Indoor Broadcasting via White LEDs and OFDM

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Abstract — *Recently, visible light communication (VLC) technology has been gaining attention in both academia and industry. This is driven by the progress of white light emitting diode (LED) technology for solid-state lighting (SSL) and the potential of simultaneously using such LEDs for illumination and indoor wireless data transmission. This paper provides an overview about the technology and describes the physical layer implementation of a VLC system based on a modified version of the classical orthogonal frequency division multiplexing (OFDM) modulation technique. Besides, the paper presents a hardware prototype for short-range broadcasting using a white LED lamp. The OFDM system runs on DSP development boards. Off-the-shelf 9 LEDs and a single photodiode (PD) are utilized to build the analog frontends. The prototype allows investigating the influence of the electrical signal-to-noise ratio (SNR), constellation order, and channel coding on the bit-error performance. Theoretical and experimental results on optical path loss show close match. In this context, the influence of the LED beam angle on the horizontal coverage is highlighted[1].*

Index Terms — **Visible light communication, orthogonal frequency division multiplexing, light emitting diodes, photodiodes.**

I. INTRODUCTION

Optical wireless (OW) technology is an intriguing alternative for radio frequency (RF) wireless technology. This technology offers a huge, unregulated, and unlicensed bandwidth to cope with the future demand of indoor wireless access to real-time bandwidth-intensive applications such as Voice over IP (VoIP), streaming video and music, and network attached storage (NAS) [1]. The infrared (IR) and the visible light regions are mostly used for OW indoor applications. Both line-of-sight (LOS) and non-line-of-sight (NLOS) link configurations exist [2]. Indoor links can be realized using low cost, power efficient, and reliable optical components, namely LEDs and PDs. The majority of IR

systems use the near IR band as a transmission medium due to the availability of effective, low-cost sources and detectors [2]. Blue chip white LEDs are typically found in most white LED bulbs available in the market and are considered by most visible light communication (VLC) researchers [3].

White LED bulbs posse clear advantages over conventional incandescent and fluorescent bulbs, which makes them a strong candidate for future illumination equipments. For example, the European Commission has decided recently to prohibit the sale of particularly energy-intensive lamps for household use in a series of stages up to 2016 [4]. As soon as high efficient white LED bulbs are manufactured cheap enough to overtake the currently favored compact fluorescent (CFLs) bulbs, an OW communications network infrastructure will be available. The fast response of the LEDs enables them to realize high-speed wireless links; thus, white LED bulbs can be utilized simultaneously as optical access points (OAPs). The maximum reported modulation bandwidth achieved is approximately 20MHz [3]. If indoor base stations (BSs) are merged with LED illumination devices and hooked into local data servers or combined with other communication networks in a way that illumination and high-speed data supply are intelligently combined, spectrally and power efficient indoor communication can be achieved.

VLC technology has been pioneered by the VLCC (visible light communication consortium) in Japan and has witnessed significant interest within the research community. This has led to the formation of an IEEE study group for VLC standardization, IEEE 802.15 WPAN Visual Light Communication Interest Group (IGvlc). In addition, VLC is considered as a candidate for broadband and electro-smog-free wireless home networking (WHN) [5].

The fast-developing VLC technology offers several benefits, among of which are the following: no interference with RF circuits electronics, which allows acceptance in airplanes and hospitals, no health concerns as long as eye and skin safety regulations are fulfilled, and significantly reduced carbon-dioxide footprint due to its low energy consumption. Further on, inter-cell interference (ICI) can effectively be limited as the optical signals do not penetrate through walls and, thus, high degree of privacy and security against eavesdropping is inherently offered.

It is predictable that indoor OW applications will most likely be based on white LEDs rather than on IR LEDs [6]. VLC offers many advantages over IR transmission:

- Data transmission along with the illumination of rooms and different interior spaces.
- The installation of a wireless network based on an existing interior lighting infrastructure would probably be easier and cost effective than setting up a separate IR network.

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- The signal is less likely to be obstructed and the LOS component is dominate in most positions in the room (the effect of multipath is small) because of the distributed ceiling installations [3].
- High signal-to-noise ratio (SNR) is obtainable [3], which is an indirect consequence of the illumination requirements.
- Especially for OFDM, a dc bias that carries no information is necessary for both IR and VLC. However, in VLC, it is required for illumination and is not causing any severe power efficiency loss [7].

A possible scenario of future wireless communication is depicted in Fig. 1. Service is established through a combination of wired and wireless technologies. The wired BSs are merged with the LED based illumination equipment to provide wireless network access. Data broadcasting through a ceiling bulb realizes a point-to-multipoint connection and a focused spotlight realizes a point-to-point connection. User requests are sent through an uplink channel with offers mobility compared to a fixed terminal scenario as shown in Fig. 1. The power over Ethernet (PoE) technology can be used to transport data traffic and supply the BSs as well as the lamps with the required power. The function of illumination is not affected by the envisaged piggy-backed communication as the blinking rate of the intensity modulated light is sufficiently rapid and cannot be detected by the human eyes.

Fig. 1. Future broadband wireless networking scenario.

VLC communication has large potentials in many applications. Local information points in public areas, e.g. shops, airports, and train stations, are considered as potential areas where this technology can be used. In addition, VLC can grant wireless access to broadband services using the LED reading lamps in airplane cabinets, passenger trains, and coach buses.

This paper presents an experimental measurements obtained using a VLC hardware broadcasting prototype based on orthogonal frequency division multiplexing (OFDM) [8]. The prototype is developed to investigate the bit-error performance for different electrical SNR values ranging from 0dB to 45dB. Several modulation schemes with different channel coding rates are considered. Finally, theoretical analysis validates the measured optical path loss results for two coverage scenarios.

The rest of the paper is organized as follows. In Section II, optical carrier modulation and demodulation techniques are introduced and the advantages of OFDM over single carrier (SC) pulsed-modulation techniques are highlighted. In Section III, the system model including the optical OFDM, hardware prototype and the optical channel is introduced. Theoretical analysis and experimental measurements are presented in Section IV. Finally, Section V concludes the paper.

II. MODULATION AND DEMODULATION

A. Optical Carrier Modulation and Demodulation Schemes

Generally, RF receivers are coherent receivers which employ a heterodyne or homodyne down-converters comprised of a local oscillator and a mixer. The efficient operation of this mixer relies upon the frequency stability of the carrier and the local oscillator. Similarly, optical coherent receivers detect the optical carrier phase. Such optical receiver requires a local oscillator, optical mixer and optical filter. Coherent receivers are experimentally evaluated using a laser diode as coherent light source [9]. In contrast, LEDs emit incoherent light. Therefore, it is very difficult to collect appreciable signal power in a single electromagnetic mode. This incoherent reception does not provide a stable carrier, which makes it impossible to construct an efficient coherent receiver.

For optical wireless links, the most viable modulation is intensity modulation (IM) in which the desired waveform is modulated onto the instantaneous power of the optical carrier. The most practical down-conversion technique is direct detection (DD) in which a photo detector produces a current proportional to the received instantaneous power. DD is much simpler to implement than coherent detection. It detects only the intensity of the optical wave, i.e. no frequency or phase information. Therefore, indoor optical applications use intensity modulation with direct detection (IM/DD) as a practical transmission to achieve simple and low-cost optical modulation and demodulation [2].

B. Electrical Modulation Techniques

The choice of the modulation scheme can significantly affect system performance. Several modulation schemes with their inherent advantages and disadvantages are considered for use in OW systems. SC pulsed modulation schemes such as on-off keying (OOK) and pulse position modulation (PPM) are widely used modulation formats in IR wireless communications [10]. In the presence of a LOS component, OOK can be used to achieve high-speed transmission beyond 100Mbits/s [11]. However, the channel delay spread is a major challenge that limits the achievable data rates in a multipath environment. For example, a non-directional IR link in a room having a dimension (5m×7.1m) is studied in [12]. The measured delay spread produces inter-symbol interference (ISI) that potentially renders OOK at bit rates above 10Mbits/s impossible, or at least poses a significant challenge. To overcome this challenge, additional receiver complexity is required.
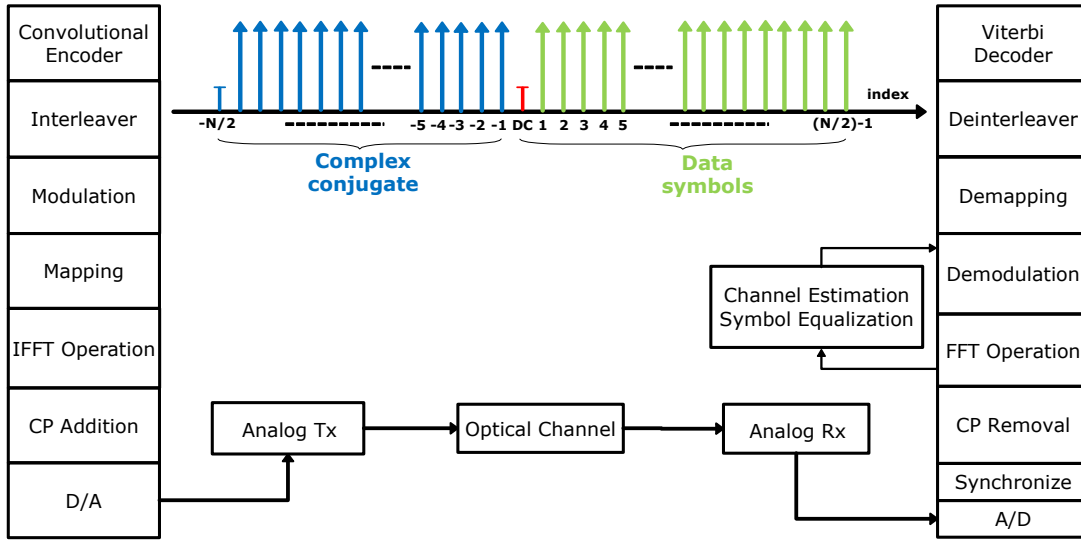
Fig. 2. The building blocks of the optical OFDM physical layer, and the subcarriers assignment. The dc and the −N/2 subcarriers are set to zero to ensure that the output consists of only real values.

Alternatively, OFDM as a practical implementation of multi-subcarrier modulation (MSM) techniques can effectively mitigate multipath induced ISI [13]. OFDM offers high bandwidth efficiency, and allows for simple equalization at the receiver. The possibility to apply higher order digital modulation schemes to provide high data rates and the possibility to easily combine OFDM with multiple access schemes such as TDMA (time division multiple access) and FDMA (frequency division multiple access), makes it a promising choice for indoor OW communications. For broadcasting applications, different broadcasting channels can be easily realized through assigning the OFDM symbols and the subcarriers to each channel based on the required data rate and quality of service (QoS).

III. SYSTEM MODEL

A. Optical OFDM

The building blocks of the physical layer are depicted in Fig. 2. The system uses a forward error correction (FEC) coding algorithm for data protection, namely a convolutional encoder. In addition, burst error protection is realized through time and frequency interleaving algorithms. One of several modulators (phase-shift keying (PSK) or multi-level quadrature amplitude modulation (M-QAM)), modulates the encoded bit stream into symbols. The generated serial stream of symbols at the modulator output is mapped into parallel streams; each is transmitted on a separate subcarrier.

So far the model is identical to that of a classical OFDM system and the first difference appears with the IFFT (inverse fast Fourier transform) operation and is related to the optical carrier IM technique. The OFDM baseband signal is used to modulate the LED intensity; hence, any complex values must be avoided. A real value OFDM baseband signal can be generated by constraining the input to the IFFT operation to have Hermitian symmetry (e.g. $X_n = X_{N-n}^*$). Half the available subcarriers are used to carry the complex conjugate

of the data symbols as illustrated in Fig. 2. Given that a large optical bandwidth is available, this loss in spectrum efficiency can be tolerated. The use of IFFT in OFDM system eliminates the complexity involved in using a large number of oscillators as proposed in discrete multiple tone (DMT) optical transmitters [14]. The IFFT operation modulates and multiplexes the subcarriers and is mathematically described as follows:

$$x_k = \frac{1}{N}\sum_{n=0}^{N-1}X_n \exp^{\left(j\frac{2\pi}{N}nk\right)} \qquad (1)$$

Where, $x_k, k = 0, \cdots, N-1$ are the N time-domain output samples and the values $X_n, n = 0, \cdots, N-1$ are the input data symbols.

After generating the OFDM symbol, a CP (cyclic prefix) is added as a guard interval to avoid multipath induced ISI (crucial for NLOS links) and to convert the linear convolution of the channel with the OFDM signal to a circular convolution. As a result, simple frequency domain equalizer can be used [8].

The generated OFDM signal envelope is bipolar and optical intensity cannot be negative. Therefore, the LED should be biased before applying the OFDM modulating signal [7]. The LED linearity is particularly important when the OFDM signal envelope variations are utilized to intensity modulate an LED with its nonlinear characteristics. Therefore, the bias current must be carefully set to consider the maximum allowable forward current of the LED, to reduce magnitude distortion, and to control signal clipping [15].

At the receiver, time synchronization and symbol equalization can be realized using the well-known training sequences and pilot carriers [16]. However, the complex conjugate requirements must be fulfilled while generating the training sequences and assigning the pilot carriers. After the

CP removal, the OFDM signal is converted back to the frequency domain by applying the fast Fourier transform (FFT) operation. In this model, the OFDM frame consists of one OFDM symbol forming the training sequence and 20 OFDM symbols with data sub-carriers. Using the training sequence, the channel is estimated and frequency domain equalization is realized using a conventional OFDM zero-forcing (ZF) equalizer. The estimated bit stream is deinterleaved and then decoded by a hard decision Viterbi algorithm.

B. Hardware Prototype

The transmitter includes two parts: the digital, which is a DSP development board[2] to generate the OFDM analog signal and interfaces with the transmitter computer, and the analog, which includes the 9 LEDs array and the driver electronics. The receiver includes an analog part, which is the PD, a transimpedance amplifier, dc blocking stage, and a preamplifier stage. A second DSP development board is used to decode the OFDM signal and interface with the receiver computer (see Fig. 3). The analog frontends are shown in Fig. 4. The lamp consists of low cost 9 LEDs which are 1cm separated and the optical receiver circuit employs a single silicon PD[3].

The DSP board has an on-board 32-bit stereo codec with 96kHz maximum sampling frequency. Therefore, the OFDM signal bandwidth is limited to 45kHz. Clearly, this low bandwidth limits the achievable data rate. However, the target of the conducted study is not to showcase high data rates; rather to study via a simple proof-of-concept hardware demonstrator achievable rates for phase-incoherent optical OFDM and to investigate performance for different electrical SNRs.

C. Optical Channel

The bandwidth of the optical channel in a LOS configuration is reported higher than 88MHz [5]. Therefore, the optical pass loss is the most important quantity to characterize the channel and relates the transmitted and received optical powers via [2],

$$P_r = H(0)P_t \quad \text{(W)} \tag{2}$$

where P_t is the transmitted optical power, P_r is the received optical power, and $H(0)$ is the optical path loss. This approximation is particularly accurate in directed-LOS links. Considering the LOS link geometry shown in Fig. 5, the LOS channel path loss is defined as [2],

$$H(0)_{LOS} = \frac{A}{d^2} R_0(\phi) T_s(\psi) g(\psi) \cos\psi \tag{3}$$

where d is the distance between the transmitter and the

receive, ϕ is the angle with respect to the transmitter, ψ is the angle with respect to the receiver, $T_s(\psi)$ is the filter gain, $g(\psi)$ is the concentrator gain, and $R_0(\phi)$ is the transmitter radiant intensity given by [2],

$$R_0(\phi) = \left[\frac{m+1}{2\pi} \right] \cos^m \phi \quad \text{(W/sr)} \tag{4}$$

$$m = \frac{\ln 2}{\ln(\cos\alpha)} \tag{5}$$
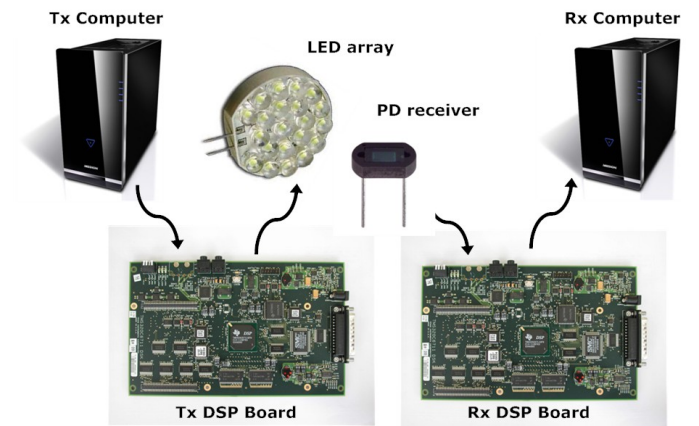
where α is the transmitter beam angle.

Fig. 3. A simplex optical link focusing on short-range indoor broadcasting applications. The demonstrator consists of two DSP evaluation boards.
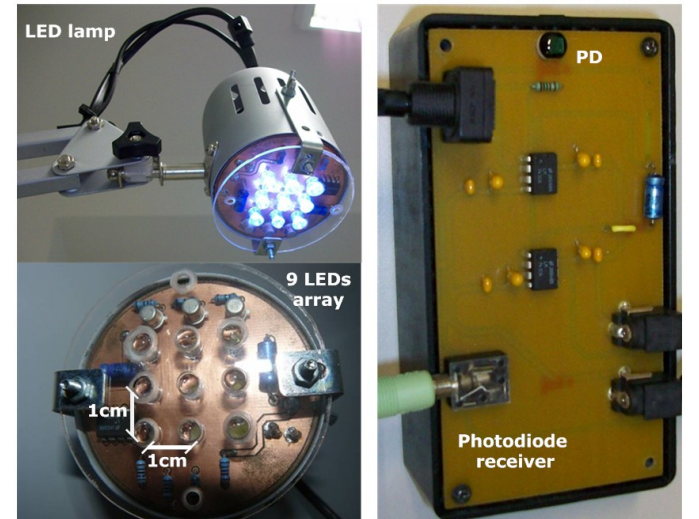

Fig. 4. The lamp with 9 LEDs and the PD receiver circuit.

IV. RESULTS

A. Transmitted Optical Power

Most data sheets of white LEDs provide only the photometric power, namely luminous flux F in lumens or the luminous intensity I_v measured in candles, which are useful

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[2] DSP development board TMS320C6713.
[3] Photodiode SLD-70BG2.

metrics for illumination design. However, the radiometric power in watts is more relevant parameter for wireless transmission. Therefore, measurements are conducted to determine the transmitted optical power P_t in watts for the considered LED. The LED operates with 20mA bias current and dissipates 62mW of electrical power.

An optical power meter[4] is used to measure the spectral power distribution $p(\lambda)$ in steps of 10nm (starting 400nm to 750nm) [20]. The optical power meter is limited to 400nm minimum wavelength and its photo detector[5] has an active area of 1cm². The obtained values are used to determine P_t and F using the following equations [2],

$$P_t = \sum_{400nm}^{750nm} p(\lambda)\Delta\lambda \quad \text{(W)} \tag{6}$$

$$F = \gamma \sum_{400nm}^{750nm} p(\lambda)V(\lambda)\Delta\lambda \quad \text{(lm)} \tag{7}$$

where $\Delta\lambda$ is 10nm, $V(\lambda)$ denotes the CIE 1931 (international commission on illumination) eye sensitivity function in the photonic vision regime and $\gamma = 683$ lm/W is the peak luminous efficacy based upon the sensitivity of the eye at 555nm [17]. A conversion factor ξ relating the photometric power to the radiometric power can be obtained by using (6) and (7),

$$\xi = \frac{P_t}{F} \quad \text{(W/lm)} \tag{8}$$

The values for I_v and the beam angle α can be obtained from the data sheet and used to calculate F as follows [18],

$$\Omega = (1 - \cos(0.5\alpha)) \times 2\pi \quad \text{(sr)} \tag{9}$$

$$F = I_v \times \Omega \quad \text{(lm)} \tag{10}$$

where Ω is the LED solid angle in steradian.

A conversion factor $\xi = 5.4$ mW/lm is calculated by using (6), (7), and (8). From the data sheet, α and I_v are 20 degree and 11cd, respectively. A 1.05lm was calculated by using (9) and (10), and the corresponding P_t is 5.7mW. This corresponds to 51mW total transmitted power from 9 LEDs.

B. Received Optical Power and Path loss

Two coverage scenarios, namely vertical and horizontal scenarios, are considered, as shown in Fig. 5. Experimental measurements are conducted to explore the received optical

[4] Power meter 1916-C.
[5] Photo detector 918D-SL-OD3.

power and the path loss for these coverage scenarios. The Tx is directed downwards and emitting towards the floor. The Rx is directed upwards towards the ceiling. The Tx-Rx separation distance is denoted by d. In a vertical coverage scenario, the Rx is moving vertically away from the Tx (d=50→225cm, in 25cm steps). In a horizontal coverage scenario, the vertical distance between Tx and Rx is fixed (b=1m) and the Rx is moving horizontally (a=0→50cm, in 10cm steps).
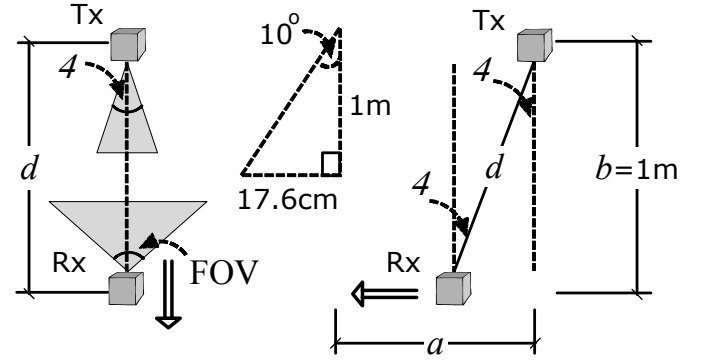

Fig. 5. Vertical and horizontal coverage scenarios.

A PD with 9.8mm² active area is considered. The optical filter and the concentrator gain are set to 1.0. The average received optical power is obtained through measuring $p(\lambda)$ and substituting in (6). The obtained values are scaled to correspond to the optical power on the 9.8mm² active area.

The calculated and the measured received optical power for the vertical coverage scenario are depicted in Fig. 6. Theoretical and measured results match closely. Along the vertical separation, a path loss variation of more than 12dB is observed. The received average optical power at 50cm is around -24dBm and reduces to -36dBm (12dB loss) at 2m.

Theoretical and measured results for the horizontal coverage scenario are shown in Fig. 7. A -30dBm optical power is measured when the Rx is directly located under the Tx. A 50cm horizontal displacement yields -37dBm (7dB loss) optical power. It can be seen that there is only a relative minor attenuation up to 20cm away from the initial position (~1dB loss). A more pronounced attenuation is observed between 20cm to 40cm horizontal displacement (~ 4dB loss). This can be attributed to the FOV mismatch between TX and RX at d>20cm. With 20 degree LED beam angle, the horizontal coverage is calculated to be 17.6cm as indicated in Fig. 5. A horizontal displacement further above 17.6cm from the initial position (at a=0cm) places the PD out of the illumination coverage. This explains the aforementioned path loss behavior. Therefore, a proper setting of the LED beam angle, the number of LEDs forming the array, the array geometry, and the FOV of the photodiode is essential to optimize the coverage. This also highlights that these effects have to be taken into account when considering co-channel interference (CCI) in such a cellular network.
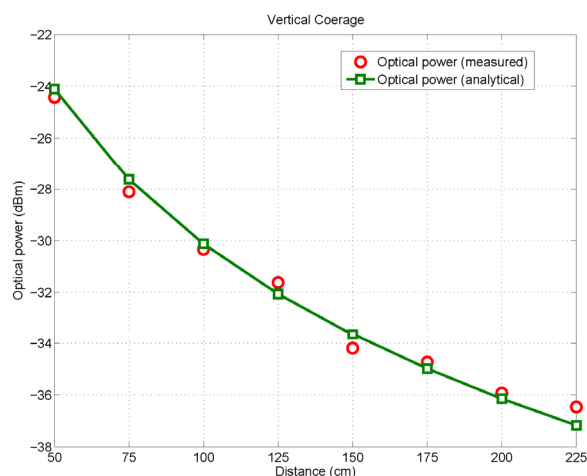
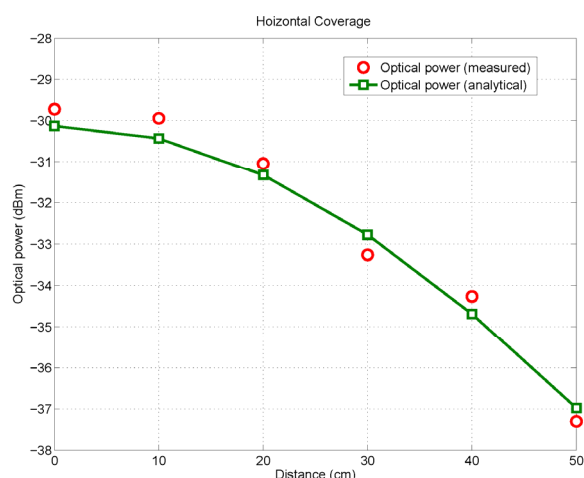**Fig. 6. The vertical coverage scenario.**

Fig. 7. The horizontal coverage scenario.

C. Bit-error Performance

All measurements are taken in a medium-sized office room and ambient daylight through windows is considered. The electrical SNR is measured over one OFDM symbol. At least ten data blocks of 10^6 bits each are sent to measure the system bit-error performance. *The BER below 10^{-6} is not recorded and that is why some graphs consist of fewer measurement points.*

Table I, outlines the important prototype parameters.

TABLE I
UNITS AND CORRESPONDING SYMBOLS

OFDM model	
IFFT length	64
Data sub-carriers	31
CP length	16 [samples]

The BER performance versus distance for the vertical coverage scenario is presented in Fig. 8. The additional y-axis at the right shows the measured electrical SNR at different receiver positions. For broadcasting applications using a reading lamp, it is practically valid to consider the target Tx-

Rx separation distance to be around 1m, and 10^{-5} as the target BER for video broadcasting. For example, MPEG-4 video transmission has slight visible degradation at 10^{-5} BER [19]. Low order modulation schemes (BPSK and QPSK) can achieve these requirements even without any channel coding. For high order modulation schemes, namely 16-QAM and 64-QAM, the 16-QAM with 3/4 channel coding rate can achieve the required targets and BER less than 10^{-6} up to 2m (18dB SNR). However, the 64-QAM with 2/3 channel coding rate can only achieve the 10^{-5} BER target with higher SNR value (33dB SNR). Finally, the 64-QAM 1/2 channel coding rate fulfils the requirements and achieves BER less than 10^{-6} up to 1.75m (18dB SNR). The uncoded modulation curves are included as references.
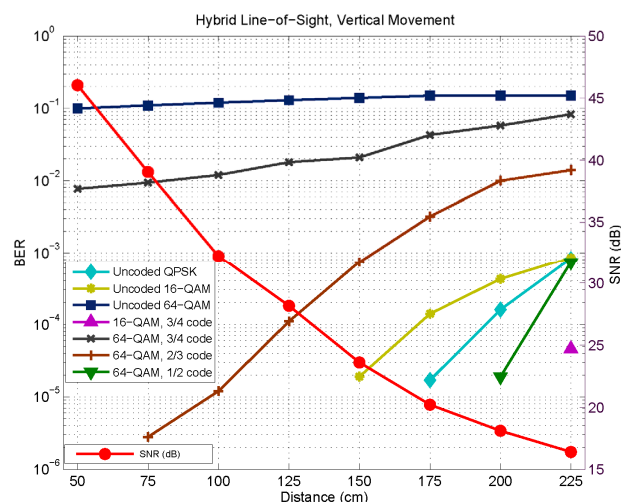

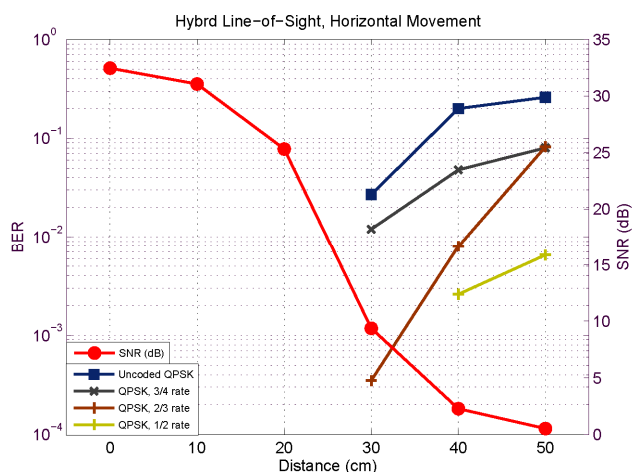**Fig. 8. The vertical coverage scenario for different modulation schemes and channel coding rates.**

Fig. 9. The horizontal coverage scenario measurements using QPSK modulation.

The BER performance of QPSK modulation versus distance for the horizontal coverage scenario is depicted in Fig. 9. A horizontal displacement of 50cm is considered to examine the cell coverage edge of an LED reading lamp. At 20cm (25dB SNR), BER less than 10^{-6} is achieved even without introducing any channel coding. However, at 30cm the SNR

value drops drastically to reach 9dB and even with 2/3 coding rate, the maximum BER that can be achieved is 3×10^{-4}. To maintain the required BER performance ones has to resort to half rate coded QPSK modulation.

Although a LOS link configuration is considered, the obtained BER vs. SNR is generally valid for OFDM based VLC systems because the illumination requirements results in a dominant LOS component in most positions in the room [3]. Even when multipath components exist, OFDM inherently combat multipath induced ISI with a proper CP length.

D. Illumination Requirements

The illuminance is measured and compared with the minimum required values according to lighting standards. The minimum illuminance required for different work spaces ranges from several hundred to thousand lux [20]. Therefore, for VLC, a high SNR is obtainable, which is an indirect consequence of the illumination requirements. In order to determine the illuminance achieved using the square array of 9 LEDs lamp, measurements are conducted using a lux meter[6]. The obtained illuminance for the vertical coverage scenario is shown in Fig. 10. At the target distance of 1m, only 20lx are measured. From the obtained values, it is expected that with the appropriate number of LEDs to achieve sufficient illuminance, high SNR values can be achieved.
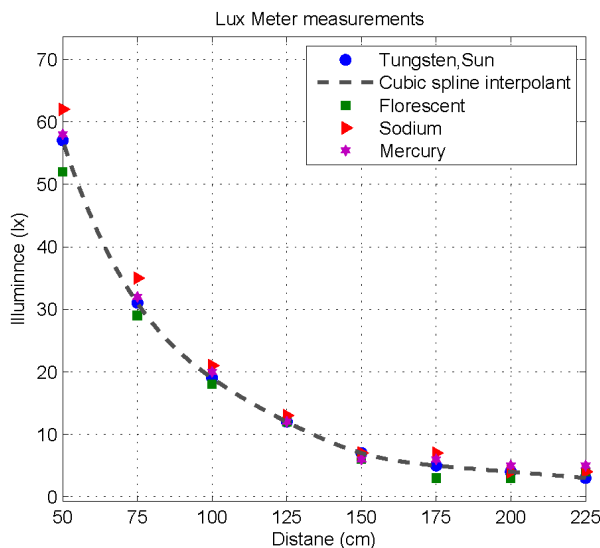

Fig. 10. Illuminance measurements – the interpolated curve using the measured data (Tungsten/Sun) is plotted.

V. CONCLUSION

Visible light data broadcasting based on OFDM has been demonstrated. The hardware prototype uses low cost commercial LEDs and PDs. Preliminary measurements showed promising results with 9 LEDs producing illuminance of about 5 times below that required for work spaces. Using bigger array structures or using several lamps to simultaneously transmit the same signal, the SNR can be boosted and the coverage area can be extended without any

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[6] Lux meter 72 6693.

ISI. The current bandwidth is sufficient for messaging or information services, several audio channels, low quality video streaming applications.

For a 1m typical distance of an object (and hence a receiver) from a reading lamp, with faster data converters and analog frontends supporting 20MHz signal bandwidth, and 20dB SNR, which is easily achieved with illuminance that is in the required range, clearly, a throughput of greater than 80Mbits/s (using 2/3 coded 64-QAM) is feasible and would be sufficient for high quality audio and video broadcasting. It also has been found that the coverage and the CCI in a cellular network can be controlled by proper setting of the LED beam-angle.

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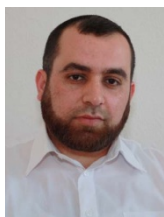
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