDW is that it attenuates faster than the constant (DC) component of light due to interference and fading problems. This tends to decrease the detrimental effects of multipath signal propagation. The latter, however, comes at the expense of the reduced signal amplitude. These detrimental effects of signal amplitude are not as strong as the bandwidth gains due to the logarithmic dependence of the Shannon capacity on the signal strength.

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