Design of Optical Wireless IR-UWB Systems for Low Data Rate Applications

Mohammed Al-Olofi, Andreas Waadt, Guido H. Bruck, and Peter Jung
Department of Communication Technologies
University of Duisburg-Essen
Duisburg, Germany
Email: info@kommunikationstechnik.org

***Abstract*—The use of Impulse Radio-Ultra Wide Band (IR-UWB) introduced a low data rate and low power consumption systems, which are suitable for sensor networks. Due to strict regulations of the power transmission and frequency use, the range and usage of IR-UWB remained very limited. To enlarge the range of UWB, this paper presents a system design on how to replace the radio part of the physical layer (PHY) of UWB by free space optics, without changing the major parts of the standard, including frame structure and coding. The performance of such a system on optical links is analyzed in Monte-Carlo simulation. The utilization of optical links will offer new configurations for uplink and downlink. This system will deal with optical noise and optical multipath channel and shows the performances of the new system in presence of Line of Sight (LOS) and diffuse links.**

Keywords- Hybrid Optical/Radio systems; IR-UWB; OWC.

I. INTRODUCTION

The Optical Wireless Communications (OWC) is an alternative technology to radio communications, which suffers from congested frequency bands as the number of mobile users increased significantly. The OWC offer a broad unlicensed free spectrum that enables high data rate, low cost, high speed, and ease of development systems. These advantages make the optical solution attractive for short range communications applications, such as smart homes, smart offices, wireless LANs, and sensor networks.

Currently, the ultra wideband systems are the best technology choice for short range communication, since they offer a large bandwidth (3.1-10.6 GHz), high speed, immune to multipath fading, multi access capabilities, and low cost transceivers. The fractional bandwidth of UWB is defined by FCC as a signal with 20% of its center frequency or 500 MHz bandwidth, when the center frequency is above 6 GHz with a limited power of -41.3 dBm/MHz [1]. The optical devices introduce a low modulation bandwidth, which does not exceed 20 MHz in case of using LED and hence limit the data rate and available broadband spectrum [2]. This limitation is caused by the characteristics of LEDs available in the market, which have a slow response to the feeding current. The 3dB frequency and hence the modulation bandwidth depends on minority carrier lifetime. To solve the limitation of modulation bandwidth problem, we recommend two solutions. We can use either special LEDs with larger modulation bandwidth similar to that used in fiber optical communications or we can use laser diodes, which offer bandwidth in GHz at expense of increasing shadowing effect due to the nature of direct light generated by laser diodes. Nevertheless, a lot of solid state electronics researches focus on optical wireless communication and this gives a sign that we will see high-speed low-cost LEDs in the next decade.

The utilization of optical wireless links in IR-UWB systems will overcome the limitations in emission power and bandwidth and/or introduce a new Radio/Optical IR-UWB system where we can take advantages of both configurations. The optical links do not interfere with the electrical systems and they are not affected by multipath fading. This design will be suitable to operate in sensitive environments like hospitals where the radio communications are prohibited.

In this paper, we have proposed a new optical IR-UWB system design to solve the problem discussed above. The conventional IR-UWB system employing radio antenna at the transmitter and receiver has been modified to be able of transmitting the information data via the optical link. To establish an optical link in our design, both antennae in transmitter and receiver are replaced by LEDs and photodetector respectively. The transmitted pulse is converted into light pulse by regulating the input current of light device to form the same shape of radio pulse. On the receiver side, the power of the received light signal will be detected by photodetector and converted at output to current levels which reconstruct the shape of transmitted pulse. The further steps of detection process are done as in IR-UWB radio systems.

The rest of paper is organized as follows. In Section II, the system design describes the transmitter and receiver is presented. Also in Section II, the optical channel impulse response regarding the environment and SNR are explained. The system simulation is introduced and the results are discussed in Section III. Finally, Section IV concludes the paper.

II. SYSTEM DESIGN

A. Transmitter Design

The transmitter of IR-UWB is modified to be able to transmit in the manner similar to optical pulses as shown in Fig. 1. We employ the Binary Pulse Position Modulation (2-PPM) as presented in [1] combined with intensity modulation.

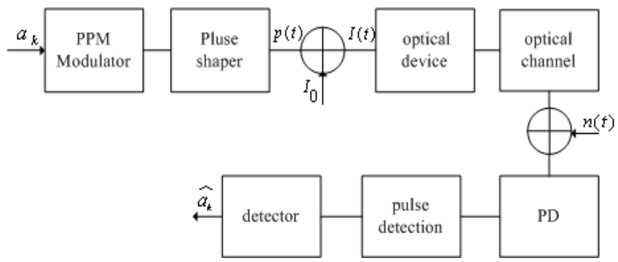

Figure 1. Optical IR-UWB system

.In this modulation scheme, the transmitted pulse $p(t)$ is shifted by ε time shift from the symbol time T_S if the transmitted bit is '1' and introduce no shift when the bit '0'.The modulated signal can be described by

$$x(t) = \sum_{k=-\infty}^{+\infty} p\left(t - kT_s - a_k \varepsilon\right) \quad (1)$$

The Gaussian monocycle pulse $p(t)$ is used to drive the LED by convert it to a set of quantized current levels as shown in Fig. 2. The pulse is quantized to L current levels and every level is mapped to a defined brightness level. The current levels represent the intensity power should be non-negative to ensure that the LED is not reversely biased.

$$I(t) = I_0 + \left|p(t)\right| \quad (2)$$

A dc-bias is chosen to boost the negative part of the radio pulse in order to keep the diode in the 'ON' state and illuminates a 10% of full brightness. The constant forward current (I_0) will keep the diode in 'ON' state even if the pulse time end and hence keep the diode operating in the active region. The modulation bandwidth should be increased since the diode rise and fall time regarding the diode switching operation is minimized.

To create a different emission power for each of current level, we suggest the white-LED lnGaN/GaN to transmit the optical pulses. This white-LED proposed in [5] shows that the emission power in the blue spectrum portion is increased relative to the injected current. Nevertheless, a blue filter at the receiver Front-end should be used to gain the blue spectrum power.

B. Optical Multipath Channel

The optical multipath channel is characterized by an impulse response $h(t)$, which describes the propagation of the optical signal between the transmitter and receiver. The propagation pattern is approximated by lambertian radiation pattern, which state that the light intensity emitted from a source has a cosine dependence on the angle of emission with respect to the surface normal [2,3]. The luminous intensity in angle ϕ is given by

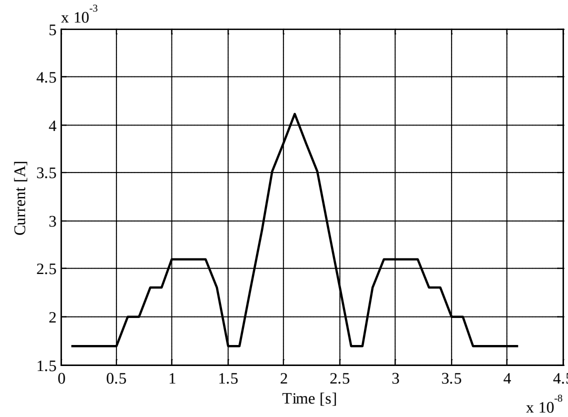

Figure 2. Quantization of the monocycle pulse

$$I(\phi) = I(0)\cos^m(\phi) \quad (3)$$

where $I(0)$ is the center luminous intensity of the LED and ϕ is the angle of irradiance, m is the order of lambertian emission and is given by the semi angle at half illuminance of the LED $\phi_{1/2}$ as

$$m = \frac{-\ln(2)}{\ln\left(\cos\phi_{1/2}\right)} \quad (4)$$

and the horizontal illuminance I_{hor} at a point (x, y, z) on the working plane is defined as

$$I_{hor}(x, y, z) = \frac{I(0)\cos^m(\phi)}{d^2\cos(\psi)} \quad (5)$$

where d is the distance between the transmitter and receiver and ψ is the angle of incidence.

In an office room environment, the light arrives receiver directly as LOS link or after number of reflections (diffuse link). The impulse response at zero reflection is given as

$$h_{los}(t) = \frac{A_r(m+1)}{2\pi d^2}\cos^m(\phi).T_s(\psi)\cdot g(\psi) \times \cos(\psi)\cdot\delta\left(t - d/c\right), \quad 0 \le \psi \le \psi_{con} \quad (6)$$

where $T_S(\psi)$ is the filter transmission, $g(\psi)$ and ψ_{con} are the concentrator gain and Field Of View (FOV) respectively.

The gain of the optical concentrator at the receiver is defined by

$$g(\psi) = \begin{cases} \dfrac{n^2}{\sin^2\psi_{con}}, 0 \le \psi \le \psi_{con} \\ 0, \quad 0 \ge \psi_{con} \end{cases} \quad (7)$$

where *n* is the refractive index.

To model the reflections, every wall is partitioned to a number of small areas, which act as a new lambertian sources when light incident on it. The impulse for the first reflection is given by

$$h_{ref}(t)=\begin{cases}\frac{A_r(m+1)}{2(\pi d_1 d_2)^2}\rho A_{wall}\cos^m(\phi_r).\cos(\alpha_{ir}) \\ \times\cos(\beta_{ir})\cdot T_s(\psi)\cdot g(\psi)\cdot\cos(\psi_r)\cdot \\ \times\delta\left(t-\frac{d_1+d_2}{c}\right), & 0\le\psi_r\le\psi_{con} \\ 0, & \psi_r\ge\psi_{con}\end{cases} \quad (8)$$

where d_1 and d_2 are the distances between the LED and a reflective point, and between a reflective point and a receiver surface, ρ is the reflectance factor, A_{wall} is a reflective area. The angles α_{ir} and β_{ir} are represent the angle of incidence to a reflective point and the angle of irradiance to a receiver, respectively, ϕ_r and ψ_r are the angle of irradiance from LED to a reflective point and angle of incidence from reflective point to a receiver.

The optical channel is characterized by the room dimensions, reflectance indices of walls and transmitter and receiver orientation. Table I describes the parameters used to simulate the channel impulse response.

The optical impulse response is used to calculate the channel gain, which is important to estimate the influence of channel on the received power. The power contained in a LOS component is larger than the power contained in the first reflection components as shown in Fig. 3 since the long distance and reflection from the surfaces introduce a power loss. The received power can be calculated when the transmitted power was 1 Watt as

$$p_r=\left(p_t\cdot H_{los}(0)+\int_{ref}p_t\cdot H_{ref}(0)\right) \quad (9)$$

Another important feature is the root mean squared (RMS) delay, which describes how much delay added by the channel. A large delay led to intersymbol interference (ISI), which make the detection of transmitted signal complicated. The RMS delay calculated from the channel impulse response as

$$\tau_{RMS}=\sqrt{\frac{\int(t-\tau_0)^2 h^2(t)\,dt}{\int h^2(t)\,dt}} \quad (10)$$

where τ_0 is the delay time and defined as

TABLE I. CHANNEL PARAMETERS

	Parameter	**Value**
Room	Room size	5×5×3 m^3
	ρ_{wall}	0.8
Transmitter	Location	(2.5, 2.5, 3)
	M	1
	Elevation	-90°
	Azimuth	0°
	Power	1
Receiver	Location	(0.5,1,0)
	A_r	1 cm^2
	FOV	85°
	Elevation	90°
	Azimuth	0°

$$\tau_0=\frac{\int t\cdot h^2(t)\,dt}{\int h^2(t)\,dt} \quad (11)$$

The RMS delay for the simulated channel is 0.49 ns, which define an upper bound for the transmission rate. For the proposed system, the symbol time is less than the RMS delay and hence no equalizer at the receiver side is needed.

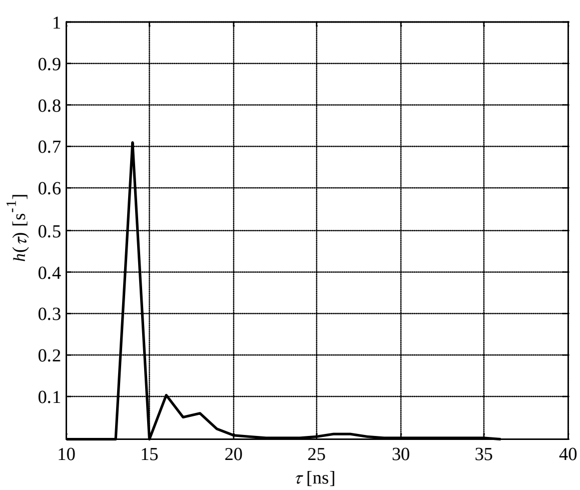

Figure 3. Optical channel impulse response

C. SNR

The SNR in optical system is defined by the received power, photo detector responsivity R [A/W] and noise variance σ^2 as

$$SNR = \frac{\left(R\, p_r\right)^2}{\sigma_{sh}^2 + \sigma_{th}^2} \tag{12}$$

In an optical wireless system, the noise is classified into two types namely the shot noise and thermal noise. The shot noise is a time-varying process generated by external light sources like background noise and quantum noise or internal source as intensity radiation, dark noise and excess noise. These sources are independent Poisson random variables and their photoelectron emission follows the distribution of Poisson distribution with mean equal to the sum of the individual processes. The variance of any shot noise process associated with photodetection are represented as

$$\sigma_{sh}^2 = 2\, q\, B \langle i \rangle \tag{13}$$

where q is the electronic charge, B is the equivalent bandwidth, and $\langle i \rangle$ is the mean current generated by $\langle n \rangle$ electron. However, if the photoelectron count is large, the generated signal current probability distribution can be approximated to be Gaussian process [6].

$$p(i) = \frac{1}{\sqrt{2\pi\sigma_{sh}^2}} \exp\left(-\frac{(i-\langle i \rangle)^2}{2\sigma_{sh}^2}\right) \tag{14}$$

Addition to the shot noise, the thermal noise caused by thermal fluctuation of electrons in receiver circuit add a currents, which is Gaussian process has a zero mean and its variance described as

$$\sigma_{th}^2 = \frac{4\kappa T_k B}{R_L} \tag{15}$$

with K is the Boltzmann's constant, T_k is absolute temperature, and R_L is the equivalent resistance. The total generated current probability distribution of thermal noise and shot noise can be represented as

$$p(i) = \frac{1}{\sqrt{2\pi(\sigma_{sh}^2 + \sigma_{th}^2)}} \exp\left(-\frac{(i-\langle i \rangle)^2}{2(\sigma_{sh}^2 + \sigma_{th}^2)}\right) \tag{16}$$

To evaluate the SNR required for a BER, the received power needed to achieve a BER of 10^{-6} is about 18dB.

D. Receiver Design

The receiver of optical system is based mainly on photo-detector employing the direct detection. The area of detector and the orientation play important roll in the receiver design and performance. The photodetector generates an output photocurrent relative to the incident light power pinging on the surface. i.e., the changes produced in intensity modulation at the transmitter are detected by direct detection at the receiver. The photocurrents induced by photodetector form a replica of the transmitted pulse. At the receiver Front-end the received signal is defined as

$$y(t) = R\, I(t) \otimes h(t) + n(t) \tag{17}$$

where $h(t)$ is the optical multipath channel, $I(t)$ is the transmitted signal, and $n(t)$ is the Additive White Gaussian Noise (AWGN). After conversation of optical signal to electrical signal, the correlation between the mask of the transmitted pulse *m(t)* and the received signal *y(t)* is performed as

$$\begin{aligned} m(t) &= I(t-\tau-kT_s) - I(t-\tau-kT_s-\varepsilon) \\ Z &= \int_{\tau}^{T_s+\tau} y(t)\, m(t)\, dt \end{aligned} \tag{18}$$

The detector in (19) compares the power of correlation Z to a threshold and decides whether the received bit is '0' or '1' [7].

$$\hat{a} = \begin{cases} Z > 0 & \hat{a} = 0 \\ Z < 0, & \hat{a} = 1 \end{cases} \tag{19}$$

III. SIMULATION RESULTS

The system design represented in Fig. 1 is simulated using MATLAB program. The Monte Carlo simulations were carried out to generate the bit-error-ratio (BER) versus E_b/N_0 figures. The information bits are modulated by 2-PPM modulator with symbol time $T_s = 240\,ns$, sampling frequency $f_c = 1GHz$, and shift time $\varepsilon = 120\,ns$. The mono-cycle pulse width $T_P = 41ns$ quantized to $L = 8$ current levels, which drive the optical transmitter device and each of the current level generates a one of the brightness level.

The optical channel impulse response in Fig. 3 is simulated in a room with dimensions of (5m×5m×3m) and a fixed transmitter and receiver are assumed. The optical pulse is convolved with the channel and added to the noise.

On the receiver side, the photo detector is percepts the incident light and converts it into current. We assume that the detector responsivity R equal to one. The received pulse constructed from current levels is correlated with the mask of transmitted pulse and the peak power is compared to the threshold in time window. This system is assumed to be synchronized and no equalization stage is performed.

In OWC systems, a unit rectangular pulse is used to transmit the power of modulated binary bits with duration $T_{s.}$ [8, 9]. In Fig. 4, the same system design was simulated using rectangular pulse and monocycle pulse to compare the BER performances of using the shaped pulse used for wireless system and rectangular pulse used in OWC systems. Fig. 4 shows that the BER for both signals are equal, which is evident that other pulses shape could be used without loss of performances. Although rectangular pulse evaluation is simpler than Gaussian pulse, the later introduces capability for utilizing advantages of a designed UWB radio wireless system communicating on optical link in sensitive environments. Nevertheless, the effects of LEDs nonlinearities and shot noise are expected to disfigurement the transmitted Gaussian pulse at transmitter and receiver front-ends. These effects will be studied experimentally in the future work to find the performance degradation for the proposed design.

Fig. 5 compares the BER performance of the proposed systems operate on LOS optical wireless channel with that on diffuse channel in the absence of LOS link. The direct path between transmitter and receiver delivers higher power than paths reach the photodetector after reflections. This explains why the BER in the presence of LOS channel is lower than that in diffuse channel by ~2dB. Also, the influences of optical wireless channel gain and delay on the proposed system increase the BER by ~4dB compared to the AWGN bound. The use of equalization techniques such as zero forcing or decision feedback equalizer will enhance the system performances because the shape of the transmitted pulse at receiver is better restored.

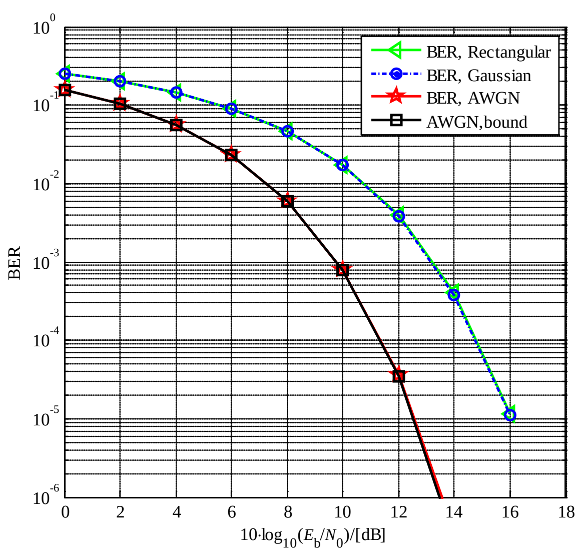

Figure 4. BER of the system with rectangular and Gaussian Pulses.

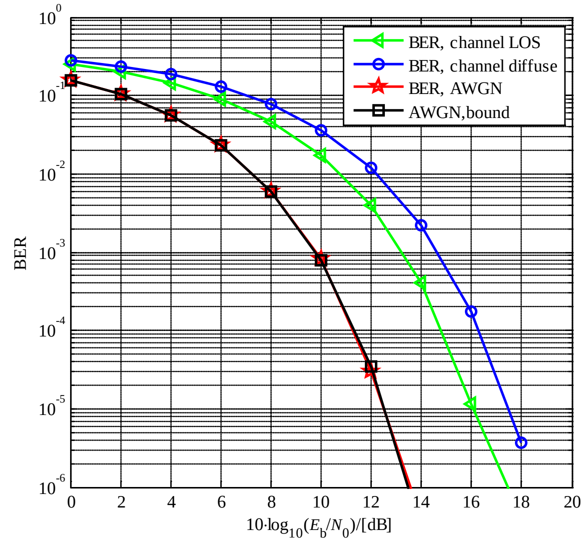

Figure 5. BER of the system with LOS and diffuse link configurations

IV. CONCLUSION AND FUTURE WORKS

In this paper, a new design of optical IR-UWB is introduced to overcome the limitations of power and bandwidth since optical links introduce unlimited bandwidth and no constrains on the emitted power. Our design will be suitable for non radio environments like hospitals or for systems that operate in both optical/radio configurations. The optical wireless link is established between the transmitter and receiver by replacing antennae with optical devices. Also, the radio pulse is quantized and offset is added to define an optical version of the radio Gaussian pulse. The optical pulse is transmitted using an optical device and received by a photodetector. The effects of the optical multipath channel are investigated and the system performance using Monte-Carlo simulations has been obtained and analyzed.

This work will be continued to introduce a better system performance using equalization techniques. Also, the LEDs characteristics effects on pulse shaping process will be investigated in order to achieve experimental results and build a demonstrator for the proposed system.

REFERENCES

[1] IST PULSERS Phase II D3a3.3: LDR-LT Concept Specifications - PHY and MAC Layers, Jul. 2008.

[2] J. R. Barry, J. M. Kahn, W. J. Krause, E. A. Lee, and D. G. Messerschmitt, “Simulation of multipath impulse response for wireless optical channels,” IEEE J. Select. Areas in Commun. vol. 11, no. 3, Apr. 1993, pp. 367–379, doi: 10.1109/49.219552.

[3] H.Q. Nguyen *et al.*, "A MATLAB-based simulation program for indoor visible light communication system," CSNDSP 2010 proceedings, July 2010, pp. 537-541.

[4] T. Komine, M. Nakagawa, "Fundamental analysis for Visible-Light Communication system using LED light," IEEE Transaction on Cunsumer Electronics, Vol. 50, No. 1, February 2004, pp. 100-107, doi: 10.1109/TCE.2004.1277847.

[5] J. Grubor, S. C. J. Lee, K. D. Langer, T. Koonen, and J. W. Walewski, "Wireless high-speed data transmission with phosphorescent white-light LEDs," in Proc. Eur. Conf. Optical Communications (ECOC 2007), Berlin, Germany, Sept. 2007, pp.1-2.

[6] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, Optical Wireless Communications: System and Channel Modelling, CRC Press, 2012, pp. 66-74.

[7] M. -G. Di Benedetto, Understanding Ultra Wide Band Radio Fundamentals, Pearson Education, 2008, pp.241-252.

[8] M.D Audeh, J.M Kahn, J.R. Barry, "Performance of pulse-position modulation on measured non-directed indoor infrared channels," IEEE Transactions on Communications, vol.44, no.6, Jun 1996, pp.654-659, doi: 10.1109/26.506380.

[9] J. Zhang, "Modulation analysis for outdoors applications of optical wireless communications," International Conference on Communication Technology Proceedings, 2000. WCC - ICCT 2000., vol.2, no, 2000, pp.1483-1487, doi: 10.1109/ICCT.2000.890940.