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Design of a RoF fronthaul link based on optical generation of mm-waves for 5G C-RANs

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ABSTRACT

In this paper, a cloud-radio access networks based (C-RANs) radio-over-fiber (RoF) system have been reported with the optical generation of 28 GHz and 57 GHz millimeter-wave using phase modulation and stimulated Brillouin scattering effect in optical fibers. As a result, a cost-effective system with improved performance is achieved by the proposed method. Based on the proposed scheme, a 28 GHz (licensed band) and 57 GHz (Un-licensed band) optical millimeter-waves are generated by simulation only using 14 GHz and 16 GHz radio frequency (RF) respectively. Because the performance of any optical transmission system is limited by the Q factor and the bit error rate (BER) and any input power of the laser into the fiber needs to be less than the Brillouin threshold in order to avoid the sharp degradation of the Q factor. Also, the Brillouin threshold for this study setup is determined which is around 6 dBm in the case of licensed band and 2 dBm in the case of unlicensed band. The simulation results show that the proposed scheme can provide 100 km single-mode fiber for 28 GHz and 25 km for 57 GHz with transmission rates of 10 Gbps for both of them. In addition, a stable millimeter-wave RoF link, high quality carriers, and a reduction in nonlinearity effects are achieved with the proposed scheme.

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1. INTRODUCTION

The millimeter-wave (mm-wave) based radio-over-fiber (RoF) technology is a promising candidate for the new broadband services in emerging communication systems [1]. It has many advantages such as high capacity, low attenuation, low cost, and mm-wave signal can be generated by utilizing photonic methods [2]. The photonic generation of mm-wave signals is one of the basic mechanisms in RoF systems. Nowadays, there are many proposed approaches for the photonic generation of mm-wave signals, among them are direct intensity modulation [3], optical external modulation [4], [5] optical heterodyne [6], and optical mode-locked of the two laser diodes [7]. Optical external modulation has many advantages such as good stability, wide tunability range, and high conversion efficiency; therefore, it is considered the most significant one among the above approaches. Based on these merits, some new schemes have been proposed via utilizing optical external modulation [8], [9]. Ying *et al.* [8], frequency 16-tupling optical mm-wave signals are generated using two cascaded dual-parallel Mach-Zehnder modulators. On the other hand, in Chen *et al.* [9], two cascaded Mach-Zehnder modulators (MZMs) are used to generate frequency sextupled and octupled optical mm-wave signals. However, due to the bias drift of the cascaded MZMs, these methods face instability issues.

The performance of cloud-radio access network (C-RAN) which provides a high efficiency of processing, less consumption of power, and a high spectral efficiency is restricted by fronthaul link that interconnects the centralized baseband units (BBUs) with remote radio heads (RRHs) [10]. Therefore, to overcome the problems of the fronthaul link and to offer a high bandwidth and cost-effective fronthaul solutions, both analog and digital RoF techniques, and the bands of mm-wave frequency are attracting attention in both academia and industry [11]. In digitized RoF, different standards already exist, e.g., common public radio interface (CPRI) and open base station architecture initiative (OBSAI). Furthermore, digital data transmission mitigates the issues of non-linearity at both sides of the system (transmitter and receiver) [12]. However, these standard protocols act as barriers in front of the achievement of high-speed fronthaul networks. In addition, a very low spectral efficiency is resulted due to the transmition of digital samples instead of the analog signal itself which is troubling for next generation communication systems. On the other hand, the complexity of cell-site is another weakness factor that digitized RoF suffers from which become very complicated and more costly especially in 5G and beyond systems because many RRHs are needed to be supported. The use of millimeter-wave frequency bands leads to the smaller cell-sites deployment which require more RRHs in result [13]. Consequently, in order to avoid these issues of digitized RoF, the deployment of analog RoF which provides the most spectrally efficient solution and most power efficient RRH is an urgent necessity [14]. The mm-wave based analog RoF transmission system has the possibility to minimize the cost and complexity of the RRH site. In this system, only optical-to-electrical conversion and RF amplification is required, because a centralized control and management of wireless signals is enabled. Furthermore, it is determined as one of the important benefits for C-RAN 5G systems, but this method is prone to nonlinearities issues [15].

Therefore, to overcome the nonlinearity issue of the mm-wave based analog RoF transmission system, another method for the optical generation of mm-wave signals is taken into account. This method which has been proposed is based on the nonlinear effects such as cross-phase modulation (XPM) [16], cross-gain modulation (XGM) [17] and four-wave mixing (FWM) [18], [19]. This type of generation method is cost-effective, can extremely simplify the structure of the system, and most importantly, it can easily achieve high frequency mm-wave signals. Within this kind of generation, the method of mm-wave generation based on FWM effect is considered the most possible scheme due to the facts that there are no restrictions on the rate and format of the modulation signal, and it has a fast speed of response [18]. Wiberg *et al.* [19] the use of FWM in a highly nonlinear fiber in addition to the filtering characteristics of matched fiber bragg gratings (FBGs) was proposed to generate mm-wave via sextupling frequency multiplication. However, it is required in this method to match the frequency of pump tightly to the zero-dispersion wavelength of the fiber in order to reach significant conversion efficiency. In this study, a different mm-wave generation method based on stimulated Brillouin scattering (SBS) nonlinearity effect in the optical fiber is demonstrated. This generation method is based on the properties of the source laser and the characterization of phase modulation with the effect of SBS in the fiber link. To generate mm-wave carrier signals with a very high stability and a low signal noise in a cost-effective system, this proposed method can be applied. The generation of mm-waves by applying the proposed method could improve the mm-wave based RoF technology to meet 5G networks demands.

The mm-wave spectrum (3-300 GHz) is thought about as a key solution for the emerging communication systems, i.e., 5G and beyond, due to its spacious available bandwidth [20]. Within the mm-wave spectrum, many bands can be appropriate for usage in the next generations of mobile broadband networks, such as: (27-31 GHz) band, (57-64 GHz) band, and (71-76 GHz, 81-86 GHz, and 92-95 GHz) which are referred to as the e-bands [21], [22]. The different mm-wave spectrum bands along with the provided bandwidth by each band are shown in Figure 1. To overcome spectrum congestions and licensing cost for 5G new radio (5G-NR) mobile networks, the operation in the unlicensed mm-wave bands is considered a potential solution due to the unlicensed bands' license-free access. However, to operate in the unlicensed bands, particular regulatory requirements must be met that vary among regions and bands, including in general complicated spectrum sharing mechanism, a minimum occupied channel bandwidth requirement, maximum channel occupancy time, and power limits [23]. Hence, due to these restrictions and the good bandwidth provided by some licensed band, the last one is still used by many systems.

As a result, the (27-31 GHz) licensed spectrum and (57-64 GHz) unlicensed spectrum are considered attractive candidates to operate 5G-NR. Due to that, this study proposes a simple setup which has the potential to support the implementation of mm-waves in both of these spectrum bands for RoF links in C-RAN 5G networks. The remaining of this paper is organized as shown in: The research method is presented in section 2, section 3 explains in details the simulation setup and results, and section 4 ends up with the conclusions that this paper has reached.

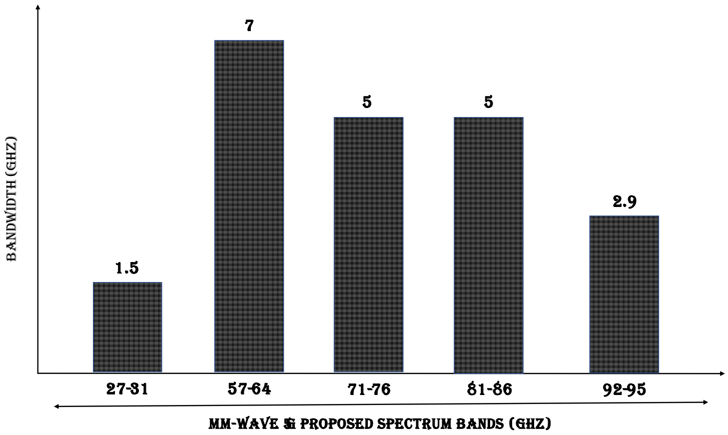


Figure 1. 5G proposed mm-wave spectrum bands (GHZ) [24]

2. METHOD

The block diagram of the proposed downlink RoF fronthaul link design is shown in Figure 2. The downlink mm-wave based RoF network consists of two basic parts: the BBU and the RRH. The BBU part consists of a continuous wave (CW) laser, which is directly modulated and driven by data signals, and a phase modulator (PM), which is driven by radio frequency (RF) sinusoidal signals of the local oscillator. The use of PM has many merits, so the RoF system that makes use of it has a larger margin. The main merits of PM include having a slight insertion loss in addition to being able to operate stably without the need for an electrical DC bias control circuit. Finally, an appropriate RF signal is used to drive the PM and the generated optical signals are then propagated to the RRH site via a standard single mode fiber (SMF).

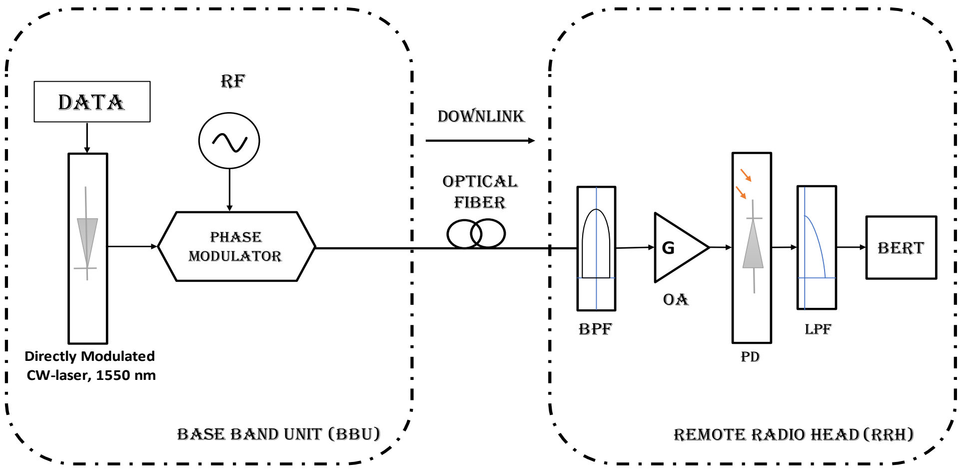


Figure 2. The block diagram of the proposed downlink RoF fronthaul link

At the RRH side, the received optical signal is filtered and amplified. Then, to generate the required mm-wave signal, it will be detected by optical receiver. Because the applied optical modulation technology is based on PM, the generated mm-wave over fiber signal is of a high quality which is required in RoF systems. After that, an antenna is operated to transmit the mm-wave wireless signal to the user equipment.

In this paper, based on both SBS and RoF, a model of photonic generation of mm-wave is proposed. In each fiber optic, Brillouin scattering exists due to thermal fluctuations and microscopic defects. It happens in the fiber because of the interaction between the light and propagating density waves or acoustic phonons. SBS is considered a significant effect among other nonlinearity effects of fiber optics. The threshold power (Pth) of SBS can be specified at that time when SBS acts as a limiting factor. It is also related to the linewidth of the laser source, where narrow linewidths result in a lower Pth for SBS. For laser sources with smaller linewidth than the Brillouin bandwidth, ρ^{th} can be estimated with (1) [25].

$$\rho^{th} = 21 \frac{K\, A_{eff}}{g\, L_{eff}} \left(1 + \frac{\zeta_s}{\iota_b} \right) \quad (1)$$

Where K (mainly equals 2) is the factor of polarization, g (equals 46×1,012 m⁄W) is the Brillouin gain, A_{eff} (equals to 80 μm2) is the effective area of fiber, ζ_s (equals 1 MHz in this study) is the laser source linewidth, and ι_b (equals 31.7 MHz for 1550 nm) is the interaction bandwidth of SBS. L_{eff} (can be calculated from (2)) is the effective length of interaction.

$$L_{eff} = \frac{1 - e^{(-\alpha L)}}{\alpha} \quad (2)$$

Where, α (equals 0.2 dB⁄km) is the coefficient of attenuation and L is fiber length.

Mm-wave signals can be generated via the heterodyning process of this nonlinear effect with the signals of the laser source. In this method of optical heterodyning technique, two optical signals are combined in a photodiode (PD) to produce the mm-waves. On the other hand, the utilization of the heterodyning process between the SBS nonlinearity effect and phase modulated signals is an alternative method to generate the mm-waves. The function of phase modulator is similar to that of MZM; the only difference is that it has a single arm. The phase modulator is fed with an optical power level of (P_{in}) by a laser signal and has a switching voltage (V_π). As a result, its output optical field ($E_{p(t)}$) can be calculated by (3) [25].

$$E_{p(t)} = e^{j\frac{\pi V(t)}{2 V_\pi}} \sqrt{2P_{in}} e^{j w_c t} \quad (3)$$

Where, $V(t)$ is the electronic modulating signal and w_c is the carrier angular frequency. In theory, the complex envelop of the optical field of the output of PM is defined by (4):

$$E(t) = e^{[j\beta \cos(\omega_m t)]} \quad (4)$$

Where $E(t)$ is the amplitude of the optical carrier, β is the index of modulation, ω_m is the angular frequency of modulating signal. So, the main optical carrier and the sidebands of the phase modulated signal are at ω_0 and $\omega_0 \pm n\omega_n$. When it is directly beating at a photodiode, it will generate the electrical signal as shown in:

$$E(t) = \sum_{n=-\infty}^{\infty} j^n\, j_n(\beta) e^{(jn\omega_m t)} \quad (5)$$

and $j_n(\beta)$ is the first kind Bessel function of order n.

The proposed scheme with transmission of analog signals on mm-wave based RoF systems has further merits than other solutions. It can solve the issues of latency and scalability, and it provides huge bandwidths. Moreover, this system is cost-effective and can save a good amount of power due to the simplicity of RRH site, while moving the complexity to the BBU site.

3. RESULTS AND DISCUSSION

In this study, optisystem simulator is used to build, analyze, and calculate the results of the proposed system. It is considered one of the best and very advanced optical simulation packages that has the properties of designing, testing, analyzing, and optimizing optical systems. The proposed scheme in this study suggests the use of mm-waves and RoF technology to overcome the challenges of emerging communication systems. In related research [26], two laser sources are used and it has been proposed that this is the easiest way to generate mm-waves. However, due to the phase mismatch between the two laser diodes and the relative instability of the frequency, mm-waves fluctuate around the central frequency. As a result, the single sideband phase noise increases and the case of residual frequency offset appears. Therefore, in this study a single laser is used as a source in order to avoid this case. Al-Dabbagh and Al-Raweshidy [27] also a single laser is used as a source as in this study, but they have used a very high RF signal (32 GHz) as a driving signal. On the other hand, they have reached only 5 Gbps transmission rate for 100 km. So, because the electrical generation of radio signals with high frequencies is very costly and challenging, whereas in this study only 14 GHz and 16 GHz RF driving signals are used. Furthermore, in this study, it is possible to get mm-wave operating in a licensed (28 GHz) band or unlicensed (57 GHz) band by using relatively low driving signals while in [27] they focused only on the unlicensed band (64 GHz) which faces congestion problems sometimes because the IEEE 802.11-based wireless gigabit (WiGig) is already in operation in this band. However, certain regulatory requirements are also needed sometimes such as regulatory restrictions on the transmission power in the unlicensed bands, like long term evolution-unlicensed

(LTE-U) [28]. In general, for the cellular networks to coexist in unlicensed band, complicated spectrum sharing mechanism, maximum channel occupancy time, a minimum occupied channel bandwidth requirement, and specific power limits must be met [23]. Hence, due to regulatory restrictions on the transmission in the unlicensed bands and the good bandwidth provided by some licensed band, the last one is still used by many systems. Therefore, both licensed and unlicensed bands are considered in this study. Finally, in this study a transmission rate of 10 Gbps is reached for the same distance of [27] in the licensed band and for 25 km for the unlicensed band which are both suitable for the proposed small cell deployment in 5G systems. To further explain the comparison between the related works and the proposed system, a brief summary of the cons of the first ones and the pros of the second is presented in Table 1.

Table 1. A comparison between the related works and the proposed system

Related Works	Proposed System
Two laser sources are used [26].	Single laser is used as a source.
Single sideband phase noise and residual frequency offset [26].	The issue of single sideband phase noise and residual frequency offset is solved.
Very high RF driving signal (32 GHz) [27].	Lower RF driving signals (14 GHz and 16 GHz).
Suffer from the high cost and challenges of Electrical generation of radio signals with high frequencies [27].	Cost-effective with less significant challenges of Electrical generation of radio signals.
5 Gbps transmission rate for 100 Km [27].	10 Gbps transmission rate for 100 Km.
Unlicensed band only [27].	Both licensed and unlicensed bands.
restricted congestion problems and regulatory requirements of unlicensed bands [27].	This work provides the possibility of working in either the licensed or the unlicensed bands.

The performance of any optical transmission system is limited by the Q factor and the bit error rate (BER). The SBS effects in fiber optics cause optical power fluctuations which degrade both of the Q factor and BER. To overcome this issue, the input power of the laser into the fiber needs to be less than the Brillouin threshold. In the case of this study setup, once the optical power reaches any power more than 6 dBm in the case of licensed band and 2 dBm in the case of unlicensed band, the Q factor starts to degrade sharply. This sharp degradation of the Q factor indicates that the Brillouin threshold for this study setup is around 6 dBm and 2 dBm for both cases as shown in Table 2. It can also be noticed that the minimum BER is obtained at these two optimum power values. The experimental configuration of the proposed C-RAN mm-wave based RoF downlink is shown in Figure 3. The corresponding simulation results for each inset highlighted in Figure 3 (a.-d.) are shown in Figures 4 and 5 respectively.

At BBU, 8 dBm power is used to pump a directly modulated CW laser source with a linewidth of 1 MHz at 1550 nm. The laser source is also driven by the electrically generated downlink binary data, which is simulated by 10 Gbps pseudorandom bit sequences. In this experimental configuration, the PM is driven by an RF sinusoidal signal (14 GHz or 16 GHz) and a 90-degree phase. In addition, the output signal from the directly modulated laser also enters the PM. Then, the signals are sent over a (100 km or 25 km) SMF for licensed and unlicensed bands respectively with an attenuation of 0.2 dB⁄km and a dispersion of 16.75 ps⁄nm⁄km. To enhance the method of mm-wave generation, PM effects are added to the proposed design. A combination between the Phase-modulated signals and the Brillouin stokes of SBS is made in the fiber. At the other end, these signals are heterodyned at the photodetector and converted into an electrical signal to generate a (28 GHz or 57 GHz) mm-wave carrier based on the chosen driving RF signal (14 GHz or 16 GHz) respectively.

Table 2. Max. the Q factor and min. BER for 28 GHz and 57 GHz transmission systems

Power (dBm)		28 GHz transmission system		57 GHz transmission system	
28 GHz	57 GHz	Max Q-factor	Min. BER	Max. Q factor	Min. BER
1	-3	33.3551	1.9532*10^-244	115.78	0
2	-2	36.6092	6.4025*10^-294	141.28	0
3	-1	37.6409	1.4317*10^-310	145.21	0
4	0	41.57	0	148.619	0
5	1	44.8803	0	149.195	0
6	**2**	**46.1764**	**0**	**154.249**	**0**
7	3	43.2839	0	122.574	0
8	4	40.3886	0	107.944	0
9	5	33.9636	2.2756*10^-253	89.990	0
10	6	28.5089	2.6552*10^-179	81.631	0
11	7	23.1439	4.9487*10^-119	60.254	0
12	8	18.5567	2.1218*10^-77	49.180	0
13	9	14.9826	2.9171*10^-51	38.436	9.8813*10^-324
14	10	11.8367	7.6781*10^-33	30.328	1.3791*10^-202

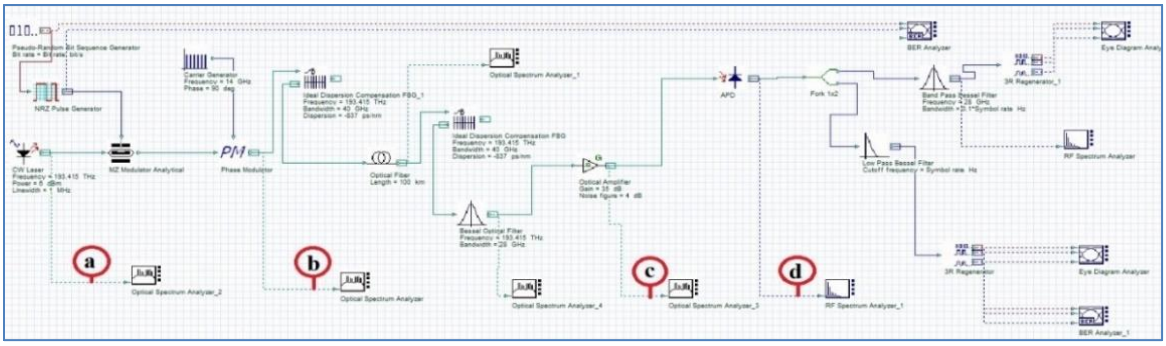
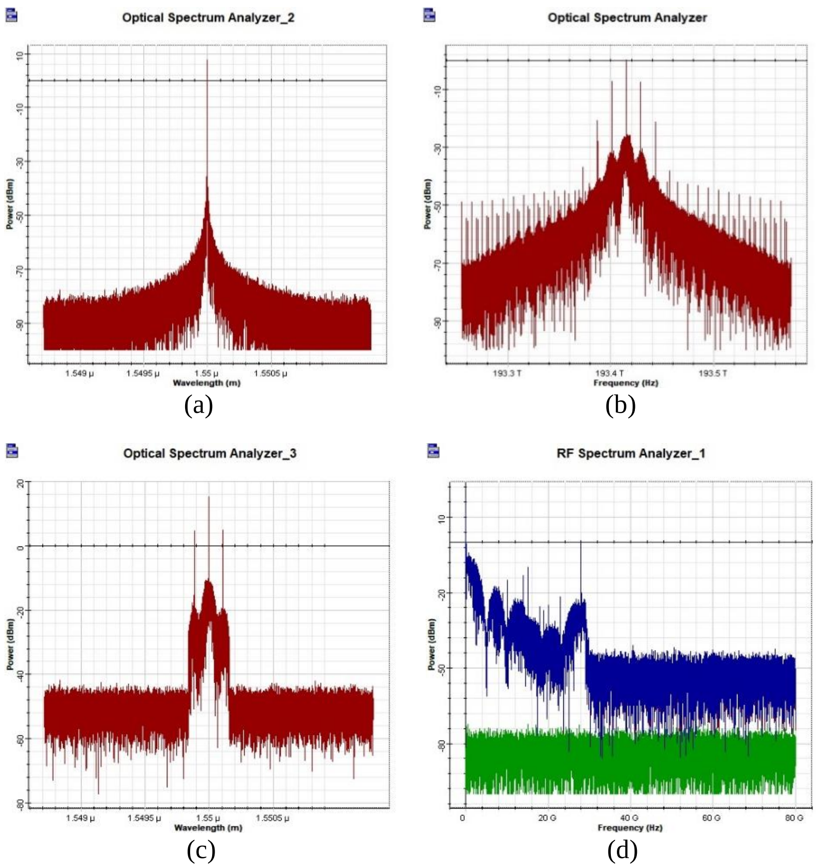


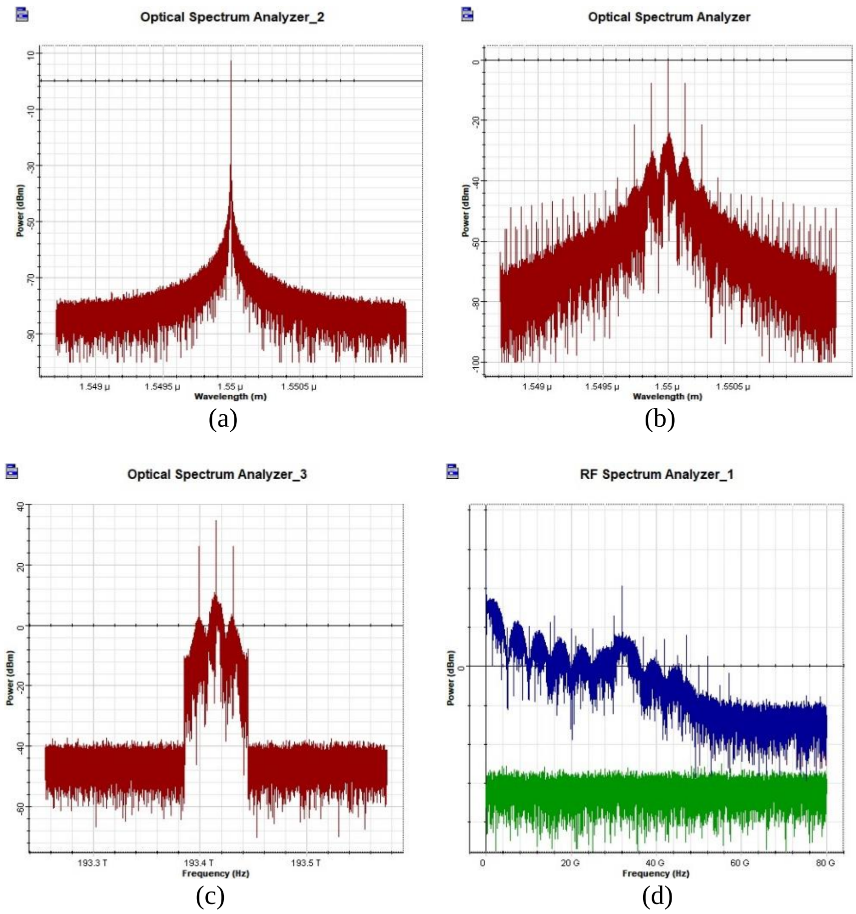
Figure 3. Simulation setup of the mm-wave based RoF downlink

The results of the optical spectrum analyzer (OSA) at the CW laser and PM outputs are shown respectively in Figure 4 and Figure 5 as (Figure 4(a) and Figure 4(b)) and (Figure 5(a) and Figure 5(b)), while Figure 4(c) and Figure 5(c) demonstrate the OSA result of the amplified optical signal after propagating via the fiber and the optical filter. Figure 4(d) and Figure 5(d) present the output of the optical receiver, which is the mm-wave carrier with data. Simulation results indicate that by using sufficient Brillouin pumping power, the stimulated Brillouin stokes have affected this generation method. The obtained results point out that high-quality mm-wave carriers are generated at a frequency of 28 GHz for the first scenario and 57 GHz for the second scenario, as shown in Figure 4(d) and Figure 5(d). Results show that the generated mm-wave carriers have low noise, which approximately equals −75 dBm and -60 dBm for the first and second scenarios respectively. Figure 6 and Figure 7 show the eye diagrams for the RoF downlink for both cases (28 GHz and 57 GHz), which explain the good performance because the eye diagrams still remain open after data is transmitted through a 100 km over fiber for the first scenario and 25 km over fiber for the second scenario.



(a) (b) (c) (d)

Figure 4. Simulation results for 28 GHz at the corresponding points in Figure 3: (a) CW laser output, (b) PM output, (c) optical filter output, and (d) optical receiver output



(a) (b) (c) (d)

Figure 5. Simulation results for 57GHz at the corresponding points in Figure 3: (a) CW laser output, (b) PM output, (c) optical filter output, and (d) optical receiver output

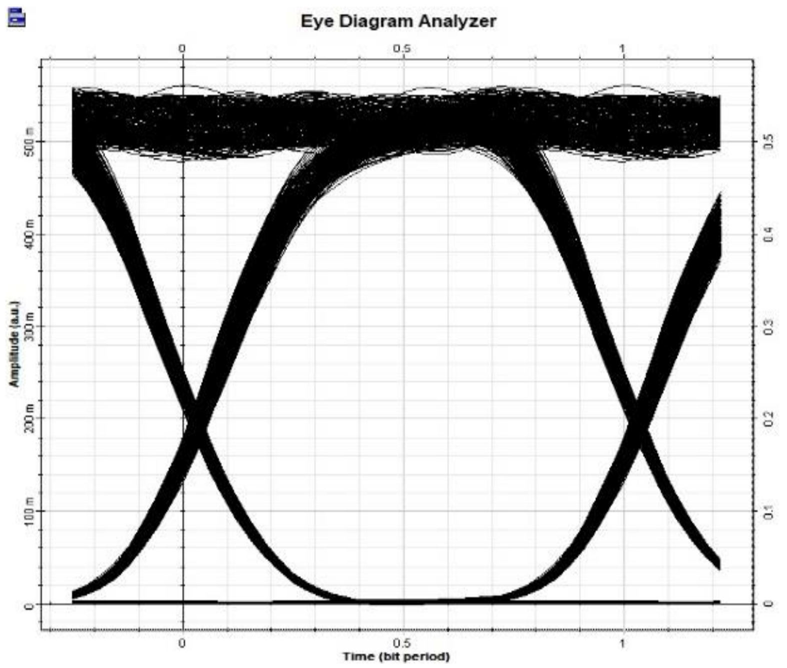


Figure 6. The eye diagram for the RoF downlink system transmitting at 28 GHz

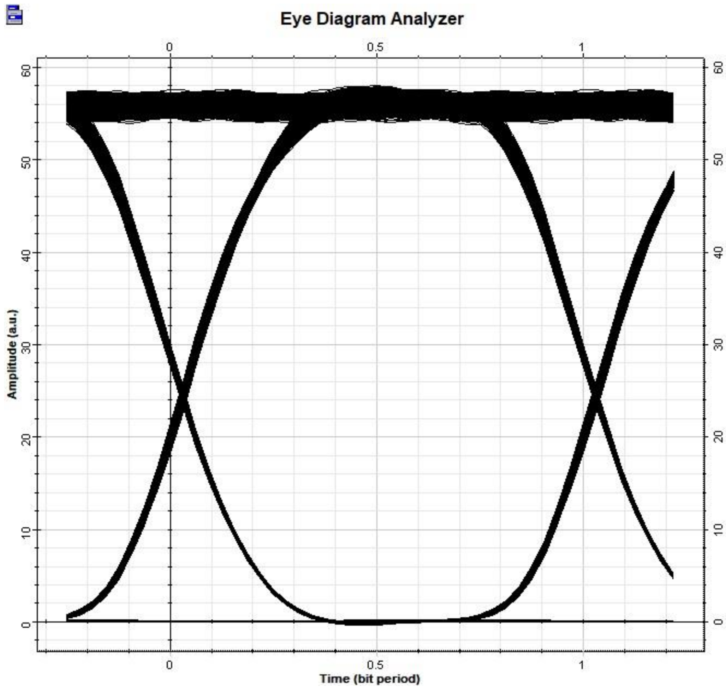


Figure 7. The eye diagram for the RoF downlink system transmitting at 57 GHz

4. CONCLUSION

In this paper, a C-RAN-based RoF downlink in the mm-wave bands for 5G systems and beyond has been proposed. The proposed system has been demonstrated with the utilization of an optical generation method of mm-wave carriers in both licensed and unlicensed bands. The proposed method to generate optical mm-wave signals is based on the use of phase modulation technique and getting benefits from the studied characteristics of the SBS nonlinearity effect in optical fibers. Based on this proposed scheme, a 28 GHz (licensed band) and 57 GHz (unlicensed band) RoF system using 14 GHz and 16 GHz RF driving signal respectively have been realized by numerical simulation. The 28 GHz mm-wave carrying 10 Gbps baseband signal is successfully transmitted over 100 km SMF and 25 km SMF for the 57 GHz mm-wave with the same data rate. In addition to the obtainment of high quality and increased stability of carrier frequency mm-wave RoF link, the nonlinearity effects are also decreased with the proposed scheme. The mm-wave shows a low noise level which approximately equals −75 dBm for 28 GHz and -60 dBm for 57 GHz. In comparison to the related works, only one laser is used as a source in this study. Also, lower RF driving signals are used to overcome the high cost and challenges of the electrical generation of radio signals with high frequencies. In addition, higher transmission rates have been reached for the same distances as the related works. Finally, to avoid the restricted congestion problems and regulatory requirements of unlicensed bands, this work provides the possibility of working in either the licensed or the unlicensed bands. The results demonstrated that the proposed scheme outperforms the related works and it is a promising choice for the implementation of mm-wave in RoF links in C-RAN-based 5G and beyond networks.

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