A 3 × 25 Mbps WDM-Ro-VLC system for amateur radio applications

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***Abstract*— Radio over visible light communications (Ro-VLC) can be a pioneering technology to provide ubiquitous radio services particularly in the radio network-permitted locations. In this work, three channels, each up-converted to a 50 MHz radio signal carrying 25 Mbps data, is transmitted over a 0.5 m visible light communications link by using the cost effective on-off key (OOK) modulation format. Three red, green and blue light emitting diodes are adopted for parallel transmission. We show simulation results, carried out using OptiSystem™ software, for the bit error rates for the proposed diffuse system for both non-return to zero and return to zero data formats.**

Keywords— radio over visible light communication, wavelength division multiplexing, on-off Key

I. Introduction

The six-meter band (SMB) (i.e., 50-54 MHz) is mainly used for amateur radio applications. Allocated by the International Telecom Union (ITU), SMB is used in the Region 1 for broadcasting with the range of 50-52 MHz and in Regions 2 and 3 for new radio applications with 50-54 MHz. However, several Region 1 countries also use portions of SMB for new radio applications [1]. There are certain locations where usage of such applications is not permitted due to its interference with other portions of the electromagnetic spectrum such as aircrafts, hospitals, defense, etc. Therefore, in such environments one could adopt alternative wireless transmission systems, which is based on light communications not the radio frequency (RF).

Light emitting diodes (LEDs) and photodetector as well as image sensor based visible light communications (VLC) is seen as a promising wireless transmission technology for the next generation network systems, which can be incorporated in any existing lighting fixtures including street and traffic lights, homes, offices, vehicles, etc. [2]. The VLC transmission system offer a number of interesting features including security at the physical layer, not effected by the RF electromagnetic interference, energy efficiency (since LEDs are much more power efficient than the existing lights), high-data rates, which makes them very attractive for a range of applications mostly in indoor environments (at the moment) [2-3]. One such applications is amateur radio, where the VLC technology can effectively be utilized to provide services especially in areas where RF cannot be used because of interference and health reasons [3].

However, the most widely commercially available LEDs (i.e., white LEDs and red, green and blue (RGB)) used for lighting have a limited modulation bandwidth (i.e., < 50 MHz) due to their large size, which is not sufficient for high transmission data rates. The most recent micro-LEDs reported in the literature offer much higher modulation bandwidth in the range of hundreds of MHz to over 1 GHz, thus enabling multi-Gbps VLC transmission a possibility. However, these LEDs have a very low illumination levels, which currently are not suitable to be used as light sources [4-5]. Previous studies have addressed the issue of LED's modulation bandwidth limit and have proposed several techniques to overcome it with aim of achieving higher data transmission. The proposed scheme includes pre-and post-equalizations, micro LEDs, and advanced detection circuits and multi-level and multi-carrier modulations [1-2]. The latter includes single carrier frequency domain equalization, multi-band carrier-less amplitude and phase modulation, orthogonal frequency division multiplexing

(OFDM), and OFDM/offset quadrature amplitude modulation [6-9]. As for modulation schemes used in VLC systems, the multi-level and multi-carrier modulation formats offers increased data rates both implementation but at the cost of increased complexity and cost as well as have a limited peak to average power ration to ensure operation within the linear region of the LED light source. On the other hand, the simple and low-cost on-off keying (OOK) scheme is more than adequate for a range of applications. In 2016 [10], the authors demonstrated transmission of 266 kbps data over 2 m VLC link by employing OOK with on-chip 8-W 85% efficiency boost LED driver. In 2017 [11], a 600 Mbps VLC system with a GaN-based micro-LED and NRZ-OOK over a transmission range of 0.6 m with an active chip tracking system was reported. In 2018 [12], the authors transmitted 400 Mbps OOK VLC system over a link span of 1.5-3 m and investigated the performance of an analog front end (AFE) circuit with an optimal equalization design in order to increase the bandwidth of LED.

On the other hand, researchers have utilized various multiplexing technologies such as WDM and MIMO for data rate upsurge in VLC systems [13-15]. The data rate of WDM-VLC is reportedly higher than that of MIMO-VLC [16] . In 2015 [17], the authors reported the offline data rate of 8 Gbps using RGBY-WDM-VLC based high-order CAP modulation with BER value of 3×10^{-3}. In 2017 [18], 4.06 Gbps data is transmitted over link span of 1 m by deploying the WDM technique in VLC system.

In this work, we have also adopted OOK to realize a simple and a low-cost radio over VLC system. Furthermore, to increase the capacity of proposed Ro-VLC system, wavelength division multiplexing (WDM) is adopted using RGB LEDs and transmitted over a diffuse link with a span of 0.5 m. In this system 25 Mbps of data is up-converted to a carrier RF of 50 MHz prior to intensity modulation of RGB LEDs for application in amateur radio. Note, that the transmission range can be increased by increasing the optical power levels. We show the measure bit error rate results for non-return to zero (NRZ) and return to zero (RZ) OOK data formats. The remainder of paper is presented as follows: section II describes system modeling, section III presents the results and discussion followed by the section IV, which presents conclusion of this work

II. System Modeling

Figure 1 shows the schematic diagram of the proposed 3 × 25 Mbps-50MHz WDM-Ro-VLC system, which is simulated using OptiSystem™ software platform. As shown in Fig. 1(a), for each channel, a 25 Mbps data in NRZ) and RZ formats is up-converted to a RF carrier of 50 MHz using a local oscillator to make it suitable for amateur radio applications. The modulated RF signal are then used for intensity modulation of RGB LEDs at the peak wavelengths of 650 nm, 530 nm and 450 nm, respectively. The lights signals are then multiplexed in the wavelength domain and transmitted over the wireless channel.
The optical mean power of LED is given by [19]:

$$P = \eta . h . f . \frac{i(t)}{q} \quad (1)$$

where h is the plank constant, n is the quantum efficiency, f is the emission frequency, q is the electron charge and $i(t)$ is the modulation current signal.

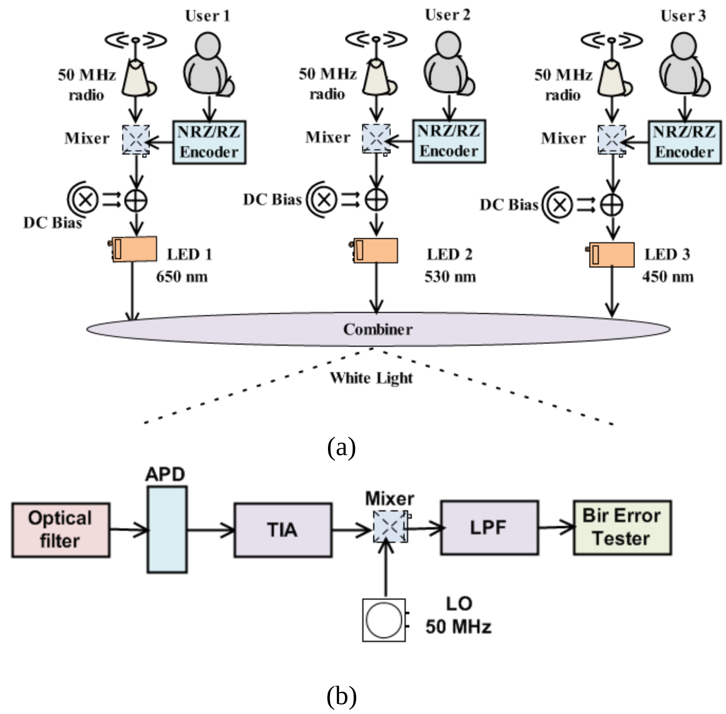

Fig. 1: 3 × 25 Mbps WDM-based Ro-VLC systems: (a) transmitter, and (b) receiver

Note that, the LED modulation bandwidth depends on electron lifespan and materials used in fabrication de of the device. Therefore, its transfer functions based on the current model is described as [19]:

$$H(f) = \frac{1}{1 + j.2\pi . f.(\tau_n + \tau_{RC})} \quad (2)$$

where τ_n is the electron life time and τ_{RC} is the RC time constant. As shown in Fig. 2, the LED output is assumed to be Lambertian, which illuminates the receiver plane. The irradiance at the photodetector is given by [20]:

$$E = \frac{L.A_s}{h^2} \quad (3)$$

where A_s is the source area, and h is the distance from the source to detector. Note, L refers to the luminous flux within a unit radiating from the projected area of a surface element to a specific direction, which can be described mathematically as [20]:

$$L = \frac{d\Phi}{d\Omega . dA_s . \cos \vartheta_s} \quad (4)$$

where $d\Phi$ is the radiant power incident on an infinitesimal element of a surface to the projected area of that element, $d\Omega$ is the infinitesimal change in solid angle and dA_s is the infinitesimal element of area of source.

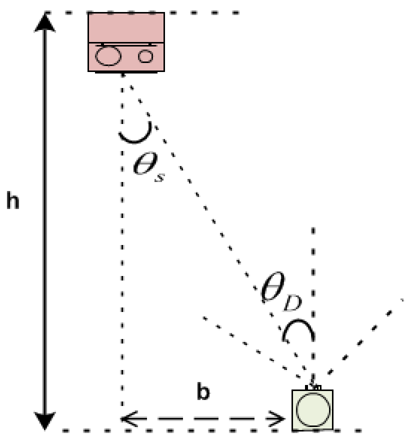

Fig. 2: A VLC link with a Lambertian source

The cosine-measured optical path loss can be described mathematically as [20]:

$$Loss = \frac{A_d . CR}{\pi h^2} . (\cos \theta_s)^2 . (\cos \theta_D)^2 \quad (5)$$

where A_s is the surface area of source, *CR* is the optical concentration factor and θ is defined as [20]:

$$\theta = \theta_s = \theta_d = \tan^{-1}\left(\frac{b}{h}\right) \quad (6)$$

where *b* is the distance of detector in horizontal direction from the source as shown in Fig. 2.

At the receiving side, optical band-pass filters is used to capture the R, G and B lights prior to photodetection using a avalanche photodiodes (APD). The output of APD is applied to a transimpedance amplifier prior to RF demodulator, which is composed of a local oscillator, a mixer and a low pass filter, in order to retrieve the original data. Finally, a bit error rate tester is used to measure the bit error rate performance of the link. The received signal in terms of the transmitted signal x(*t*) and the channel response *h*(*t*) is given by:

$$y(t) = x(t) \otimes h(t) + n(t) \quad (7)$$

where ⊗ represent the convolution, and *n*(*t*) the additive white Gaussian noise (AWGN), which is composed of the shot noise, dark current noise and thermal noise. We have assumed that the background light induced shot noise is negligible.

All the key system parameters adopted in simulation are outlined in Table 1.

TABLE I. SIMULATION PARAMETERS

Item	Parameter	Value
Simulation window	Bit rate	25 Mbps
	Time window	5.12e-006s
	Sample rate	800e+006 Hz
	Sequence length	128 bits
LED	Wavelength	650nm (Red), 530 nm (Green) and 450 nm (Blue)
	Carrier lifetime	5e-009
	RC constant	5e-009
	Bandwidth	5 MHz
	Output power	20.3 dBm
	Slope efficiency	0.5 W/A
	Quantum efficiency	0.05
Diffuse channel	Irradiance half angle	0 deg
	Incidence half angle	0 deg
	Detection surface area	1 mm^2
	Optical concentration factor	1
APD photo diode	Width	10 µm
	Responsivity	1.2 A/W
	Gain	3
	Dark current	10 nA
	Thermal noise power spectral density	100e-024 W/Hz
	Ionization ratio	0.9

III. SIMULATION RESULTS

Results obtained from the simulation and modeling of the proposed WDM-Ro-VLC system are presented and discussed in this section. Also shown in the inset are the eye diagrams. Fig. 3 shows the BER as a function of the transmission distance for both NRZ and RZ formats for the Channel 1 for LED at a wavelength of 650 nm. It shows that NRZ display improved BER performance compared to RZ. E.g., at the distance of 0.5 m the BER values are 1.9×10^{-4} and 1.4×10^{-3} for NRZ and RZ data formats, respectively.

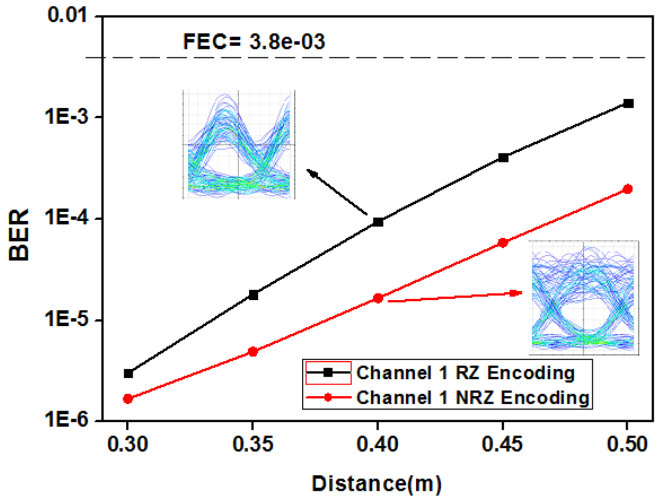

Fig. 3: BER against the transmission distance for the Channel 1 and for NRZ and RZ

However, both values are lower than the forward error correction (FEC) limit of 3.8×10^{-3}.

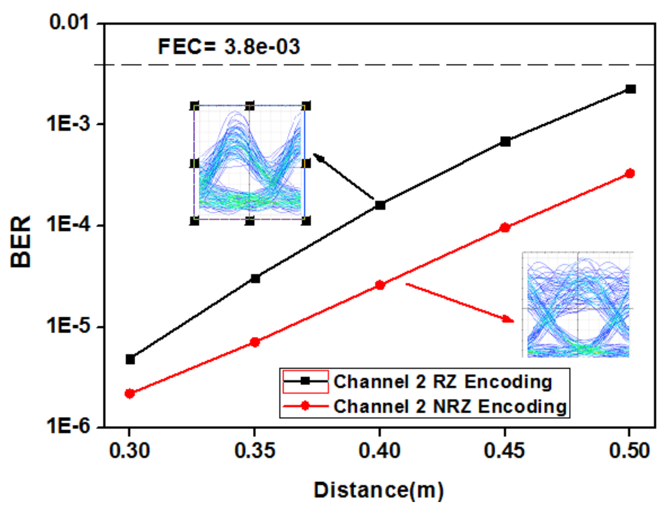

Fig.4: BER against the transmission distance for the Channel 2 and for NRZ and RZ

Figs. 4 and 5 shows the measured BER for the Channels 2 and 3 using LEDs with wavelengths of 530 nm and 450 nm. At the transmission distance of 0.50 m, the values of BER are (*i*) 3.3×10^{-4} and 2.2×10^{-3}, for NRZ and RZ, respectively for the Channel 2; and (*ii*) 5.7×10^{-4} and 3.7×10^{-3}, respectively.

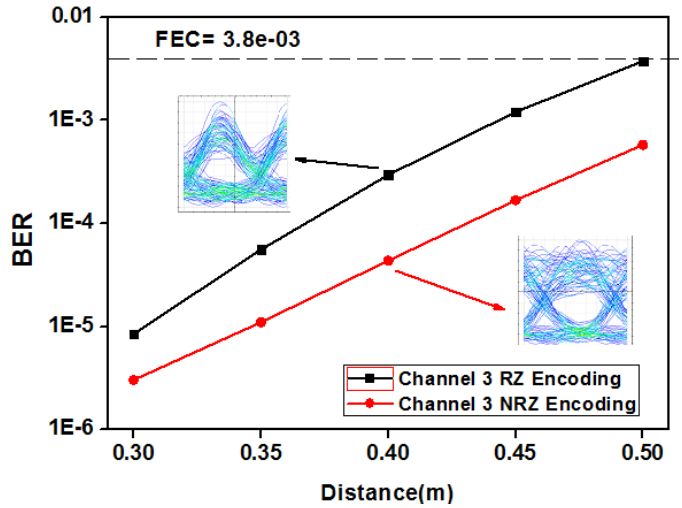

Fig.5: BER against the transmission distance for the Channel 3 and for NRZ and RZ

The clear opening of measured eyes diagrams also shows the successful transmission of data over the Ro-VLC link for both encoding formats.

IV. CONCLUSION

In this work, WDM-based Ro-VLC system was proposed for amateur radio applications, which used the six-meter radio bands. Three LED's with the wavelengths of 650 nm (red), 530 nm (green) and 450 nm (blue) were used for transmitting 25 Mbps of data per channel that were up-converted to 50 MHz radio signals. The simulation and modeling of the proposed system was carried out in OptiSystem software. The reported results showed successful transmission of three channels over 0.50 m diffused visible link with acceptable BER values below the FEC limit of 3.8×10^{-3}. This work can further be extended by means of real-time experiment implementation and evaluation.

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