Coherent Optical Wireless: An Alternative Technology for Broadband Indoor Communications

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ABSTRACT

Coherent detection technology which is commonplace in optical fiber-based systems, may serve as a means to compensate for path loss in line-of-sight and diffuse optical wireless systems. In this study, a high-speed optical wireless communication system based on coherent detection is investigated. Our analysis includes the laser phase noise which, to the extent of our knowledge, has not been adequately addressed in the literature in the field of optical wireless. Our results indicate that coherent detection may significantly alleviate the power budget of line-of-sight and non-line-of-sight configurations. It can enable Gbps wireless data transmission under moderate transmission powers compliant with eye safety regulations and the operational properties of optical transmitters typically found in the commercial marketplace.

Keywords: Coherent detection, laser phase noise, optical communication, wireless LAN.

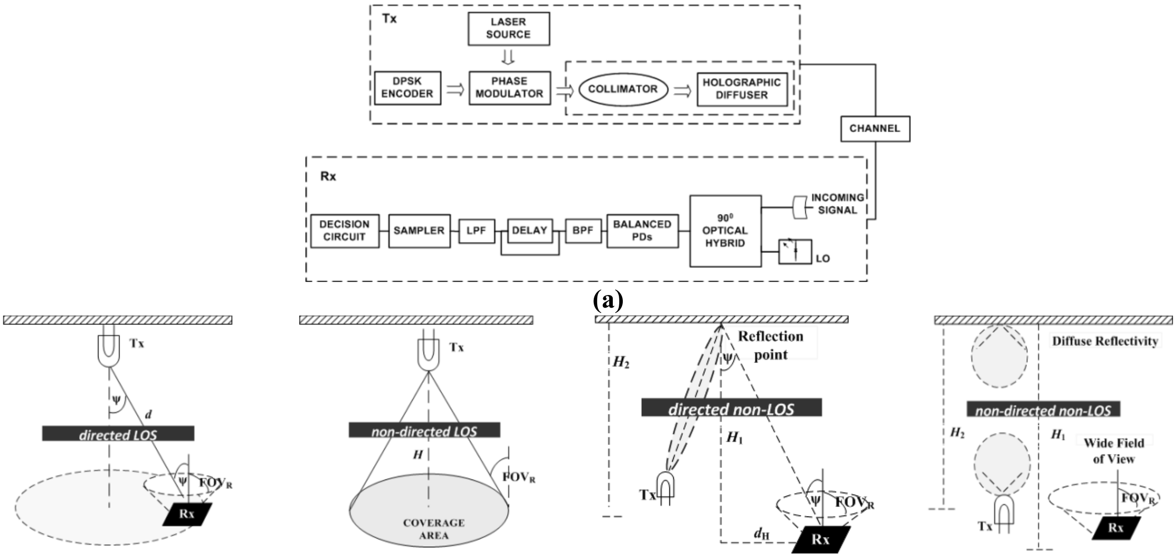
1. INTRODUCTION

The broadband landscape for the "last mile" continues to evolve, debating over whether access networks will be built out in fiber or they will rely on high-capacity wireless technologies, such as WiMax (Worldwide Interoperability for Microwave Access) or its rival LTE (Long-term Evolution) thereby avoiding the significant investment required for fiber-to-the-home deployments. Attention is also drawn towards alternative technologies able to cope with high-throughput demands for local area wireless networks in an indoor environment. Ultra-wideband (UWB) technology may be considered a candidate for short-range wireless communications; however it provides data rates that are limited up to few hundred Mbps and suffers from strong interference [1]. The physical layer of 802.11n is limited to 600Mb/s at best, even when a multiple input multiple output (MIMO) configuration is used. At millimeter wave frequencies, 60GHz systems promise license-free continuous bandwidth with a sufficient spectral space of 5-7GHz and high data rates on the order of a few Gbps. Although the capabilities of the 60GHz systems extend far beyond conventional wireless solutions in terms of capacity, major challenges still exist [2].

An alternative technology that may be ideally suited for ultra-high-speed short-range communications, being able to accommodate multi-gigabit connections and also enabling simple system design and providing attractive features such as electromagnetic interference (EMI) immunity, unregulated bandwidth and inherent high degree of privacy and security [3] is o*ptical wireless* (OW) communications operating in the infrared regime. Coherent detection technology which is commonplace in optical fiber-based systems, may serve as a means to compensate for path loss which can be significant particularly in systems relying in diffuse propagation. In this study we investigate a high-speed optical wireless communication system based on coherent detection. Our analysis includes laser phase noise which, to the extent of our knowledge, has not been adequately addressed in the literature in the field of optical wireless. The simulation model used to describe the system in question will perform a clear numerical analysis, taking into account the noise statistical properties that will alter the phase and the amplitude of the signal. Our results indicate that coherent detection may significantly alleviate the power budget of line-of-sight (LOS), in terms of establishing an unobstructed direct connection between the transmitter and the receiver, and non-line-of-sight (non-LOS) configurations. It can enable Gbps wireless data transmission under moderate transmission powers consistent with eye safety regulations and the operational properties of optical transmitters typically found in the commercial marketplace.

2. CURRENT STATUS & ISSUES OF CONCERN

Standardization efforts, protocol introduction and transceiver designs carried out by IrDA [4] have contributed to the establishment of OW as a strong candidate technology for local area high-capacity network applications. It is more than evident that the capacity provided by OW technology is not realizable by its RF-based counterparts, particularly up to the millimeter-wave frequencies. Legacy intensity modulated / direct detected (IM/DD) systems for LOS configurations have well been addressed in literature [5]-[6]. High-volume data transmission in a point-to-point topology has been demonstrated with a link capacity of 10Gbps [5]. Widespread techniques used to improve bandwidth utilization, such as wavelength division multiplexing, may be incorporated and have been reported to achieve data capability of at least 40Gbps in wireless direct connections [6]. LOS topologies result in increased received optical power and as a consequence in improved system performance and data transfer rates. This comes at the expense of limited end user mobility / limited coverage area, vulnerability to shadowing, high blocking probability and strict alignment requirements that lead to increased installation complexity. In order to overcome these limitations, a non-directed or diffuse configuration can be considered, where wide-angle transmitters and receivers are employed and the signal undergoes one or several reflections before reaching its destination. As a result of the diffuse multipath nature of such an arrangement, the ensuing power reduction of the received signal needs to be canceled out. Increasing laser's output power to compensate for the introduced path loss is not recommended. Restrictions posed by eye and skin safety regulations may result in strict limits on the amount of the transmitted power [7]. Many authors have also proposed power efficient signaling schemes, such as those derived from pulse-position modulation (PPM) [8], to compensate for path loss.



(a)

(b)

Figure 1. Block diagram of the system and different link types. (a) block diagrams of the DPSK transmitter and heterodyne coherent receiver
[**13**]*,(b) different link types considered.*

Coherent detection may also be applied to relax this extra power budget required in a diffuse optical wireless link; it produces a beating signal by mixing the incoming and the LO signals, thus providing additional gain at the receiver side. In fiber-based systems, the invention of the erbium-doped fiber amplifiers (EDFAs), made the low sensitivity privilege of coherent detection less significant. Moreover, the complexity associated with the need of phase tracking and control in homodyne coherent systems, as well as performance degradation originated from polarization misalignment issues between the incoming and the LO signals, had led coherent detection technology to spend many years on the shelf. Recently however, advances in digital signal processing (DSP) that enables system performance degradation factors to be tracked and controlled in the digital domain [9] and the application of spectrally efficient modulation formats [10] have led coherent detection to the forefront. In the field of optical wireless, this technology is still embryonic and appears to pose a significant number of challenges at a research level, which remain unanswered up to date. This study represents the first attempt to develop a clear numerical model to characterize an OW communication system that includes LOS and non-LOS link configurations and takes into account the statistical properties of laser phase noise along with those of the additive noise contributions. Multipath fading and multipath-induced intersymbol interference (ISI) and the means to mitigate them, i.e. electronic equalization and orthogonal frequency-division multiplexing (OFDM) [11] for coherent systems may be a subject of future consideration. Although the resilience of IM/DD OW systems to multipath fading is well known [12], further investigation for coherent systems is required.

3. MODEL DESCRIPTION & RESULTS

The system's block diagram is illustrated in Fig.1a. The phase modulator imprints the information in the phase of the laser beam. Assuming a 2-level differential phase-shift keying (DPSK) signal, the modulator introduces a phase shift equal to π between two consecutive pulses to be transmitted to represent digital bit "0", while the phase remains unaltered for digital bit "1". The choice of the laser diode (LD) as optical source is made due to the coherent nature of the emitted radiation which allows phase recovery at the transmitter. The use of the holographic diffuser results in a more uniform illumination and increased coverage area and ensures power safety according to skin and eye safety concerns. Figure 1a also illustrates the block diagram of the conventional DPSK receiver structure. This standard delay-and-multiply type optical heterodyne binary-DPSK receiver has been analyzed previously

[**13**]. The key element of the receiver is an optical 90^0 hybrid for mixing the incoming optical signal and an optical local oscillator (LO) signal, resulting in a signal at an intermediate frequency (IF) in the output ports of the coupler. In order to increase the sensitivity of the system and to fully utilize the received signal dual-balanced photo-detection is required. The produced photocurrent is mixed with a delayed replica of itself, using a delay line. A low-pass filter (LPF) removes remnants of the intermediate frequency and recovers the baseband signal. The resulting signal is sampled and led to the decision circuit.

We have considered four different link configurations, as those indicated in Fig.1b. A directed LOS, where a direct connection between the transmitter and the receiver is established and narrow-angled transceivers are employed. A non-directed LOS connection, where the use of a system consisting of a collimator lens and a holographic diffuser spreads the infrared radiation in a wider area. A directed non-LOS link type, where the signal reaches its destination after being reflected at the ceiling, and finally a diffuse configuration, where the single-bounce model is used to define the channel DC gain, given in the table below.

Table 1. Channel models for different link types. Parameters: m: Lambertian radiation order, $\mathrm{FOV_R}$: *field of view of the receiver*, A_{det}: *physical detector area*, n: *internal refractive index of the receiver's concentrator*, ρ: *reflection coefficient of the ceiling*, (x_1,y_1): *transmitter placement on the horizontal plane*, (x_2,y_2): *receiver placement on the horizontal plane*, $H(0)$: *the channel DC gain.*

Link Types	Channel Models	Ref.
directed LOS	$H(0)=\frac{m+1}{2\pi d^2}(\cos^m\psi)A_{\mathrm{eff}}\ ,\ A_{\mathrm{eff}}=n^2A_{\mathrm{det}}\cos\psi/\sin^2(\mathrm{FOV_R})\ ,\ \psi\le\mathrm{FOV_R}$	[12]
non-directed LOS	$H(0)=A_{\mathrm{eff}}/A_{\mathrm{cov}}\ ,\ A_{\mathrm{cov}}=\pi H^2\tan^2(\mathrm{FOV_R})$	[14]
directed non-LOS	$H(0)=\frac{\rho A_{\mathrm{det}}H_1\cos\psi}{\pi\left(H_1^2+d_{\mathrm{H}}^2\right)^{3/2}}\frac{n^2}{\sin^2(\mathrm{FOV_R})}\ ,\ \psi\le\mathrm{FOV_R}$	[12]
diffuse	$H(0)=\frac{\rho n^2A_{\mathrm{det}}H_1^2H_2^2}{\pi^2}\iint\limits_{\mathrm{ceiling}}\frac{1}{[H_2^2+(x-x_1)^2+(y-y_1)^2]^2[H_1^2+(x-x_2)^2+(y-y_2)^2)]^2}dxdy$	[12]

Laser phase noise undergoes a Brownian-motion-type process that may be expressed by the following equation

[15] and approximated in the discrete time domain.

$$\theta(t)=2\pi\int_0^t\mu(\tau)d\tau\cong2\pi\Delta\tau\sum_{i=1}^N\mu_i \tag{1}$$

where the N samples of $\mu(t)$ are located at $t_i=(i-1)\Delta\tau$, $\Delta\tau$ is the sampling period and μ_i is the discrete version of the white Gaussian noise $\mu(t)$, with a two-sided spectral density of $R_\mu=\Delta v/2\pi$ (Δv is the laser's linewidth). We assume that μ_i are independent identically distributed zero mean Gaussian random variables with variance σ_μ^2. It can be easily shown that since $\mu(t)$ is zero mean, $\theta(t)$ is also zero mean and by setting equal the variance of $\theta(t)$ expressed in the continuous and discrete time domain, we conclude that:

$$\sigma_\mu{}^2=\frac{\Delta v}{2\pi\Delta\tau}. \tag{2}$$

This approach allows us to incorporate the phase noise directly in our model.

Taking into account not only laser phase noise, but also additive noise contributions, such as shot and thermal noises, we have conducted simulations with parameters defined in Table 2. The BER performance of the system is evaluated in terms of different levels of received optical power and over a range of laser linewidth values. The simulation results are displayed in Fig.2. To obtain an acceptable level of performance, i.e. BER value in the order of 10^{-3}, lasers with linewidths up to 40MHz may be used at -50dBm received power. Assuming a laser linewidth of 20MHz, the same BER performance is obtained at -60dBm suggesting that low receiver sensitivities can be obtained at 1Gbps data rates significantly relaxing link budget limitations.

Table 2.Simulation Parameters.

Parameters	Value Range	Parameters	Value Range
bit rate	1Gbps	FWHM / $\mathrm{FOV_R}$	15^0- 45^0/ 60^0
laser wavelength	850nm	$\mathrm{A_{det}}$ / receiver responsivity	$1\mathrm{cm}^2$/ 1.0018 A/W
room dimension /	(20x20x3) m^3	$\mathrm{n_{CPC}}$ / reflection coef. ρ	1.85 / 0.8
Tx position / Rx position	(10,10,z) m / (x,y,0.3) m	3dB BW of BPF	10GHz

The results shown previously can be extended to include channel loss thus enabling the analysis of the different system setups presented previously (Fig. 1b). Initial results concern the numerical evaluation of the BER for different transmission power levels, as illustrated in Fig. 3. The horizontal distance between the transmitter and the receiver or between the transmitter and the reflection point for the directed non-LOS arrangement is set equal to 1m. According to Fig. 3, 1Gbps wireless transmission under moderate transmission powers consistent with eye and skin safety regulations is feasible for a typical value of laser linewidth in the order of 20MHz and for all system setups. However, an almost 5dB power penalty is observed over a range of BER values of 10^{-3}-10^{-4} between the directed non-LOS case, which under the specific arrangement indicates the best performance and the diffuse configuration, which constitutes the worst case scenario.

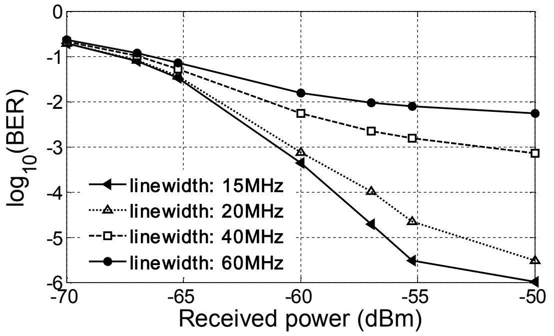


Figure 2. BER as a function of the received power for different laser linewidth values. LO power: 0.1mW.

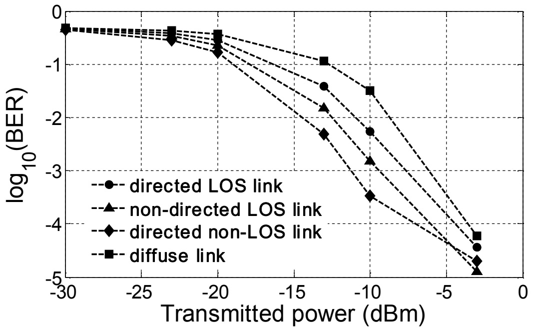


Figure 3. BER as a function of the transmission power for different link types. Laser linewidth: 20MHz.

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