Coherent Optical Wireless Systems for High Speed Local Area Networks with Increased Resilience

Katerina Margariti

Department of Informatics and Telematics
Harokopio University of Athens
Omirou 9, Tavros, Athens Greece GR17778
+302109549432
kmargariti@hua.gr

Thomas Kamalakis

Department of Informatics and Telematics
Harokopio University of Athens
Omirou 9, Tavros, Athens Greece GR17778
+302109549406
thkam@hua.gr

ABSTRACT
Optical wireless systems constitute an interesting alternative for supporting next generation local area networks with high speed gigabit-per-second connectivity. Their advantages include a vast license-free spectrum, an abundance of transmission bandwidth, limited health side-effects and zero electromagnetic interference with existing legacy radio networks and other devices. On the other hand, coherent detection is being widely considered in fiber-optic communication systems as a means to provide optical gain at the receiver while at the same time achieving increased spectral efficiency and wavelength selectivity. In this paper we propose to make the best of both worlds combining coherent detection and optical wireless. The improved power budget may ensure better coverage conditions, higher data rates and resilience against shadowing and beam obstruction effects. We discuss the factors that may contribute to the performance degradation in such systems such as laser phase noise, etc. We present some basic calculations and attempt to provide a first indication on the influence of these factors.

Categories and Subject Descriptors
C.2.1 [Computer-Communication Networks]: Network Architecture and Design

General Terms
Design, Performance, Verification

Keywords
Wireless networks, home networks, photonic technologies.

1. INTRODUCTION
The development of truly broadband, multi-gigabit per second capable wireless local area networks is a long sought Holy Grail in view of the potential applications [1].

PCI '14, Oct 02-04 2014, Athens, Greece ACM 978-1-4503-2897-5/14/10.
http://dx.doi.org/10.1145/2645791.2645800

One potential market for such applications is data center interconnections [2] where the aggregate bandwidth requirements can quickly exceed 10 or even 40Gbps. Establishing high-speed wireless connections will lead to a more flexible data center allocation with significantly less cable spaghetti. Another potential market for optical wireless is home and office networks [3]. In the not so distant future, it is foreseeable that content providers will be required to distribute ultra high definition video-on-demand which even in a compressed state, will require data rates of the order of 1Gbps [4]. Such data rates could be accommodated by a fiber-to-the-home (FTTH) access network up to the customer premises but distributing this traffic indoors is quite a challenge. Optical wireless links [5] can be envisioned to carry this data traffic up to the user terminals in a reliable and efficient manner.

There are many advantages in using optical wireless links in such applications. In effect, optical wireless is optical communications without the fiber. One could expect that since optical technologies allow terabit-per-second data rates in the long-haul and metropolitan area networks, ultra broadband connectivity will in principle be possible in the wireless indoor environment as well. Although this is a reasonable argument one must not forget that cost is much more crucial factor in last meter applications than in core or metro networks. One cannot simply use the same transceivers and must resort to more cost effective solutions. Another advantage of optical wireless is the abundance of unregulated bandwidth (several hundred THz) in the infrared or even visible part of the spectrum that can be used for data transmission. This vast available bandwidth allows many optical wireless connections to be active simultaneously carried by different wavelengths using coarse wavelength division multiplexing (CWDM). On the downside, optical beams are susceptible to blocking by obstacles inside the room unlike radio signals which do not require line-of-sight communication unless the carrier frequency is high, as is the case in millimeter links. Diffuse propagation, where a certain amount of the transmitted optical power reaches the user terminal through reflections from the walls of the room may provide a way of establishing communication even if there is no line-of-sight path between the transmitter and the receiver. However, diffuse propagation is usually accompanied by a poor link budget and increased intersymbol interference due to the multipath propagation.

The first IR system was demonstrated by Gfeller and Bapst [6] was a diffuse link operating at 1Mbit/s. A diffuse system operating at 50Mbit/s was later demonstrated using intensity modulation / direct detection (IM/DD) [7]. In later demonstrations and because of multipath dispersion and poor link budget which limit the system performance in the diffuse propagation regime, attention was recently shifted towards line-of-sight systems. The ICT-OMEGA project demonstrated a multiple element IM/DD transceiver operating at 1.25Gbit/s [8] using low-cost commercial of the shelf components. Recently, 12.5Gb/s connectivity has been demonstrated with the signal being fed by a remote central office node (~6Km distance) without any optoelectronic conversion at the room hotspot [9].

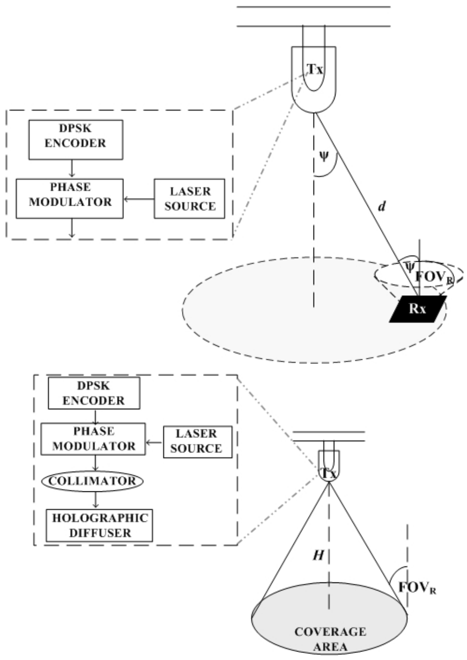
2. COHERENT DETECTION

From the perspective of coherent optical detection in optical communications, the first wave of the intense interest appeared in the 1980s and early 1990s, when coherent detection was viewed as a promising technique to improve the receiver sensitivity [10]. The earlier realizations of coherent receivers were complicated and typically included high speed analog electronics for demodulation from the carrier or for optical phase locking, and also active optical components for polarization control. However, the ensuing invention of the erbium doped fiber amplifier (EDFA) reduced research on coherent communication to peripheral interest. Recent years have seen a revival of coherent detection schemes in fiber-based systems where in view of the bandwidth constraints of optical amplifiers and ultimately the fiber itself, it is important to maximize the spectral efficiency but at the same time keep the transmitted power low enough in order to prevent signal-to-noise ratio degradation due to fiber nonlinearity [11]. In optical wireless communications where small size, low cost components are needed, the use of optical amplifiers such as EDFAs or semiconductor optical amplifiers (SOA) is prohibited. In recent implementations of coherent receivers, the functionality of phase locking is performed in the digital domain using digital signal processing (DSP). Provided that the DSP hardware and also the necessary optical passive components can be produced in volume at low cost, the new version of the coherent receiver will be cost-effective compared to direct detection, and is likely to be widely deployed. There are several coherent receivers already commercially available in integrated form offering polarization diversity.

To compensate for the effect of the frequency selective channel, equalization methods such as OFDM can be applied. OFDM has emerged as the leading physical-layer interface in wireless communications in the past decade. It is a special form of a broader class of multicarrier modulation where a data stream is carried with many lower-rate subcarrier tones [12]. OFDM has been widely studied in mobile communications to combat hostile frequency-selective fading and has been incorporated into wireless network standards (802.11a/g WiFi, HiperLAN2, 802.16 WiMAX) and digital audio and video broadcasting (DAB and DVB-T) in Europe, Asia, Australia, and other parts of the world. The synergies between coherent optical communications and OFDM are twofold. The coherent system brings OFDM a much needed linearity in RF-to-optical (RTO) upconversion and optical-to-RF (OTR) downconversion. OFDM brings coherent system computation efficiency and ease of channel and phase estimation. The complementary metal–oxide semiconductor (CMOS) application-specific integrated circuit (ASIC) chips recently demonstrated for single carrier coherent systems [13] signify that the current silicon speed can support 40 Gbit/s OFDM transmission systems. Because of its superior scalability with the bit rate of the transmission systems, coherent OFDM (COFDM) is well-positioned to be an attractive choice of modulation format for the next generation of 100 Gbit/s wireline transmission.

3. SYSTEM ARCHITECTURE

Figure 1 shows the possible transceiver configurations and propagation regimes [14]. In Figure 1(a), a directed line-of-sight (LOS) link is shown that relies upon an unobstructed path between the transmitter and the receiver. Figure 1(b) shows a non-directed LOS link where a holographic diffuser is used for reasons discussed directly above. Figure 1(c) shows a directed non-LOS (or hybrid) link where there is no direct path between the transmitter and the receiver. A directional transmitter is placed at some height above the ground and the optical signal reaches the receiver after being reflected by the ceiling. None of the above mentioned configurations are ideally suitable for indoor communications, since they provide only limited coverage. In order to achieve enhanced mobility, a non-directed non-LOS (or diffuse) system setup should also be considered. Such an arrangement employs a Lambertian-radiation-pattern transmitter and along with a wide field-of-view receiver and the signal undergoes one or several reflections before reaching its destination. One can assume a single-bounce model, where the transmitter and the receiver are placed at some height above the ground and pointed straight upward (Fig 1 (d)). Although in general diffuse configurations offer more robust optical links in terms of coverage, they suffer from poor link budget due to the increased attenuation associated with the diffuse propagation and at the same time are impaired by multipath dispersion [14].



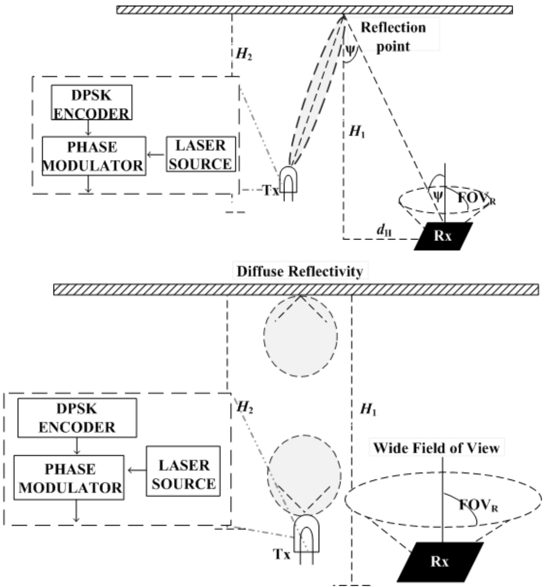


Figure 1. Optical wireless transceiver configurations

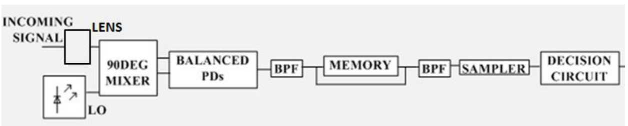


Figure 2. Optical coherent receiver

Figure 2, illustrates the block diagram of the conventional DPSK receiver structure considered in this paper. This standard delay-and-multiply type optical heterodyne binary-DPSK receiver has been analyzed previously [15]. The key element of the receiver is an optical 90^o 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.

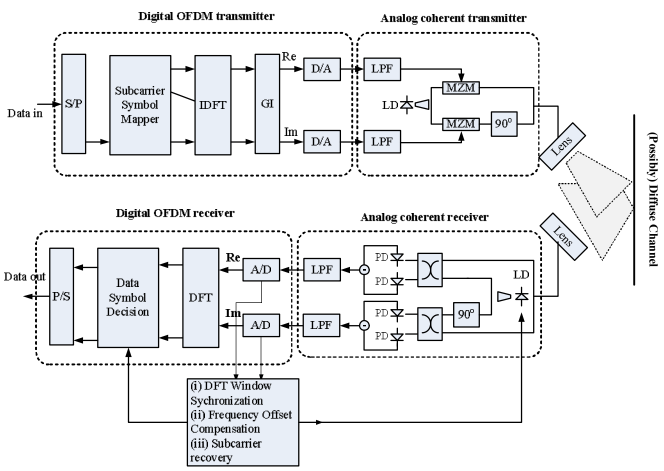


Figure 3. Optical coherent transceiver based on OFDM

Figure 3 shows a coherent optical wireless link employing OFDM modulation inspired by its fiber-based analog [16]. As seen in the figure, the input data pass through a serial to parallel converter and then to a subcarrier symbol mapper, which maps the incoming bits to transmitted symbols. The symbol stream then passes though an inverse discrete Fourier transform (IDFT) which estimates the OFDM waveform samples. A guard interval (GI) is inserted in order to ensure that subsequent symbols do not interfere. The digital-to-analog converters (D/A) converters synthesize the real (Re) and the imaginary (Im) part of the ODFM waveform. These are fed to the Mach-Zehnder modulators (MZM) which imprint the waveform in the carrier emitted by the transmitter laser diode. At the receiver the optical signal is mixed with the signal of a local oscillator laser diode at the four photodiodes which are differentially placed in two groups, one detecting the real and the other the imaginary part of the signal. These signals are fed at the analog-to-digital (A/D) converters and pass through the discrete Fourier transform (DFT) module and after removing the guard interval, the subcarrier symbols and the corresponding output are estimated.

4. OBJECTIVES OF THE COWS PROJECT

The "Coherent Optical Wireless Systems for Next Generation Home and Corporate Networks" (COWS) project is funded by the “ARISTEIA II” Action of the “Operational programme Education and Life Long Learning” and is co-funded by the European Social Fund (ESF) and National Resources. Its main objective is to demonstrate the applicability and merits of coherent detection in optical wireless systems. More specifically, the project aims:

a) to provide valuable proof-of-concept on the applicability of coherent optical detection as a means to increase range, coverage and capacity of optical wireless systems which do not necessarily rely on a line-of-sight path between the transmitter and the receiver.

b) to investigate the performance of various equalization methods such as OFDM as a means to mitigate multipath dispersion and increase the transmission rate.

c) to undertake a thorough investigation of design parameters at a component and a system level (transceiver and local oscillator type, transmission wavelength, modulation level, pre distortion techniques, etc). System design will take into account performance, cost and safety parameters.

d) to investigate multiple transmitter / multiple receiver (MIMO) techniques as a means to improve the overall link capacity and coverage.

e) to implement a coherent optical wireless testbed in order to ascertain the applicability of this technology in real world conditions.

5. RESULTS AND DISCUSSION

In this section we present some initial results regarding the performance of a coherent optical wireless link. Figure 4 shows the bit error rate (BER) floor calculated assuming only the influence of phase noise and the DPSK coherent receiver of Figure 2. The BER is calculated as a function of the ratio of the laser linewidth Δf to the system bit rate R_b, $L=\Delta f/R_b$ using Monte Carlo simulation. We deduce that $L<0.02$ provides an acceptable

BER (<10^{-5}). Assuming a Δf=1MHz linewidth we see that for data rates $R_b>\Delta f/0.02$=50Mb/s, phase noise does not pose significant limitations in the performance of the system. It is interesting to note that the influence of phase noise diminishes with increasing data rate, since the bandwidth of the signal becomes larger than the phase noise spectrum. This implies that for a targeted data rate of R_b=1Gb/s the impact of phase noise will be significant less.

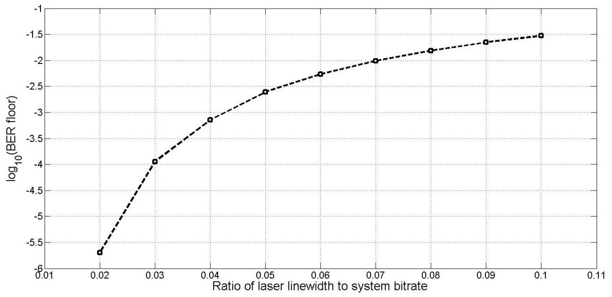


Figure 4. Phase noise error floor

Table 1 discusses the main parameters used in the system simulations. The laser linewidth is now taken equal to 20MHz which according to Figure 4, will produce a BER below 10^{-5} at R_b=1Gb/s. We assume a room configuration of 20m x 20m x 3m in order to calculate the DC optical channel gain using well known expressions. The transmitter's semiangle $\Phi_{1/2}$ is related to the radiation pattern of the transmitter. Assuming a Lambertian pattern, one can simply relate the radiation pattern to the Lambertian order m through $m=-\ln 2/\ln(\cos(\Phi_{1/2}))$.

Table 1. Simulation Parameters & Configurations for Indoor optical wireless system

Parameter	Value Range
Bit Rate	1Gbps
Laser Wavelength	850nm
Laser Linewidth	20MHz
Room Dimension	20x20x3 m^3
Tranmsitter's semiangle	15^0
FOV of the receiver	60^0
Local oscillator optical power power	1mW
Receiver Responsivity	1.0018 A/W
Physical area of the photodetector	$1cm^2$
Refractive index of the compound parabolic concentrator	1.85
Reflection coefficient (ceiling)	0.8

Position & Orientation / Configuration	A	B	C	D
Transmitter				
x(m)	10	10	---	10
y(m)	10	10	---	10
z(m)	3	3	0.8	0.8
elevation	-90^0	-90^0	$+90^0$	$+90^0$
Receiver				
x(m)	---	---	---	---
y(m)	---	---	---	---
z(m)	0.3	0.3	0.3	0.3
elevation	$+90^0$	$+90^0$	$+90^0$	$+90^0$

The results shown previously can be extended to include channel loss thus enabling the analysis of the different system setups presented previously (Fig 1). Initial results concern the numerical evaluation of the BER for different transmission power levels, as illustrated in figure 5. The results obtained involve 1Gbps data transmission for the different link topologies considered, incorporating a LD with a linewidth value in the order of 20MHz and a 60^o field-of-view receiver. These configurations include: a) directed LOS transmission where a typical directed transmitter (Lambertian order m=20) is employed, b) non-directed LOS link incorporating a holographic diffuser element, c) directed non-LOS (or hybrid) transmission where the signal reflects off the ceiling with the reflection coefficient being 0.8 and d) non-directed non-LOS (or diffuse) link configuration, considering the single-bounce approach. The received power is obtained as the product of the corresponding channel DC gain, representing the path loss, and the transmit power. For the directed LOS, the non-directed LOS and directed non-LOS configurations the channel DC gain is calculated using well known formulas in the literature [14]. In either case, 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. The path loss for the non-directed non-LOS (or diffuse) configuration is set equal to -53dB, according to the results obtained in [17] for a diffuse link setup modeled using the one-bounce approach, corresponding to the path loss for 1m horizontal distance between the transmitter and the receiver.

According to figure 5, when the transmitted power is kept at relatively low levels (i.e. in the order of -10dBm), a significant variation of the BER performance between the different configurations examined, is observed. This picture is altered at higher levels of emitted power, with the different arrangements exhibiting a quite similar performance. Further increase in power is not feasible (in the case of directed optical wireless links) due to existing restrictions on radiation for safety concerns. In either case, the diffuse topology indicates the worst performance, in terms of the level of transmitted power required to achieve a given BER, when compared with the other arrangements. This was expected, since diffuse configurations offer more robust links at the expense of higher path losses.

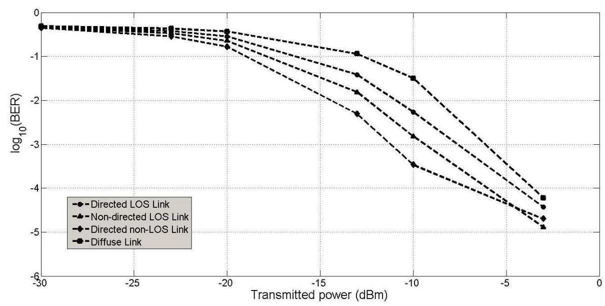


Figure 5. Impact of transmitted power in the BER performance of the system

6. CONCLUSIONS AND OUTLOOK

We have discussed the merits of coherent detection in optical wireless systems and presented some key results regarding the feasibility of the application of such systems in local area networks. We have shown that linewidths measured in commercial laser diodes can support gigabit-per-second data rates. At the same time, the inherent gain of coherent detection can be used to lower the optical power requirements at the transmitter or provide enhanced protection against shadowing and blocking.

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8. ACKNOWLEDGMENTS

The research reported in this paper was fully supported by the "ARISTEIA II" Action ("COWS" project) of the "Operational programme Education and Life Long Learning" and is co-funded by the European Social Fund (ESF) and the Greek state.