Studies on System Design for Indoor Infrared Wireless Communication

屋内赤外線通信用システム設計に関する研究

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Graduate School of Global Information and Telecommunication Studies
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Dimitar Radkov KOLEV

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LIST OF ACRONYMS

AEL	Acceptable Emission Level
AOA	Angle of Arrival
APD	Avalanche Photo Diode
ASE	Amplified Spontaneous Emission
AWGN	Additive White Gaussian Noise
BEP	Bit Error Probability
BER	Bit-Error Rate
CATV	Cable TV
CCD	Charge Coupled Device
CM	Ceiling Module
CMOS	Complementary metal–oxide–semiconductor
CNDR	Carrier to Noise plus Distortion Ratio
CPC	Compound Parabolic Concentrator
CTM	Ceiling Transmit Module
DTM	Discovery Time Window
EDFA	Erbium-Doped Fiber Amplifier
EMS	Electrical Modulation Spectrum
E/O	Electro-Optical
EPON	Ethernet over Passive Optical Network
FOV	Field of View
FSO	Free-Space Optics
FTTH	Fiber to the Home
GPON	Gigabit-capable Passive Optical Network
HDTV	High Density Television
IFFT	Inverse Fast Fourier Transformation
IMD	Intermodulation Distortion
IMD3	Third Order Intermodulation Distortion
IM/DD	Intensity Modulated Direct Detection
IR	Infrared

IrDA	Infrared Data Association
ISDB-T	Integrated Services Digital Broadcasting International
LAN	Local Area Network
LD	Laser Diode
LED	Light Emitting Diode
LLID	Logical Link ID
LLN	Law of Large Numbers
LOS	Line-of-Sight
LTE	Long-term Evolution
MAC	Media Access Control
MD	Mobile Device
MEMS	Micro Electro Mechanical Systems
MPE	Maximum Permissible Exposure
NHZ	Nominal Hazard Zone
OA	Optical Amplifier
OFDM	Orthogonal Frequency-Division Multiplexing
OLT	Optical Line Terminal
OMI	Optical Modulation Index
ONU	Optical Network Unit
OOK	On-Off Keying
OWC	Optical Wireless Communications
PAN	Personal Area Network
PD	Photo Diode
P2MP	Point-to-Multi-Point
PIN-PD	p-i-n Photo Diode
PLC	Power Line Communication
PON	Passive Optical Network
PSD	Power Spectral Density
OLED	Organic Light Emitting Diodes
QPSK	Quadrature Phase-Shift Keying
QAM	Quadrature Amplitude Modulation

RF	Radio Frequency
RIN	Relative Intensity Noise
RoF	Radio over Fiber
RoFSO	Radio over Free Space Optics
RxM	Receiver Module
SEP	Symbol Error Probability
SNR	Signal-to-Noise Ratio
TDFA	Thulium Doped Fiber Amplifier
TDM	Time Division Multiplexing
TIA	Transimpedance Amplifier
TV	Television
VLC	Visible Light Communications
WDM	Wavelength-Division Multiplexing
WiMAX	Worldwide Interoperability for Microwave Access

LIST OF SYMBOLS AND NOTATION

a	Distance between two neighbor ceiling modules
a_3	Third order nonlinearity coefficient
a_n	In-phase modulation symbol
A_r	Receiver aperture surface
B	Bit rate
b_n	Quadrature modulation symbol
B_N	Receiver bandwidth
c	Speed of light in vacuum
C	Expected desired signal power
$\mathrm{C_j}$	Junction capacitance
c_L	Light speed
$CNDR_n$	Received carrier to noise plus distortion ratio per subcarrier
d	Delay between signals from neighbor receivers/transmitters
$D_2(N, n)$	Number of intermodulation distortion products
$D_3(N, n)$	Number of intermodulation distortion products
d_r	Receiver aperture diameter
D_w	Working distance
E_b	Bit energy
$E(\theta)$	Emitter radiant intensity
$\mathrm{f_{BW}}$	Photo diode bandwidth
$\mathrm{f_c}$	Carrier frequency
f_L	Focal length
FOV	Field of view of the detector
$\mathrm{G_0}$	Optical gain
G_{OA}	Optical amplifier gain
h	Height between the communication plane and the ceiling
h_l^0	The impulse response of the direct light
$h_{\mathrm{k}}^{\mathrm{m}}(\mathrm{t})$	m^{th} impulse response of the k^{th} source
hv	Photon energy

$I(r)$	Irradiance distribution of Gaussian beam
$i(t)$	Received photocurrent
$\langle i^2_{ase} \rangle$	Mean square beat noise current
I_{ASE}	ASE current
I_{BN}	Current in the PD due to the background light
I_d	Average dark current
$\langle i^2_N \rangle$	The mean square optical noise current
I_{PD}	Current in the pin PD
I_{ph}	DC value of the received photocurrent
I_s	Current in the PD
$\langle i^2_{shot} \rangle$	Total shot noise
$\langle i^2_{th} \rangle$	Thermal noise mean square value
k	Optical wave number
K	Number of micro surface from Lambertian reflector
K_B	Boltzmann's constant
$L1$	Distance between the transmitter 1 and the receiver
$L2$	Distance between the transmitter 2 and the receiver
L_{beam}	Loss due to partially received beam in the receiver aperture
$L_{coupling}$	Coupling loss
L_m	Loss margin
L_p	Path loss
L_{split}	Splitter insertion loss
L_{tot}	Total loss
Δl	Optical path difference
M_{APD}	APD internal gain
m_n	Optical modulation index for each subcarrier
m_t	Amplifier factor
m_{Total}	Total OMI
N	Number of subcarriers
$\vec{n}$	Normal vector to the surface
N_0	Noise energy

N_1	Populations of lower laser level
N_2	Populations of and upper laser level
n_a	Angular spread of the beam
n_k	Angular spread of the k-th element
$n_{opt}(t)$	Noise containing the AWGN with a double-sided power spectral density
n_{OW}	Additive white Gaussian noise
N_R	Number of reflecting elements
n_{sp}	Completeness of the population inversion for the amplifier
P_{Ar}	Received power in the aperture
$\mathrm{P_{ASE}}$	ASE noise optical power
P_b	Bit error probability
$P_{b,n}$	Bit error probability per subcarrier
P_D	Total transmitted power in the plane
$\mathrm{P_{eye}}$	Maximum optical power to enter the eye
P_N	Noise power
$P(r)$	Power, contained within a radius r in Gaussian beam
P_{out}	Total emitted power
$P_{R,G,indirect}$	Average received power from reflected light
$P_{R,G,Tot}$	Total received power from the laser source
$\mathrm{P_{r,OW}(t)}$	total optical power, directly received from the transmitter aperture
$P_{r,k}$	Received power in the k^{th} small area
P_s	Symbol error probability
$P_{s,n}$	SEP per subcarrier
P_T	Transmit power
q	electron charge
r	Distance from the z-axis
R	Distance from the light emitter to the detector
r_1	Distance from center of the beam to the receiving aperture
R_{in}	Feedback resistance
$\mathrm{R_{LOAD}}$	Load resistance
R_r	Radius of the eye aperture

r_z	Spot waist
SF	Smallest feature
SNR_d	Signal to noise ration in the downlink
$S_{OFDM}(t)$	OFDM signal
SR	Sensor resolution
S_s	Sensor size
ΔS	Ring surface of the beam spot
T	Absolute temperature
t_r	Rise time response
T_s	OFDM signal duration
X_n	Complex data symbol in the n^{th} subcarrier
z	Distance on the z-axis between the transmitter and the current plane
η	quantum efficiency
θ	Angle of divergence
$\theta_{Lambertian}$	Angle from the normal to the emitting surface
λ	Optical wavelength
Δv_f	Bandwidth of the optical band pass filter
ρ_i	Reflectivity of the surface
ρ_k	Reflectivity of the surface of the k^{th} source
ρ_{APD}	APD responsitivity
ρ_{RX}	PIN-PD responsitivity
σ^2_{IMD}	Third order intermodulation distortion power
φ	Angle of irradiance
ω	Distance out from the center axis z of the beam where the irradiance drops to $1/e^2$ of its value on axis
ω_0	Beam radius at the waist
ω_n	Set of N orthogonal frequencies

Summary

In the fast-changing and dynamic world today information and telecommunication technologies play a key role in our daily lives that increases every day. Broadband access services have wider coverage and higher quality. Companies often introduce new mobile devices such as notebooks, tablets and smart phones and different applications for them. While all this advanced technology eases us in daily life it challenges the transmission networks and their capacity to transmit big data. Fiber networks have been widely spread in the backbone networks because of their high capacity and low attenuation. Networks have been constantly evolving from fiber to the node (FTTN), providing broadband access to a neighborhood, to fiber to the home (FTTH) and even fiber to the desktop (FTTD) providing optical connection to the home or office and even to a workstation. Fiber data rates are constantly increasing by using dense wavelength division multiplexing (DWDM), multi-core fibers and other technologies. However, the wireless network faces a big struggle for bandwidth. The new devices and applications for them allow watching high-definition (HD) video, video-conversations, multiplayer games, etc. and require very high data rates. The insufficient bandwidth is especially noticeable in indoor spaces with high user density. The current radio-frequency (RF) technologies, such as WiMAX, LTE, Wi-Fi, etc., are very useful and comfortable at home or small office. However, in bigger offices, libraries, trains, and conference halls and so on, these systems cannot meet the user bandwidth requirements and form a bottleneck between the high speed fiber optic backbone network and the end user devices.

Optical wireless communications (OWC) are considered a very attractive alternative to the RF wireless technologies. They offer very wide bandwidth. Their coverage is limited to the areas where line of sight (LOS) or reflections can reach, which offers much better security. Most of the RF systems suffer electromagnetic interference and, for example, there are often conflicts between neighbor Wi-Fi networks. OWC electromagnetic interference immunity allows its usage together with RF systems and in RF restricted areas, such as planes, hospitals, etc. Recently, the device power consumption has also become a very important issue to consider. Telecommunication companies are one of the major energy consumers. OWC require less energy compared to the RF systems.

The main focus of this thesis is the indoor infrared (IR) OWC. There are no significant atmospheric effects on the link. Often, the indoor communication is point-to-multipoint compared to FSO links where the links are point-to-point. A conventional indoor IR OWC link assumes the usage of light emitting diode or a laser diode with wavelength around 800nm to 1000 nm as a light source. There are several significant problems that prevent these systems from becoming the dominant indoor network access technology. First, in a system that converts the optical signal from the fiber to electrical one and then modulates the light source this electro – optical conversion is a bottleneck for the overall system performance. Second, for these wavelengths the ambient noise is quite strong and the responsitivity of the photodiode is relatively small (<0.6A/W for Si photodiode). Finally, for the laser sources the laser safety regulations limit the transmitted optical power level. In this thesis a novel system that uses the fiber end as a light source is proposed. Such system removes the electro-optical conversion and allows direct usage of fiber bit rates in the wireless link. Furthermore, the ambient noise is much smaller and the photodiode responsitivity is much higher (0.9A/W for InGaAs photodiode) which strongly improves the performance. Last but not least, the permitted transmit power due to eye safety for the fiber wavelengths is much higher than the one for the wavelengths of conventional system. So far, when indoor optical wireless network is discussed, only Lambertian optical source has been considered. In the proposed system though the source is Gaussian beam and a new propagation model is presented. In the theoretical analysis are considered the main noise components – ASE noise from the optical amplifiers, shot noise, including the ambient noise in it, and thermal noise, which has the strongest effect in the system. For better evaluation of the OFDM signal transmission RIN noise is also considered.

The indoor OWC have are divided in two main types – LOS and diffusive. The diffusive links rely on reflections from different surfaces and provide excellent coverage. However, because of the reflections high transmitted power is required and the multipath distortion limits the bit rate. Therefore, the main accent of this thesis is on the LOS type of link – non-directed, directed and hybrid. Up to now, directed and hybrid networks are considered to work only in point-to-point networks due to the alignment complexity. In this work very fast tracking systems with high-resolution positioning systems are presented that allow point-to-multipoint communication for these configurations. For simplicity in the link design and transmission analysis only a network with single user has been considered.

The first work presented in this thesis is a non-directed LOS optical wireless link based on EPON. The first issue such system will have is the high attenuation in the wireless part due to the fact that only a small portion of the transmitted optical power will reach the receiver aperture and the Gaussian beam distribution. To guarantee flawless link performance in any spot of the covered area a careful investigation of the received power in each spot of the Gaussian beam is conducted and overlapping is considered. Due to overlapping arises the second main issue in the system – interference. In this work the interference in terms of time delay distribution and signal strength have been considered and possible data rates for particular configurations have been discussed. The link budget and eye safety considerations are also taken into account. In the downlink analysis two different signals were considered because of the capabilities of EPON to transmit signals on different wavelengths. Apart from the on-off-keying (OOK) modulation that is typical for internet access and other network communications, a transmission analysis for ISDB-T television broadcasting, which is based on orthogonal frequency-division multiplexing (OFDM), has been presented and its performance for some practically possible link configurations has been discussed. As a conclusion non-directed system, based on the proposed direct fiber coupling technology is not suitable for indoor communication systems because of its difficult deployment (multiple transceivers), limited speed (up to 1Gbps) and big receiver aperture that cannot be integrated in most of the portable devices. Furthermore, the proposed system cannot transport 64-QAM signal with the required BEP.

In the second work in this thesis is a study on directed and hybrid indoor LOS links. In this type of links it is important to have a positioning (localization) and tracking system to establish and maintain the link for mobile devices. The tracking system based on MEMS mirrors and imaging sensor that is typically used in FSO communications to mitigate angle of arrival effect has been adopted. In the proposed directed system the imaging sensors are used to detect the directed transmitter on the other side of the wireless link and the MEMS mirrors are used for transmission axis alignment. The presented link is considered to be a part of EPON network and the link alignment relies on the optical signal, sent for the protocol messages during the new device discovery time window. Maintaining of the link is relatively simple since corrections are done simultaneously with every beam change in the communication signal that is detected in the imaging sensor. The mathematical results show that the system is capable to provide gigabit speeds at very low power consumption. The receiver apertures can be in the order of a millimeter, which allows their integration in all portable devices. The main drawback remains the complexity due to the localization and tracking systems, especially in the mobile side.

The main accent in the presented hybrid configuration is to shift all the complexity to the ceiling module allowing it to operate at high data rates (10Gbps) and lower power consumption because of the directed downlink. A novel localization system based on imaging sensor and corner reflector with passive mobile device side has been presented and its capabilities- discussed. One of the main conclusions in this work is the possibility to combine the localization system together with the uplink receiver in a single module and deploy these modules on the ceiling forming grid. The simple non-directed uplink provides 1Gbps link with relatively low power consumption, especially when compared to RF solutions. Furthermore, the uplink design requires no optical amplifier and allows flexible choice of the wavelengths in the wireless part.

At the end of the thesis a critical analysis of the work and proposals for system enhancement for multiple users and multiple transmitters have been presented.

CHAPTER 1

INTRODUCTION

In the last decades the telecommunication technology has become a big and important part of our daily life. New portable devices with higher and higher technical specifications, such as smart phones and tablets, providing ease of use and full functionality at any place and any time have been constantly introduced to the market. The rapidly increasing number of users and the growing market of applications lead to an "explosion" of contents and create a constant demand for wider bandwidth. The deployment of fiber networks for different purposes from inter-continental connections to custom local networks and technologies like fiber to the home has significantly eased the bandwidth problems for the carriers and internet providers. Optical communications have many advantages compared to the electrical ones, namely small attenuation, high security and wide bandwidth. However, there are some areas, in which fiber networks are not applicable due to high price or convenience and radio frequency (RF) wireless technologies are implemented so far (e.g. big river crossing, building to building communication, last mile problem, etc.). Unfortunately, such RF technology cannot provide enough bandwidth, compared to the fiber one, and its usage forms a bottle neck in the network. Therefore, in the last decades many researches have been concentrating their studies on optical wireless communications (OWC) for both outdoor and indoor applications to remove the RF bandwidth limitations and allow big data transmission [1]. Of special interest are the new generation systems, based on direct fiber coupling that allow the deployment of all-optical networks with no electro-optical or optic-electrical conversion, which also normally forms a bottle neck for the network [2].

There are big challenges for the outdoor OWC due to the specifics of the transmission media. First, the attenuation in the atmospheric path can change in very wide intervals according to the weather. In sunny weather with high visibility the attenuation is extremely low but when rain, snow or fog are present the attenuation increases drastically and can lead to link disconnect. Also, when the transmitted optical beam propagates through the atmosphere, it is affected by the refractive-index random variations, caused by inhomogeneities in the air [3].This could lead to signal fluctuations that can result in a burst error or even temporal unavailability of the free-space optical (FSO) link, which defines the low bit-error rate (BER) in on-off keying (OOK) modulation based systems as another big challenge. The most popular methods for atmospheric effects mitigation are signal modulation or combination of modulation and improved transmission and reception technologies [4-6]. To increase the received power and to soften some of the atmospheric effects, tracking systems are also widely used [7]. Outdoor FSO links are mainly used for point-to-point communication which limits their use to carrier's networks and they cannot be used for user access networking. There are some commercially available FSO systems, but they cannot guarantee the reliability required to become a part of the backbone links and completely substitute the fiber when necessary.

From practical point of view, it is important to consider the end user behavior regarding the time and place he or she needs broadband access. From the telecommunication provider networks we can observe that there are a limited number of users in the rural areas and basically with a single base station a several kilometer area can be covered. Respectively, the bandwidth requirements of such small number of users can be covered with current RF technologies. However, in the city areas especially in the busy areas the base stations are separated from each other on hundred meters and still cannot provide enough bandwidth. Furthermore, it is unlikely for the user to use a broadband access outdoors when moving. The places with high probability for users to require fast internet connection remain indoor spaces. Nowadays, RF technologies are still able to provide network access for personal area networks (PAN), but for public places, such as offices, libraries, conference halls, trains, etc. the insufficient bandwidth has already become a serious issue. Indoor OWC are considered a very good potential alternative to RF technologies to provide broadband wireless connection in indoor spaces. The main purpose of this research is to explore the OWC systems current issues and provide a solution that can push the OWC from potential to actual alternative that can provide sufficient broadband network access to multiple users in indoor spaces.

1.1 Indoor optical wireless communications (OWC)

Constantly new mobile technologies as Worldwide Interoperability for Microwave Access (WiMAX) [8] and Long Term Evolution (LTE) - Advanced (formally submitted as a candidate 4G system to ITU-T and finalized by 3GPP in March 2011) [9] are developed but their speed is unable to support a large number of users, concentrated in one place. New modulation and encoding schemes are developed for RF to meet the user demands but the limited bandwidth will sooner or later lead to exhaustion in new RF technologies. Furthermore, in the license-free spectrum more often RF conflicts occur (widely used Wi-Fi networks [10]). Considering the above issues indoor optical OWC have become a very attractive alternative. They operate in the gigahertz spectrum and offer significantly wide bandwidths at frequencies that are not subject to license. Optical waves cannot propagate through walls which can be considered as drawback opposed to RF waves. However, that also increases the network security since the network cannot be used outside the closed indoor space and if a third party attempts to intercept the signal that will basically lead to link disconnect. Another important feature of the OWC is their low power consumption. Telecommunication equipment is one of the biggest power consumers in worldwide scale. Furthermore, with the vast popularity of mobile devices in the last decade and introduction of new portable devices such as Smartphone and tablet with very high computing capability and wider and wider coverage of telecommunication service companies the mobile users that require broadband connection drastically increases. Networks alone are big power consumers but in close future the millions or even billions of new smart devices will increase the power needs further. The new telecommunication technologies should not only provide high speeds, sufficient for the consumer needs but also must provide very high energy efficiency. Last but not least, OWC networks operate in a different part of the RF spectrum that makes them immune to electromagnetic interference. Important difference between OWC and RF is the spatial diversity that allows several different optical links to operate on the same place without actually interfering with each other.

There are two distinguishable brands of optical communications – visible light communications (VLC), [11], and infrared (IR) laser communications [12]. VLC, also referred to as Li-Fi, relies on exchanging current light sources with light emitting diodes

(LED) and modulates their intensity in order to build a communication line. The main advantage of VLC is the double function of the current lighting system that will be used not solely for lighting but also for network access, broadcasting, localization, etc. However, there are several serious issues that limit such systems performance. First, this type of network relies on power line communication to connect the light with actual backbone network. Power line communication can become a bottle neck between the fast backbone network and possible future gigabit VLC links. Another important issue is the light source itself – LED. The LED used for lighting is white. There are two main technologies to produce white light- by mixing the light from three different small LED – red, green and blue and blue LED with phosphor cover [13]. If such diodes are to be used for communication the synchronization of these three components will be the biggest issue since smaller changes will result in different light and that would have effect on people. The other technology is a blue LED with phosphor cover, which also results in white light. However, the phosphor leads to very long rising times which severely limit the bandwidth that can be used. Lately, organic light emitting diodes (OLED) have become a hot topic among the VLC researchers [14-16]. Currently, their practical efficiency is much lower than the LED and the theoretically anticipated one and they are not applicable for lighting systems. Furthermore, OLED can have very big size and form that means their junction capacitance is very high, which also limits the bandwidth of the system. Another important issue with the VLC technology is that it provides connectivity only when the light is on, which means such network is not applicable in all possible cases. Also, users do not like to have a strong light in their eyes when they look at the portable device, which assumes to use a different technology for the uplink and use VLC only for downlink. Important issue in these networks is that they operate in the visible light spectrum, which means that most of the ambient noise in this spectrum is hard to be filtered. Also, the transmitted power limits are much lower compared to the IR communications because of the effects that excessive power levels on this wavelengths can have on human eye.

Communications, based on infrared laser diodes are more expensive and complex since they do not use the current lighting system. However, they can offer much higher data rates and full time system operation regardless of the room lighting. It is possible to connect the fiber directly to the wireless link that removes the electro-optical and optic-electrical conversion which is considered a bottleneck in the network. Furthermore, the ambient noise, which is critical for this type of communications, is much weaker in the infrared spectrum compared with the visible one and the communication signal can be easily separated from the noise by using optical filters. Also, the power limitations due to eye safety are much higher for wavelengths in the range of 1550nm. Higher power allows higher data-rate transmission and bigger coverage compared to the VLC links.

Of particular importance for IR OWC to become a widely used technology in commercial applications [17-21] is to allow wireless connection to a backbone cabled local area network (LAN) using the IEEE 802.11 standards without the need of changing the LAN protocols. Some commercial products that operate on Ethernet and Token ring networks were available two decades ago [22]. There has been also a research on using IR signal to transfer signals with IEEE 488 and RS-232/RS-423/RS-422 format [23-24]. IR is widely used for low cost consumer appliances such as remote controls, transmission of high quality audio signals to small portable devices [25-26] or theater stereo speakers [27-28].

One of the most successful implementations of IR technology for data communication is the Infrared Data Association (IrDA). This technology that provides interoperable, low cost, low-power, half-duplex, serial data connection has been used for two decades and even today it is available in most of the mobile devices. Its data rates increase with the network development and nowadays gigabit communication is possible. The main drawback of this technology remains to be the short operating distance and the need of directing of the devices that prevents it to be preferred in front of Wi-Fi networks.

Recently, many researches work towards an IR network that can become a part of the Ethernet network and provide the high data rates, available in the fiber networks with the mobility that RF links allow.

The research in this thesis goes one step further by considering seamless connection between the fiber network and the indoor open space and direct implementation in Ethernet over passive optical network (EPON) networks. Such solution, as shown later, could eliminate most of the problems in the conventional OWC systems because of the usage of laser diode at fiber-communication wavelengths. However, the optical source in this case is not a diode with typical Lambertian distribution but the fiber end that has Gaussian distribution. That requires a new indoor propagation model and transmission analysis for all configurations so that precise performance evaluation can be achieved. Since the main accent is on the transmission analysis and link performance, for simplicity a single user network is considered. In future research, based on the collected data, the configuration with best performance can be chosen and multi-user network considered.

1.2 Main research contribution

The main goal of this research is to build analytical model for indoor propagation of an IR Gaussian beam. By using the presented model here several custom designs with line-of-sight (LOS) configurations have been proposed and their performance evaluated.

So far, in indoor OWC links only Lambertian distribution has been considered [29-30], since no direct fiber coupling technology is used. For first time in the indoor OWC the Gaussian beam propagation was considered. The first primary research contribution presented in this thesis is a complete transmission analysis for a Gaussian beam for both LOS and non-LOS configurations and an approximation for the relationship between the whole optical power in a wide beam spot in the communication plane and the received power in a very small receiver aperture in it has been presented. This analysis has been used as base in the calculations for OWC system capabilities. There are many papers, showing experimental results of similar systems with seamless connection between the fiber and the air [31]. However, these works are based only on experimental setup and they lack mathematical model. Comparison between the presented analytical model and such experimental setups shows their design flaws, for example huge receiver aperture, and defines such setups as not practical solutions for future indoor OWC (the receiver aperture is not mentioned, but the analysis showed that its size in the considered experiment is huge, which was confirmed later in discussion with the paper authors). In other experimental setups the results cannot be considered correct because ambient noise power was considered in a horizontal direction, because of the link setup. However, in horizontal direction the ambient noise values are much lower because the main shot noise is from reflections, compared to a practical solution when the receiver aperture is pointed vertically and the light from sunlight or lighting system is direct.

The second important contribution is the indoor Gaussian beam propagation model for an RF signal, which is sent directly in the indoor open space from radio-over-fiber (RoF) based fiber, similar to radio-over-FSO (RoFSO) networks. However, in the RoFSO networks the communication is often point-to-point and main issue are the atmospheric effects. In the indoor network the communication is often point-to-multipoint and main problems are the ambient light noise and the multipath distortion due to reflections from different surfaces. Mathematical model for the indoor transmission of orthogonal frequency division multiplexing (OFDM) based services has been described and example with integrated services digital broadcasting international (ISDB-T) television (TV) transmission considered [32].

Based on the theoretical model, discussed above, the performance of several custom LOS configurations has been evaluated. The first work, combining OOK signal and OFDM signal in a non-directed indoor OWC is presented because of its simplicity, compared to the directed ones. The system is based on EPON standard where simple wavelength division multiplexing (WDM) can be used, combining both gigabit internet access and ISDB-T TV broadcasting. The design presented in this thesis is the latest improvement with implemented transimpedance amplifier (TIA) and more thorough noise analysis including amplified spontaneous emission (ASE) noise and relative intensity noise (RIN) that has serious effect on the OFDM signal. Other important issues, such as multiple ceiling receivers for the uplink and synchronization of the neighbor transceivers due to overlapping have been examined.

So far, for point-to-multipoint indoor access network only non-directed configuration has been considered due to its wide field of view (FOV) and broadcasting principle. The next contribution is consideration of directed and hybrid configurations for multiuser network access. An indoor OWC system with directed configuration for mobile devices high speed access, based on direct fiber coupling technology, has been presented. In directed configuration the establishing and maintaining of the link is considered to be a very sophisticated matter because of the need of tracking system. In this work novel complete scheme of scanning and tracking systems have been presented. The tracking system is based on micro electro mechanical systems (MEMS) mirror that can be used not only to track a mobile device, but also to switch between multiple users is time-division multiplexing (TDM) is implemented. The link is compatible with EPON standard which simplifies its integration in the currently available networks without the need of new standards and protocols. The scanning system uses the EPON discovery time window and its sequence to establish the link. Tracking system has very high response because it uses the communication signal (1Gbps) to correct any position changes. Using the propagation model above mathematical analysis of the BER shows the low power consumption in the system. The complex tracking system in the mobile device side has provoked further interest for better uplink solution. That leads to the third design, presented in this thesis of a hybrid network with high speed directed downlink (10Gbps) and an uplink with diverged beam and a grid of multiple ceiling transceivers has been proposed. Furthermore, a novel localization technique that does not require transmit power from the mobile side was introduced and its performance has been evaluated. Again, full mathematical analysis of the system performance has been conducted.

1.3 Organization of the thesis

This thesis has been organized in 5 chapters detailing the theory of indoor OWC with analytical models and several link designs with their full transmission analysis.

In Chapter 2 a conventional indoor OWC system and the new generation system with direct fiber coupling technology are explained and compared. The main focus is on the ambient noise sources, which optical and electrical modulation spectrum are shown and the main methods for their mitigation are discussed. Since the proposed links use laser diode (LD) as an optical source of particular importance are the transmit power limitations due to the eye safety regulations. The maximum permitted emission (MPE), accessible emission limit (AEL) and nominal hazard zone (NHZ) have been discussed for a diverged beam and figures with example configurations are shown. A novel mathematical model for indoor Gaussian beam propagation is introduced for both diffusion and LOS systems. For diffusion systems the model is quite similar to the one for Lambertian distribution but the Gaussian source strongly affects the end signal. Regarding the LOS systems, the most important issue is to define the received power in a small receiving aperture in the communication plane, where the diverged Gaussian beam forms a wide beam spot. Simple approximation method is introduced and is used in all the models, when the ratio between total optical beam power and received power is considered. Both diffusive and LOS systems advantages and disadvantages are discussed and the decision to evaluate only LOS performance is explained. Furthermore, the three LOS configurations – directed, non-directed and hybrid are introduced with simple comparison of their performance to settle preliminary performance expectations for the analysis results.

In Chapter 3 thorough transmission analysis for non-directed LOS configuration is presented considering the link budget and the main noise components, such as ASE noise, ambient light noise and thermal noise in the receiver. For the case of indoor optical transmission of RF signals, particularly OFDM-based services, such as ISDB-T TV transmission, where even small signal fluctuations can strongly affect the system performance, the RIN noise of the transmitter is also considered.

In Chapter 4 a directed LOS network, based on EPON standard with localization and tracking of the mobile device (tablet, notebook, etc.) is discussed. The tracking and localization is based on MEMS mirror and imaging sensors in both ceiling module and mobile device. Simple system performance is also presented. Furthermore, in Chapter 4 a hybrid network with 10Gbps directed downlink and 1Gbps uplink is presented. Novel localization system with very simple and passive mobile side is proposed and discussed in detail. Furthermore, the performance of a novel non-directed uplink with a grid of multiple ceiling receivers is described. The non-directed system requires higher transmit power than the directed one. In the simulation analysis is shown that event these higher power levels normally do not exceed the eye safety allowed AEL and is much lower than RF networks with similar capabilities. It is important to note that so far directed and hybrid configurations have been considered for point-to-point communication only excluding the possibility for multiple user connection. In this research I present tracking systems that not only support mobile users but also by implementing TDM they allow point-to-multipoint and multipoint-to-multipoint communications.

In Chapter 5 I provide a critical analysis of the work, presented in this thesis. The main issues of the presented configurations are discussed and possible solutions for improved system performance have been presented. Also, so far the main work was concentrated on the link transmission analysis and actual network with multiple users has not been considered. In this chapter the cases with multiple users and transmitters for directed and hybrid configurations have been discussed.

Finally, Chapter 6 provides the concluding remarks of this thesis work. All the results are discussed and future research work is outlined.

CHAPTER 2

INDOOR OPTICAL WIRELESS COMMUNICATION SYSTEMS

2.1 Introduction

With the wide spreading of the fiber-to-the-home (FTTH) technology practically the high-speed network access is available to every indoor space. Due to the high cost and time consumption of reconfiguring and maintaining of wired systems for clustered computers in offices, education institutions, libraries and so on, wireless technologies are often preferred. Furthermore, with the growing market of portable devices such as smart phones and tablets and different applications for them the need of high speed network access increases rapidly. The widely used RF technologies today cannot provide the necessary speed between the end user and the high speed fiber network and turn into bottle neck especially in places with high user density (Fig. 2-1). Because of the license restrictions in the RF spectrum, all the networks use the license-free spectrums around 2.4GHz and 5.7GHz. This is the reason for often conflicts between neighboring networks due to their big coverage out of the indoor boundaries and raises security issues. Last but not least, telecommunication equipment is one of the main power consumers in worlds scale and power efficient networks are top priority for future development.

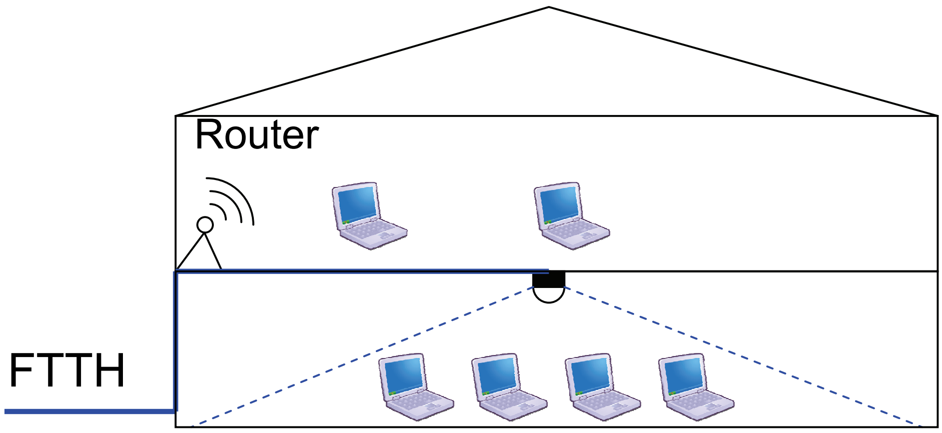


Figure 2-1: Indoor wireless network examples for RF and optical links [33]

Considering the above issues, indoor optical wireless systems are good alternative that can provide high speed and high security with much lower power consumption. The comparison between RF and IR communication technologies is shown in Table 2.1.

Table 2.1: Comparison of RF and IR properties for indoor wireless communication

	Radio	Infrared
FCC/RSA regulation	Yes	No
Security	Possible	High
RF interference	Yes	No
Technology cost	Variable	Potentially low
Main noise source	Other user interference	Ambient light
Coverage	Medium	Low
Mobility	Yes	Some configurations
Bandwidth limitation	Regulatory	Photodetector/preamplifier, diffuse channel
Multipath dispersion	Yes	Some configurations
Multipath fading	Yes	No
Path loss	High	High

There are two different technologies – VLC and IR laser communication (Fig. 2-2). The VLC technology relies on future change of the incandescent and fluorescent lights with much more power efficient LED. Its main idea is to provide a dual function of the lighting system by providing connectivity. By intensity modulation of the LED communication can be established. There are several issues regarding this technology. First, to be able to send communication signal to each LED array either power line communication (PLC) [34-35] or VLC communication between light sources is necessary. Both will limit the maximum bit rate in the network. Another issue is the LED intensity modulation limit. Furthermore, VLC communication is affected much stronger by the ambient light noise compared to IR one, as explained later in this chapter, but the transmit power for visible light is much smaller than the permitted for IR due to eye safety limitations [36-37]. IR communications provide high speed and with feasible connection between fiber and open space fiber network speeds can be reached in the wireless network.

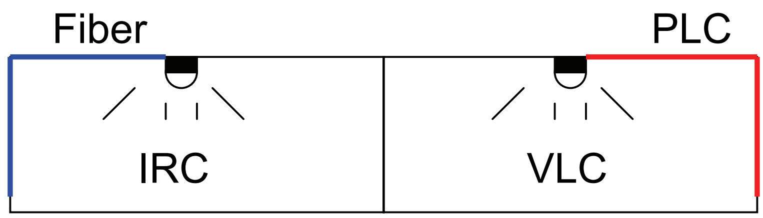


Figure 2-2: Indoor OWC technologies – VLC and IRC

2.2 IR OWC systems

The conventional IR OWC downlink is shown on Fig. 2-3a. The optical signal from the backbone is converted to an electrical one in the local network. Such OWC uses intensity modulated direct detection (IM/DD). The optical source is an IR diode or LD with wavelength typically in the range of 800-1000nm. Such optical sources are described with the Lambertian law, according to which the angular distribution of the emitter radiant intensity $E(\theta)$ is [38, 39], Fig. 2-4:

$$E(\theta) = P_{out} \frac{n_a + 1}{2\pi} \cos^{n_a}(\theta_{Lambertian}) \tag{2.1}$$

Where P_{out} represents the total emitted power and $\theta_{Lambertian}$ is the angle from the normal to the emitting surface. The angular spread of the beam is defined by n_a.

The main problems in such system are the limited speed due to the E/O conversion and the strong ambient noise. Another issue for the laser-based systems is the eye safety limitations for the transmitted optical power. I address these problems by proposing a new generation indoor OWC link, based on seamless connection between the fiber and indoor open space (Fig. 2-3b). Such system should be able to provide the same bit rate as the fiber communications and will be independent on the signal modulation allowing wireless transmission of radio signals, coming from RoF technology. Important feature of the new signal is that the laser source is actually the fiber end and the beam is not Lambertian but rather Gaussian. In this Chapter first, a performance comparison between the proposed system and the conventional one is presented and then a complete indoor propagation model for Gaussian beam is derived.

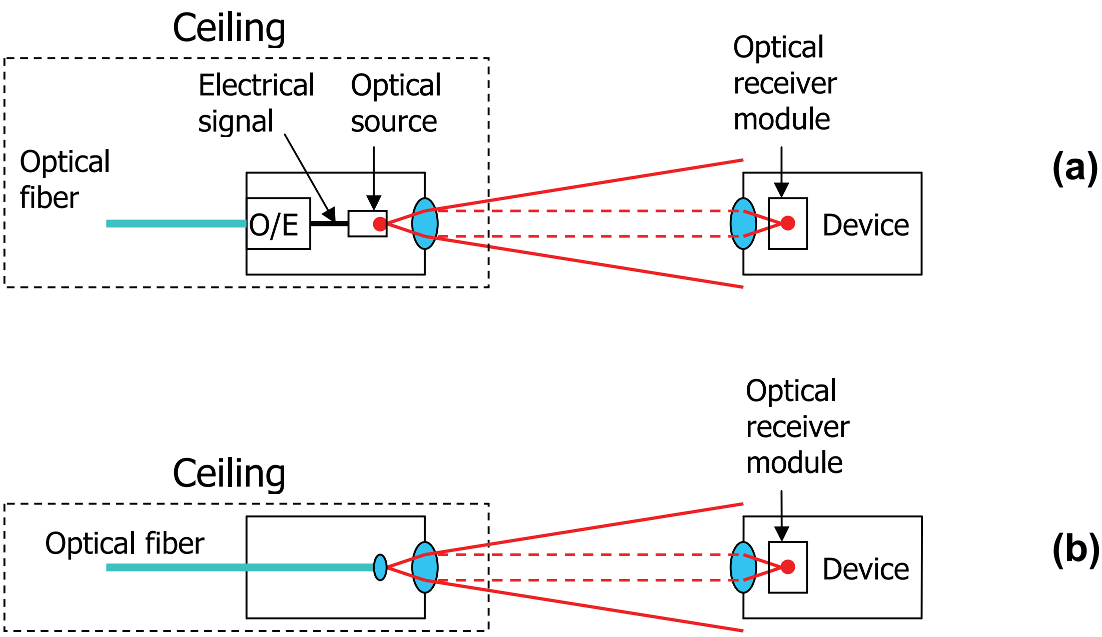


Figure 2-3: Indoor IR OWC downlink: a) conventional system; b) proposed system;

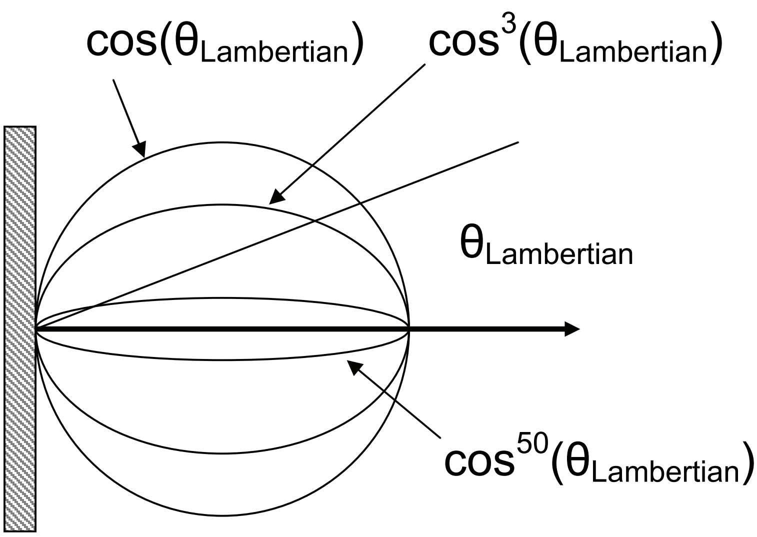


Figure 2-4: Angular distribution of the emitter radiant intensity for Lambertian source

2.3 Ambient light noise

In both systems the signal is transmitted in to the open space and is received in the receiver aperture together with the ambient noise. Most common ambient noise sources in an indoor environment are tungsten lights, fluorescent lights, IR devices and daylight

[40-42]. Fig. 2-5 shows the optical spectral power densities of these light sources. Fluorescent light has just a small amount of IR radiation, but daylight and incandescent light present a higher amount. Tungsten is the worst source. Fluorescent light has a low power density at the wavelengths used by PD. Daylight may be a problem when terminals operate near windows. It can be suppressed by using a narrowband optical filter before the photodetector that allows just the IR frequencies used by the transmitter to hit the detector [43-44]. These kinds of filters, however, have a narrow FOV that limits their usage possibilities. The effect of the three sources of light can be considerably reduced by restricting the FOV of the receiver and by using optical filters before detection of the photodiode. As can be observed in Fig. 2-5, the ambient noise levels for the wavelengths, used by the conventional system are much higher than the ones for fiber communications wavelengths, used in the proposed new generation system.

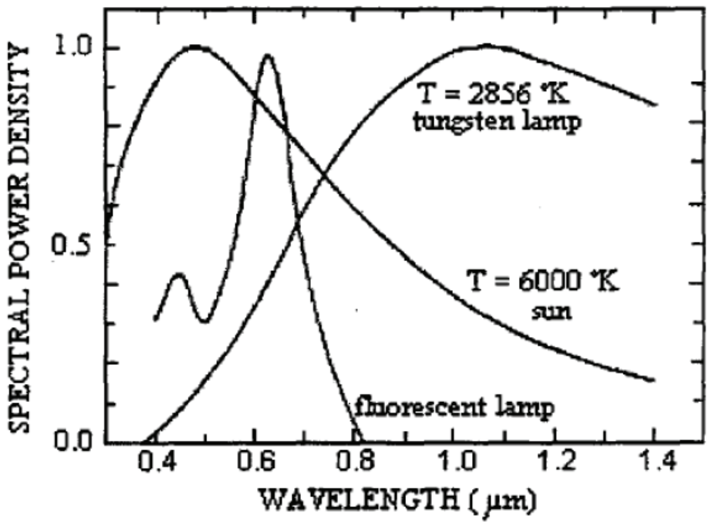
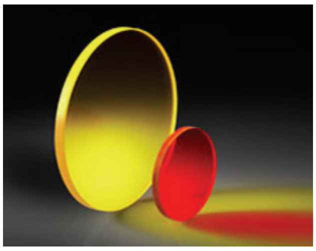
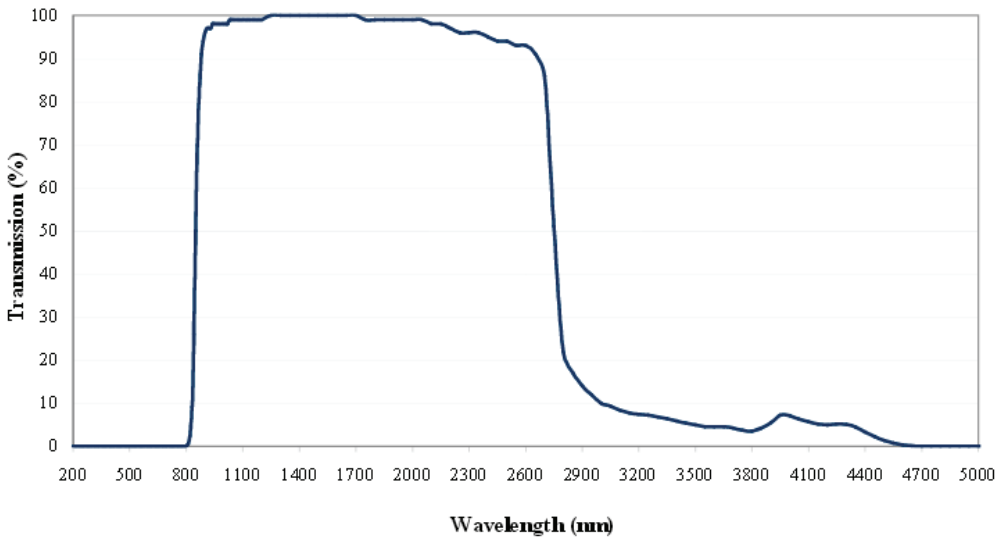


Figure 2-5: Spectral power densities of three ambient light sources [42]

The IR receivers typically have either long pass or band pass optical filters to attenuate ambient light. Long pass filters can be thought of as essentially passing light at all wavelengths beyond the cutoff wavelength. Usually, they are constructed of colored glass or plastic, so that their transmission characteristics are actually independent of the angle of incidence. A common long pass filter and its transmission are shown on Fig. 2-6, [45]. Long pass filters are used in almost all present commercial IR systems.



(a)



(b)

Figure 2-6: Long pass filter transmission [45]

Band pass filters are constructed of multiple thin dielectric layers, and rely upon the phenomenon of optical interference. These filters can achieve narrow bandwidths, leading to superior ambient light rejection (filters with bandwidths under 1 nm are available on the market). In order to maximize the signal-to-noise ratio (SNR), however, the transmitter optical spectrum must lie within the filter bandwidth, implying that when the filter bandwidth is made small, LD transmitters need to be used. Such a filter must be implemented carefully if the receiver is intended to achieve a wide FOV. Furthermore, the band pass filters are more expensive than long pass filters and are good for WDM applications but currently not preferred for OWC links.

Long pass filters are the most commonly used in commercial infrared systems, as their transmission characteristics are greatly independent of the angle of incidence. Basically, these kinds of filters restrict the passage of light before the cutoff frequency, and, when combined with silicon photodiode, perform jointly as a band pass filter. As this type of filter greatly depends on the receiver incident angle, it must be used with an adequate concentrator to be suitable for diffuse systems. Band pass filters are constructed of superposed dielectric slabs, and can achieve narrow optical bandwidths.

Apart from the optical spectrum of the noise sources it is important to consider the electrical modulation spectrum (EMS). In [40] the EMS for most common lighting sources has been experimentally derived.

Tungsten filament lights are the most common lighting sources nowadays. Being banned from Europe and fast replaced by the cheap, power saving, long-lasting LED bulbs in future they will no longer be an issue for the OWC. However, they are still widely spread and their effect on OWC systems must be considered. Their optical spectrum is shown on Fig. 2-5. It can be noticed that they will strongly affect optical wireless communications especially in the IR spectrum. Optical filters cannot provide effective protection against them. On Fig. 2-7 is shown their EMS. It can be noticed that the spectrum consists of very low frequencies, compared to the ones used for optical communication. Thus it is easy to filter this noise by using an electrical filter.

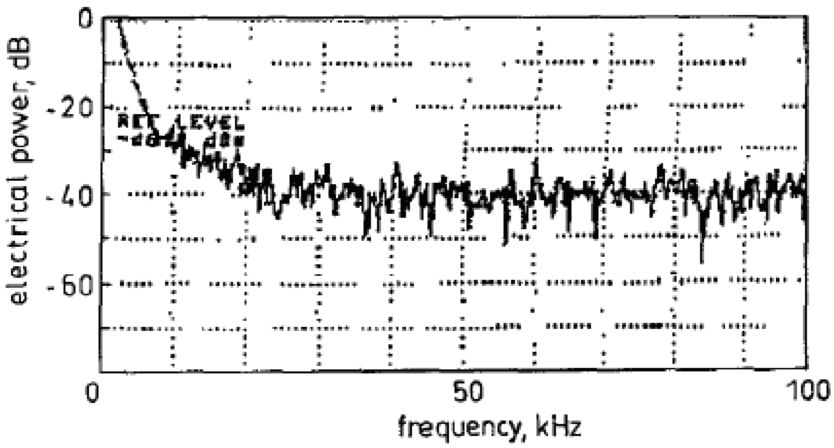
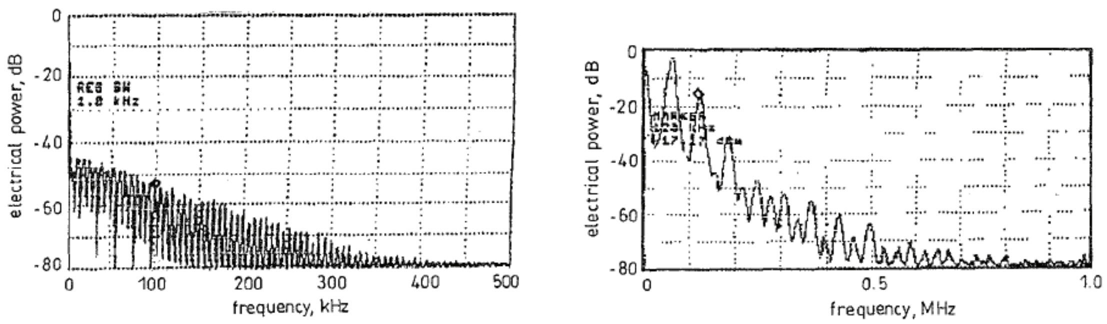


Figure 2-7: Electrical modulation spectrum of tungsten filament lights [40]



(a) **(b)**

Figure 2-8: Electrical modulation spectrum of: (a) low frequency fluorescent lights; (b) high-frequency fluorescent lights [40]

The optical noise from fluorescent lights can be significantly reduced by using optical filter. On Fig. 2-8 is shown the EMS of both low-frequency and high-frequency fluorescent lights. These frequencies are much higher but can still be filtered on electronic level.

Strongest ambient noise will come from interference with other IR appliances, since their signal cannot be filtered with optical filter and their EMS will consist of very high frequencies.

2.4 Optical receiver

A part of the transmitted optical power will reach the receiver aperture. In an optical wireless receiver, the dominant source of shot noise in the detector arises from the ambient light levels in the environment, and the use of optical filters in many applications is required.

To be able to catch as much of the signal as possible photodiodes with large areas are required. However, such photodiodes will have high capacitance that will limit the bandwidth of the receiver. One of the widely used methods to collect maximum optical power and bring it to a small size photodiode is to use optical concentrators. Concentrators may be of the imaging or nonimaging. The telescopes used in long-range, free-space optical links represent examples of imaging concentrators. Most short-range infrared links use nonimaging concentrators.

The hemispherical lens is an important nonimaging concentrator [46-48], and is widely used in commercial infrared systems nowadays (see Fig. 2-9(a) and (b)). It achieves a wide FOV and omnidirectional gain, making it suitable for use in non-directed links. When long pass filtering is employed, a planar long pass filter can be placed between the hemisphere and the detector, as shown in Fig. 2-9(a). When band pass filtering is utilized, it is not desirable to employ a planar filter in the configuration shown in Fig. 2-9(a). As the angle from which rays are received, shifts, so does the angle at which light strikes the filter. This shifts the filter pass band. Instead, as shown in Fig. 2-9(b), the band pass filter should be deposited or bonded onto the outer surface of the hemispherical concentrator [47-48]. Regardless of the angle from which the signal is received, rays that reach the detector are incident upon the filter at small values of the angle, minimizing the shift of the filter pass band, and maximizing its transmission. Thus with a hemispherical filter, it is possible to simultaneously obtain a narrow bandwidth and wide FOV.

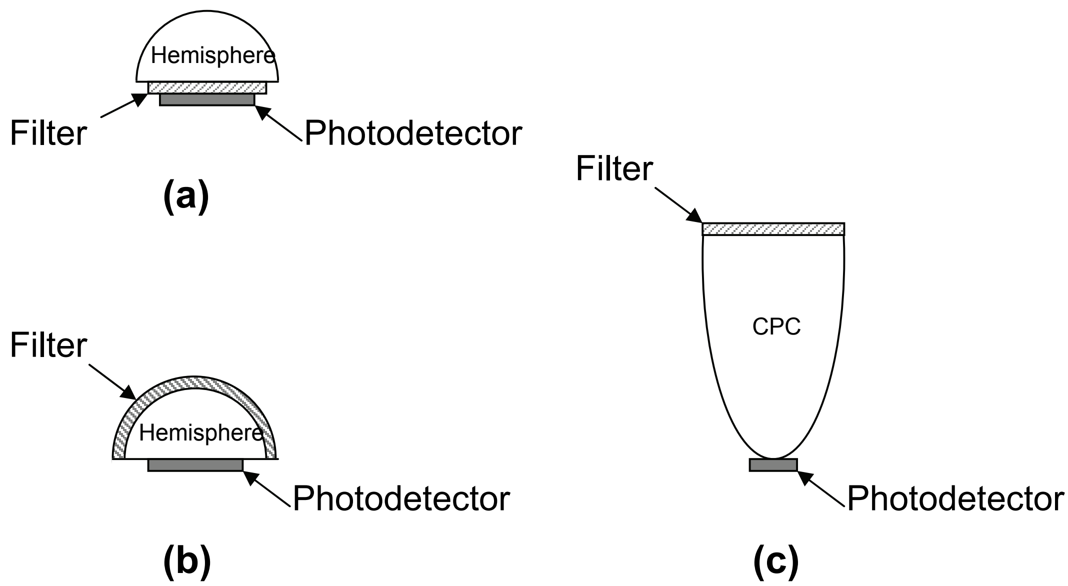


Figure 2-9: Nonimaging optical concentrators: (a) hemisphere with planar optical filter, (b) hemisphere with hemispherical optical filter, (c) CPC with planar optical filter

The compound parabolic concentrator (CPC) [49] is another nonimaging concentrator that is widely used in infrared links [50]. It can achieve much higher gain than the hemisphere, but at the expense of a narrower FOV, making it very good choice for directed links. As shown in Fig. 2-9(c), a long pass or band pass filter can be placed on the front surface of the CPC.

There are several important characteristics of the photodiode (PD) that strongly affect the OWC performance. The quantum efficiency η is the number of the electron–hole carrier pairs generated per incident–absorbed photon of energy hν and is given by:

$$\eta = \frac{I_s / q}{P_{Ar} / h\nu} \tag{2.2}$$

I_s is the photocurrent generated by a steady-state optical power P_{Ar} incident on the photodetector, q is the electron charge and hν is the Plank constant.

In a PD, responsivity measures the electrical output per optical input and is given by [51]:

$$\rho_{RX} = \frac{\eta q}{h\nu} \tag{2.3}$$

The equation (2.3) is valid for p-i-n photo diode (PIN-PD). Avalanche photodiodes (APD) have an internal gain M_{APD}.

$$\rho_{APD} = \rho_{RX} M_{APD} \tag{2.4}$$

The responsivity of the PD is different for different wavelengths and depends from the semiconductor, used to create the PD as shown on Fig. 2-10. It is important to choose a PD that can detect the transmitted optical signal from the laser diode and combine with optical filters accordingly. A closer look in Fig. 2-10 shows that the typical PD for conventional systems with wavelengths 800nm to 1000nm is the silicon one which has responsivity under 0.6A/W. In comparison, the fiber communication wavelengths 1310nm and 1550nm require InGaAs PD which is more expensive, but has responsivity around 0.9A/W. Therefore, the proposed system will have much higher efficiency than the conventional ones.

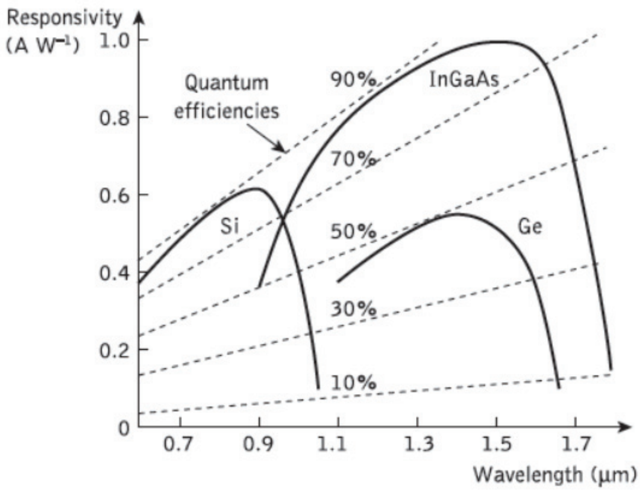


Figure 2-10: Responsivity of different photodiodes [52]

Junction capacitance (C_j) is another important characteristic of the photodiode as this can have a significant effect on the photodiode's bandwidth and response. It should be noted that larger diode areas encompass a greater junction volume with increased charge capacity. In a reverse bias application, the depletion width of the junction is increased, thus effectively reducing the junction capacitance and increasing the response speed. A load resistor will react with the photodetector junction capacitance to limit the bandwidth. For best frequency response, a 50 Ω terminator should be used in conjunction with a 50 Ω coaxial cable. The bandwidth (f_{BW}) and the rise time response (t_r) can be approximated using the junction capacitance (C_j) and the load resistance (R_{LOAD}) [51].

$$f_{BW} = \frac{1}{2\pi R_{load} C_j}$$
$$t_r = \frac{0.35}{f_{BW}} \tag{2.5}$$

2.5 Eye Safety

The high level of ambient noise and big angle of divergence of the beam increase the demands of higher transmit optical power in order to achieve sufficient SNR. Since some of the conventional systems and the proposed one use LD and will be used in close contact with people for long time (several hours) it is important to consider the effect on the human body and guarantee that it is not dangerous. Of special concern in such IR networks is the fact that lasers are used for communication. The skin is much less sensitive than the eye and therefore if a system is eye safe it is safe for the human body generally. Laser effect on human eyes changes with the laser wavelength. The eye focuses visible and near-infrared light onto the retina. A laser beam can be focused to intensity on the retina which may be up to 200,000 times higher than at the point where the laser beam enters the eye. Most of the light is absorbed by melanin pigments in the pigment epithelium just behind the photoreceptors, and causes burns in the retina. Ultraviolet light with wavelengths shorter than 400 nm tends to be absorbed by lens and 300 nm in the cornea, where it can produce injuries at relatively low powers due to photochemical damage. Infrared light mainly causes thermal damage to the retina at near-infrared wavelengths and to more frontal parts of the eye at longer wavelengths. The table below summarizes the various medical conditions caused by lasers at different wavelengths, not including injuries due to pulsed lasers.

Table 2.2: Medical conditions caused by lasers at different wavelengths

Wavelength	Pathological effect
180 - 315nm	photokeratitis (inflammation of the cornea, equivalent to sunburn)
315 - 400nm	photochemical cataract (clouding of the eye lens)
400 - 780nm	photochemical damage to the retina, retinal burn
780 - 1400nm	cataract, retinal burn
1.4 - 3μm	aqueous flare (protein in the aqueous humour), cataract, corneal burn
3μm - 1mm	corneal burn

When a high intensity laser light from the visible spectrum enters the eye, the normal protection is blinking which will decrease the laser effect and will warn the human to avoid direct looking in the laser beam. IR lasers are very dangerous because a human cannot see them and there is no blinking. Therefore, it is necessary to obey the eye safety laser restrictions as defined by standard ANSI Z 136.1 and IEC 60825-12 [36-37].

Lasers have been classified by wavelength and maximum output power into four classes and a few subclasses. A Class 1 laser is safe under all conditions of normal use. This means the MPE cannot be exceeded when viewing a laser with the naked eye or with the aid of typical magnifying optics (e.g. telescope or microscope). A Class 1M laser is safe for all conditions of use except when passed through magnifying optics such as microscopes and telescopes. Class 1M lasers produce large-diameter beams, or beams that are divergent. The MPE for a Class 1M laser cannot normally be exceeded unless focusing or imaging optics are used to narrow the beam. A Class 2 laser is safe because the blink reflex will limit the exposure to no more than 0.25 seconds. It only applies to visible-light lasers (400–700 nm). A Class 2M laser is safe because of the blink reflex if not viewed through optical instruments. A Class 3R laser is considered safe if handled carefully, with restricted beam viewing. With a class 3R laser, the MPE can be exceeded, but with a low risk of injury. A Class 3B laser is hazardous if the eye is exposed directly, but diffuse reflections such as those from paper or other matter surfaces are not harmful. Class 4 is the highest and most dangerous class of laser, including all lasers that exceed the Class 3B AEL. By definition, a class 4 laser can burn the skin, or cause devastating and permanent eye damage as a result of direct, diffuse or indirect beam viewing. Since the indoor OWC will operate in close contact to people for long intervals of time and human eye has no protection to IR spectrum it is essential that the system adheres to Class 1 laser type and be safe under all normal conditions.

There are two parameters that have to be considered – AEL, which defines the maximum total power of radiation that can be emitted from a laser of a particular class, and MPE, which is the minimum irradiance or radiant exposure that may be incident upon the eye without causing biological damage. The MPE is related to AEL by the limiting aperture of the eye, which is itself a function of wavelength and exposure time. For 1550nm laser in the MPE tables it can be found that for eight-hour exposure ($3x10^4$s) the Class 1 MPE is $1000Wm^{-2}$ and the limiting eye aperture diameter is 3.5mm or $S(A_r)=9.61mm^2$. Following the formula for collimated laser beam

$$AEL_N = A_r MPE, \tag{2.6}$$

The well known AEL_N for 1550nm narrow laser beam of 10mW (9.61mW) is received. In most indoor OWC systems though, the beam is not collimated but, on the contrary, it is significantly diverged. Also in indoor OWC NHZ can be introduced. The NHZ relates to the space within which the level of direct, reflected, or scattered radiation during normal operation exceeds the appropriate MPE. For example, in normal conditions, the downlink transmit modules of the OWC will be mounted on the ceiling and under normal conditions human eye will not be closer to the transmitter than a certain distance (ceiling is higher than the human height). That would allow to define a NHZ in which the diverged beam is not Class 1, but Class 1M and allow higher level of transmit power. Class 1M laser is not dangerous for the naked eye which will eliminate possible accidental direct look from close distance from user but will require proper eye safety equipment during maintenance. The relation between NHZ and AEL of diverged beam for a fixed MPE for Class 1 laser systems will be shown below.

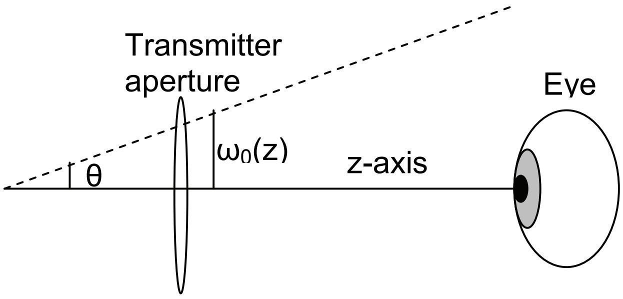


Figure 2-11: Maximum received power into the eye

The maximum power that can enter in the eye for fixed angle of divergence θ is on the z-axis and will be (Fig. 2-11, the power contained within a radius R_r in a Gaussian beam):

$$P_{Eye}(z) = P_T\left(1 - e^{\frac{-2R_r^2}{\omega^2(z)}}\right) \leq AEL_N. \tag{2.7}$$

P_T is the transmit power, R_r is the radius of the eye aperture and $\omega(z)=z\tan\theta$. Actually, if $P_{Eye}=AEL_N$ then

$$P_T(z) = \frac{AEL_N}{1 - e^{\frac{-2R_r^2}{\omega^2(z)}}}. \tag{2.8}$$

where P_T is actually the modified AEL for the diverged beam laser source.

The dependence on z will actually define the NHZ for the system. In the worst case scenario, the transmitter aperture and the eye will be in the same plane ($z=0$) and the eye will collect maximum power. Since the transmitter is mounted on the ceiling, can be assumed that there will be a zone of at least 20-50cm in which normally no human eye will be present (if the ceiling is 2.6m high then even 2.1m tall person looking directly in the transmitter will be at more than 50cm distance). Therefore, if due to ambient noise or big angle of divergence higher power is necessary, NHZ can be increased still guaranteeing Class 1 eye safety requirements under normal conditions.

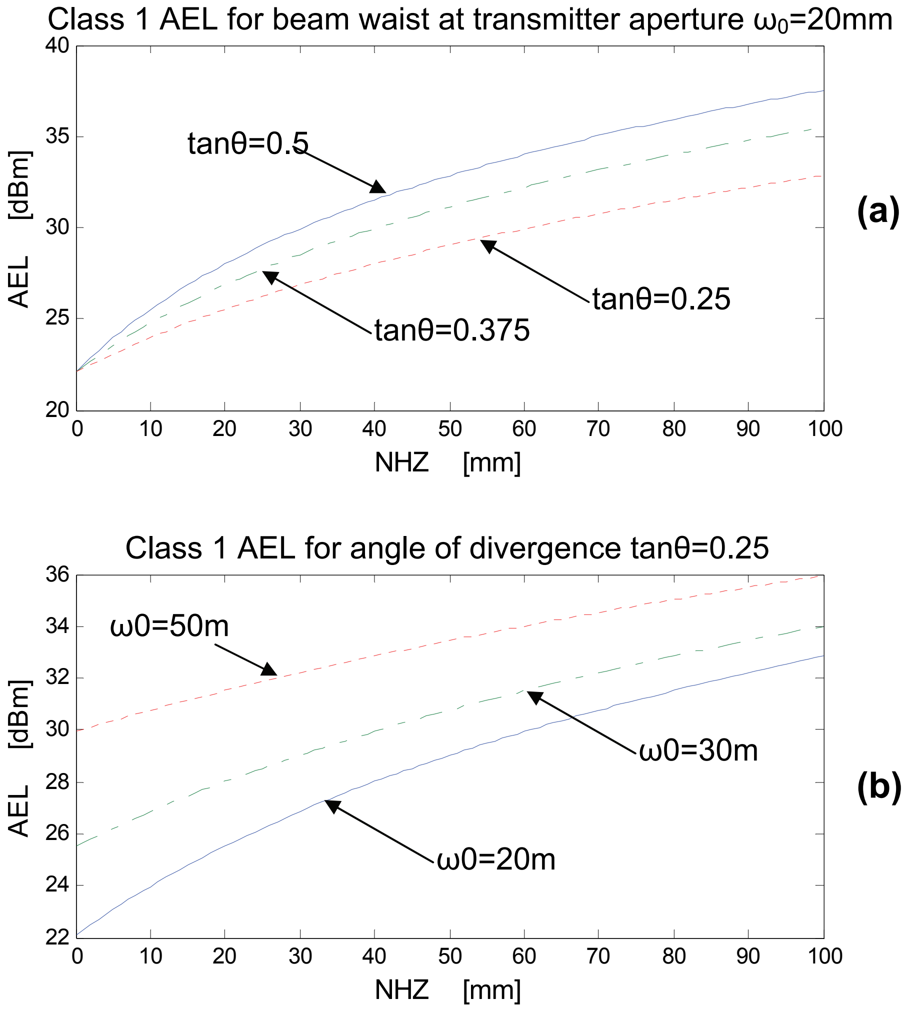


Figure 2-12: AEL dependence on NHZ for different beam waists ω_0 and angles of divergence θ in the transmitter aperture: (a) For fixed ω_0=20mm and different tanθ; (b) For fixed tanθ=0.25 and different ω_0

I have calculated the AEL dependence on NHZ from equation (2.8) and show results for fixed beam waist in the transmitter aperture ω_0=20mm and different angles of divergence (*tanθ*) in Fig. 2-12a, and for fixed *tanθ*=0.25 and different ω_0 in Fig. 2-12b. It can be observed that for relatively narrow beam waist in the proposed system- ω_0=20mm, the AEL for *NHZ=0* is 22dBm. By setting NHZ=100mm, which is relatively short and safe under normal conditions distance, according to the angle of divergence the AEL can be increased to more than 30dBm. All the proposed systems though, should obey the AEL limits as currently defined by the working standards (Table 2.3).

Table 2.3: Accessible emission limits for continuous-wave lasers [53]

Wavelength range (μm)	Emission duration (s)	Class 1 (W)
0.7 to 1.05	≥10	$\leq 0.4 \times 10^{-3}$ to $\leq 1.9 \times 10^{-3}$
1.05 to 1.15	≥10	$\leq 1.9 \times 10^{-3}$
1.15 to 1.2	≥10	$\leq 1.9 \times 10^{-3}$ to 1.5×10^{-2}
1.2 to 1.4	≥10	$\leq 1.5 \times 10^{-2}$
1.4 to 100	>10	$\leq 9.6 \times 10^{-3}$

From Table 2.3 can be observed that the permitted AEL for fiber communication wavelengths is much higher than the one for conventional OWC systems which would lead to higher SNR and respectively to better BER.

2.6 Beam propagation model for indoor space

Often the indoor surfaces such as walls and floor are considered to be Lambertian reflectors obeying the same Lambertian law as the one used to describe fundamental indoor IR OWC systems. In my system analysis I use the new generation optical wireless networks that have feasible connection between the fiber and the open space. Therefore, the source in my analysis will be not Lambertian but Gaussian. Furthermore, no diffuser has been implemented. Before I derive mathematical model for diffusive indoor system, I will define the received power in a small receiving aperture, located into a wide Gaussian beam spot.

The transmitted Gaussian beam has an irradiance distribution:

$$I(r) = \frac{2P_{out}}{\pi\omega^2} e^{-2r^2/\omega^2}, \tag{2.9}$$

where ω is the distance out from the center axis z of the beam where the irradiance drops to $1/e^2$ of its value on axis given by (shown on Fig. 2-13a):

$$\omega(z) = \omega_0 \left[1 + \left(\frac{\lambda z}{\pi \omega_0^2} \right)^2 \right]^{1/2}, \tag{2.10}$$

where ω_0 is the beam radius at the waist and λ is the laser wavelength. r is the transverse distance from the axis. z shows the distance on the z-axis between the transmitter and the current plane.

Because of the large angle of divergence, instead of using equation (2.10) it is more convenient to calculate ω from the equation for Gaussian beam when $z \to \infty$:

$$\tan\theta = \frac{\omega(z)}{z}, \tag{2.11}$$

where θ is the angle of divergence. The power, contained within a radius r, is easily obtained by integrating the intensity distribution from 0 to r:

$$P(r) = P_D \left(1 - e^{\frac{-2r^2}{\omega^2}} \right), \tag{2.12}$$

where P_D is the total transmitted power in the plane, in which the beam is analyzed.

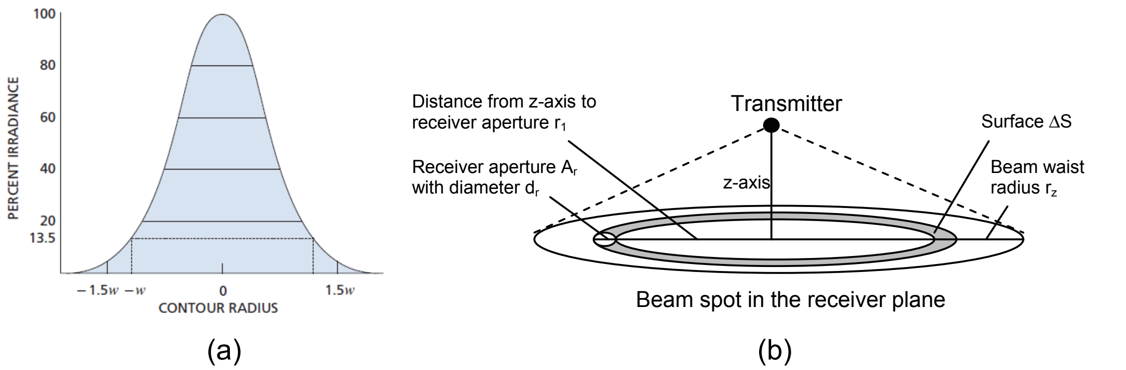


Figure 2-13: Gaussian beam: a) distribution [54]; b) spot and received power approximation

In Fig. 2-13b the beam spot in a plane, received from diverged Gaussian beam is shown. It is important to define the spot waist r_z as the radial extend of the Gaussian beam spot in the communication plane, where the irradiance has dropped to $1/e^2$ of its value in the spot center. The Gaussian distribution defines high irradiance fluctuations in different points of the spot according to their distance to the beam center. Therefore, the received power in a small receiving aperture with diameter d_r will vary in very wide interval and will be strongly dependent on the distance from the z-axis as can be seen from equation (2.12). I propose a good approximation for estimating of the received power by relating the surfaces and the optical powers, received in them. As shown in Fig. 2-13b, from equation (2.12) the power contained in the circles with radius (r_1+d_r) and r_1 - $P(r_1+d_r)$ and $P(r_1)$ can be found. Also the surfaces $S(r_1+d_r)$ and $S(r_1)$ can be calculated. The energy contained in the ring surface of the beam spot ΔS can be calculated by:

$$P(\Delta S) = P(r_1 + r_2) - P(r_1). \tag{2.13}$$

Due to the radiant symmetry and the relatively small receiver aperture compared with the beam radius, I propose to calculate the received power in the aperture P_{Ar} by relating the surfaces of the receiver aperture and ΔS:

$$P_{Ar} = P(\Delta S)\frac{\pi d_r^2/4}{S(r_1+d_r)-S(r_1)} = P(\Delta S)\frac{d_r}{8r_1+4d_r}. \tag{2.14}$$

If equation (2.12) is substituted in equation (2.13) and the result in equation (2.14) the equation for received optical power in the downlink P_{Ar} is received:

$$P_{Ar} = P_D\left[e^{\frac{-2r_1^2}{r_z^2(z)}} - e^{\frac{-2(r_1+d_r)^2}{r_z^2(z)}}\right]\frac{d_r}{8r_1+4d_r}. \tag{2.15}$$

$P_D(z)$ depends on z because of the path loss and $r_z(z)$- because of the big angle of divergence as defined in equation (2.11).

For non-directed, hybrid and diffusive systems, because of the wide beam spot, some of the light will reach the receiver aperture after one or several reflections from different surfaces (walls, floor, etc.). It is important to consider this received light with multiple reflections because it can be thought of as the main source of received power (diffusive links) or noise (LOS link), because the reflected signals will be delayed and effects such as jitter and interference can be observed.

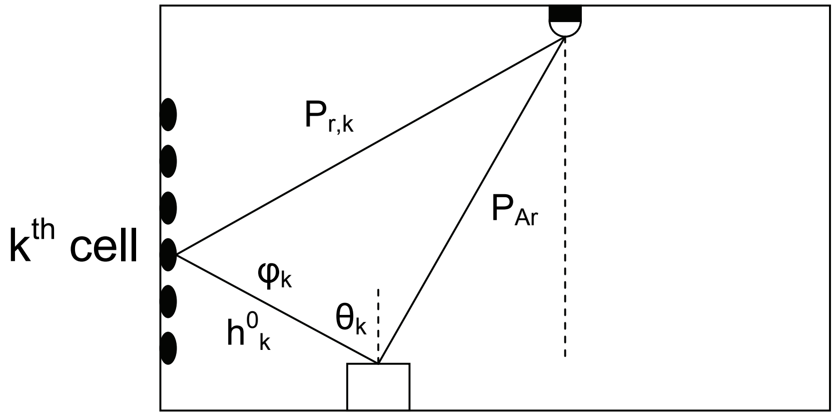


Figure 2-14: Gaussian beam propagation in indoor space

Since all the surfaces in the room can be described as Lambertian reflectors [29], I can separate them in K small areas in which the received power is $P_{r,k}$ ($P_{r,k}$ can be calculated by equation (2.15) when $d_r \to 0$ and r_1 and P_D are different for every k-source according to the plane, in which it is located). Thus each of these K points can be considered as a Lambertian source with angular intensity distribution [29] (Fig. 2-14) as in equation (2.1):

$$I_k = P_{t,k} \frac{n_k + 1}{2\pi} \cos^{n_k}(\varphi), \tag{2.16}$$

where the average transmit power is:

$$P_{t,k} = P_{r,k} \rho_k . \tag{2.17}$$

ρ_k is the reflectivity of the surface of the k^{th} source. Thus the impulse response from the direct light from the Lambertian k-source (Gaussian beam light with one reflection) that reaches the receiver with aperture A_r can be calculated by [29, 30]:

$$h_k^0(t) = \frac{n_k + 1}{2\pi} \frac{\cos^{n_k}(\varphi)\cos(\theta)A_r}{R^2} \times rect(\theta / FOV)\delta(t - R/c_L), \tag{2.18}$$

where φ is the angle of irradiance, θ is the angle of incidence, R is the distance from the light emitter to the detector, c_L is the light speed. FOV is the field of view of the detector. $\delta(t-R/c_L)$ is delayed Dirac delta function. The rectangular function is defined by:

$$rect(x) = \begin{cases} 1, |x| \leq 1 \\ 0, |x| > 1 \end{cases} \quad (2.19)$$

It is important to consider also the multiple bounce impulse responses of the *k*-source. The m^{th} impulse response of the k^{th} source h_k^m (t) can be approximated by [29]:

$$h_k^m(t;S,R) \approx \frac{n_k+1}{2\pi}\sum_{i=1}^{N_R}\frac{\rho_i \cos^{n_k}(\varphi)\cos(\theta)}{R^2} \times rect(2\theta/\pi) h_k^{m-1}\left(t - R/c_L; \{r; n^{\rightarrow}, 1\}, R\right)\Delta A, \quad (2.20)$$

where N_R is the number of reflecting elements, ρ_i is the reflectivity of the surface, and $n^{\rightarrow}$ is the normal vector to it. It is important to note that h_l^0 is the impulse response of the direct light of the Lambertian source but not the Gaussian beam.

The total impulse response of the *M*-reflections of the k^{th} source will be:

$$h_{k,Total}(t) = \sum_{m=0}^{M} h_k^m(t). \quad (2.21)$$

The relative average received power from the k^{th} source will be [55]:

$$P_{R,G,k} = G_0 P_{t,k} = P_{t,k}\int_{-\infty}^{\infty} h_{k,Total}(t)dt \quad (2.22)$$

and for total average received power from all sources:

$$P_{R,G,Indirect} = \sum_{i=1}^{K} P_{R,G,i}. \quad (2.23)$$

The total received power from the laser source is (Fig. 2-14):

$$P_{R,G,Tot} = P_{R,G,Indirect} + P_{Ar}, \quad (2.24)$$

where $P_{R,G,indirect}$ is the total average received power from reflected light and P_{Ar} is the directly received light from the transmitter antenna as calculated in equation (2.15). It is important to note that in a diffusive system the direct incident power P_{Ar} will be considered to be "*0*" and in case of LOS system, the $P_{R,G,Indirect}$ will be considered as noise or "*0*" according to the system configuration.

2.7 Indoor OWC configurations

The configurations of IRC links have been classified, relying on the existence of LOS between transmitter and receiver, and the degree of directionality (directed, hybrid and non-directed, [12, 56]). The six possible configurations are shown on Fig. 2-15.

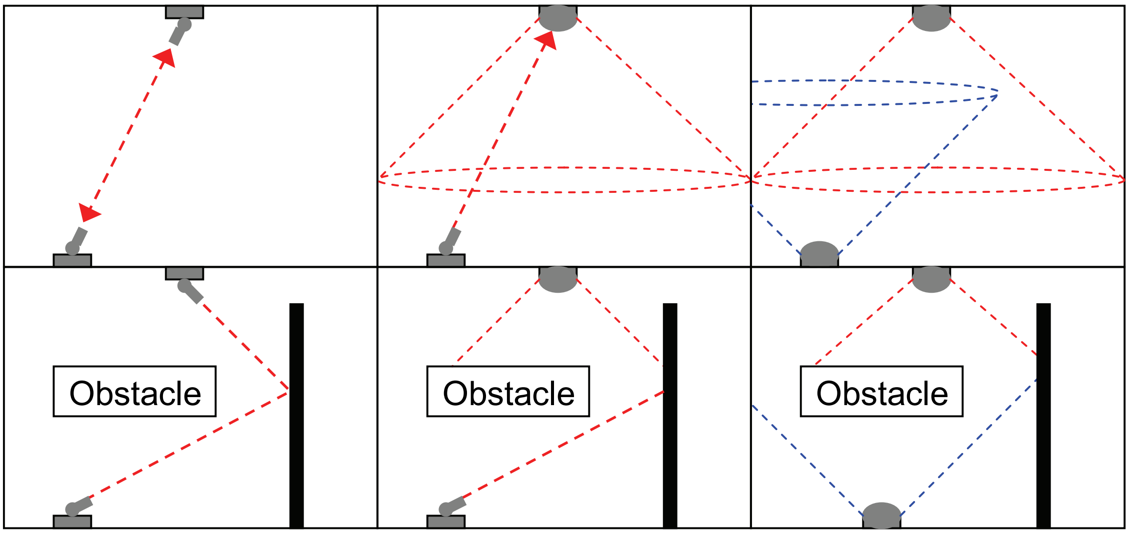


Figure 2-15: Configurations of infrared links

The non-LOS configurations rely on reflections from the ceiling, walls and other surfaces and provide excellent coverage and link robustness as they allow the system to operate even when obstacles are placed between the transmitter and receiver, and alignment is not required [57-58]. However, due to the reflections the transmit power has very high levels and due to the multipath distortion the system speed is limited.

The LOS links improve the power efficiency and allow much higher speeds. The directed system provides best performance in terms of low power consumption and high data rates, but it requires alignment of the receiver and transmitter, which makes it hard to establish and, especially for mobile devices, maintain the link. Directed LOS links improve power efficiency because the transmitted power is concentrated into a narrow optical beam, making possible to use narrow FOV receivers. Also, this system does not suffer from multipath distortion. The drawback is that such system is susceptible to blocking and requires aiming of the receiver and transmitter. The most attractive configuration is the non-directed LOS because it does not require alignment between the receiver and transmitter. Furthermore, with appropriate setup the multipath distortion can be severely mitigated and the lack of alignment allows such system to be used for mobile devices access. Compared to directed one, the design is simpler, but the transmit power has higher levels due to the big beam spot in the receiver plane and the bit rate is lower.

Finally, the hybrid configuration has the pros and cons of both directed and non-directed configuration and in particular cases can be much more efficient.

2.8 Conclusion

In this section, the conventional and proposed system designs have been discussed and performance comparison has been conducted. It is clear that a system, based on fiber laser source, can provide higher speeds and will have better performance due to the lower ambient noise, higher PD responsitivity and higher eye safety limit levels. Because the beam of a light source as the fiber end is Gaussian an indoor propagation model for all configurations was developed. The theoretical model for an indoor optical wireless link is much different than the outdoor one. In the outdoor FSO links most critical are the atmospheric turbulence and losses due to rain, fog, etc. In the indoor space there are no significant path losses and the atmospheric effects can be neglected due to their insignificant effect on the link. Since in the indoor network normally point-to-multipoint communication is considered (outdoor FSO links are point-to-point), a big issue is the beam loss due to the wide beam spot, formed in the receiver plane and limited receiver aperture.

CHAPTER 3

NON-DIRECTED LOS INDOOR OWC FOR GIGABIT EPON ACCESS AND ISDB-T TELEVISION BROADCASTING

3.1 Introduction

As discussed in Chapter 2, LOS links offer much better performance in terms of speed and low power consumption compared to the diffusive ones. Non-directed configuration has limited performance but is characterized with simple structure. I propose the usage of a non-directed indoor optical wireless link for high speed internet access and TV transmission. Similar research for indoor optical wireless system was conducted before [59]. However, this is the first time a system that combines internet access and TV broadcasting is considered. Furthermore, so far only experimental data is presented with no detailed mathematical analysis. For the internet access I chose EPON standard [60] because it provides seamless connectivity for IP-based communications, scalable bit rates for the users, and is widely used and cost effective. EPON is applicable in the proposed system because of its communication principle – in the downlink the signal is broadcasted from the optical line terminal (OLT) to all the optical network units (ONU) (resembles the wide beam spot with multiple receivers in it) and in the uplink the signals are individual for every ONU and time-division multiplexing is used. Another important feature is that the downlink is using 1490nm and the uplink – 1310nm. 1550nm spectrum is reserved for TV transmission. Since the direct fiber coupling offers transparent connectivity regardless of the bit rate, wavelength and modulation, I propose the 1550nm wavelength for connecting a fiber with RoF technology to the wireless system that would provide OFDM-based ISDB-T TV signal [32], independent from the main internet stream. Similar research for interconnection between RoF and RoFSO was already conducted [61]. However, there are different atmospheric effects that degrade the system performance in the outdoor FSO link. In the indoor network there are no significant atmospheric effects to take place. The accent falls on ambient light noise [40-41], indoor beam propagation and eye safety because of the close contact to human eyes [36-37]. Furthermore, in the outdoor RoFSO networks the connection is typically point-to-point and in the indoor systems often the connection is point-to-multipoint.

When a non-directed configuration is considered, there are two possible system designs for the downlink – single transmitter and multiple transmitters. There are different constraints for the transmitter module such as transmitted optical power limitation (eye safety), diverging angle, etc. Therefore, for wider indoor spaces multiple transmitters must be used and their beams in the communication plane will form cells. For better coverage the beam spots of the neighbor transmitters must be overlapped. In my proposal I use direct fiber coupling for seamless connection between the fiber and the open space. Therefore, the beam is not Lambertian, as normally considered in similar indoor optical communication systems [62-63], but Gaussian. It is important to define the spot waist r_z as the radial extend of the Gaussian beam spot in the communication plane, where the irradiance has dropped to $1/e^2$ of its value in the spot center. The Gaussian distribution defines high irradiance fluctuations in different points of the spot according to their distance to the beam center. I have already discussed the received power in a small receiving aperture with diameter d_r, positioned on distance r_1 from the center of a wide Gaussian beam spot with spot waist r_z in Section 4. As a final formula for the relationship between total transmit power P_D from the ceiling module and the received I use equation (2.12).

L_{beam} can be considered as loss, showing how much optical power from the beam spot is received in the small receiver aperture, and can be used when the link budget is calculated. In Fig. 3-1 is shown the relation between L_{beam} and the distance r_1 to the beam center for an example setup with spot waist $r_z=1m$ and receiver aperture with diameter d_r=20mm. From the graph can be seen that such non-directed indoor optical wireless setup can provide a reliable link in a beam spot with radius 1m.

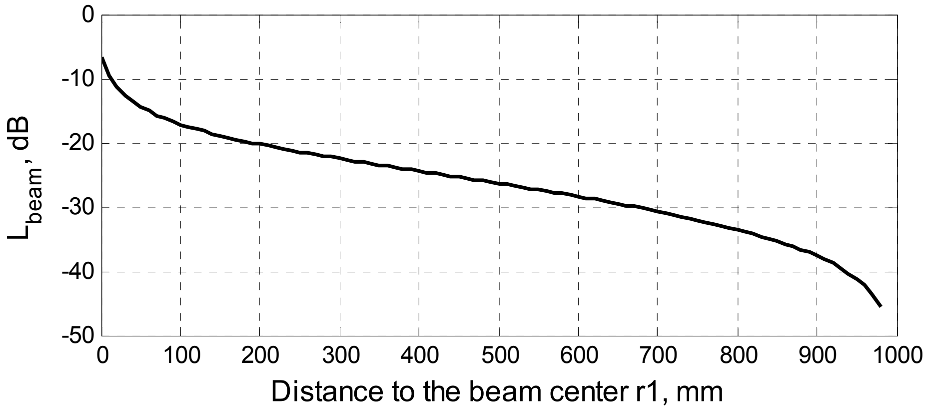


Figure 3-1: L_{beam} distribution in the beam spot

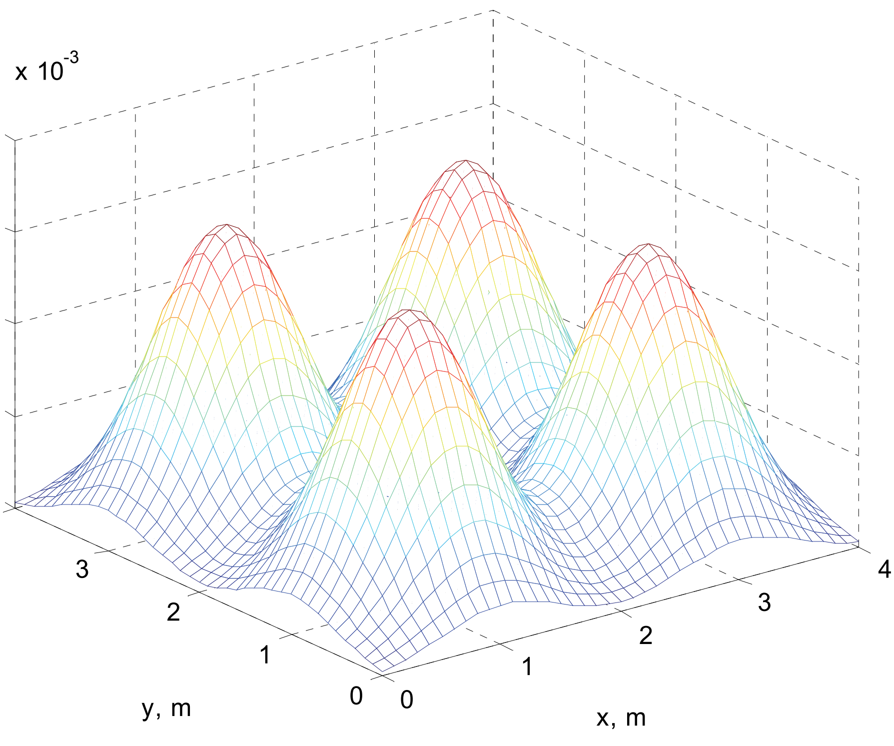


Figure 3-2: Multiple ceiling transmitters for full room coverage

For big indoor spaces it is necessary to decrease the link speed or to use multiple ceiling transmitters, as shown on Fig. 3-2. Increasing the transmitted optical power is limited due to eye safety considerations. Furthermore, it is important to notice that in the uplink the beam spot cannot be wide enough to cover the whole ceiling. Therefore, I propose the usage of a grid of multiple ceiling receivers to assure that there will be at least one receiver aperture in the beam spot on the ceiling as shown in Fig. 3-3.

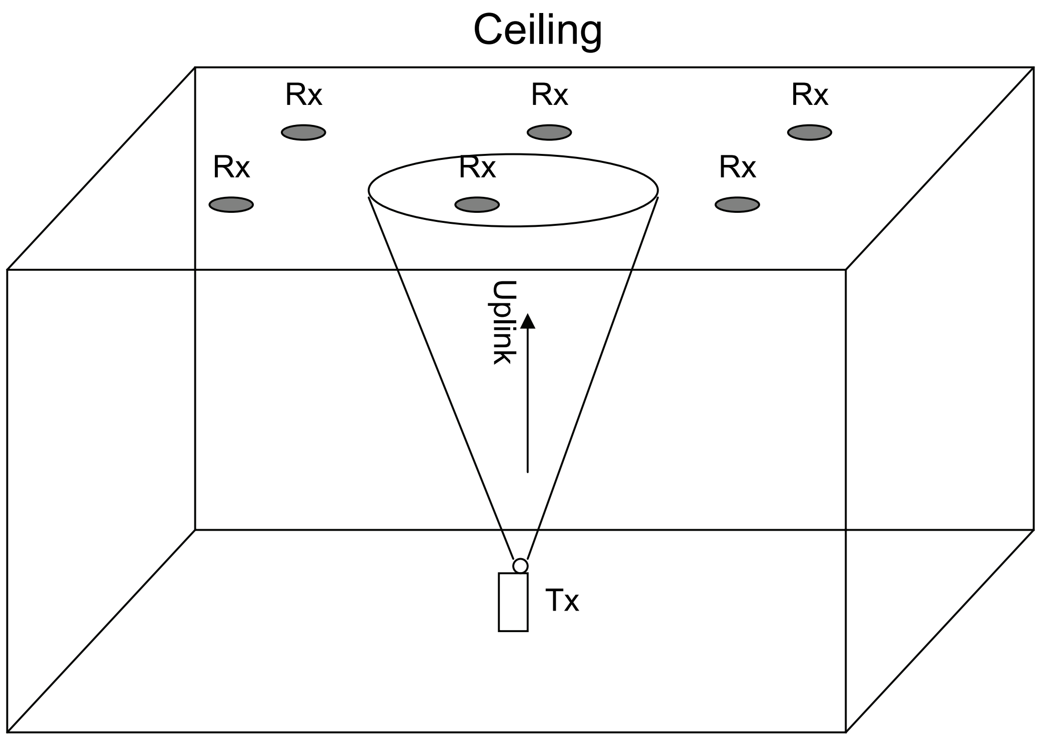


Figure 3-3: Non-directed uplink with a grid of ceiling receivers

When multiple transmitters and receivers are used, it is important to decide the network characteristics. Each beam spot can be considered as a picocell and by choosing different wavelengths for neighbor spots to achieve independent high speed in each beam spot with no interference from the adjacent spots. However, such method requires a sub-system handling the handover for mobile users when cells are changed. Also, because of the wavelength division the system design will be more complex. I propose to use the same wavelength and have a broadcasting downlink. Thus the system design is very simple and no handover issues occur. The main drawback is the interference between optical signals from neighbor beam spots, which effect must be considered.

3.2 Synchronization

EPON provides seamless connectivity for any type of IP-based or other "packetized" communications [60]. Since Ethernet devices are ubiquitous from the home network all the way through the regional, national and worldwide backbone networks, implementation of EPON is highly cost-effective. In terms of bit rate, EPON service levels for customers are scalable from T1 (1.5Mbps) up to 1Gbps. Compared with similar standards as Gigabit-capable Passive Optical Networks (GPON) (ITU-T G.984), EPON supports an unlimited number of ONU that makes it a better choice for indoor spaces with high user density – conference rooms, libraries, trains, etc. The EPON also supports cable television (CATV) overlay on 1550nm so that the main stream on 1490nm is free for other applications' traffic.

I propose a passive indoor wireless optical system to extend the existing EPON network reach to the mobile end user. Thus I combine the functionality of a well established standard with the ability to provide high-speed mobile network access into a new generation communication network. To be able to create such a system I use the direct fiber coupling technology, because the transceivers are cheap and simple – no laser source or PD is used. Furthermore, such a system is optically transparent due to its independency on the wavelength, bit rate and modulation, used in the rest of the optical network.

The EPON 802.3ah standard deals with the mechanism and control protocols required to reconcile the point-to-multipoint (P2MP) topology into the Ethernet framework. The P2MP medium is a passive optical network (PON). When PON is combined with Ethernet protocol, the network is referred to as an EPON. P2MP is an asymmetrical medium, based on a tree topology. A typical EPON network is shown in Fig. 3-4a. In the downstream the signal from the OLT passes through a splitter and reaches all the ONU. In the upstream direction the signal from the ONU will reach the OLT and no other ONUs. In Fig. 3-4b is my proposal. The downstream signal passes through a splitter but instead of an ONU, at the end of the fiber optical link, a ceiling module (CM) is connected. In the CM a wide Gaussian beam is formed in order to cover a greater area in the communication plane. The connection between the CM and the ONU is wireless optical.

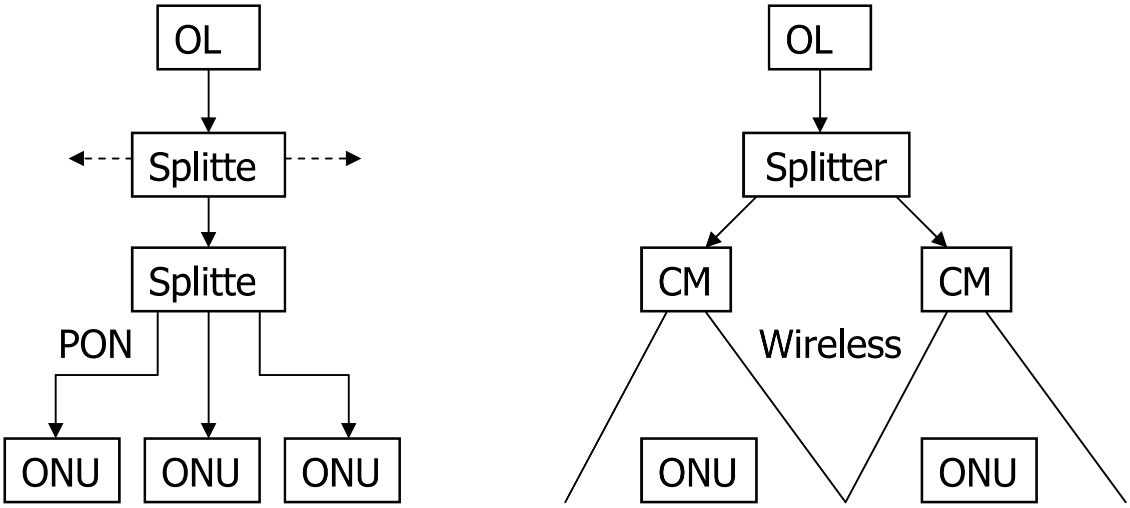


Figure 3-4: Comparison between: a) EPON structure; and b) proposed structure

In the proposed scenario the high speed downstream broadcasts to all devices. Due to the broadcasting the ONU can be mobile within the range of the wireless network and no handover issues are apparent. However, it is important to synchronize the CM's so that they will broadcast the same information at the same time with no delay. This can be achieved by adding extra delay in the shorter lines between the splitter and the CM (Fig. 3-5) that can be up to milliseconds long [64]. In Fig. 3-5 I also show optical amplifier (OA), which need will be explained later in this chapter. It is important to consider the delay not only in the fiber but also in the wireless part.

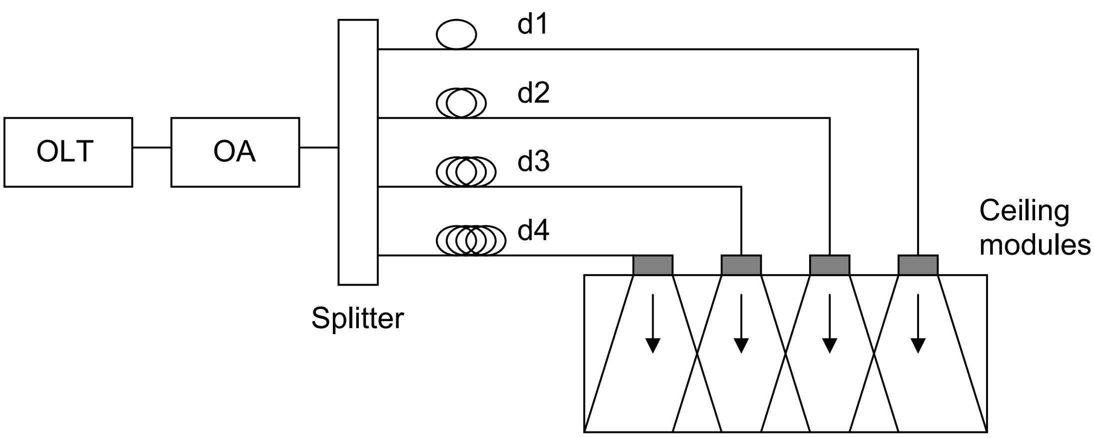


Figure 3-5: Delay equalization in the fiber part

In Fig. 3-6a is shown the uplink beam spot on the ceiling when it covers four receivers at the same time. The system can be designed in such a way that the four receiver apertures are positioned on the beam waist thus minor movement in any direction will result in only one or two receivers in the beam spot. When there is only one receiver in the spot there will be no multiple received signals. When there are four receivers, due to the grid pattern the distances between the center of the beam and the receivers are equal. Therefore, the delays will be equal and no signal disruption will be observed. The biggest delay will be reached when only two receivers are positioned in the beam spot and the difference in the distances from them to the center of the beam spot is maximal. This case is shown in Fig. 3-6c. As it can be seen, the maximum difference will be achieved when the distances between Rx1 and Rx2, respectively, are *(a-*r_z*)* and r_z, where *a* is the distance between the centers of the two receivers and r_z is the radius of the beam spot.

In the downlink, on the communication plane will be present the beam spots of the ceiling transmitters as shown in Fig. 3-6b. The neighbor spots are overlapping so that no uncovered space is available between them. I can calculate *a* as a function of r_z: $a=sqrt(2)* r_z$.

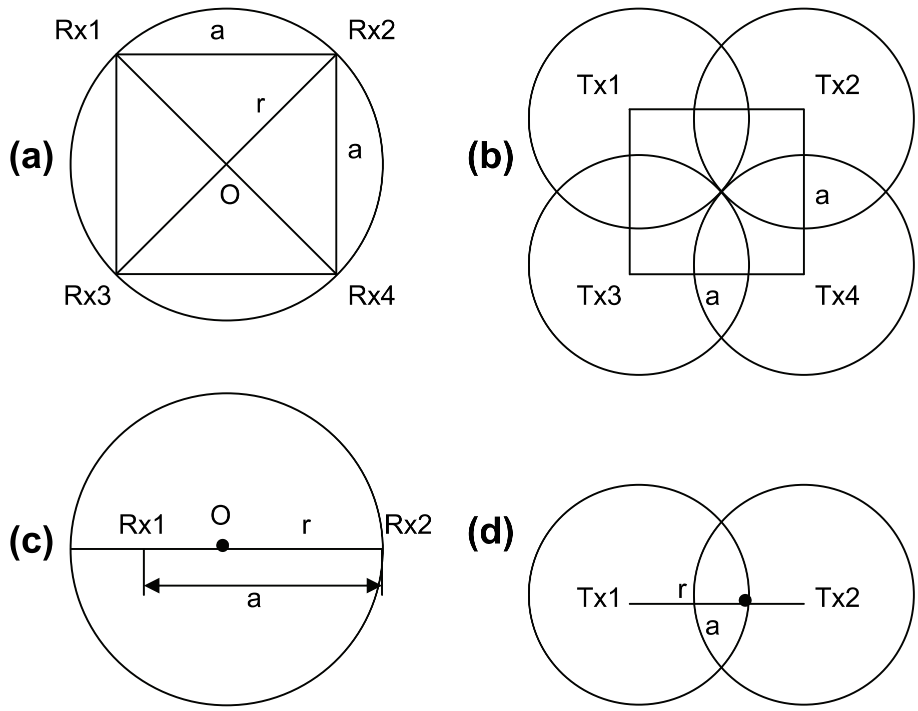


Figure 3-6: Cell arrangement: a) ceiling; b) communication plane; c) maximum distance in the ceiling grid; d) maximum distance in the communication plane

Due to the form of the beam spot and the typical rectangular indoor spaces, either there will be an uncovered space close to the walls or there will be a noise coming from the wall reflections because for full coverage part of the spot will reach the walls and reflect back. I will not consider these special cases in this research. I will only estimate the delay in such systems due to the different wireless paths.

In Fig. 3-6d is shown the case with maximum possible delay in the downlink- the distances to Tx1 and Tx2, respectively, are r_z and $(a- r_z)$, which is the same result as for the uplink. Assuming that the spot size is the same in the both uplink and downlink and the vertical distance between the communication plane and the ceiling can be considered as constant, it can be concluded that the maximum delays are equal for both ways of communication.

The distances between the two transmitters and the receiver L_1 and L_2 can be calculated as (Fig. 3-7):

$$L_1 = \sqrt{h^2 + r_z^2}$$
$$L_2 = \sqrt{h^2 + (a - r_z)^2} = \sqrt{h^2 + r_z^2\left(\sqrt{2} - 1\right)^2} \quad (3.1)$$

From here the delay $d=(L_1-L_2)/c$, where c is the speed of light.

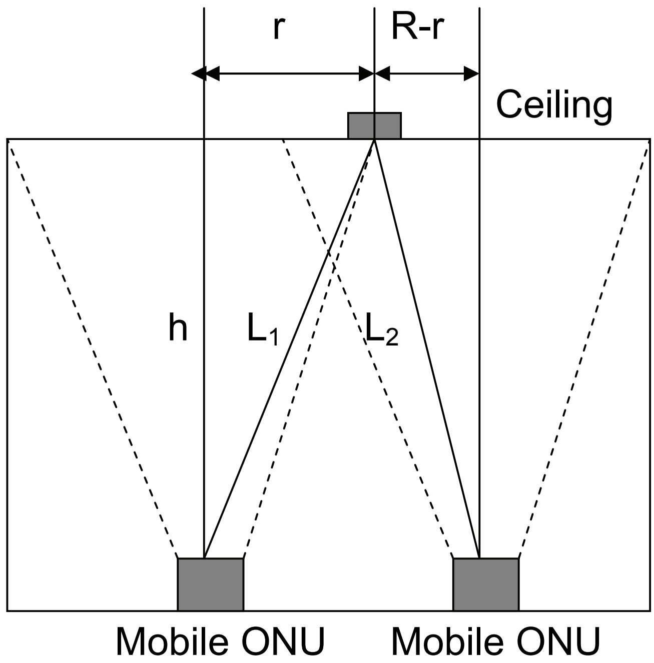


Figure 3-7: Different paths for different transmitters

In Fig. 3-1 it can be observed that L_{beam} varies in a wide interval of values. Especially, for r_1 values over 900mm the loss sharply increases. If overlapping of two neighbor spots is considered in order to provide better coverage of the room it is a good option to choose the r_1, for which the loss sharply increases for the middle distance between the centers of the two spots. Thus, the highest beam loss in a beam spot will be around 36dB. In the overlapped areas, signals from two different transmitters will reach the receiver in different time forming a delay between the fast signal (close transmitter) and the slow one (far transmitter).

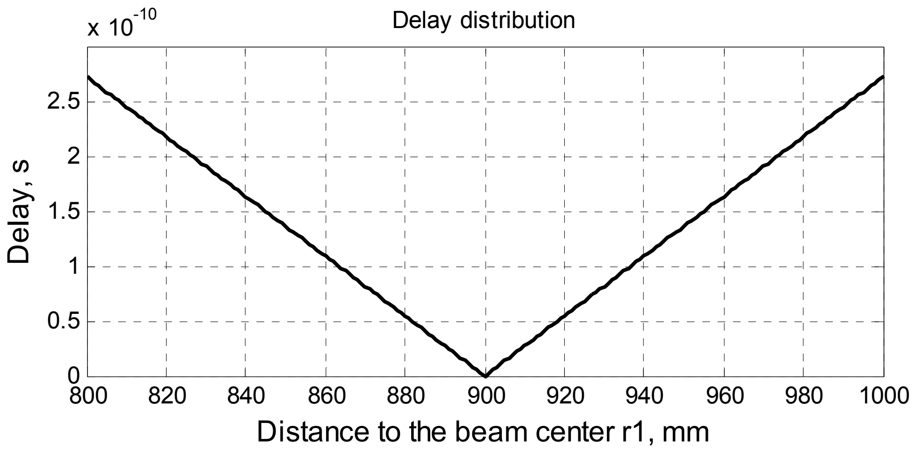


Figure 3-8: Optical signals delay distribution in the overlapped area

In Fig. 3-8 is shown such delay distribution for the overlapped zone of two spots with spot waist $r_z=1m$ and distance between the transmitters 1.8m, and height between the ceiling and the communication plane of 2m. As it can be observed, the highest delay is less than 0.3ns. Considering that the optical power of the slower transmit signal is lower (it is far from the beam center) and that the pulse width for a 1Gbps signal is 1ns, it can be concluded that there will be no significant effect on the system performance due to the overlapping. Future research could show more clear connection between the system BER and the delays. Better performance can be achieved if there is no overlapping. For example, there can be some distance between the beam spots to remove the overlapping but this will result in areas with no connectivity within the communication plane. Another solution is to change the beam shape to, for example, square thus removing the overlapping and guaranteeing full communication plane coverage.

The synchronized broadcasting in the downlink and the uplink with a beam spot, wide enough to assure at least one ceiling receiver in it guarantees flawless two-way communication in any place of the room for mobile users. For better understanding of the new device discovery process and multiuser communications I will discuss the EPON standard more thoroughly. Discovery is the process whereby newly connected or off-line ONUs are provided access to the PON [60]. The process is driven by the OLT, which periodically makes Discovery Time Windows (DTW) available during which off-line ONUs are given the opportunity to make themselves known to the OLT. The discovery process is shown in Fig. 3-9.

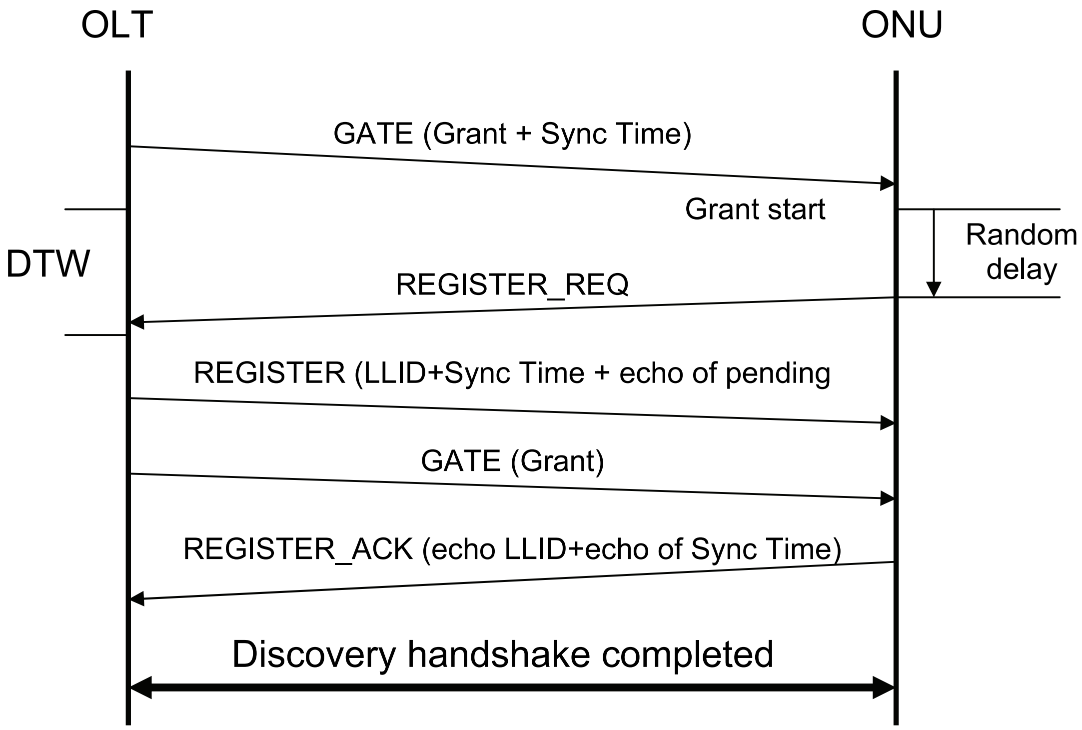


Figure 3-9: Discovery process

In a period of time, which is specified by the implementer, OLT signifies that DTM is occurring by broadcasting a discovery gate message, which includes the starting time and length of the DTM. Upon receiving the message, the off-line ONUs wait for a random period of time and transmit a REGISTER_REQ message to the OLT, containing their media access control (MAC) address and number of maximum pending grants. Only during the DTM multiple ONU can access the PON simultaneously and transmission overlap can occur. When the REGISTER_REQ is received, the OLT registers the ONU, allocating and assigning a new port identity (logical link ID - LLID) and bonding corresponding MAC to it. Then the OLT sends a register message to the newly discovered ONU, containing the LLID and required synchronization time. Also, the maximum number of pending grants is echoed. OLT schedules the ONU for access to the PON and transmits a standard GATE message allowing the ONU to transmit REGISTER_ACK message. When the REGISTER_ACK message is received, the discovery process for the ONU is complete and normal message traffic can begin. There can be cases when the OLT requires the ONUs to go through the discovery sequence again and cases when ONUs need to deregister.

3.3 Internet access - downlink

In Fig. 3-10 is shown the system scheme for the downlink. For EPON downstream from the OLT, OOK modulation is used and the wavelength is 1490nm. Typical optical power output of the OLT is -5dBm to 0dBm. To be able to send the signal to different indoor spaces and also to several ceiling transmitters in the same place for full communication plane coverage I use optical splitters. For example, a 1 x 16 port optical splitter has typical loss $L_{split}=13dB$ and the direct fiber coupling loss $L_{coupling}=3dB$.

$$L_{tot,dB} = L_{split} + L_{coupling} + L_m + L_{beam}, \tag{3.2}$$

The total loss in the downlink will be $L_{tot,dB}=53dB$ for $L_{beam}=36dB$ and margin $L_m=1dB$. The sensitivity of a 1Gbps optical receiver is -23dBm. From here can be concluded that a system with transmit power 0dBm will not operate normally without optical amplifier with optical gain $G_{OA}=30dB$. I consider to use OA, based on doped fiber because of its low noise figure, high flat gain (>20dB) and ability to operate in WDM networks, which is important for the proposed system. One of the biggest disadvantages of the optical amplifiers though, is the ASE noise that strongly degrades the SNR. It is important to consider also the fact that currently common Erbium-doped fiber amplifier (EDFA) configuration is C/L band (C-band: 1530-1565nm, L-band: 1565-1625nm) [65]. However, due to the EPON specifications I need to use Thulium doped fiber amplifier (TDFA) for the downlink and TV transmission (S-band: 1460-1530nm).

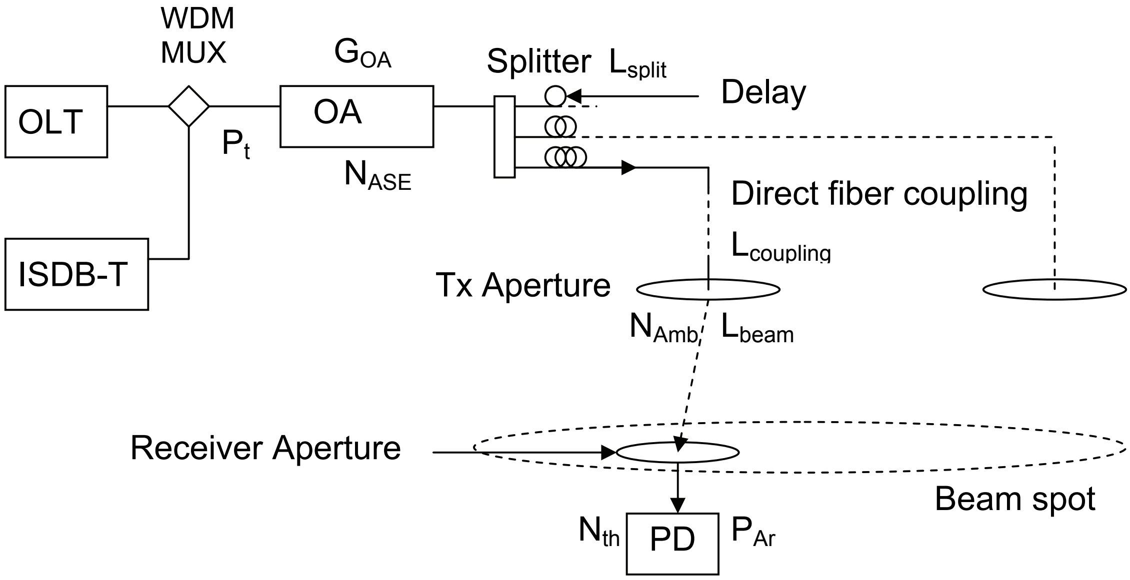


Figure 3-10: Proposed scheme – Downlink

From Fig. 3-10 can be defined the received optical power in the PD P_{Ar} as a function of the transmit power P_t as:

$$P_{Ar} = P_t L_{tot}, \tag{3.3}$$

The current in the PIN-PD with responsitivity ρ_{RX} from the received optical signal, defined in equation (3.3) will be:

$$I_{PD} = P_{Ar}\rho_{RX}. \tag{3.4}$$

Since the proposed system is LOS, it is assumed that there will be no multipath distortion. I calculate the SNR in the proposed system by the formula:

$$SNR = \left(P_{Ar}\rho_{RX}\right)^2 \Big/ \left\langle i_N^2 \right\rangle, \tag{3.5}$$

where $<i^2_N>$ is the mean square optical noise current and it consists several components.

In Fig. 3-10 the three main noise components in the downlink – ASE noise [65] from the EDFA, shot noise that includes the ambient light noise and thermal noise in the receiver are noted. The ASE power is [65]:

$$P_{ASE} = m_t n_{sp} h\nu\Delta\nu_f. \tag{3.6}$$

I assume that the factor m_t=2 because two orthogonal optical polarizations can propagate in the amplifier. n_{sp} is a measure of the completeness of the population inversion for the amplifier and can be calculated by $n_{sp}=N_2/(N_2-N_1)$, where N_1 and N_2 are populations of lower and upper laser levels, respectively. $h\nu$ is the photon energy and $\Delta\nu_f$ is the bandwidth of the optical band pass filter, which follows the EDFA. The corresponding ASE current is [65]:

$$I_{ASE} = \rho_{RX} P_{ASE}. \tag{3.7}$$

ρ_{RX} is the PD responsitivity. Noise arises from a beating of the ASE with the optical signal and the mean square beat noise current is [65]:

$$\left\langle i_{ase}^2 \right\rangle = 4 I_s G_{OA} I_{ASE} L_{tot}\, B/\Delta\nu_f\,, \tag{3.8}$$

where B is the operating bit rate, G_{OA} is the optical amplifier gain and $I_s=P_{Ar}\rho_{RX}$ is the current in the photodiode.

The total shot noise including ambient light, quantum and dark current components can be calculated by:

$$\left\langle i_{shot}^2 \right\rangle = 2eB\left(I_{BN} + I_{PD} + I_d\right), \tag{3.9}$$

where I_{BN} is the current in the PD due to the background light and I_d is the average dark current.

The thermal noise mean square value in the TIA following the PD can be calculated as:

$$\left\langle i_{th}^2 \right\rangle = 4 K_B T B / R_{in}\,, \tag{3.10}$$

where K_B is the Boltzmann's constant, T is the absolute temperature and R_{in} is the feedback resistance.

As a final equation for the SNR in the receiver for the downlink can be written:

$$SNR_d = \left(P_{Ar}\rho_{RX}\right)^2 / \left(\left\langle i_{ase}^2 \right\rangle + \left\langle i_{bn}^2 \right\rangle + \left\langle i_{th}^2 \right\rangle\right) \tag{3.11}$$

In my proposed system an OOK modulation is employed, so the BER can be written as:

$$BER = 0.5 erfc\left(\sqrt{SNR/2}\right). \tag{3.12}$$

3.4 OFDM-based services - downlink

As shown in Fig. 3-10, the TV signal will reach the building by fiber using RoF technology. Then it is combined with the internet signal from the OLT, amplified in the OA and split to multiple ceiling receivers to be broadcasted in the indoor space. The OFDM scheme for RoF transmitter and receiver and their connection with the proposed system is shown in Fig. 3-11. OFDM spectrum is shown in Fig. 3-12. RoF was thoroughly studied in the last decades so I will concentrate my work on the new indoor wireless system and its transmission analysis in terms of OFDM signal. I have already conducted similar research in [66], but no OA and TIA were considered and the system performance was relatively poor. Here I present a mathematical model with deeper noise analysis including the ASE noise and shot noise due to dark current.

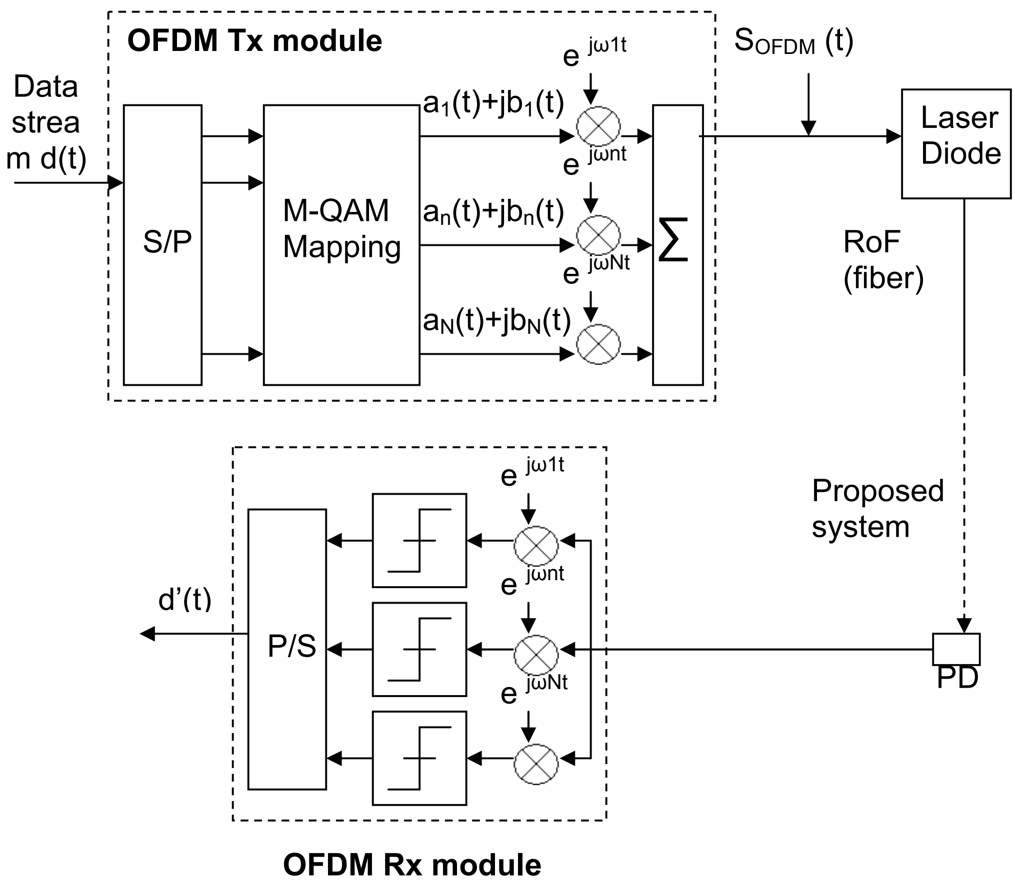


Figure 3-11: OFDM communication structure

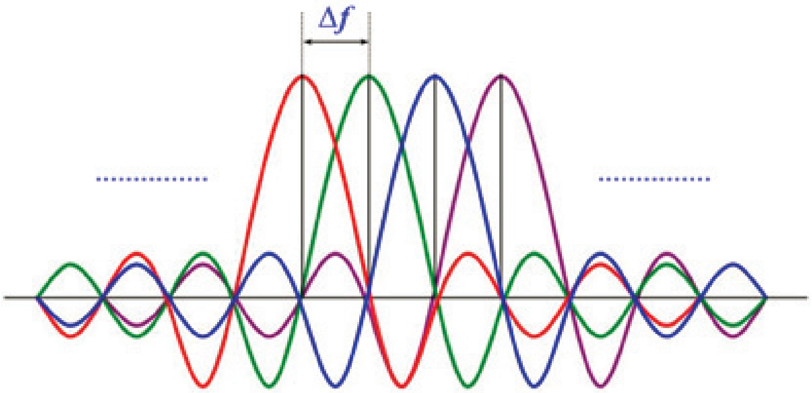


Figure 3-12: OFDM signal spectrum

As it was discussed [66], OFDM signal for N subcarriers, after up-conversion to the wireless service carrier frequency f_c is:

$$S_{OFDM}(t) = \sum_{n=0}^{N-1} S_n(t) = \sum_{n=0}^{N-1} X_n \exp\left(j(\omega_n + 2\pi f_c)t\right), 0 = t < \mathrm{Ts}, \tag{3.13}$$

where $\{\omega_n = (2\pi n/T_s)$, n=0, 1, …, N-1$\}$ is the set of N orthogonal frequencies, T_s is the OFDM signal duration, and $X_n=a_n+jb_n$ is the complex data symbol in the n^{th} subcarrier, with a_n and b_n the in-phase and quadrature modulation symbols, respectively. The first raw data are mapped according to different types of modulation techniques (Quadrature phase-shift keying (QPSK), Quadrature amplitude modulation (QAM) - 16QAM, 64QAM), depending upon data rate. Each symbol X_n is amplitude modulated on orthogonal subcarriers using inverse fast Fourier transform (IFFT), which guarantees that all the subcarriers are orthogonal to each other over the symbol interval. As in [66], I set the guard interval to zero and thus the OFDM symbol duration T_s is equal to the Fourier analysis window.

Using the signal $S_{OFDM}(t)$ the optical intensity of the LD to be transmitted through the fiber can be modulated. Nonlinearity of LD causes mixing of users signals, resulting in generation of harmonics and inter-modulation distortions (IMD). The optical power output from the LD is readily given by [67]:

$$P(t) = P_t\left(1 + \sum_{n=0}^{N-1} m_n s_n(t) + a_3\left[\sum_{n=0}^{N-1} m_n s_n(t)\right]^3\right), \tag{3.14}$$

where P_t is the average transmitted optical power, a_3 is the third order nonlinearity coefficient, and m_n is the optical modulation index (OMI) for each subcarrier, where the total OMI m_{Total} is given by:

$$m_{Total} = \frac{1}{N}\sqrt{\sum_{n=0}^{N-1} m_n^2}\,. \tag{3.15}$$

The total optical power at the receiving plane, directly received from the transmitter aperture can be mathematically described as follows:

$$P_{r,OW}(t) = P(t)L_{tot}G_{OA} + n_{OW} = P_{TX}G_{OA}L_{tot}\left(1 + \sum_{n=0}^{N-1} m_n s_n(t) + a_3\left[\sum_{n=0}^{N-1} m_n s_n(t)\right]^3\right) + n_{OW}\,, \tag{3.16}$$

where n_{OW} is additive white Gaussian noise (AWGN).

The output current of the PD considering only the directly received signal can be expressed as:

$$i(t) = I_{ph}\left(1 + \sum_{n=0}^{N-1} m_n s_n(t) + a_3\left[\sum_{n=0}^{N-1} m_n s_n(t)\right]^3\right) + n_{opt}(t), \tag{3.17}$$

where I_{ph} is the dc value of the received photocurrent $i(t)$:

$$I_{ph} = \rho_{RX} P_{TX} G_{OA} L_{tot}\,. \tag{3.18}$$

$n_{opt}(t)$ is the noise containing the AWGN with a double-sided power spectral density (PSD) of $N_0/2$ and the current, received from the optical noise n_{OW}. For simplicity in my analysis I assume that there are no multiple reflections and calculate the I_{ph} only from the directly received optical power.

The Gaussian noise models the noise processes in the proposed link, which is the sum of thermal noise, shot noise, RIN, and ASE noise. Furthermore, in my equation the shot noise is a function of the mean optical power, including the power from ambient light and the dark current in the optical receiver. The RIN is a function of the square of the optical power, whereas the thermal noise is signal independent. The total noise power is defined as:

$$N_0 = 4I_{ph}G_{EDFA}I_{ASE}L_{tot}/\Delta\nu_f + 2e(I_{BN} + I_{ph} + I_d) + 4kT/R_{in} + (RIN)I_{ph}^2\,, \tag{3.19}$$

If it is assumed that all the tones are to be modulated with the same modulation index m_n, the OMI per subcarrier m_n is:

$$m_n = m_{Total} / \sqrt{N}, n = 0,1,...,N-1. \tag{3.20}$$

The desired signal with respect to subcarrier frequency ω_n can be expressed as

$$C = 0.5m^2 I_{ph}^2. \tag{3.21}$$

The third order intermodulation distortion (IMD3) which falls into carrier ω_n among N equally-spaced carriers can be described as [67]:

$$\sigma_{IMD}^2 = 0.5\left(0.75a_3 m_n^3 D_2 + 1.5a_3 m_n^3 D_3\right)^2 I_{ph}^2, \tag{3.22}$$

where $D_2(N, n)$ and $D_3(N, n)$ represent the number of intermodulation distortion products which influence the desired carrier and are given by [67]:

$$D_2(N,n) = 0.5\left(N - 2 - 0.5\left(1-(-1)^N\right)(-1)^n\right), \tag{3.23}$$

$$D_3(N,n) = 0.5n(N - n + 1) + 0.25\left((N-3)^2 - 5\right) - 0.125\left(1-(-1)^N\right)(-1)^{N+n}. \tag{3.24}$$

The received carrier to noise plus distortion ratio (CNDR) per subcarrier $CNDR_n$ for indoor optical wireless link can be defined statistically as a function of the expected desired signal power C, the third order intermodulation distortion power $\sigma^2_{IMD,}$ and the optical noise power per subcarrier N_0/T_s:

$$CNDR_n = \frac{C}{N_0/T_s + \sigma_{IMD}^2}, \tag{3.25}$$

I further analyze the performance of OFDM systems with M-QAM modulation by computing the symbol error probability (SEP) P_s and bit error probability (BEP) P_b. I assume that the intermodulation distortion noise is Gaussian distributed so that the total noise defined in equation (3.25) is Gaussian. The SEP per subcarrier $P_{s,n}$ for the received MQAM- OFDM signal, where $M = 2^k$ and k is an even number, is given by

$$P_{s,n} = 2\left(1 - \sqrt{M}^{-1}\right) erfc\left(\sqrt{A \times CNDR_n}\right), \tag{3.26}$$

where $A=3/[2(M-1)]$, and *erfc(.)* is the complementary error function. Assuming that the Gray-coded mapping is used at the transmitter, the BEP per subcarrier $P_{b,n}$ can be obtained from equation (3.26) as

$$P_{b,n} = \frac{1}{\log_2(M)} P_{s,n}, \tag{3.27}$$

When the number of subcarriers is large, the total bit error probability P_b over the entire OFDM band can be derived based on law of large numbers (LLN)

$$P_b = \frac{1}{N} \sum_{n=0}^{n-1} P_{b,n}, \tag{3.28}$$

3.5 Internet access – uplink

The scheme of the uplink internet stream is shown on Fig.3-13. In order to assure user mobility and link simplicity I use diverged Gaussian beam that will form a big spot on the ceiling. The ceiling receiver aperture has no requirements for small size as the receiver aperture in the mobile device. This leads to much lower losses due to beam divergence (L_{beam}) and allows the implementation of wider beam spot with bigger coverage at lower optical transmit power. The optical signal is directly received in a PD, so no OA, respectively no ASE noise, will be present. I chose conventional uplink instead of direct fiber coupling because of the link budget and transmit power limitations. Since no direct coupling is used, I can use 1550nm wavelength for the wireless optical uplink that would allow transmit power up to 10dBm, and then in the receiver side I will use electro-optical (E/O) convertor and send 1310nm signal to the OLT. Thus, the link budget is 33dB (10dBm transmit power and -23dBm receiver sensitivity). By using equation (2.12) I can calculate that for receiver aperture diameter in the interval 80mm to 100mm and spot waist $r_z=1m$ the beam loss at 0.9m distance (due to overlapping) is 30 to 32dB and $L_{tot}=L_{beam}$ for the defined link.

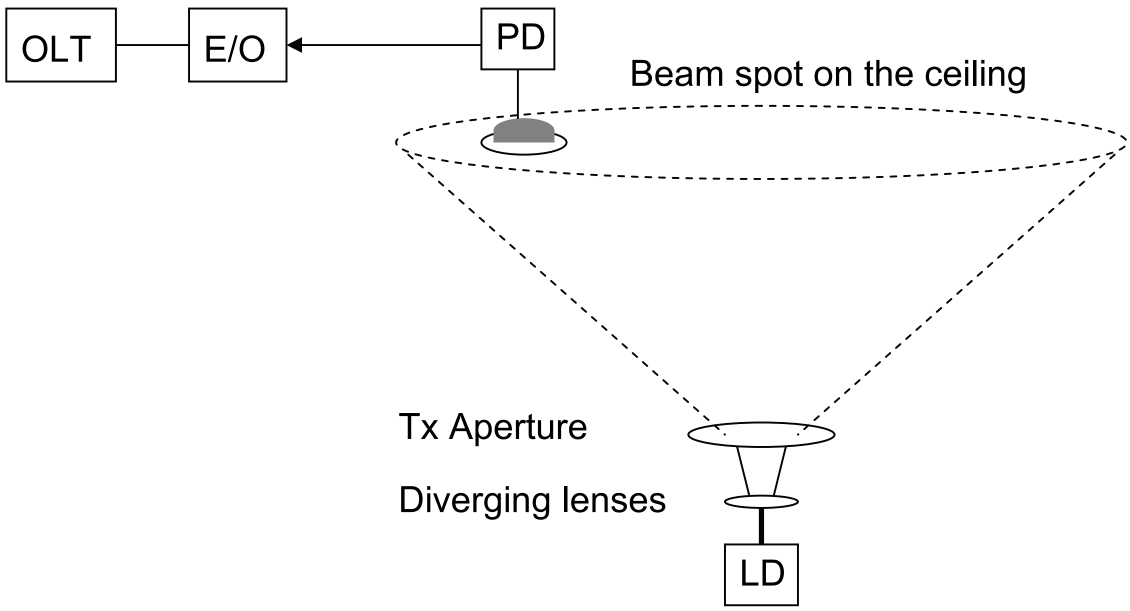


Figure 3-13: Proposed scheme - Uplink

The final formula for the SNR is:

$$SNR_u = \frac{(P_{Ar}\rho_{RX})^2}{\langle i_{bn}^2 \rangle + \langle i_{th}^2 \rangle} = \frac{(P_{t,u}L_{tot}\rho_{RX})^2}{2eB(I_{BN} + I_s + I_d) + \frac{4K_B TB}{R_{in}}} \quad (3.29)$$

In my system an OOK modulation is employed for the internet signal, so the BER can be calculated from equation (3.12).

The proposed system will operate in close contact with human eye for a long period of time. Therefore, it is very important to consider the eye safety regulations when the system is designed. As discussed above, the system loss in the downlink, prior to the ceiling transmit aperture, is in the order of 15 to 20dB. Assuming that the input optical signal is 0dBm and that the OA gain is 30dB I can conclude that the transmitted optical power from the ceiling aperture will be 10 to 15dBm. For 1550nm wavelength the power limit for Class 1 laser systems is 10dBm, which means that for some configurations a careful choice of the optical gain is necessary to guarantee that the proposed system does comply with the eye safety limitations. Furthermore, as I will show below, for the OFDM signals according to the configuration higher transmit optic power is necessary. This should also be considered when each network is designed due to eye safety limitations. It must be considered though, that the beam is widely diverged which will significantly decrease the optical power, that can enter in a human eye and the proposed system will still remain safe (as already discussed in [66]).

3.6 Results and discussion

I make simple mathematical calculations, based on the equations in this section to evaluate the system performance. The fixed parameters are shown in Table 3.1. It is important to note that due to the Gaussian beam power distribution the received power in different location will have different levels. In my mathematical analysis I assumed that the receiver aperture is located at distance $0.9r_z$, since this is the most distant position from the beam spot and lowest power level is expected. Because of the overlapping, bigger distance will result in higher received power from the neighbor transmitter spot, for which the distance to the beam center will be less than $0.9r_z$.

Table 3.1: Mathematical analysis parameters

Parameter	Symbol	Value
Photodetector responsitivity	ρ_{RX}	0.8
Absolute temperature	T	300K
TIA load resistor	R_{in}	3500Ω
Orthogonal Polarization factor	m_t	2
Population inversion factor	n_{sp}	2.25
BP filter bandwidth	$\Delta\nu_f$	$12.4\text{x}10^9$Hz
Bit rate	B	$100\text{x}10^6$bit/s
Fixed fiber losses	L_c	20dB
OLT output power	$P_{t,d}$	0dBm
Receiver dark current	I_d	4nA
Ambient noise power	P_{BN}	10µW
Relative intensity noise	RIN	-130dB/Hz
Third order IMD	a_3	0.17
Boltzmann's constant	K	$1.3807\text{x}10^{-23}m^2kg\ s^{-2}K^{-1}$
Elementary charge	e	$1.6022\text{x}10^{-19}$C

In the downlink the OLT output power and the losses before the wireless part are fixed so that the BER change for different beam spot and receiver aperture sizes can be observed. Instead of changing the transmit power, which normally is fixed by the OLT manufacturer, I change the OA gain and observe its effect on the system. In Fig. 3-14 is shown the relationship between the BER and the OA gain G_{OA} for different beam spot and receiver aperture sizes. As discussed above, due to the link budget restrictions it is realistic to consider beam spot diameter D=2m. Bigger size is also possible, but the optical gain must be higher (37dB) or special photodiodes with high sensitivity (-30dBm) must be used. Also, such setup will have more serious eye safety issues. As can be seen, for the proposed setups the BER has very low levels. The receiver apertures are in the range of 15 to 20mm in diameter, which is applicable for notebooks and tablets, but not for smart phones.

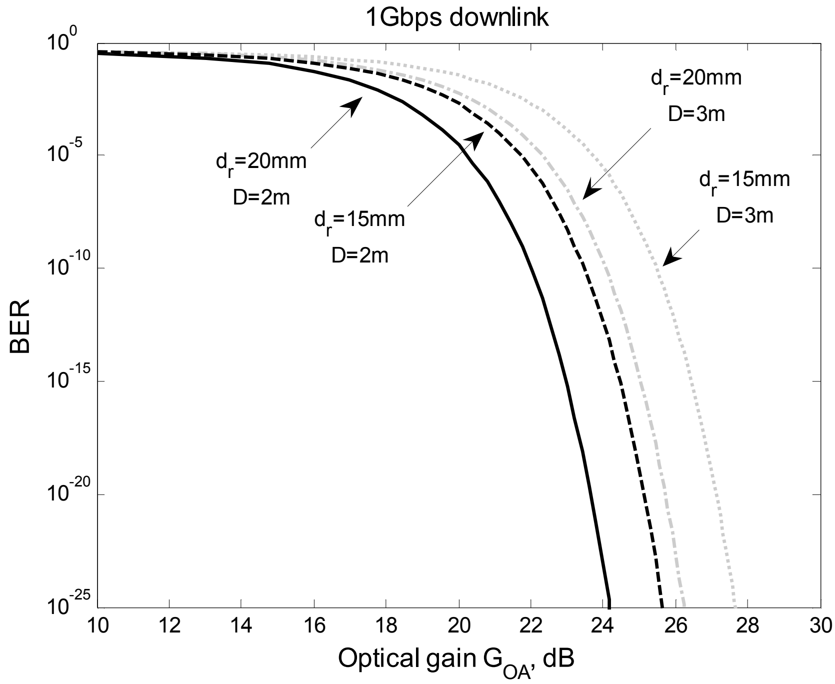


Figure 3-14: BER vs G_{OA} for 1Gbps downlink for different receiver apertures and beam spot diameters

As discussed in Section 1, the internet downlink signal uses 1490nm wavelength according to the EPON standard. The 1550nm wavelength is reserved for TV services. I presented a theoretical model for OFDM services transmission in the indoor optical system. A good practical TV broadcasting standard, based on OFDM is ISDB-T. ISDB-T system uses the frequency band between 470MHz and 770MHz. The 300MHz bandwidth is separated into 50channels numbered from 13 to 62. Each channel is further divided into 13 segments. One segment is for mobile receivers – LDTV, Radio and data (Layer A) and the rest of the segments can be allocated as one (Layer B) for high-definition television (HDTV) (Fig. 3-15). In Table 3.2 the three ISDB-T modes with their parameters are shown.

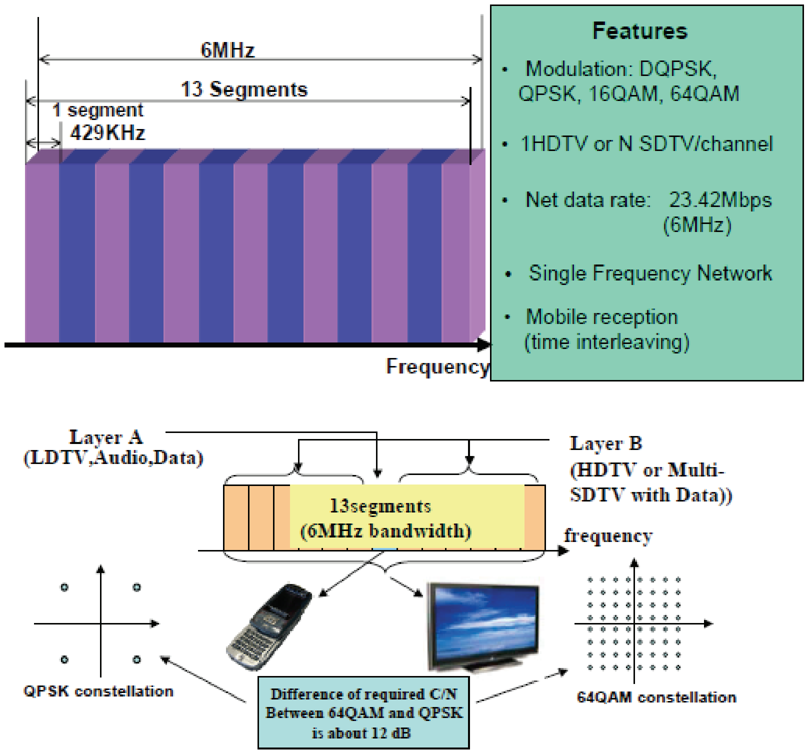


Figure 3-15: ISDB-T television standard

Table 3.2: ISDB-T standard parameters

Transmission parameter	Mode 1	Mode 2	Mode 3
No. of OFDM segments	13		
Bandwidth (MHz)	5.575	5.573	5.572
No of carriers	1405	2809	5617
Symbol length (ms)	252	504	1008
No of symbols per frame	204		
Guard interval length	1/4,1/8,1/16,1/36		
Carrier Modulation	QPSK, 16QAM, 64QAM		
Information bit rate	3.65Mbps-23.23Mbps		
Hierarchical transmission	Maximum 3 layers (A,B,C)		

In Fig. 3-16 is shown the CNDR for a fixed system configuration (beam spot diameter D=2m and receiver aperture diameter d_r=20mm for ISDB-T Mode 1) and its dependence on the G_{OA} and OMI. I assumed that the input signal in the proposed signal coming from the RoF is 0dBm.

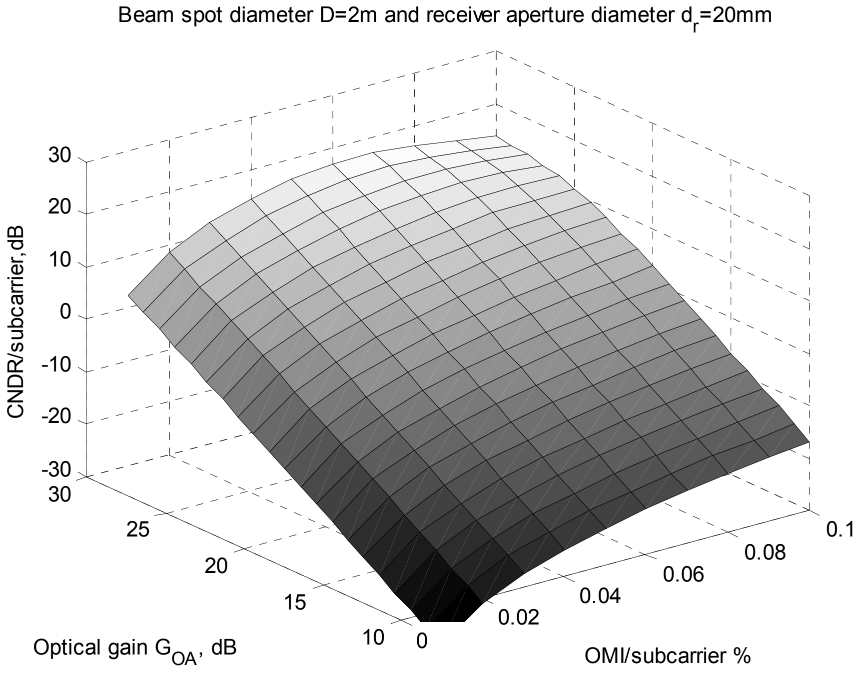


Figure 3-16: CNDR vs G_{OA} and OMI/subcarrier for D=2m and d_r=20mm

In Fig. 3-17 and Fig. 3-18 are shown two different configurations that would allow observing the CNDR change when the beam spot and the receiver aperture size are changed compared to Fig. 3-16.

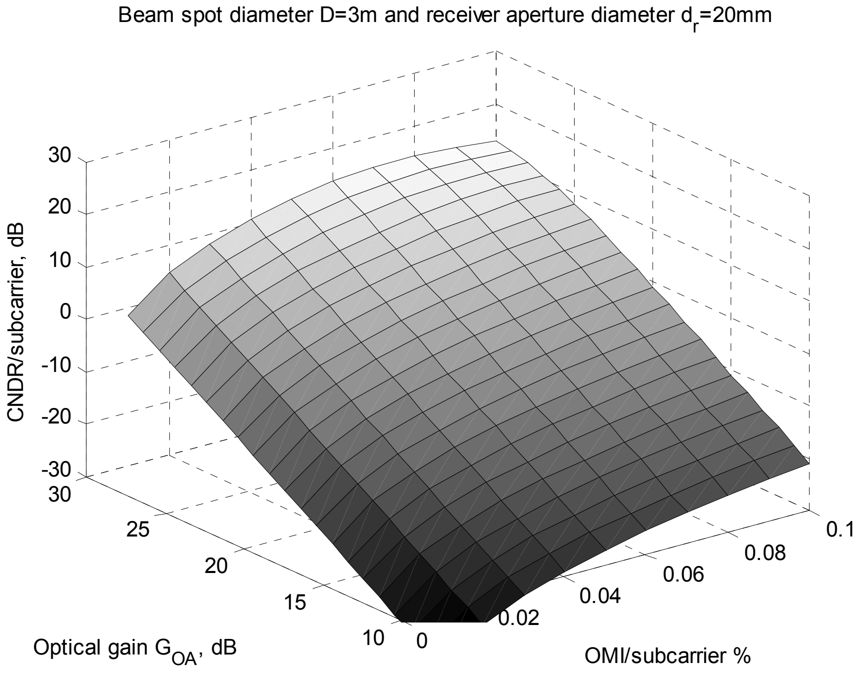


Figure 3-17: CNDR vs G_{OA} and OMI/subcarrier for D=3m and d_r=20mm

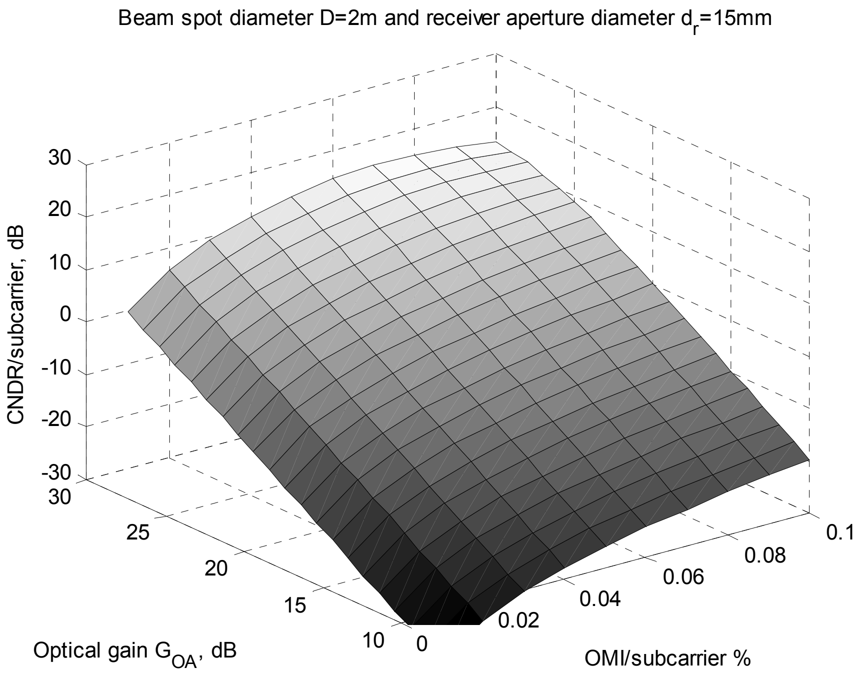


Figure 3-18: CNDR vs G_{OA} and OMI/subcarrier for D=2m and d_r=15mm

From Fig. 3-16 – 3-18 it is seen that the optical gain G_{OA} is critical for the system performance. The presence of optimal value of OMI can be explained with equation (3.25). The noise in the system, as defined in equation (3.19) is much stronger than the negligible intermodulation distortion for low values of the received power. With increasing of the received power though (not only by increasing the G_{OA}, but also by narrowing the beam spot size or increasing the receiver aperture size I can increase the collected power from the total power in the beam spot), the intermodulation distortion becomes dominant and OMI degrades the system performance.

Fig. 3-19 shows the BEP, calculated from equation (3.28), for the three types of modulation, typically used in ISDB-T transmission – QPSK, 16-QAM and 64-QAM. I chose $m_{opt,n}$=0.07% when the *CNDR* has peak values. As can be seen, errorless link can be established with reasonable values of OA gain (There are three BEP levels – minimal required CH-BER (2.4 x 10^{-4}), HDTV required HD-BER (2.4 x 10^{-6}) and for perfect quality – ER-BER (10^{-8}). [64]). However, with the proposed setup and current level of optical gain the 64-QAM signal cannot be transported.

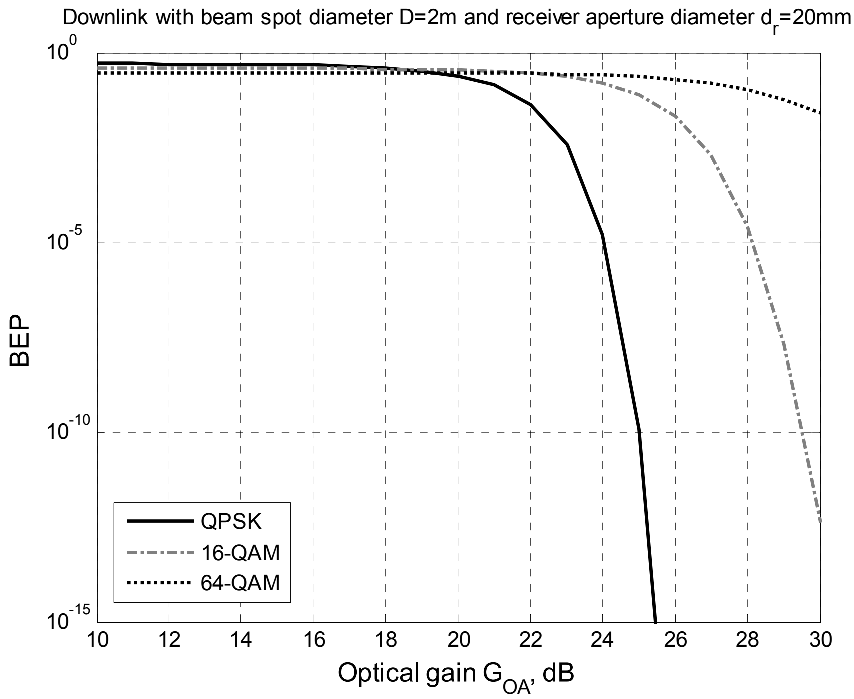


Figure 3-19: BEP for QPSK, 16-QAM and 64-QAM related to G_{OA}

In Fig. 3-20 the 1Gbps uplink is shown. Excellent system performance can be observed for parameter setups as in the downlink at very low transmit power levels. That allows the implementation of cheap laser diodes and high speed transmission with low power consumption, compared to RF links [68], is possible. Furthermore, the low transmit optical power eliminates eye safety considerations. It is possible to decrease the transmission speed which will allow decreasing of the ceiling aperture to much smaller sizes.

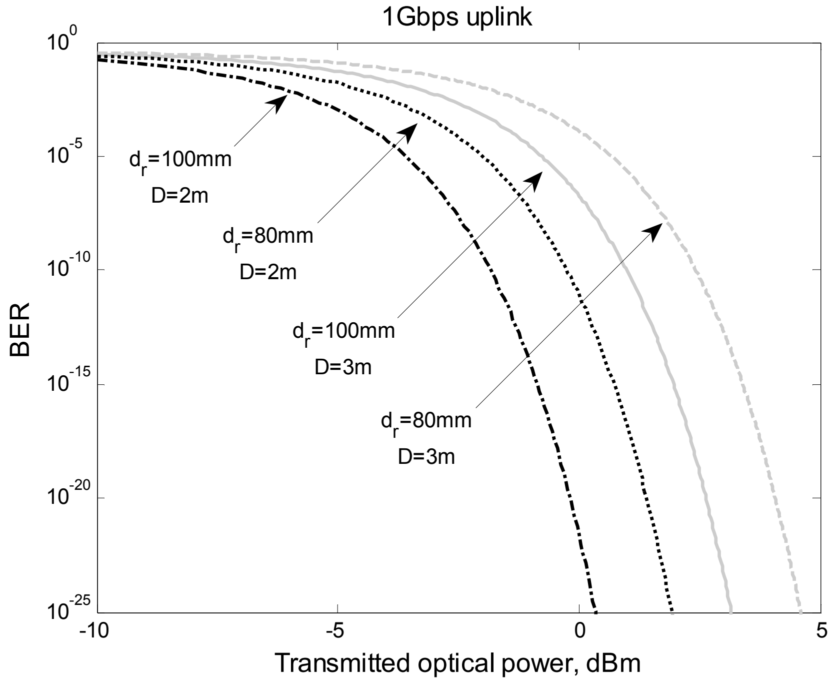


Figure 3-20: BER vs transmitted optical power for 1Gbps Uplink

3.7 Conclusion

In this section a non-directed configuration with multiple transceivers on the ceiling has been presented. The novelty in my research is that the system provides not only 1Gbps duplex network access at 1490nm, but also ISDB-T TV broadcasting at 1550nm by using simple WDM. A complex theoretical model, considering the main noise components in an indoor environment and the use of TIA in the receivers has been developed and presented. Furthermore, synchronization issues in due to beam overlapping and attenuation distribution in the beam have been analyzed. Uplink was further simplified by using conventional structure (direct detection PD) instead of direct fiber coupling technology. In the results section I show that 1Gbps link is possible. Although the system has very simple design, its setup is complex because of the multiple transceivers on the ceiling. Furthermore, because of the Gaussian distribution in the diverged beam the intensity close to the beam spot is much lower than the one at the end of the beam which limits the beam spot diameter (2-3 meter diameter) in order to guarantee errorless connection. Another issue is the low received power that requires very big receiving aperture (1.5-2cm), which is hard to be integrated into all portable devices and also requires a PD with bigger surface. The big surface PD has higher junction capacitance which limits its bandwidth and bit rates over 1Gbps are difficult to achieve. The high beam losses and the need of splitter for connecting multiple transceivers also bring the need of optical amplifier that further increases the system price. Finally, the current design cannot transport a 64-QAM signal with the required BEP of 10^{-4} for ISDB-T transmission.

CHAPTER 4

CUSTOM LOS DIRECTED AND HYBRID INDOOR OWC LINKS FOR MOBILE USERS

4.1 Custom LOS directed indoor OWC network for mobile users

4.1.1 Introduction

In Chapter 3 a non-directed LOS communication system was described. For such link usually one transmitter covers the whole indoor space (Fig. 4-1a) or an array of multiple transmitters forming a cellular configuration (Fig. 4-1b). Such system design though (Fig. 4-1b), is not cost-effective for PAN with one user due to the multiple receivers. Also, for a mobile user handover and cells overlapping will be necessary that would further increase the system complexity. The wide FOV in the transmitter leads to higher transmit power levels. In terms of receiver, for non-directed link the wide FOV assumes high ambient noise level. The above issues urge a research for the performance of alternative LOS configurations.

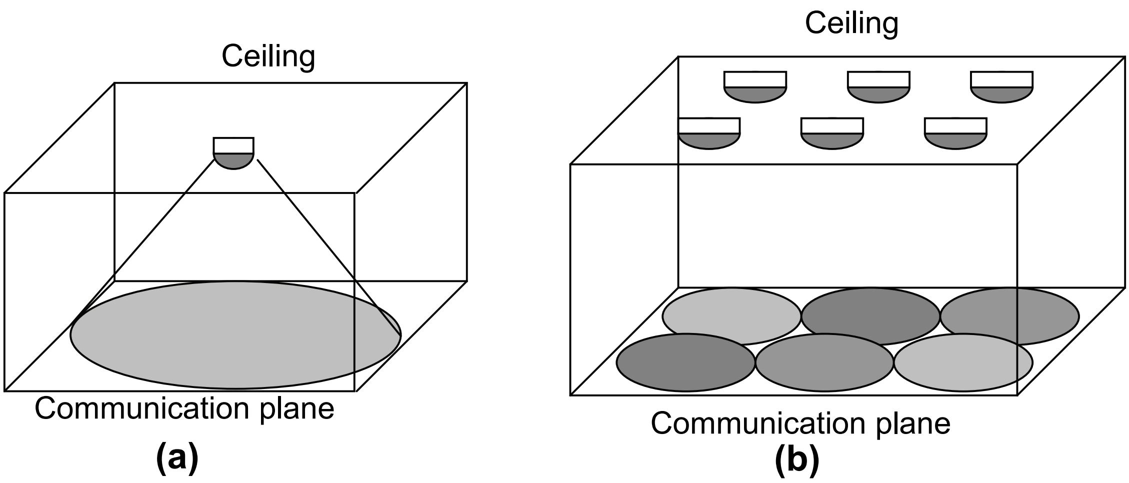


Figure 4-1: Ceiling module with wide beam configuration: a. single transmitter; b. array of transmitters

I propose a directed LOS indoor laser communication link that is able to connect multiple mobile devices to the backbone network optically as shown in Fig. 4-2.

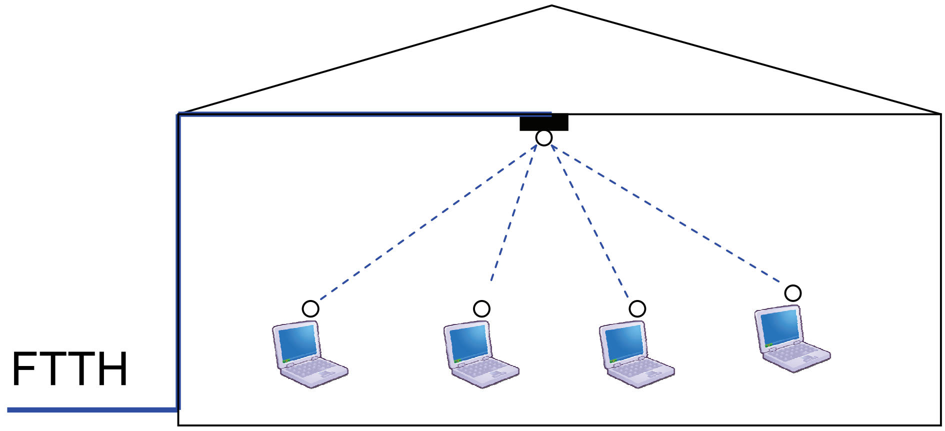


Figure 4-2: Directed LOS indoor optical wireless link [33]

To be able to locate the devices and track them during moving I propose a technique with MEMS mirrors (e.g. 2D MEMS mirrors as [69-70], Fig. 4-3a) and image sensors (e.g. charge coupled device (CCD) image sensor – Sony ICX694ALG [71], Fig. 4-3b, or Complementary metal–oxide–semiconductor (CMOS) image sensor Onsemi NOIV1SN5000A [72]) for tracking system thus guaranteeing a stable connection and full mobility of the user device in the indoor space. The chosen configuration guarantees best performance compared to similar optical wireless systems in terms of high speed and low power consumption. MEMS mirrors and image sensors make the system more complex, but compensate for it achieving best performance even for a mobile device. Furthermore, such design allows not only tracking for mobile users, but TDM for multiple users. Due to the direct fiber coupling the proposed scheme is independent on the signal wavelength, bit rate, multiplexing and modulation. For a practical use I describe a concrete example of an EPON [60], in which my system is the wireless connection between the OLT and a mobile indoor ONU (notebook, smart phone, etc.).

(a) **(b)**

Figure 4-3: a) 2D MEMS mirror; b) CCD image sensor

4.1.2 System design

The structure of the proposed system is divided in two subsystems – indoor area scan system and communication system (Fig. 4-4). The scanning system consists of an 850nm laser source, which beam is diverged and broadcasted (Fig. 4-4a). There are two possible configurations in terms of the diverged beam spot size and communication plane size. It is possible to have a widely diverged beam that covers the whole surface as shown in Fig. 4-1a. In this case the device is relatively simple, but the required transmit power is very high. The second possible configuration is to have a beam spot with smaller size and split the communication plane in cells as on Fig. 4-1b. Since my system relies on single ceiling transmitter, it is possible to use a MEMS mirror to move the beam spot between the different cells in a fixed pattern. I consider the case, when a single wide beam covers the whole area and MEMS mirrors are used only for the communication system. For link establishing I use the "Discovery processing" algorithm as described in [60], Section 64.3.3. The process is driven by the OLT, which periodically makes available Discovery Time Windows during which offline ONU's can make them known to the network. Periodicity of these windows is unspecified and left up to the implementer by standard. The OLT Discovery Time Windows is synchronized with the 850nm laser source driving system thus guaranteeing a laser signal broadcasting in the whole indoor space during these windows. The time between two time windows is defined to be one to several seconds to guarantee fast discovery of an ONU when it enters in the area of coverage.

The lack of constant laser emission increases the power efficiency of the proposed method. When a mobile device enters in the covered area, it receives the pulse. According to the position of the ceiling transmitter and device receiver, there will be a different angle of arrival (AOA) in the receiver aperture that can be registered with the usage of an image sensor (Fig. 4-4b), [73]. Based on the received spot position, a MEMS mirror can be moved to point the communication channel of the mobile device to the ceiling transmit aperture. Then after a random delay (as defined in [60]) the mobile device sends a signal, acknowledging its presence in the coverage area (REGISTER_REQ, [60]) to the ceiling unit and respectively it reaches the OLT. For this purpose it uses its laser source (Fig. 4-4b) that reaches directly the ceiling receiver aperture, due to the earlier pointing of the MEMS mirror to it. When this signal is received in the ceiling-module image sensor, the mobile ONU's position is decided and the MEMS mirror is adjusted to point to its aperture. The next step in the process is for the OLT to transmit a Register message to the ONU, containing the ONU's LLID, and the OLT's required synchronization time. Also, the OLT echoes the maximum number of pending grants. The OLT schedules the ONU for access to the PON and transmits a standard GATE message allowing the ONU to transmit a REGISTER_ACK. Upon receipt of the REGISTER_ACK, the discovery process of the ONU is complete and normal message traffic can begin [60].

The communication system is based on direct fiber coupling so the signal, coming from the OLT is directly sent in the downlink and the uplink signal is directly sent back to the OLT. In different cases wavelength converters could be necessary because of the system independence to the optical signal characteristics. In the EPON example the downlink wavelength is 1490nm and the uplink wavelength is 1310nm.

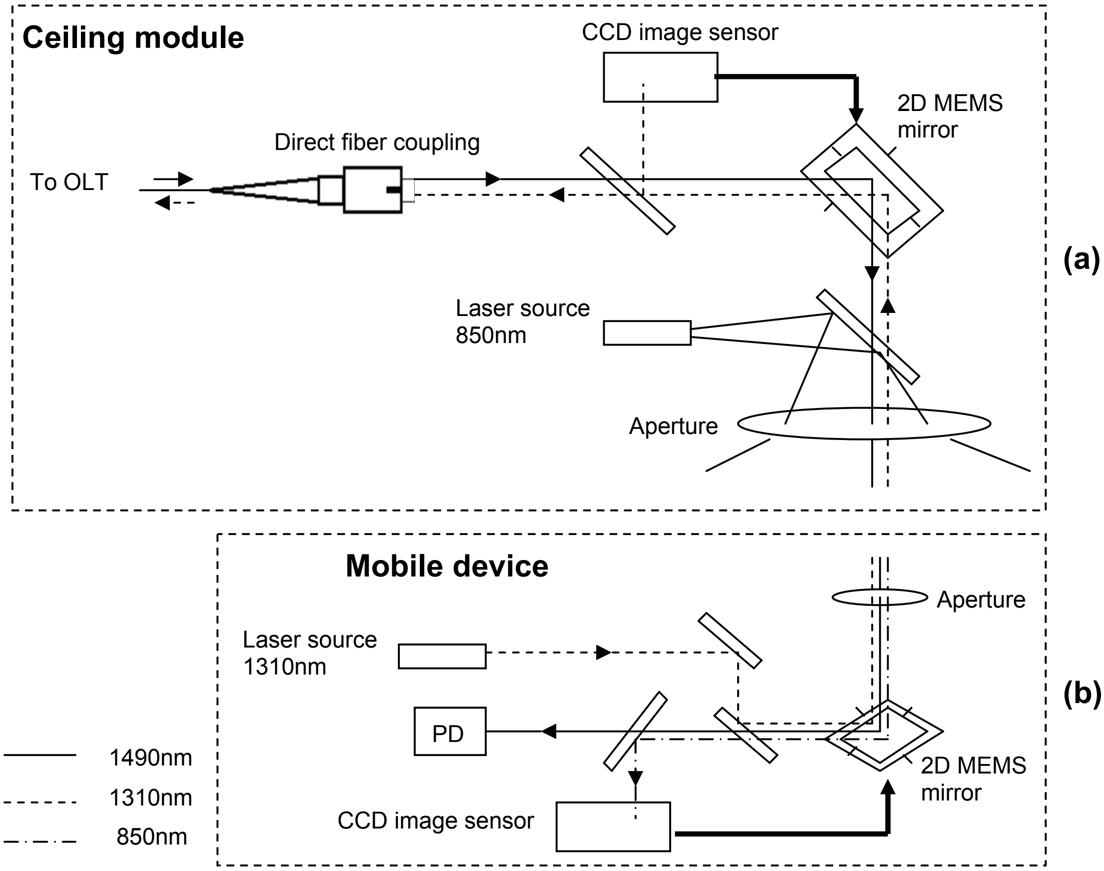


Figure 4-4: System design: a. Ceiling module; b. Mobile device module

The real time tracking of the link during the communication is maintained by separating a part of the communication signal and sending it constantly to the image sensors in the both receivers thus guaranteeing constant MEMS mirror correction with the frequency of the communication signal so that normal movements would not interrupt the communication link. The tracking system allows the use of narrow beams for both uplink and downlink which increases significantly the received power and relatively lowers the BER. It is important to consider that systems with two independent MEMS mirrors have a state, in which both mirrors are constantly moving trying to compensate for the movement of each other. This effect is normally compensated by establishing a sequence for the MEMS mirrors in which they adjust their location to guarantee that one mirror is not moving when the other one is adjusting the beam. More deep study of this effect and possible solutions will be conducted in future work.

It is important to note that I concentrate on the basic principle of the proposed system and analyze its characteristics in terms of BER. For simplicity I consider a PAN with a single mobile device in the indoor space. Actually the system can be used for multiple mobile users with some differences and further complexity. First, the position scan system will collect updated information about the position of all the users and checks if a user joins or leaves the network. Also, multiple access technology must be considered. In this case the MEMS mirror will not just be used for tracking system for the current link, but also to switch between users that would resemble a TDM. Due to the mobility of the devices, it is easier to update the table with all the device positions every time without saving the previous data. Thus, each time a device is connected a new session sequence must be performed. Such solution will slightly decrease the system performance but will eliminate possible device confusion and data mismatch. A complete design of an indoor system for multiple users based on the proposed method will be built in future research when all the extra complexities are considered and particular design is made.

4.1.3 Results and discussion

Assuming that the relative photodiodes for uplink and downlink connection according to the laser wavelength and equal ambient noise are used, the BER for the both links will have the same value for equal transmit power and beam spot size. For OOK modulated signal the BER of the system can be calculated by:

$$BER = 0.5 erfc\left(\sqrt{E_b/N_0}\right) \quad (4.1)$$

where the bit energy $E_b = P_{Ar}/B$; P_{Ar} is the received power and B is the bit rate of the link. The noise energy is $N_0 = P_N/B_N$; P_N is the noise power and B_N is the receiver bandwidth.

In Fig. 4-5 the relationship between the received optical power and the BER of a system with 1Gbps link is shown. The ambient noise power normally is in the order of several μW, [59], so I choose $P_N=10\mu W$ and receiver bandwidth $B_N=6.99GHz$. Because of the short distance I assume that there is no path loss so that $L_p=1$ and transmitted and received power are equal. As mentioned above, it is important to assure link availability for mobile users and have in mind the possible tracking error. For this reason it will be better to use a beam with small, several-centimeter spot to guarantee better performance. In Fig. 4-5 three cases of laser beam for a short indoor line with fixed small receiver aperture with diameter D_r=*10mm* are shown. For calculating the narrow beam BER it is assumed that transmit and received power are equal. For the wide spot though, I use equation (2.12) for the received power and calculate the BER for the case, when the receiver is at the end of the beam spot (next to the beam waist), where the received energy will have minimal value.

From the graph can be seen that due to the tracked narrow beam the required received power is very low- for BER=10^{-12} received power of about -15dBm (32μW) is required. Using wider beam spot though increases the transmit power to several mW, but link unavailability due to tracking errors or fast movements is less possible.

If the light enters in a human eye that would mean the link is broken and laser emission will be stopped. Therefore, considering eye safety the power restrictions not for a long-time exposure to continuous wave, but for short-time accidental exposure should be applied. That would allow the usage of higher levels of transmit power compared to Hybrid and Non-directed configurations, where constant laser exposure is observed.

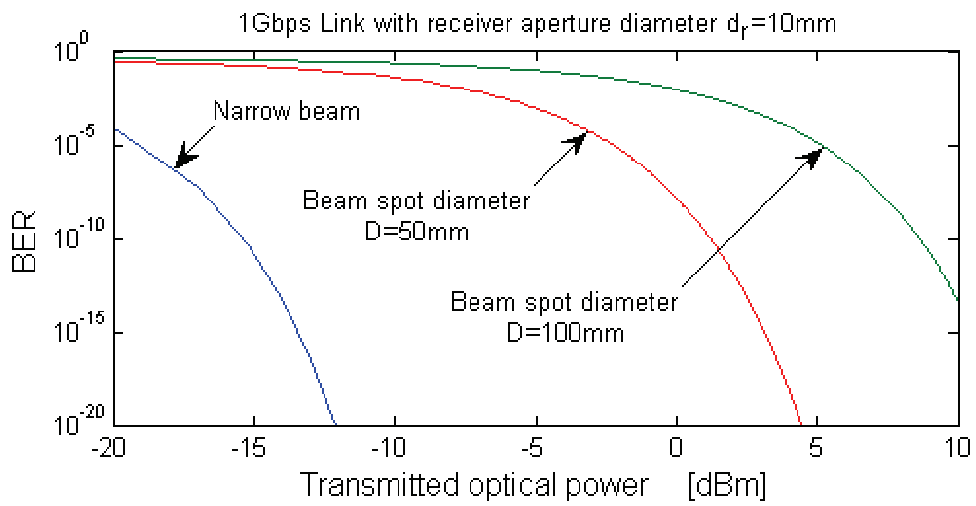


Figure 4-5: Relation between BER and Transmitted optical power for 1Gbit/s indoor laser link

From Fig. 4-5 it can be concluded that the downlink covers the requirements for a Class 1 laser product even for long-term exposure [36-37]. For the uplink, due to the shorter wavelength, the allowed transmit power is limited but for accident eye exposure it is still safe. Furthermore, the extremely small levels of transmit power make the proposed system power efficient, especially if narrow beam can be used.

4.1.4 Conclusion

In this section a high-data rate (1Gbps) directed link for mobile users has been presented. The system uses the EPON initialization protocol for new devices to find new users in range and adjust the MEMS mirrors for communication. The proposed link has excellent performance in terms of high speed and low power consumption (≤10mW), compared to other configurations. However, due to the need to establish and maintain a directed link, the both ceiling module and mobile device side are quite complex and expensive. Furthermore, the mobile side has extra power consumption for the pointing process and the two independent MEMS mirrors need special sequence for tracking that will be a subject of future study.

4.2 Custom LOS hybrid indoor OWC network for mobile users

4.2.1 Introduction

As discussed in Chapter 3, the non-directed configuration has the advantage of simple design and no need of handover. However, the transmit power is high and the link speed is limited. In Chapter 4 I proposed a directed configuration, working with EPON protocol. Its power consumption is very low (≤10mW) and the speed can be more than 1Gbps with very big coverage. Main problem is the complicated mobile side due to the tracking system. By combining the two configurations a hybrid system, combining the advantages and eliminating the disadvantages can be created.

I propose a hybrid configuration with directed narrow beam in the downlink for 10Gbps connection and non-directed uplink for 1Gbps speed (Fig. 4-6). Also, a positioning and tracking system for the downlink beam spot is presented.

The downlink in the proposed system uses technology that provides seamless connection between the fiber and the air [2]. This allows us to send directly the high speed optical signal from the OLT wirelessly to the user device at the same wavelength as in the fiber network (1550nm). To assure proper reception of such signal though, I have to consider the receiving PD in terms of its size and capacitance that could lead to narrower bandwidth. Therefore, it is important to keep the beam spot very small and use precise location and tracking system. For tracking, I use the same technology, as previously proposed in [74], where the laser beam is directed to the receiver by using 2-dimension MEMS mirror. Similar directed configuration is proposed already in [75]. However, authors considered Wi-Fi network for device localization. That would increase the power consumption in the mobile side. Furthermore, the localization method is not very precise and the beam spot is relatively wide. As a result, the transmit speed is limited to 1Gbps as my proposed non-directed uplink. Another important matter is the direct fiber coupling in the uplink in both [74] and [75]. Such technology is quite expensive and limits the uplink wavelength to the wavelength to be used in the fiber network. In the proposed design I consider direct detection in a PD and later conversion to optical signal with wavelength, appropriate for fiber transmission thus allowing the system to use different wavelengths in the wireless media.

In order to be able to direct the narrow beam spot to the small receiver aperture (≤1cm), the exact receiver location should be estimated very precisely. In my previous research I have used a scanning system on the ceiling with a light source sending pulses on a short interval of time. The tracking of both uplink and downlink was achieved by completing the EPON protocol for finding new network devices. However, in that research the mobile device also participates as an active side in the localization process. Also, the tracking in the uplink is complex and expensive. I propose a new scanning system design, in which the locations of all the available mobile device receiving apertures are found without activity on the user side as shown on Fig. 4-7.

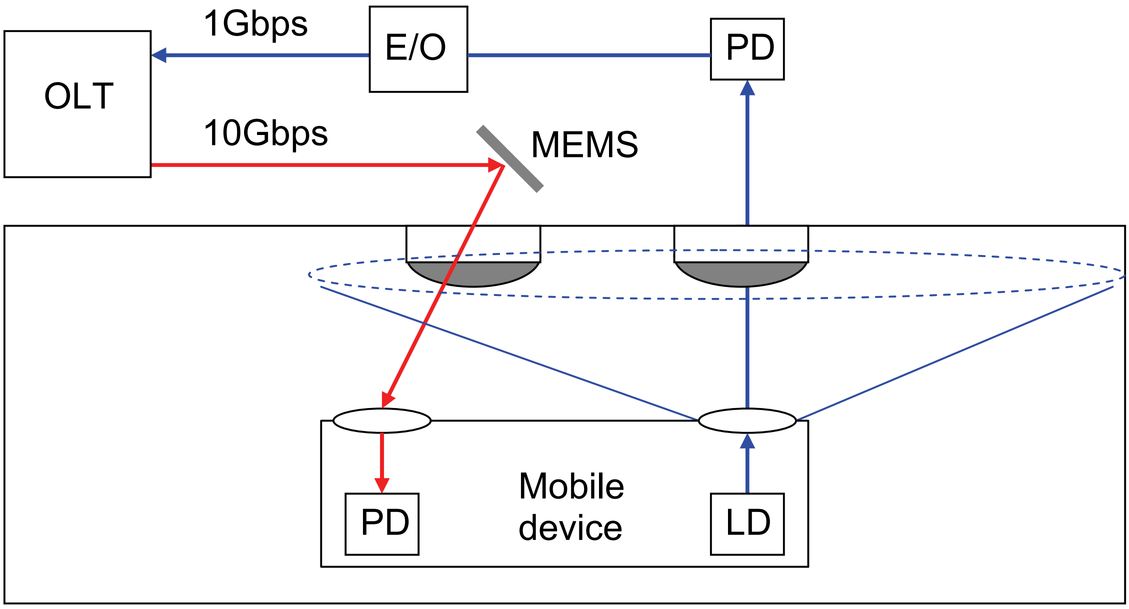


Figure 4-6: Proposed system for hybrid indoor LOS network

4.2.2 Positioning system

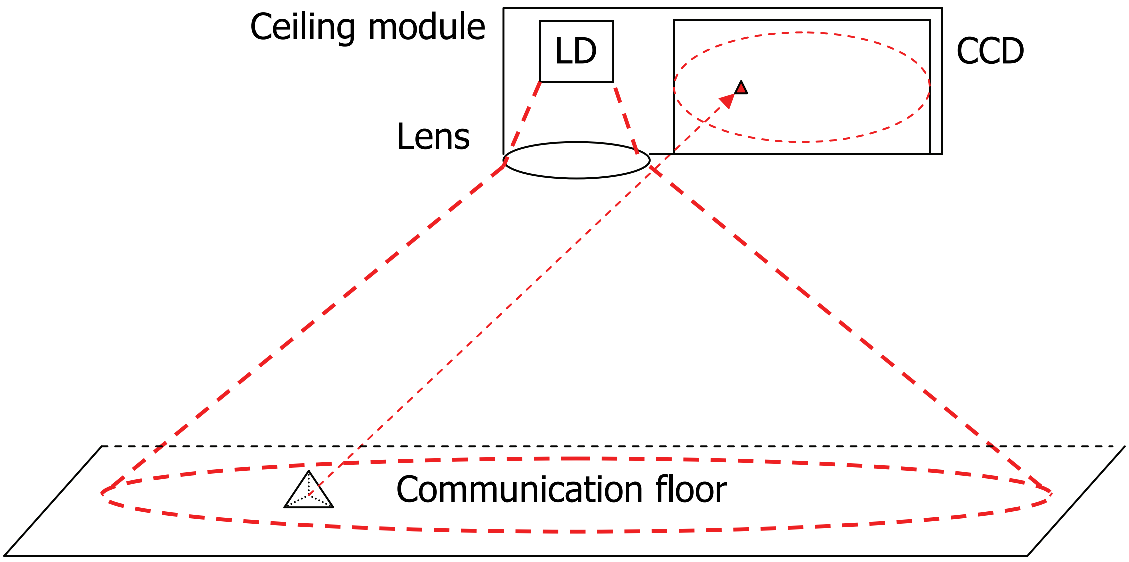


Figure 4-7: Positioning system

A laser diode, forming a wide beam spot sends pulses on fixed intervals of time. When the optical signal reaches a mobile device, part of it is reflected from corner reflectors, situated next to the receiving aperture, and returns to the CCD sensor. The number, size and location of the corner reflectors can vary for different systems and applications. The position of the device is obtained from the imaging sensor. The usage of a corner reflector simplifies the mobile device decreasing its price and power consumption compared to my previous research [74] and allows using of non-directed uplink.

The main problem to be discussed in the localization system is to recognize the corner reflection in the image sensor. Therefore, the lens focal length and sensor resolution must be considered when building the system. The three important parameters are FOV, defined as area under inspection that the camera needs to acquire, smallest feature – the size of the smallest feature that must be detected in the image and the working distance – distance from the front end of the lens to the object under inspection.

For the resolution I use the ready formula from [76]:

$$SR = 2(FOV/SF), \tag{4.2}$$

where SR is the sensor resolution and SF is the smallest feature. The coefficient 2 shows that the smallest element will be represented in the image sensor by two pixels.

The focal length f_L can be calculated from the formula [76]:

$$f_L FOV = S_S D_W, \tag{4.3}$$

where S_s is the sensor size and D_w is the working distance.

4.2.3 Downlink with tracked narrow beam

The downlink scheme is shown on Fig. 4-8. The optical signal from the OLT with transmit optical power P_t is sent to the ceiling transmit module (CTM). The usage of EDFA is necessary because of the tight link budget. The optical gain is limited to 10dB so that Class 1 laser eye safety regulations are obeyed. To point the beam directly to the receiver aperture of the mobile device the location data from the imaging sensor of the positioning system is used to adjust the MEMS mirror. Advantage of the MEMS mirror based tracking system is that the mirror can be used not only to establish and maintain a link with a mobile device (MD), but also to switch between different devices achieving time-division multiplexing.

The received optical power in the PD P_{Ar} can be described as a function of the transmit power P_t with equation (3.3).

There are two main loss components in the total loss L_{tot} when link budget is considered (equation (3.2)) – the coupling loss $L_{coupling}$ and loss due to partially received beam in the receiver aperture L_{beam}. Also, a reasonable loss margin L_m should be included. In best case scenario the $L_{beam}=1$ and all the beam optical power enters in the receiver aperture. However, if the beam is wider than the receiver aperture, that would ensure better connectivity in case of positioning and tracking error or device movement. L_{beam} can be calculated as the ratio between the total transmit power in the beam spot with beam waist r_z, and the received power P_{Ar} in a receiver aperture with diameter d_r on distance r_1 from the center of the beam spot with the approximation from equation (2.12), where $P_D=L_{coupling}P_t$ is the total power in the beam at the receiver plane.

The current in the PIN-PD with responsitivity ρ_{RX} from the received optical signal can be derived from equation (3.4).

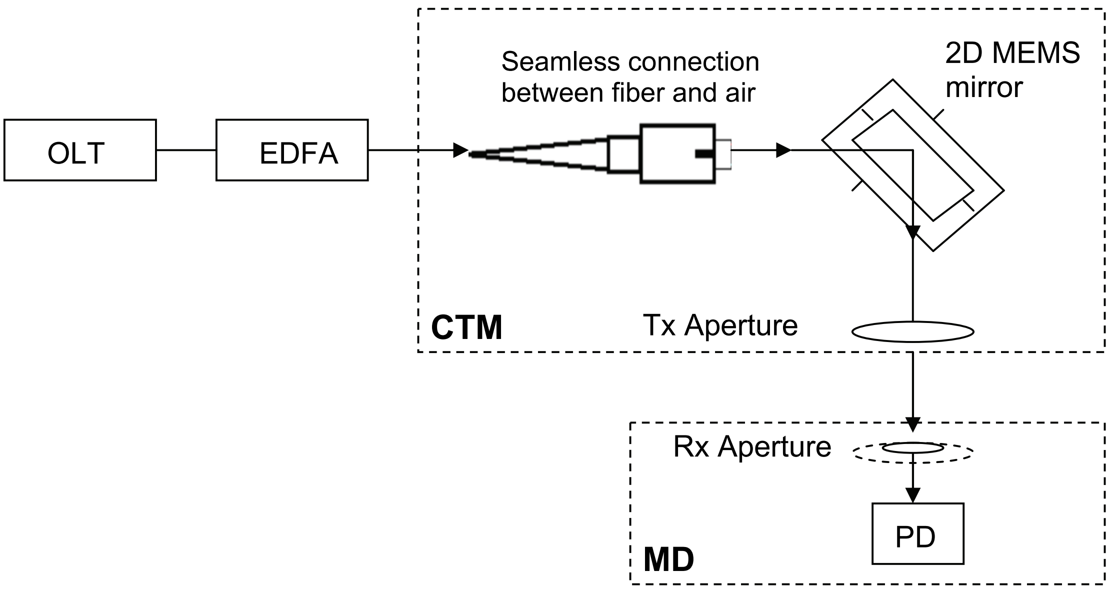


Figure 4-8: Downlink scheme

Since the proposed system is LOS, it is assumed that there will be no multipath distortion. I calculate the SNR in the proposed system by using equation (3.5). The noise with the noise components have been described already in equations (3.6 – 3.10). The final formulas for the SNR and BER are already provided in equation (3.11) and equation (3.12).

4.2.4 Non-directed uplink

Of special concern is the uplink in an indoor optical wireless system especially in the MD. The transmitter must be simple and cheap with low power consumption. Using a directed uplink as in [74] will result in extra complexity. I propose the usage of diverged beam for the uplink as shown on Fig. 4-9. To guarantee the receipt of the uplink signal I propose the usage of a grid of ceiling receivers as in [77]. The transmit power will be relatively low due to the bigger receiver aperture and lower bit-rate, compared to the downlink. Compared to previous research [77], where I proposed direct coupling to the fiber in the proposed system the optical signal is directly received in a PD with TIA is used. Thus, the need of EDFA and expensive direct coupling to the fiber is eliminated. Furthermore, it is much easier to use a receiver module (RxM) to decide which of the multiple received signals to use and process further to the E/O module instead of synchronization of the network. Another very important feature of this design is the possibility to have different wavelengths in both wireless and fiber part. For example, 1550nm wavelength can be used in the wireless part because eye safety limit is much higher and later the signal can be changed to different wavelength in the fiber according to the standard.

In the uplink, the same mathematical model as for the downlink can be used. However, it is important to note that there is no coupling loss $L_{coupling}$, no ASE noise component and no optical gain.

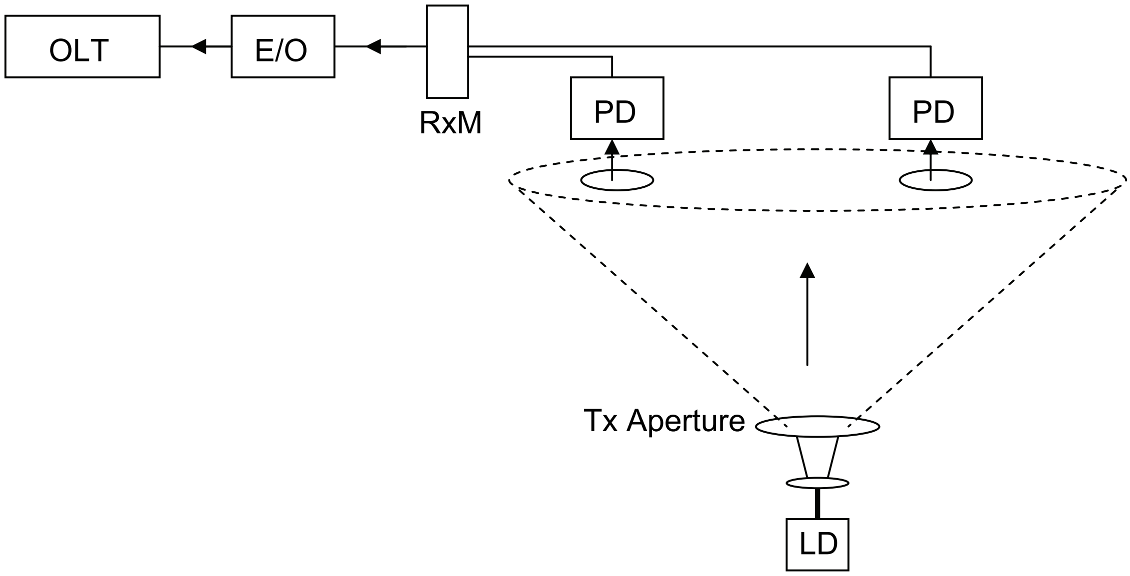


Figure 4-9: Uplink scheme

4.2.5 Results and discussion

For proper operation of the proposed system a careful design of the localization system is required. By equation (4.2) the sensor resolution *SR* can be calculated. For example, if the corner reflector has a side of 2mm and the FOV is 3m x 3m, a sensor resolution of 3000 x 3000 pix or totally 9Mpix is necessary to be able to detect the reflector. If the detection system is located on the ceiling and the working distance between the ceiling and the communication plane is 2m, from equation (4.3) the focal length for a sensor with size 1/2.33" can be calculated to be 25mm or less. From these calculations a conclusion that a localization system with FOV 2 to 4m is realistic can be derived.

By using equation (3.12) the BER in the both downlink and the uplink can be calculated. In Table 4.1 some of the parameters, used for the calculations, are shown.

On Fig. 4-10 is shown the relationship between the BER and the transmit power for two different receiver apertures and beam spots on the ceiling. As can be seen, reliable errorless 1Gbps uplink can be created by positioning multiple receivers on distance 2 to 3 meters from each other. Considering the similar results for the localization system capabilities, from engineering point of view it is best if the uplink ceiling receiver and the localization system are combined in a single unit and such units form a grid on the ceiling.

It is important to consider also the transmit power levels. The power is limited to 10dBm, which is the emission limit for class 1 safety products for 1550nm wavelength. If shorter wavelength is to be used, the transmit power should be decreased more and the receiver apertures must be bigger.

On Fig. 4-11 is shown the relationship between BER and the optical gain of the EDFA. The transmit power of the OLT is fixed by the manufacturer and I considered 0dBm for the calculations.

Table 4.1: Mathematical analysis parameters

Parameter	Symbol	Value
Photodetector responsitivity	ρ_{RX}	0.8
Absolute temperature	T	300K
TIA load resistor	R_{in}	3500Ω
Orthogonal Polarization factor	m_t	2
Population inversion factor	n_{sp}	2.25
BP filter bandwidth	$\Delta\nu_f$	$12.4\text{x}10^9$Hz
Fixed fiber losses	L_c	5dB
OLT output power	$P_{t,d}$	0dBm
Receiver dark current	I_d	4nA
Ambient noise power	P_{BN}	10μW

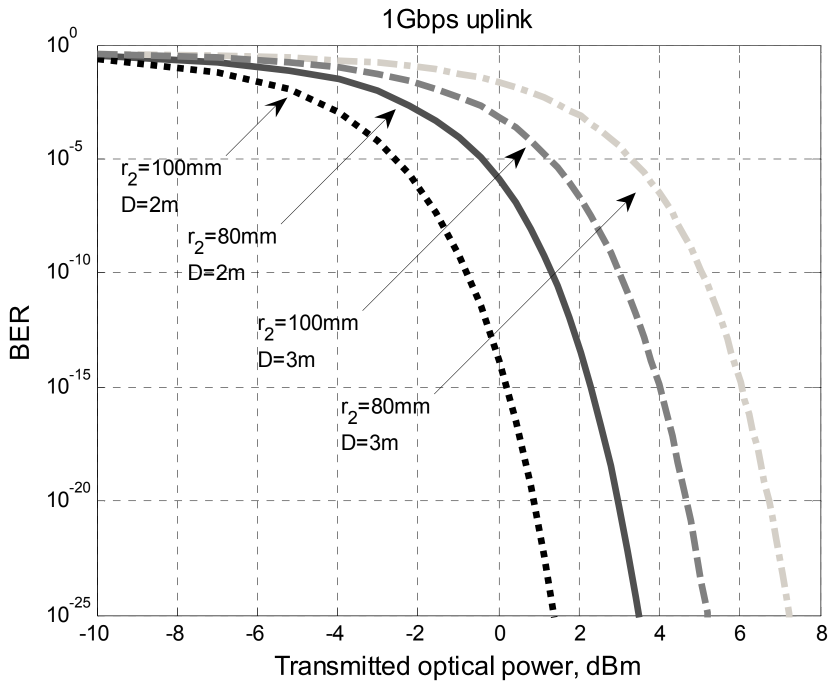


Figure 4-10: BER vs Transmitted optical power for a 1Gbps Uplink

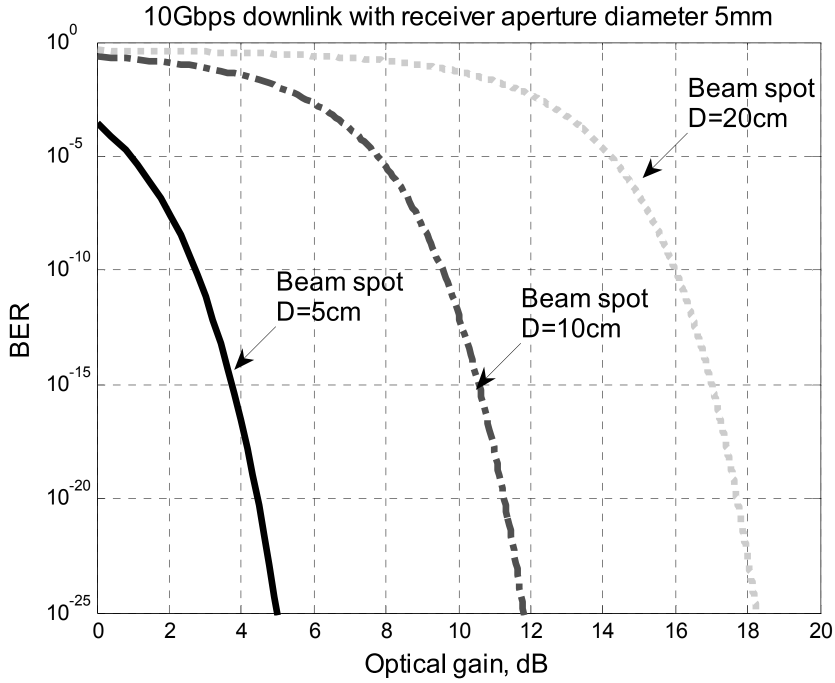


Figure 4-11: BER vs Optical gain in a 10Gbps downlink

To ensure that the laser beam will reach the receiver aperture even with some localization error and to mitigate link breaks due to small movements I use a beam spot, slightly bigger than the receiver aperture. The results for several different beam spot sizes are shown but must consider that the optical gain is limited to 10-15dBm due to eye safety limitations. Although the performance appears to be good even when no EDFA is installed, the tight link budget requires it.

4.2.6 Conclusion

In this section a high data rate hybrid indoor infrared optical wireless with novel localization system has been proposed. The all-optical downlink and directed narrow beam allow downstream speed of 10Gbps. My analysis shows that such design also leads to very small receiver aperture (5mm considered in the calculations) that basically allows the system to be integrated in all mobile devices. So far, with non-directed links as in Section 3 the receiver aperture size is calculated to be not smaller than 1-2cm diameter.

In order to be able to point the beam directly in the receiver aperture, a very precise localization system is necessary. I have proposed a localization system with multiple ceiling modules, containing a laser diode and imaging sensor that is able to identify very small objects (2mm size was considered). The system has better performance than the one in Section 4 because the mobile device is passive – instead of laser diode to send signal to the localization system, a corner reflector is used to reflect the light, sent from the ceiling module. In the uplink I have used a grid of ceiling receivers as in Section 3. My analysis shows that it is possible to combine the localization system and the uplink receiver in a single module and use these modules to form a grid in the ceiling located at 2-3 meters from each other.

CHAPTER 5

CRITICAL ANALYSIS OF THE RESULTS AND PERFORMANCE ENHANCEMENT

5.1 Critical analysis

In Chapter 3 and Chapter 4 I have shown the performance of the three LOS configurations for the proposed indoor IR system with Gaussian beam propagation.

The non-directed LOS link, considered in Chapter 3, provides a high speed 1Gbps symmetric connectivity. Also, by simple WDM multiplexing it provides TV signal broadcasting. However, there are several design and performance issues that would turn the system into bottleneck in future high-speed networks. First, to be able to achieve big coverage in the communication plane in the downlink, it is necessary to widen the beam as much as possible. While a highly diverged beam can cover the whole indoor space, my theoretical analysis shows that the received power levels become extremely low. To be able to receive an optical signal, strong enough to guarantee sufficient SNR it is possible to increase the transmit power. However, because of the close contact with human eyes, there are strict limitations due to eye safety considerations. Furthermore, the proposed system is assumed to become a part of already deployed EPON network which results is already set transmit power values. The only way to increase the transmitted optical power in the wireless part is by using an optical amplifier, for example EDFA which also has limited possibilities. The proposed solution in my work is to deploy a grid of ceiling transmitters with smaller beam sizes (in the order of two-meter diameters) to cover the whole space and provide good connectivity. As can be noticed, the main drawbacks in the downlink are the system complexity and high price due to the optical amplifier and multiple transmitters, low possible speed and big receiver aperture (1-2cm diameter). In the case of OOK-modulated signal, such link design will not be able to propose speeds higher than 1Gbps for several reasons. First, it is difficult to collect enough power and send directly to a small size PD. As discussed in Chapter 2, the size of the PD has very strong effect on its bandwidth. Also, the simulation results show that even with the current configuration with multiple small beams the system cannot transmit 64-QAM signals for the TV transmission which further limits its capabilities. The big receiver aperture in this design limits the technology implementation in portable devices – it can be included in laptops but for tablets and smart phones smaller size is necessary. Another important issue to consider is the overlapping of the neighbor beams and the interference that will arise. As shown in the analysis the signals in the overlapped areas will have big difference in the levels and the delay is in the order of hundred nanoseconds. This can guarantee flawless system performance for speeds of hundred Mbps or 1Gbps, but the effect will be significant for faster speeds. Advantage of the proposed network is that it is possible to use the multiple beams to form different Pico-cells in the communication plane thus guaranteeing 1Gbps network access in each different cell. Such solution though would require handover handling system.

The uplink in the non-directed configuration has very good performance in terms of speed (1Gbps). In the non-directed configuration the uplink assumes that there is a grid of ceiling transceivers in order to provide full downlink coverage, so that if in the uplink a beam with similar size is used it will reach at least one ceiling receiver. The first concern in this design is the diverged beam on the mobile side that leads to higher transmit power levels. My analysis show that the transmit power is not so high compared to RF systems because the ceiling receiver aperture has much bigger size than the small aperture in the mobile device in the downlink. On another hand, the wide beam also limits the possible speeds in the link. Very important is to mention the direct fiber coupling technology, implemented in the ceiling receivers. While it allows direct transmission of the wireless signal to the fiber network there are several drawbacks of this method. First, currently this method is extremely complex and expensive and the setup time will be quite long. On second place is the fact that the wireless link is limited to use only the wavelength, prescribed for usage in the fiber network uplink. Another important issue to consider is the interference in the case when more than one ceiling receiver receives the upstream signal and the complexity to reduce this effect on optical level.

The non-directed uplink has been significantly improved in the hybrid system, proposed in Chapter 4 (Fig. 5.4). The optical signal that reaches the ceiling receivers is directly converted into electrical one in the PD. While such solution requires E/O conversion of the signal to be sent into the fiber network it has several advantages. First, the wavelengths of the wireless link and the fiber network can be different which allows the usage of different wavelength in the wireless part, for example 1550nm for links where high transmit power is necessary and eye safety regulations must be obeyed or cheap 850nm IR LD for low cost solutions. Second, because of the direct receiving in the PD, the link budget is much better than the one with direct fiber coupling, where extra losses are inserted. This fact eliminates the necessity of optical amplifier in the uplink. Finally, a new receiving module can be used to compare the electric signals from all the ceiling receivers and chose only the strongest one to pass to the fiber network.

While the non-directed configuration proposes simple network with very good coverage its speed possibilities are limited and the power consumption is higher than the one in directed links, as shown in Chapter 4. So far, directed links are considered only for point-to-point communication and main issue in them is the establishing and maintaining of the link. In this thesis I have presented designs with two different positioning systems and a tracking system that allow switching of the point-to-point link between users and thus by implementing of TDM a point-to-multipoint or multipoint-to-multipoint network can be created. The system is relatively complex because of the positioning and tracking system but offers speeds close to the fiber ones (10Gbps). Another important advantage is the possibility to decrease the receiver aperture size to less than 5mm allowing system implementation in all portable devices and high speed connection (wide PD bandwidth). Because of the narrow FOV the transmit power has very low levels and for most configurations optical amplifier is not required which significantly reduces the price. Furthermore, low power consumption will increase the operation time of the mobile device.

It is important to note that the downlink design in the Hybrid configuration, presented in Chapter 4 lacks a mechanism on the receiver side for axis alignment. In the directed configuration alignment is achieved due to the MEMS mirror and imaging sensor on the both sides. However, it is necessary to include extra equipment to compensate the angle of arrival in the PD in the mobile device and increase system performance. One possible way to do that is to send a part of the received optical signal to a slow quadrant photodiode that can detect the beam deviation. The deviation data can be used by a micro motor to adjust the fast-speed receiving PD and achieve axis alignment.

With the new applications and possibilities of portable devices as games and video conversations in future communication networks asymmetric links are expected to be changed with symmetric ones. Indoor IR network with directed configuration would allow multi-gigabit symmetric connectivity.

The work presented in this thesis can be used as a base for future design of indoor IR communication systems. It offers complete transmission analysis of all configurations for LOS links. However, because of the link analysis the work was limited to single device and only point-to-point communication is described without presenting a concept for multipoint-to-multipoint network.

5.2 Performance enhancement – multipoint-to-multipoint network

As stated above, indoor IR communication systems are proposed as an alternative of the RF networks for indoor spaces with high user density where the required bandwidth is very big and only optical signals can achieve it. Therefore, it is important to consider an indoor OWC network that can handle multiple mobile devices.

5.2.1 Localization system

The first issue to be addressed in a multipoint-to-multipoint network with mobile devices and directed link configuration is to be able to find the location of all the devices and refresh the data fast enough to guarantee easy link establishing. The localization data should be collected and stored in memory forming a table as shown in Table 5.1, from where the switching system can derive device position data and cyclically establish connection to all devices.

Table 5.1: Device position information table

Device ID	Device position
1	position 1
2	position 2
…	
N	position N

In terms of switching pattern it is important to consider also the communication protocol capabilities. For example, the EPON network and the DTW allow resetting each session after each disconnect in the TDM. That leads to two possible solutions in the current design. First, when a device enters in the indoor space, during the DTW it will be assigned with LLID. Then all the devices will be switched in order, determined by their initial LLID and the sessions will not be reset. Such solution would theoretically provide better service since each device will have a data transfer window at the same time as shown on Fig. 5-1. However, for mobile devices it is possible to have some movements and mix the original positions. That can lead to mismatch between the localization system and communication layer. Furthermore, the switching times will increase since the logically neighbor devices are no longer neighbors in space (see Fig. 5-1).

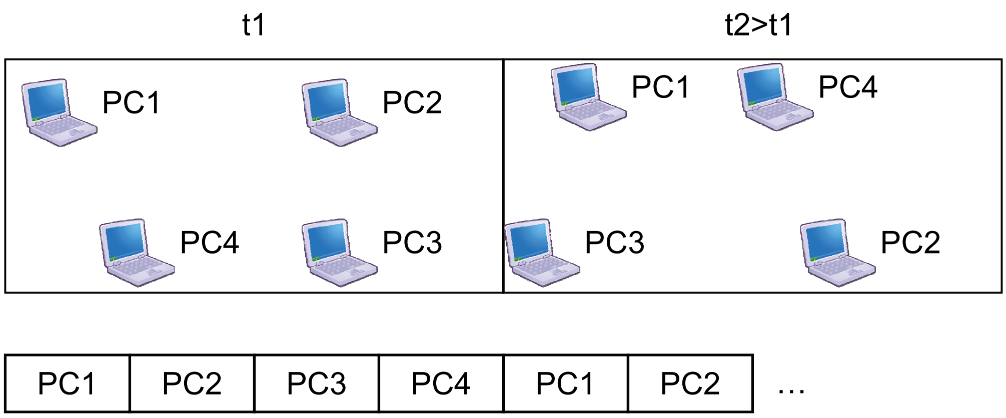


Figure 5-1: Position of mobile devices and data transfer windows in a cycle

The second possible solution is to reassign a new LLID each time a device is found. Such approach will decrease the system capacity since in each DTW the devices must be reassigned. Also, it can degrade system service since the time windows for data transmission are not the same in each cycle. In this scenario though, there is no danger of mismatch between the localization system and the network layer.

The localization system itself can have several different designs. In terms of modules, respectively imaging sensors, it can have a single sensor or a grid of sensors. However, as CCD sensor resolution calculations in Chapter 4 show, a single sensor cannot collect enough data from big spaces except it has very high resolution. This is the primary reason to propose a grid of low-cost sensor with combination of LD sources to cover wider indoor spaces. There is another method that was not discussed above. This is the case when a single imaging sensor is used and either expensive sensor with very high resolution is used or by MEMS mirror different areas are scanned with a sensor with low resolution as shown in Fig. 5-2. One of the advantages of this method is that the positioning system will actually detect only devices in LOS. In the case of grid, complete position information about all the devices will be received but still there is no guarantee that there is LOS between the ceiling transmitter and the portable device as shown in Fig. 5-3. When the positioning system is based on single imaging sensor with MEMS mirror though, it will need more time before being able to refresh the devices position in the same area again. That can have effect on the link if the portable device moves very fast. To minimize this issue it is possible to create a refresh algorithm where all the devices are refreshed in the DTW, but when a communication with a particular device starts, the imaging sensor is actually scanning only the area, where the device being connected is located. This method will increase the system reliability in cases of fast device movements.

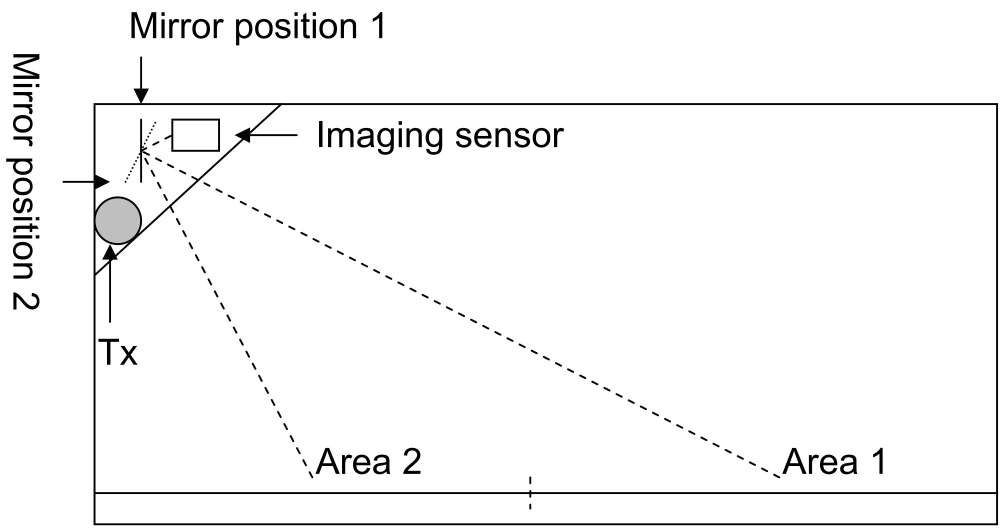


Figure 5-2: Positioning system with a single imaging sensor

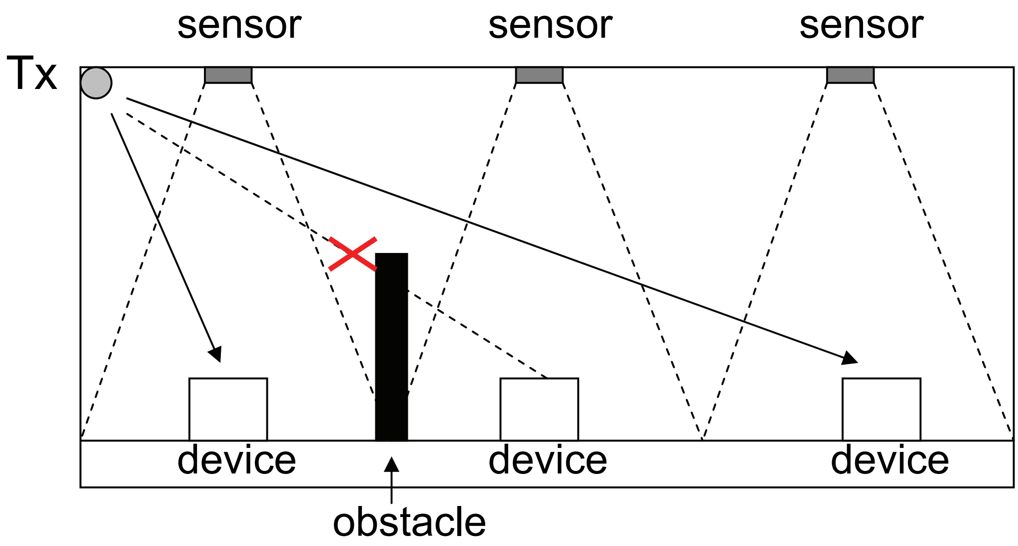


Figure 5-3: LOS issues for design with single transmitter and grid of sensor modules

Another viable solution to eliminate the effect of fast movements is, as already mentioned in Chapter 4, to widen the beam spot diameter. This would allow some small movements before actual link disconnect and will give more time to refresh the positioning system and adjust the tracking system before link interruption. Another advantage of wider beam spot is the fact that it compensate for positioning system errors. For example, in the proposed technology with corner reflector on the mobile side, the corner reflector will be located next to the receiving aperture which will lead to positioning error. The drawback of such method is that the received power in the receiver aperture, and respectively the PD, will only be a fraction of the total beam spot power which, as shown in Chapter 4 can lead to the necessity of optical amplifier in the downlink.

Big disadvantage of localization system with passive mobile side is the fact that the imaging sensor can actually detect reflections from other objects in the scanned area. This problem can be mitigated by using special patterns in the portable device, for example, several corner reflectors forming a recognizable pattern. Another possible solution is to send signal to each detected point and if there is no answer during the DTW to assume this is a false reflection. Data with false reflections must be stored in a table so that when devices' position refresh occurs and new devices are possible to be detected the system can filter only the real communication devices. Another technique that can guarantee better performance is to remove the laser source from the ceiling module and the imaging sensor will actually wait to detect a signal from portable device that want to connect to the network.

5.2.2 Tracking system and multiple devices

The positioning system able to detect multiple portable devices has been discussed above. The tracking system is based on 2D MEMS mirrors for two main reasons. First, when a device changes its position, this change will be registered by the positioning system and the MEMS mirror will be adjusted to the new location. The refresh rate is limited from the CCD, where low-cost solutions would provide 20-30 fps. Second, MEMS mirror can be easily used for time-division multiplexing since its position can be used not only for mobile device tracking but also for switching between different devices. It is important to consider that the MEMS switching time is extremely long and the sequence switching/communication time should be balanced for maximum performance. Another possible solution is to have several transmit modules working together. Such design would mitigate the switching time issue (Fig. 5-4) and guarantee better coverage since LOS communication can be possible for one transmitter when another one is in shadow (Fig. 5-5).

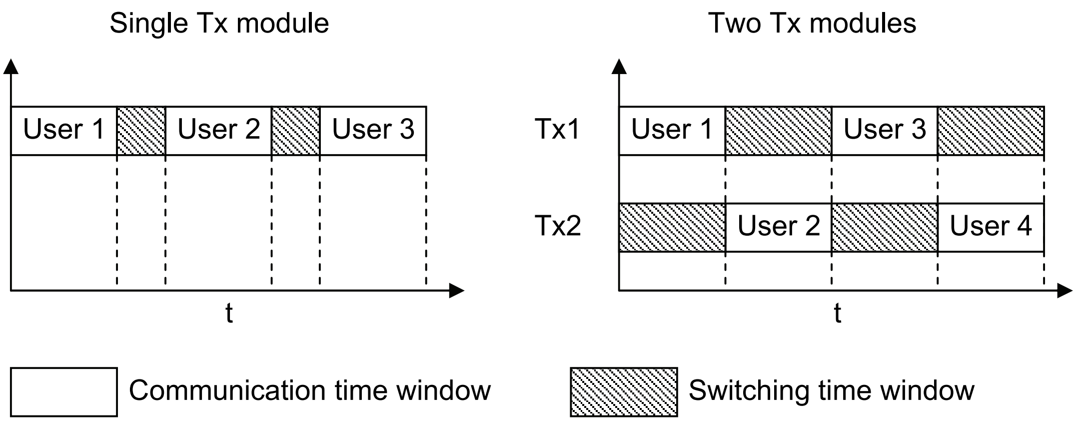


Figure 5-4: Communication and switching time windows for system with single and double transmitters

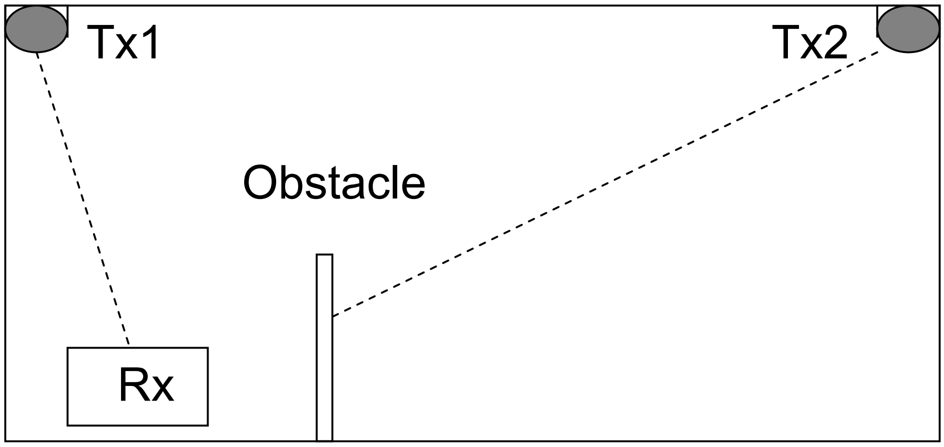


Figure 5-5: Better coverage with multiple LOS transmitters

5.3 Conclusion

Some basic issues when the proposed system is implemented in point-to-multipoint and multipoint-to-multipoint network have been discussed. One of the main areas for improvement is the localization system. The current solution in the hybrid configuration is quite complicated and cannot guarantee LOS between receiver and transmitter although the localization is correct. Localization system with single sensor, mounted together with the transmitter would simplify significantly the network and will be possible to integrate in directed links also.

Another possible enhancement is to use multiple transmitters that would provide better utilization of the fiber bandwidth during the switching times or just higher bit rate in an indoor space, where each wireless transmitter is connected to separate OLT. Such solution would also increase the network coverage since the probability for LOS between a receiver and different transmitters is much higher.

CHAPTER 6

CONCLUSION

6.1 Summary of the studies

Wireless optical links are not only a good alternative for short distance outdoor solutions, but appears to be very attractive technology for future high-speed indoor wireless networks. It provides high security and low power consumption. Compared to outdoor networks, there are no significant atmospheric effects in the indoor space. However, the ambient noise has much stronger levels and the close contact to human eyes strongly limits the transmit power levels. In conventional IR systems the low photodiode responsitivity (under 0.6A/W for Si photodiode) and low bit rate due to the E/O conversion further decrease its performance making it impossible to substitute RF technology today. I have proposed a new generation IR system, in which the light source is the fiber itself. Such design removes the E/O bottleneck and allows direct transmission of optical signals at fiber network speeds. Furthermore, for the used wavelengths (1310nm, 1550nm) the ambient noise is much weaker, the photodiode responsitivity is around 0.9A/W because an InGaAs photodiode is used and the permitted transmit power level is higher because the wavelengths are longer than the ones in the conventional system. I have concentrated my studies on LOS systems because the non-LOS ones have very high transmitted power and the limited speed due to multipath distortion is not competitive to similar RF designs. Because of the special light source, instead of Lambertian beam the system works with Gaussian beam. Therefore my first step was to provide an indoor propagation model and a simple approximation for calculating the power, received in a small receiver aperture in a Gaussian beam spot, located on a random distance from its center.

My first contribution was to propose a non-directed system with multiple ceiling transceivers. By implementing simple WDM in the downlink, as defined by EPON standard, two different services – OOK-based network access (1490nm) and OFDM-based ISDB-T TV broadcasting (1550nm) are considered. Full theoretical model for the beam propagation is developed and presented. Another important part of the research is the approximation of the received optical power in a small aperture, placed in a wide Gaussian beam. So far, in indoor OWC only Lambertian source has been considered because fiber end was never considered as light source. The results show that for wide indoor spaces several transceivers (D=2 to 3m) are necessary for full coverage. To get sufficient signal in all locations in the beam spot the receiving aperture must be quite big (1.5 – 2cm) which makes it hard to integrate in portable devices and requires big size PD, which has high junction capacitance, and therefore limited bandwidth.

In the next research phase I have considered configurations, in which one or two sides of the link are directed and need localization and tracking system. First, I presented a directed LOS system for low power high speed links. To be able to locate the mobile device and maintain the link MEMS mirrors in both ceiling and mobile device are implemented. The system provides excellent performance for 1Gbps duplex network. However, the MEMS mirrors increase the complexity of the network. Furthermore, the localization of the mobile device is connected with power consumption on the mobile side, where power must be saved. Another important issue is the usage of direct fiber coupling in the uplink, which is difficult and expensive and fixes the uplink wavelength to 1310nm. In the second part of the research phase I have considered a novel hybrid design, where the localization system is active only on the ceiling and uses reflected signal from corner reflectors on the mobile device. The downlink is the same as the previous research, because the MEMS mirror in the ceiling transceiver allows fast switching between multiple mobile devices. The speed is enhanced to 10Gbps and much better theoretical model of the indoor noise and the BER is presented. The 1Gbps uplink is greatly simplified by changing it to non-directed configuration. Thus no MEMS mirror is necessary. Furthermore, instead of direct fiber coupling, the ceiling receiver is with PD allowing much lower cost and implementation of different wavelengths in the wireless part compared to the fiber one. To be able to reduce the transmit power in the non-directed uplink though, a grid of multiple ceiling receivers is considered. As the theoretical calculations show, the localization sub-system and the uplink can be combined in a single node of the grid.

Finally, the critical analysis of the work show several points in the system design that need to be developed for further performance enhancement. Also, a network with multiple users has been discussed.

6.2 Future work

In the research so far a have considered only single mobile device and concentrated only on transmission analysis. Next step is to consider multiple mobile users and develop other network levels above the physical one. Also, different configurations for achieving excellent coverage in the indoor space should be considered.

To confirm the theoretical models presented and show a working indoor OWC a prototype will be created. Such prototype will allow further tests on the link performance for different scenarios. First step is to build the localization system, by using a small corner reflector and an imaging sensor. Then with a MEMS mirror a complete directed downlink can be presented. Another step is to create a laser source with wide Gaussian beam and collect experimental data to confirm the approximation precision. Finally, by combining the both components a complete hybrid OWC can be demonstrated and further experiments will be possible.

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APPENDIX List of academic achievements

Category (subheadings)	Paper Title
Articles in refereed journals	○ Dimitar R. KOLEV, Mitsuji MATSUMOTO, Kazuhiko WAKAMORI , Takahiro KUBO, "Transmission Analysis of Non-directed Indoor Optical Wireless Network for Gigabit EPON Access and ISDB-T Television Broadcasting," *IIEEJ Transactions on Image Electronics and Visual Computing*, Vol.1, No. 1, pp. , Dec. 2013. ○ Dimitar Kolev, K. Wakamori, M. Matsumoto: "Transmission Analysis of OFDM-Based Services Over Line-of-Sight Indoor Infrared Laser Wireless Links," *Lightwave Technology, Journal of* , vol.30, no.23, pp.3727,3735, Dec.1, 2012. ○ Dimitar Kolev, Kazuhiko Wakamori, Mitsuji Matsumoto: "A Gigabit Single-Wavelength Optical-Transparent FSO Link with FEC Using Bit-Interleaving and Delay Lines for Enhanced Digital TV Transmission," *Journal of IIEEJ*, Vol.41, No. 5, pp. 546-553, Sept. 2012.
Presentations at international conferences	○ Dimitar Kolev, K. Wakamori, M. Matsumoto, T. Kubo, T. Yamada, N. Yoshimoto, "Hybrid Line-of-Sight Indoor Infrared Laser Wireless Link with 10Gbps Downlink and 1Gbps Uplink," *International Workshop on Optical Wireless Communications (IWOW), 2013 International Workshop on* , vol., no., pp. , 21-23 Oct. 2013. ○ Dimitar Kolev, T. Kubo, T. Yamada, N. Yoshimoto, K. Wakamori : " Non-Directed Indoor Optical Wireless Network with a Grid of Direct Fiber Coupled Ceiling Transceivers for Wireless EPON Connectivity," *ITU Kaleidoscope: Building Sustainable Communities (K-2013), 2013 Proceedings of* , vol., no., pp.1,8, 22-24 April 2013. ○ Dimitar Kolev, Mitsuji Matsumoto, "A Study of a Low Speed Uplink, Based on Diverged Laser Beam and Multiple Ceiling Transceivers for Indoor Optical Wireless System," *IEVC2012*, Malaysia, 21-24 Nov. 2012. ○ Dimitar Kolev, K. Wakamori, M. Matsumoto, T. Kubo, T. Yamada, N. Yoshimoto, "Gigabit Indoor Laser Communication System for a Mobile User with MEMS Mirrors and Image Sensors," *Optical Wireless Communications (IWOW), 2012 International Workshop on* , vol., no., pp.1,3, 22 Oct. 2012.

Presentations at domestic conferences	○ Dimitar Kolev, Mitsuji Matsumoto: "Indoor HDTV Broadcasting through Line-of-Sight Optical Wireless Link with Direct Fiber Coupling Transmitter," *IIEEJ 40th Annual Conference*, Tokyo, 23-24 June 2012. ○ Dimitar Kolev, Mitsuji Matsumoto: "Study of Increasing the Traffic Speed in WDM Systems by Simulating High Pulse Speed and Level Encoding", *IIEEJ Annual Conference*, Kanagawa, 26-27 June 2010.
Others	○ Dimitar Kolev, Mitsuji Matsumoto, "Indoor Optical Wireless Technology for Future High-Speed Mobile Network Access," Fujitsu Lab Technical Exchange Meeting, 20th Feb, 2013. ○ Dimitar Kolev, Mitsuji Matsumoto: "ICT for Safe and Reliable Society", PhD Academy, Waseda University, 2012. ○ Dimitar Kolev, Kazuhiko Wakamori, Mitsuji Matsumoto, "Study of Refractive Index Structure Parameter Fluctuations in Time", *Asia-Pacific Microwave Photonics 2012*, poster session, Kyoto, 25-27 Apr 2012. ○ Dimitar Kolev, Kazuhiko Wakamori, Mitsuji Matsumoto, "Improving the Bit-error Rate in Wireless Optical Systems Using All-optically Implemented Hamming Code and Bit-scattering", *GCOE*, Poster Session, July 2011.