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A novel hybrid radio over fiber VLC system combining 5G mmWave and coarse wavelength division multiplex grid

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ABSTRACT

Visible light communication (VLC) has gained attention for enabling gigabit data transmission over a short-range. In radio over fiber (RoF), modulated radio frequency (RF) is carried over optical fiber. Millimeter-wave (mmW) range also offers a vast amount of spectrum and enables integration with RoF. We propose a novel hybrid network using mmWave based RoF backhaul and coarse wavelength division multiplexed (CWDM)-VLC for indoor communication. Three different optical tones were introduced to produce the desired mmW signal using optical heterodyning with one of them carrying modulated data and the other two carrying unmodulated data. Optical sideband signal with the carrier (OSSB+C) is used for uplink communication. Modulated mmWave signal is used for VLC downlink to drive a multi-color CWDM system. The performance of the VLC downlink is measured using different optical filters such as Bessel, Trapezoidal, Gaussian, and Fabry Perot. A maximum data rate of 2.64 Gb/s and 6.58 Gb/s were achieved with 10 and 20 channels off the shelf LEDs with 16 quadrature amplitude modulation (QAM) with reasonable BER for downlink VLC communication. The uplink communication was carried out using mmW with 2.5 Gb/s data rate using on-off keying (OOK) modulation and the data from this communication down converted at central office (CO) through RoF backhaul.

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1. INTRODUCTION

Visible light communication (VLC) was first introduced in 2003 [1]. Light emitting diode (LED) is one of the possible sources for VLC as a transmitter, since it can be used for illumination and communication. A combination of multi-color red, green, blue, and yellow (RGBY) LEDs are mostly used to increase the data rate using the concept of wavelength division multiplexed (WDM)-VLC system [2]. Recently, CWDM-VLC was proposed in [3] to increase the data rate even further for indoor communication utilizing the full visible spectrum. Radio over fiber (ROF) is the concept of carrying RF signals over the optical fiber medium. The RoF network is used by fifth generation (5G) wireless technology to transmit data between the central office (CO) and customers. For 5G connectivity, a huge spectrum in the super-high frequency (SHF) ranges between 3 and 30 GHz and extremely high frequency millimeter wave (mmW) ranges 30 and 300 GHz is accessible. The frequency range from 5 GHz to 300 GHz with wavelength separations of 1 mm to 100 mm is commonly referred to as the millimeter-wave band [4]. RoF systems face noticeable difficulties with mmWave optical signal production and spectrally efficient backhaul connections to indoor consumer units [5].

VLC and millimeter-wave (mmW) both have huge bandwidths as advantages, but both heavily rely on line-of-sight (LoS) to work well [6], [7]. For indoor downlink communication, VLC performance is relatively good in terms of data rate, but it has some limitations in achieving such data rate for uplink communication [8]. Different types of sources have been proposed to improve the uplink communication-radio frequency (RF) [8], IR LED (850nm) [9], laser diode (LD) [10], and UV LED (375 nm) [11]. We are proposing an ROF-VLC hybrid network where mmWave signal is used for uplink to increase data rate and connect to the wider internet through RoF backhaul.

Table 1 contrasts several RoF-VLC hybrid network model-based works that are already in existence. The maximum data rate that has been attained using simulations is 600 Mb/s over an 80 cm VLC link, where 30 km of single-mode fiber (SMF) and 150 m of MMF were used as backhaul [12]. Another project used IR-LED for the uplink and connected it to a 50 km optical fiber link to achieve a 1.87 Gb/s data throughput. The bidirectional VLC model used in this was WDM CO-OFDM-PON [13]. A hybrid RoF-VLC system has been shown to transfer data at 54 Mbit/s over a practical distance (1 km SMF, 3 m free space) in experiments [14]. With LED-based VLC, the greatest data throughput is 450 Mb/s over a 1 m indoor link [15]. It has been established that a bidirectional WDM hybrid fiber-VLC system based on quantum dash-laser diode (QD-LD) can transmit data at 10 Gbps over 50 km SMF and 40 m optical free space. A data rate of 2.5 Gb/s across 10 m of clear space was attained for uplink [16]. 16 QAM-OFDM signals with two LD at the transmitter and reception ends, 20 km of single mode fiber, and a 15 m indoor VLC connection range were used to reach a data throughput of 2.5 Gb/s [17]. Using a passive optical network (WDM-PON), a WDM system was deployed in a hybrid RoF-VLC link in [18], [19]. They were able to reach data rates of 150 Mb/s with 2 PAM and 600 Mb/s with 8 PAM, respectively. Different optical filters, such as Bessel, Trapezoidal, Gaussian, and Fabry Perot optical filters, can be used to examine the performance of an optical wireless communication (OWC) channel [20], [21].

Table 1. A comparison among different types of hybrid VLC system

Name	Outdoor link	VLC link range	Data rate	UP/Down link	Modulation
Pavan and Jeyachitra [12]	30 mSMF+150 m MMF	80 cm VLC	600 Mb/s	Downlink	16/64 QAM-OFDM
Kaur *et al.* [13]	50 km SMF	150 cm IR LED	1.87 Gb/s	UP‖DW link	OFDM-WDM
Khalid *et al.* [14]	1 km RoF	1-3 m	54 Mb/s	UP+DW link	64 QAM
Huang *et al.* [15]	430-m FSO	30 cm VLC	450-Mb/s	Downlink	OOK
Mandal *et al.* [16]	50 km SMF	10 m FSO/LD	2.5 Gb/s	UP‖DW link	OOK
Chen *et al.* [17]	20 km SMF	15 m (LD)	2.5 Gb/s	UP‖DW link	16 QAM-OFDM
Thomas *et al.* [22]	100 km SMF	6 m VLLC (LD)	2.65 Gb/s	Downlink	16 QAM-OFDM

To boost data-rate while employing LED sources for the first time, we suggest a hybrid RoF-VLC system that is coupled to an indoor CWDM-VLC grid through 5G mmW wireless backhaul. Since LED sources may also be utilized for lighting, utilizing them for downlink is often preferred. The Bessel, Trapezoidal, and Rectangle optical filters have all improved BER performance [22]. For the first time, mmW frequency reuse for uplink communication [23] is also suggested.

2. HYBRID SYSTEM ARCHITECTURE

An overview of the hybrid RoF-VLC system with 5G mmW backhaul is shown in Figure 1. In CO, an array of laser modules generates optical tones with predetermined separations in frequency that match to the required triple tone mmW signal. Three distinct light waves are generated by three separate continuous wave (CW) LDs.

Through a 20 km fiber link, CO is connected to the VLC customer unit (CU), and a band pass filter (BPF) at the VLC access point divides the required mmW signal from the baseband signal. The signal is down-converted to baseband via electrical self homodyning. The base band signal is then routed to an indoor VLC point and transformed to a visible light signal using an LED after being discovered. VLC transmitter is structured to carry CWDM signals to increase the number of data channels. After the downlink data is received, it is retransmitted back to RoF backhaul through uplink communication, and this uplink data is down converted at CO.

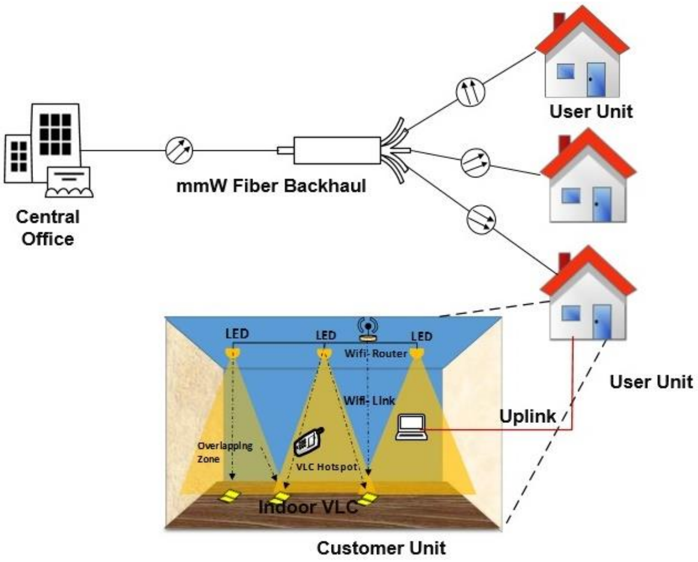


Figure 1. Proposed hybrid 5G mmWave based RoF-CWDM-VLC model for indoor communication

3. PROPOSED SYSTEM MODEL

In this section, we describe the mathematical model of the RoF-VLC system. The electric field intensities of three independent optical signals generated by laser diodes at the CO are shown in (1)-(3). Three independent optical signals are shown as;

$$E_1 \exp j(2\pi f_1 t + \varphi_1) \tag{1}$$

$$E_2 \exp j(2\pi f_2 t + \varphi_2) \tag{2}$$

$$E_3 \exp j(2\pi f_3 t + \varphi_3) \tag{3}$$

where E is the peak amplitude of the electric field of each laser. f_1, f_2 and f_3 are optical frequencies, and ϕ_1, ϕ_2 and ϕ_3 are distinct phase characteristics of three lasers. In this scheme, the optical signal from LD_1 is modulated see in Figure 2, which is achieved by applying Taylor series expansion and combined with two unmodulated signals from LD_2 and LD_3, which can be represented by [24];

$$A(t) = A_1(t) + A_2(t) + A_3(t)$$

$$A_1(t) = \exp j(2\pi f_1 t + \varphi_1)[1 + jmcos(2\pi f_m t)]$$

$$A_2(t) = \exp j(2\pi f_1 t + \varphi_1) + A_2(t) + A_3(t)$$

$$A_3(t) = \exp j(2\pi f_1 t + \varphi_1) + A_2(t) + A_3(t) \tag{4}$$

the overall combined signal $A_{\mathrm{f}}(t)$ passes through SMF. This received signal gets distorted by the SMF and is shown as;

$$Af(t) = Af_1(t) + Af_2(t) + Af_3(t) \tag{5}$$

$$A_{\mathrm{f1}}(t) = [\exp j(2\pi f_1 t + \emptyset_1 + \varphi_1) + \frac{m}{2}\exp \quad j(2\pi(f_1 + f_m)t + \emptyset_1 + \varphi_1) + \frac{m}{2}\exp \quad j(2\pi(f_1 + f_m)t + \emptyset_1 + \varphi_1) + \frac{m}{2}\exp \quad j(2\pi(f_1 + f_m)t + \emptyset_1 + \varphi_2)] \tag{6}$$

$$A_{\mathrm{f2}}(t) = [\exp j(2\pi f_2 t + \emptyset_2 + \varphi_3) \tag{7}$$

$$A_{\mathrm{f3}}(t) = [\exp j(2\pi f_3 t + \emptyset_3 + \varphi_4) \tag{8}$$

where $\varphi 0$, $\varphi 1$, $\varphi 2$, $\varphi 3$ and $\varphi 4$ are spectral phase delays of the SMF. The optical signal is subsequently received at the CU, where it passes through a number of structural processes. The optical light signal from (8) is isolated from the signal using an optical bandpass filter for uplink carrier utilization since a wavelength re-use structure is utilized. The photodetector (PD) picks up the other two signals, which are then transmitted through the down-conversion channel. To create baseband data, this approach employs the same self homodyning technique as CU. The signal in (8) is employed as the optical carrier in a Mach-Zander modulator (MZM), which receives the downconverted uplink data as the modulation data. Using Taylor series expansion, the outcome of the MZM $B_1(t)$ is;

$$B_1(t) = \exp j\,(2\pi f_3 t + \emptyset_3)[1 + \mathrm{j}\tfrac{N}{2}\exp(2\pi f_n t) = \exp j\,(2\pi f_3 t + \emptyset_3)$$
$$[1 + \tfrac{N}{2}\exp j\,(2\pi f_n t + \exp j - 2\pi f_n t) = \exp j\,(2\pi f_3 t + \emptyset_3) + \tfrac{N}{4}\exp j\,[2\pi t(f_n + f_3) +$$
$$\emptyset_3 + \tfrac{N}{4}\exp j\,[2\pi t(f_3 - f_n) + \emptyset_3] \quad (9)$$

which shows the optical signal at center frequency of f_3 with data bandwidth of f_n, carrying the laser phase of ϕ_3. This signal is sent back to the CO through SMF link. After back transmission, the signal can be expressed as (10);

$$B_{\mathrm{f}\,1}(t) = \exp j\,(2\pi f_3 t + \emptyset_3 + \varphi_8) + \frac{N}{2}\exp j\,(2\pi(f_3 + f_n)t + \emptyset_3 + \varphi_9) +$$
$$\tfrac{N}{2}\exp j\,(2\pi(f_3 + f_n)t + \emptyset_3 + \varphi_{10}) \quad (10)$$

where φ_8, φ_9 and φ_{10} are the phase noise induced by fiber dispersion. At CO, the optical signal is detected using a direct PD which outputs;

$$i_{\mathrm{p}}(t) = \mathrm{R}\ \times B_{\mathrm{f1}}(t) + B^*_{f1}(t) \quad (11)$$

where R is responsivity of the PD and $B^*_{f1}(t)$ is the complex conjugate of (10).

At the VLC access point, optical self-heterodyning produces signal at baseband which is known as baseband replica as shown (12);

$$i_{\mathrm{p}}(t) = \mathrm{R}\ \times [(A_{\mathrm{f1}}(t) + A_{\mathrm{f2}}(t) + A_{\mathrm{f3}}(t)) \times +(A^*_{f1}(t) + A^*_{f2}(t) + A^*_{f3}(t))] \quad (12)$$

here $Af1\times(t)$, $Af2\times(t)$, and $Af3\times(t)$ are complex conjugates of the (6)-(8) and R is the responsivity of PD. At the CU, the received mmWave signal arrives with desired data carrying tone and mixed with itself as a self-homodyne detection method to make baseband signal which is shown as (13);

$$m\cos\{2\pi t\,(f_d + \varphi_{\mathrm{d}})\} \quad (13)$$

which has a center frequency of f_d and has a phase noise of φ_d. This signal is used for indoor communication through LEDs which is described as;

$$R_{\mathrm{i}}(\emptyset) = (m_l + 1)cos^m(\emptyset)/2\pi \quad (14)$$

$$m_{\mathrm{l}} = -\ln 2/\ln(\cos(\emptyset_{\frac{1}{2}}) \quad (15)$$

where $\emptyset$ is irradiance angle where as LED's semi-angle at half power is $\emptyset_{1/2}$ and Lambertian emission's order is m_l in (15). On the otherhand, the horizontal luminance E_{hor} has shown (16);

$$E_{\mathrm{hor}} = \mathrm{I}(0)cos^{ml}(\emptyset)/r^2\cos(\varphi) \quad (16)$$

where r is the distance of between transmitter and receiver and transmitted LED's total power is $P_0\,(t)$, which can be mentioned as (17);

$$P_{\mathrm{o}}(\mathrm{t}) = (P_{LED}[1 + m_i x(\mathrm{t})] \quad (17)$$

where P_{LED} is the optical power of LEDs, m_i is defined as modulation index, and $x(t)$ is imput data bit rate signal. Moreover, we know that output signal depends on the LED's electron lifetime, RC constant, and LED's materials. So 3dB bandwidth of a LED can be explained as [16];

$$f_{3dB} = \frac{\sqrt{3}}{2\pi(\tau_n + \tau_{rc})} \quad (18)$$

where τ_n is an electron carrier lifetime, and τ_{rc} is the RC constant of semiconductor device. The visible light passes through a wireless channel, and the DC gain or the power of this channel is [14].

$$H(0) = \frac{(m_l+1)Acos^{ml}(\theta)\cos(\varphi)T_s(\psi)}{2\pi r^2}\ [\varphi \leq\ \psi FOV] \tag{19}$$

here A is the photo sensor surface area of the PD, r is the channel length between transmitter and receiver, T_s (ψ) is the optical filter's gain, ψ is the incidence angle, and ψ_{FOV} is the field of view (FOV) of the photo diode. Optical filters use for rejecting the ambient noise and high bandwidth. Frequency transfer function of gaussian filter H(f) [21];

$$H(f) = \alpha e^{-ln(\sqrt{2})(\frac{f-f_c}{\frac{B}{2}})^2} \tag{20}$$

α is the insertion loss, d is the parameter depth, fc is the center frequency of the filter, and B is the filter bandwidth. Therefore, rectangular filter' transfer function is defined as (21);

$$H(f) = \begin{Bmatrix} \propto, (f_c - \frac{B}{2} < f < f_c + \frac{B}{2}) \\ d \end{Bmatrix} \tag{21}$$

for the bessel filter, the (22) is;

$$H(f) = \alpha \frac{d_0}{B_N(s)} \tag{22}$$

where BN (s) is the order of the filter, and d0 is a stabilizing constant, which can be explained as;

$$B_N(s) = \sum_{k=0}^{N} d_k S^k \tag{23}$$

where,

$$d_k = \frac{(2N-k)!}{2^{N-K}.k!(N-k)!} \tag{24}$$

and,

$$S = j\left(\frac{2(f-f_c).W_b}{B}\right) \tag{25}$$

where W_b is the normalized 3 dB bandwidth of the LED (for $N \geq 10$). With the filter order we define the total amount of light passing through the optical fiter.

At LD1=1550.2 nm, LD2=1550.016 nm, and LD3=1549.715 nm, three separate continuous waves (CW) laser diodes (LDs) are employed to create the three distinct light waves. Between LD1 and LD2, the frequency spacing has been set at 22.5 GHz, while between LD2 and LD3, it has been set at 37.5 GHz. The optical signal from the first laser is modified using 16 QAM or the non-return to zero (NRZ) on-off keying (OOK) random sequence. For improved bit-error-rate (BER), gray code differential coding is then applied to the input binary bit sequence. Figure 2(a), which depicts the data on top of the optical carrier, shows the modulator's output. By using optical heterodyning, the other two CW lasers are linked with the modulated tone while remaining unmodified, creating a triple tone spectrum, as shown in Figure 2(b). With low insertion loss and high isolation loss between port 1 and port 3, the signal next enters an optical circulator. Following its emission from port 2, the light travels down a similar circuit for 20 kilometers before reaching the receiver end. When the light leaves port 3, an optical coupler divides it. One of the coupler's outputs is coupled to a PIN PD, and the output of the PD is displayed in subset Figure 2(c), where the baseband signal is downconverted using the electrical self homodyning technique. The beating of the modulated light wave (LD1) and the free-running tone of the LD3 combine to provide the necessary mmW signal at 60 GHz with modulated data. An optical band pass filter (OBPF) receives the remaining output at 37.5 GHz, which is utilized for uplink communication as a reference in Figure 2(d). In order to feed this signal into LED for interior VLC (CU), an electrical BPF chooses the tones at 60 GHz transmission to VLC access point (VAP) using an LPF filter. after filtering the received data using lpf and off line process, uplink data back to the fiber backhaule through MZM in the Figure 2(e) [25]. Through a bias tee, the received baseband signal is sent to an LED array. The CWDM-VLC technology is used by this multicolored LED array. It has the capacity for 10 or 20 channels. The channel range between the LED grid transmitter and PD array receiver is adjusted to 3m, and the visible light signal travels across the optical wireless channel. Four different optical filters sucha as Gaussian, Trapezoidal, Bessel, and Rectangle have been used at the receiver end to increase the transmission bandwidth and indoor link performance. The indoor user will send the uplink data to the CO by reusing another mmWave frequency through RoF backhaul. All numerical parameters related to the system stability for this proposed hybrid RoF-VLC model have been tabulated in Table 2.

Table 2. Global parameters

Component	Parameter	Value
Global parameter	Bit rate	2.5 Gb/s
	Samples per bit	64 samples
	Time window	5.12e-006s
	Sequence length	64 bits
Customer unit (CU)	Wavelength	
Transmitter (LED)	10 CHs	390, 430,470,510,550, 590,630,670,710,750
	20 CHs	390,410, 430,450, 470, 490,510,530, 550,570, 590,610,630, 650,670, 690,710,730, 750,770
	Carrier lifetime	3.95e-09s
	RC content	3.95e-09s
	Modulation BW	50 MHz
	Slope efficiency	0.8 W/A
Free space channel	Beam divergence	1-10 (mard)
	Tx aperture dia	10 mm
	Rx aperture dia	25 mm
	Range	3 m
Receiver APD	Responsivity	0.65 A/W
	Bandwidth	1 GHz
	Dark current	10 nA
	Load resistance	50 Ohm
SMF	Length	km
	Ref wavelength	1550.2nm
	Attenuation	0.2 dB/km
Central office (CO)		
CO LDs	LDs frequencies (nm)	1550.2, 1550.016, 1549.715
	Bit rate	2.5 Gb/s
	Modulation types	OOK, 16 QAM
	Laser power	-3 dB

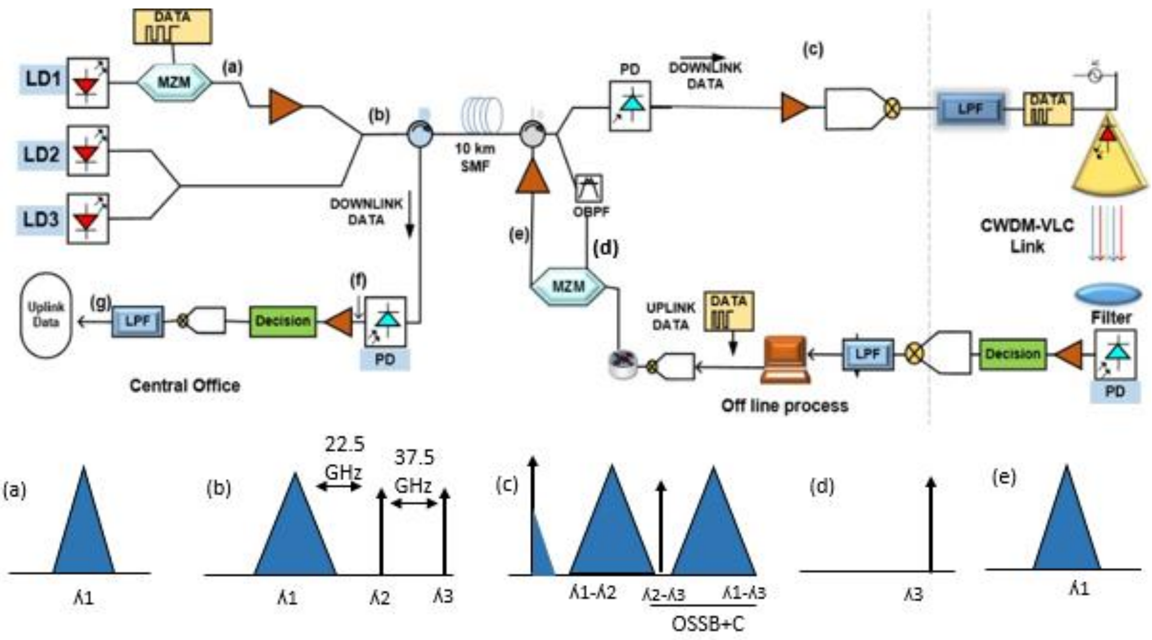
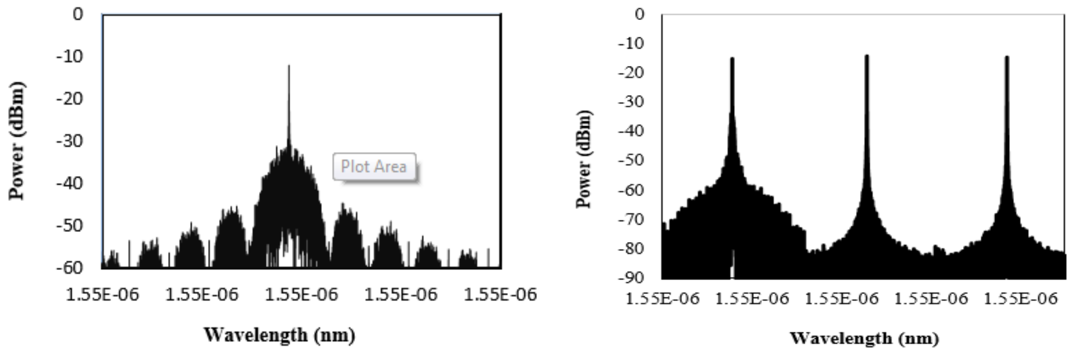


Figure 2. Triple tone generation with mmW hybrid system for wavelength reuse; (a) transmitted data on top of the optical carrier, (b) triple tone spectrum, (c) downconverted baseband signal, (d) received 37.5 GHz signal uses for uplink communication, and (e) uplink data back to the fiber backhaule through MZM

4. RESULTS AND DISCUSSION

Results are obtained from the proposed RoF-mmW-VLC hybrid system, and this model is tested with several iterations to achieve the best results. We considered optical fiber backhaul connected to an indoor room with 9 m^2 (3m×3m) dimension. The mmW generation is based on a multi-tone optical ROF methodology at coin Figure 3. Using a single drive MZM, Figure 3(a) displays transmitter-modulated signals on the LD1 at a wavelength of 1550.2 nm. A triple tone optical spectrum is created by coupling this modulated light signal to the other two unmodulated signals at 1550.014 nm and 1549.715 nm, as illustrated in Figure 3(b). The transmission level of all three tones is set at-10 dBm. A short-haul link is used for the transmission, therefore little optical power isneeded. As predicted, the spectrum that results from the detection of optical signals at various wavelengths produces a number of tones. An OBPF with a central wavelength of 1552.524 nm is used to separate this optical signal from the receiving signal so that it may be used for uplink transmission. After receiving the optical signal. Using PD, an electrical BPF selects the tones at 37.5 GHz and 60 GHz to transfer to CU in Figure 4. As illustrated in Figure 4, these comprise a mmW signal that transmits baseband data at 60 GHz, an unmodulated mmW tone at 37.5 GHz, and another data-transmitting signal at 22.5 GHz. At this stage, the signal power is increased by an electrical amplifier by 30 dB, and a low pass filter (LPF) is utilized to downconvert the baseband signal for adjusting with an LED driver to drive this signal into LED which is explained in Figure 5. The baseband signal at the client unit, operating at 2.5 GHz, is shown in Figure 5(a) and will transmit to an LED driver for an indoor VLC access point (VLC-AP). According to Figure 5(b), the driver LED's initially bandwidth was 50 MHz. Using Bessel, Trapezoidal, and rectangular filters at the receiver, LED bandwidth may be increased up to 70 MHz. Additionally, it can be increased with a Gaussian optical filter up to 100 MHz. When utilizing the OOK modulation scheme. Filters assist in maintaining BER within the FEC limit of 2.8×10^{-3} for certain data speeds.



(a) (b)

Figure 3. Output of the tramitted laser and generated triple tone, in (a) transmitted laser spectrum at 1550.2nm and (b) optical spectrum of triple tone signal

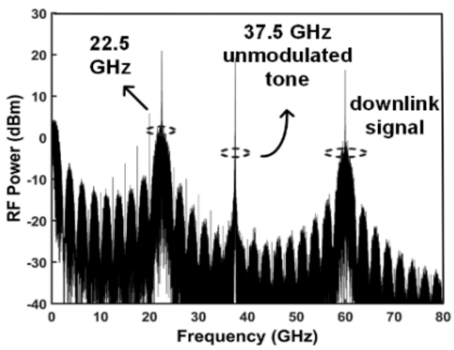


Figure 4. Downlink tone at 60 GHz, an unmodulated tone at 22.5 GHz and 37.5 GHz

Figure 6 displays the 16 QAM constellation diagram at the receiver point along with the original data bit stream from CO and the received OOK bit stream at VLC receiver (inside). To decrease the signal BER, beam divergence of the free space channel is set to 1 mard based on the relationship of BER to beam divergence as shown in Figure 7. Lowest BER of 10^{-25} has been achieved for 1 mard. Beam divergence is an angular measurement of LED collimator in the transmitter aperture. We measured the total optical power distribution from each VAP within 9 m^2 room size and it has a maximum value of 2.9 mW as shown in Figure 8. The range of power values shown across the room are enough to provide proper lighting within the room. BER and data rate performances by OOK for 10 and 20 channel CWDM LEDs are shown in Tables 3 and 4, respectively. In the 10-channel setup, the 10 channels were used for communication. LEDs could be added in the wavelengths between these each pair of these 10 channels for illumination. The total data rate achieved with the 10-channel set up was 660 Mb/s using OOK and 3.2 Gb/s using 16 QAM. With OOK modulation, the data rate is comparatively strong, and each channel's BER is below the FEC threshold of 2.8×10^{-3}. The spectral power distribution (SPD) of various wavelengths at the receiver causes the variation in the data rate that can be attained for each channel. The overall aggregate data rate for 20 channels utilizing the CWDM-VLC model and complete 400 nm visible spectrum utilization is shown in Table 4. OOK and 16 QAM both allow for data rates of 1.64 Gb/s and 6.58 Gb/s, respectively. In Figure 9 users use the same RoF link and unused mmWave to transport 2.5 Gb/s of data from a transmitter site to the central office for uplink. The baseband signal, which is 2.5 GHz employing OOK modulation and was downconverted at CO before being broadcast from the consumer unit is shown in Figure 9(a). The 2.5 Gb/s uplink data that is received from CU is carried by this signal after it has been modulated by another single drive MZM. Transmitted signal received at the photodetector, and RF signals power was-20 dBm and side mode suppression ratio (SMSR) was 26 dB. Uplink transmitted and received bit streams are shown in Figure 9(b), where the recorded BER was around 10^{-17} using OOK. This shows that a hybrid bidirectional communication system could integrate CWDM based VLC system for VLC downlink and mmW based system uplink.

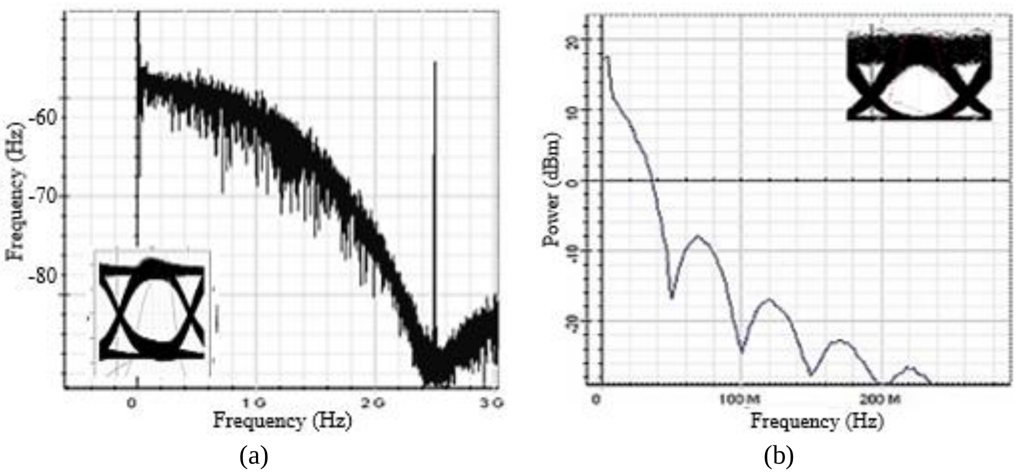


Figure 5. Output of the LED driving signal (a) indoor baseband signal 2.5 GHz and (b) downlink signal 50 MHz LED bandwidth

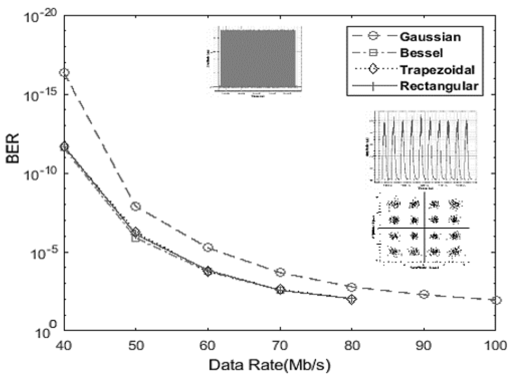


Figure 6. BER vs data rate using different optical filters

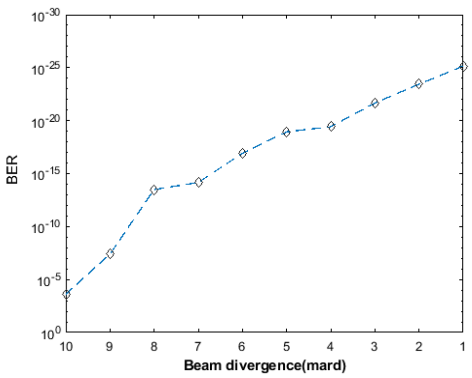


Figure 7. Maximum BER versus beam divergence for short range applications

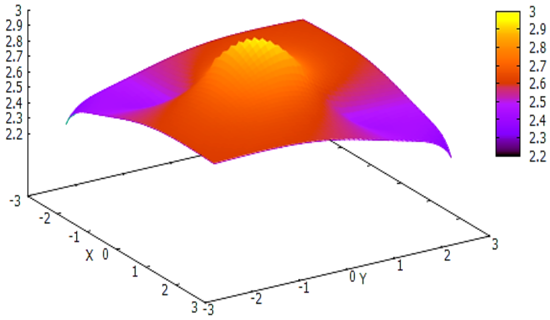


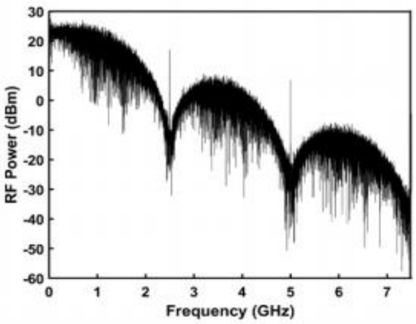
Figure 8. Optical power level of VAP in 9m^2 room size

Table 3. Total data rate of 10 channels of CWDM-VLC models

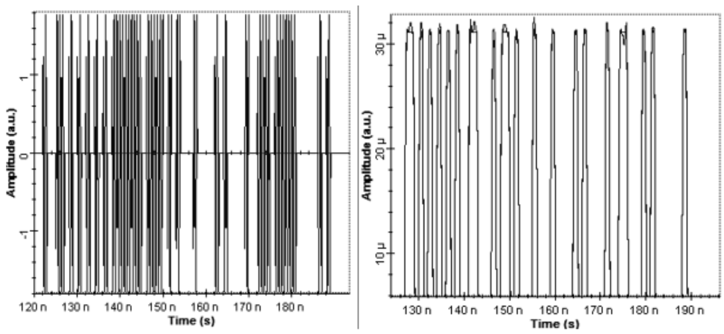
Peak wavelength	BER	Data rate (Mb/s)
390	1.50×10^{-3}	55
430	1.93×10^{-3}	60
470	1.04×10^{-8}	70
510	3.77×10^{-6}	65
550	1.32×10^{-7}	85
590	2.21×10^{-8}	90
630	1.73×10^{-8}	70
650	8.31×10^{-6}	65
670	3.06×10^{-5}	60
710	7.45×10^{-4}	55
750	5.51×10^{-3}	50

Table 4. Total data rate of 20 channels

Peak wavelength	BER	Data rate (Mb/s)
390	3.29×10^{-3}	55
410	2.35×10^{-5}	65
430	1.91×10^{-5}	80
450	3.85×10^{-6}	90
470	7.88×10^{-4}	100
490	7.81×10^{-4}	110
510	1.09×10^{-4}	95
530	5.75×10^{-6}	90
550	5.74×10^{-5}	95
570	5.79×10^{-6}	100
590	9.87×10^{-8}	105
610	1.26×10^{-6}	80
630	5.29×10^{-4}	10
650	8.31×10^{-6}	90
670	1.59×10^{-6}	100
690	1.05×10^{-4}	90
710	2.32×10^{-5}	80
730	2.21×10^{-6}	75
750	6.28×10^{-4}	75
770	3.28×10^{-4}	60



(a)



(b)

Figure 9. 2.5 GHz baseband signal received at the receiver in (a) downconverted RF spectrum at the CO and (b) uplink transmitted bit and received bit

5. CONCLUSION

Two technologies that hold potential for the deployment of 5G networks for indoor as well as outdoor communications are mmWave and VLC. The production of mmW signals and RoF backhaul access to the VLC link for indoor communication are the main topics of this article. mmW frequency reuse was proposed for the first time for uplink connectivity. The unlocked heterodyning method was used to generate a 5G mmW by beating three different LDs. The performance of the downlink channel depends on link parameters such as length, beam divergence, received power level and BER of the signal. The CWDM-VLC system was integrated with ROF to increase the data rate of the VLC downlink with acceptable BER. mmWave signal is used to improve the performance of uplink communication, carrying the customer's data through RoF backhaul to the central office. For the downlink, Gaussian optical filter can be used to increase the bandwidth of the received signal. When employing 16 QAM, it is clear that the downstream link performs better than the uplink. With a 2.5 Gb/s data throughput and an acceptable BER range of 10^{-17} for a hybrid VLC network, mmWave-based wired system uplink performs better than OWC.

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