All optical millimeter-wave signal generation and transmission for radio over fiber (RoF) link

Norliza Mohamed¹, Sevia Mahdaliza Idrus², Azza Hamzah³, Suriani Mohd Sam⁴, Norulhusna Ahmad³, Hazilah Md Kaidi⁴, Rudzidatul Aknam Dziyauddin⁷

¹Department of Electronic System Engineering (ESE), Malaysia-Japan International Institute of Technology (MJIT), Universiti Teknologi Malaysia, Malaysia
²School of Electrical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Malaysia

ABSTRACT

Fiber-based wireless system has become a promising solution as a cost-effective communication and it offers high capacity network with millimeter-wave (mm-wave) signal transmission. The system significantly offers superior possible bandwidths for both fiber and free-space applications. Hence, with the increased capacity as well as wireless mobile network applications particularly at mm-wave signal, radio over fiber (RoF) technology is the utmost option. Nevertheless, when high frequency signal transmission is involved, power fading or dispersion effect limits the performance of RoF link. Therefore, this work proposed a RoF system by integrating remote optical local oscillator (LO) with frequency up-conversion at the base station (BS). All optical mm-wave signals are generated and transmitted for the RoF link. The effects of the changes of fiber loop length, optical power of the continuous wave (CW) optical laser carrier and responsivity value of the p-i-n photodiode (PD) mainly at 40 GHz are investigated and the power fading effects are discussed.

Copyright © 2019 Institute of Advanced Engineering and Science. All rights reserved.

Corresponding Author:
Norliza Mohamed, Engineering Department, Razak Faculty of Technology and Informatics, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia. Email: norlizam.kl@utm.my

1. INTRODUCTION

Currently, increasing number of users and requirement of high speed and high date rate exclusively for wireless communication system is undeniable. Therefore, in order to deliver such services over a radio link, a broader spectrum of radio frequency is required. As a result the radio link should use higher frequency carriers due to the spectrum congestion at lower frequencies. Therefore, a lot of research works have been reported and optical mm-wave signal generation has become a leading technique in radio over fiber (RoF) system [1-7]. Mm-wave signal generation techniques that are not only limited in RoF have also been proposed by number of works with different techniques including the use of stabilized mode-locked laser diode [8], employing frequency-quadrupling phase-locked optoelectronic oscillator [9], using a frequency-tunable optoelectronic oscillator [10], polarization multiplexing [2-3], exploiting the nonlinearity of the Mach-Zehnder modulator (MZM) [11] with carrier suppressed frequency eightfold [4], as well as by using the stimulated Brillouin scattering (SBS) [12-14]. In spite of that, RoF offers flexibility to the wireless access networks and ultimately increase the capacity and mobility of optical networks. Integration of optical and wireless networks is a promising technique especially in reducing costs in the access network. Due to the
benefits compromises by RoF network specifically in reducing the complexity at the base station and ability of frequency sharing, therefore, in this work the concept of RoF is employed.

Three major RoF system architectures have been reported for commercial in-building wireless deployments [8, 15-16]. They are radio frequency (RF) transmission over fiber, intermediate frequency (IF) transmission over fiber and digitized IF transmission over fiber. The most general configuration is an RF transmission over fiber because it is uncomplicated and more cost-effective in terms of design implementation. Nevertheless, it is vulnerable to fiber chromatic dispersion and power fading effect that affects the transmission distance [17-20] and frequency generation above 40 GHz is still a huge challenge in RoF system. Additionally, power fading effect usually limits the mm-wave RoF system performance mainly during signal transmission through the link [21-24]. Therefore, this work proposes a system that is capable to reduce the dispersion effect that usually limits the mm-wave RoF system performance, in which the frequency up-conversion is done at the base station (BS). The integration between the all optical signal generation based on stimulated Brillouin scattering (SBS) technique and the frequency up-conversion seemed to be more practical by omitting the necessity of local oscillator (LO) at the BS.

This paper presents detail description on the modeling and simulation of LO signal generation at frequency of 40 GHz. The simulation was carried out by considering the important parameters setting that are stated clearly. The simulated system model is discussed in Section 2. Later, the results and performance analysis of the simulation are discussed in Section 3 of this paper by taking into account the effect of changing and varying some of the parameters which are the SBS fiber loop length, the optical carrier power of the CW laser and the effect of different responsivity, R value of the p-i-n PD, particularly at frequency of 40GHz. Finally, conclusion of the modeling and simulation of the signal generation is given in Section 4.

2. THE PROPOSED SYSTEM

The simulation model of optical signal generation based on SBS technique is done by considering the advantages of the nonlinear effect and low input power requirement in SBS. The optical signal is generated as a result of the SBS stokes generation. The optical signal has been generated at four different frequencies: 10 GHz, 20 GHz, 30 GHz and 40 GHz. However, only the generated signal at 40 GHz is discussed. The front-end optical receiver utilizing remote optical local oscillator for RoF system proposed in [21] is referred. The proposed system focuses only on the downlink transmission of the system. Hence, the signal is transmitting from the BS to the CS and finally sent to the end-users wirelessly. The IF block of the system represents the modulated intermediate frequency signal that carries the baseband data. In this work, IF signal is simply generated using direct signal generator. While the LO block as shown in Figure 1 represents the LO signal that will be sending remotely to the BS. This LO signal is generated using SBS technique and will be further explained in this section. The parameters setting of the simulation model can be referred in [21] as tabulated in Table 1. Three key parameters investigated in this study are the CW laser input power, the SBS fiber loop length and the responsivity, R of the p-i-n PD. Power fading for mm-wave signal transmission related to these three parameters with different configurations will be discussed.

![Figure 1. Block diagram of the SBS configuration](image)

The simulated system model consists of an optical input power and an electrical signal with frequency of 10 GHz which was modulated by the Mach–Zehnder modulator (MZM). MZM generates harmonics or sidebands when the modulation takes effect. The optical spectrum consists of several spectral
lines spaced by the frequency of 10 GHz. In this work, the sine electrical wave generator with frequency of 10 GHz was chosen since we were only interested with the optical generated frequencies in the range of 10 to 40 GHz. Moreover, it can simplify the computation of the gain in the 10 GHz.

### Table 1. Parameters Setting of SBS Simulation Model

| Parameters                  | Values                        |
|-----------------------------|-------------------------------|
| Bit rate                    | 10 Gbps                       |
| Time window                 | 1.28e-0.08 s                  |
| Sample rate                 | 640 GHz                       |
| Sequence length             | 128 Bits                      |
| Sample per bit              | 64                            |
| Optical Power of CW laser   | -30 to 10 dBm                 |
| Wavelength frequency of CW laser | 1552.52 nm             |
| Linewidth of CW laser       | 1 MHz                         |
| Frequency of Sine Generator, fLO | 10 GHz                     |
| Frequency of Pump Laser 1 (PL1) | 193.09 THz                |
| Frequency of Pump Laser 2 (PL2) | 193.11 THz                |
| Responsivity, R of the p-i-n PD | 0.1 to 1.0 A/W            |
| EDFA length                 | 5 m                           |
| Optical Fiber Loop Length   | 1 to 50 km                    |
| Dispersion of Optical Fiber | 17 ps/nm/km                   |
| Attenuation of Optical Fiber| 0.2 dB/km                     |
| Brillouin Gain, gB          | 4.6e-11 mW                    |

The PL1 and PL2 of the pump lasers used in this circuit model were assigned to wavelength frequencies of 193.09 THz and 193.11 THz respectively. The output spectrum of the coupled signals was then fed to the circulator for the SBS to happen. The output spectrum of the circulator consists of both counter-propagating signals and the amplified modulated signal from the MZM. In an attempt to generate and deliver only the desired frequency signal, hence two types of filters were used during the simulation, which are the inverted rectangle optical filter and the rectangle optical filter. Optical signals obtained from the circulator output port were first filtered by the inverted rectangle optical filter followed by the rectangle optical filter. At frequency of 40 GHz, bandwidth of both inverted and non-inverted rectangular optical filters are set accordingly in order to get only the desired frequency signal. In the setting, the second stoke of both lower and upper sidebands were selected for the generation of the 40 GHz signal. The filtered optical signal was then amplified by an optical amplifier before it was delivered to the receiver through another single-mode fiber (SMF). At the receiver, the optical signal was then detected by a p-i-n PD.

### 3. PERFORMANCE ANALYSIS AND DISCUSSIONS

This section discusses on the performance of the proposed system particularly in the generation of 40 GHz LO signal. The power fading effects at 40 GHz at different parameters setting of SBS fiber loop length, different optical power of the CW optical laser carrier and responsivity value of the p-i-n PD are discussed and explained. The optical spectrum of the inverted rectangle optical filter and 40 GHz generated RF spectrum detected at the p-i-n PD is depicted in Figure 2. The filtered signal was amplified by an optical amplifier and conveyed to the receiver side. The 40 GHz detected signal was directly sent to the receiver without any filtering since the signal was sent without any harmonics. Through the simulation, it was found that the detected power of the 40 GHz signal was lower than the detected power of lower frequencies. It was proven that the higher the generated frequency, the lower the output power that will be detected.

For the signal transmission mainly for RoF link, the transmission of 40 GHz through the link was observed. By considering the effect of different optical fiber loop lengths, Figure 3 shows the detected output power of 40 GHz generated signal at different optical input power of CW laser in the function of fiber loop length. The SBS fiber loop length was varied between 1 to 50 km and the optical amplifier gain was set to be at 20 dB. While, at the receiver, the responsivity, R of the p-i-n PD was fixed at 0.8 A/W. The detected signal shows more nonlinear at all input power values due to the nonlinearity effects of the SMF especially at higher frequency. The nonlinearity was emerged at about 10 km to 25 km of the optical length before the signal started to decreased slowly. The fiber loop was about 16 km when the output signal was at the peak. With that, the best fiber loop length for the SBS model to generate the optical signal is between 10 km to 25 km with the maximum value at about 16 km. The longer the transmissions distance, the lower the output power at the BS.
All optical Millimeter-wave signal generation and transmission for… (Norliza Mohamed)
Responsivity value of the photodetector also contributes to an important role during the photodetection of the generated signal. Responsivity and quantum efficiency, $\text{R}$ and $\text{$\eta$}$, are the main characteristics of a PD which contribute to the sensitivity of an optical receiver. It is where the minimum input power is required for the receiver for optimum operation. The SBS fiber loop length is predetermined at 25 km as well as the wavelength of the CW laser still remained at 1552.52 nm. The optical carrier power level is set at -10, -5, 0 and 5 dBm while the optical amplifier gain is retained at 20 dB.

In Figure 5, it shows the detected output power of 10 GHz generated signal at different optical input power of CW laser in the function of responsivity of p-i-n PD. When the input power levels were increased, the output power levels remained constant even though the responsivity values were changed. Moreover, as the responsivity values of the PD are increasing, the detected output power has increased at a certain proportion. Referring to Figure 6, when input power was set at -10 dBm, the output power was extremely increased at about 128.7% as the responsivity changed from 0.1 A/W to 0.2 A/W. Conversely, from 0.2 A/W to 0.3 A/W, the output power was increased at about 32.9%, while from 0.3 A/W to 0.4 A/W, the increment percentage is about 17.6% and so on. It was found that as the responsivity increases, the increment rate is decreasing. Therefore, from the figure, it was proven that the responsivity of a typical p-i-n PD was in the appropriate region which in between 0.6 A/W to 0.9 A/W. The trend shows very small increment in the detected power level within the region. It was expected that the increment remains unchanged as the responsivity increases.
4. CONCLUSION

This paper has presented the simulation model of signal generation based on SBS technique. The simulation was carried out by considering the key parameters setting which were the optical carrier power of the CW laser, the length of the SBS fiber loop and the responsivity, R of the p-i-n PD, particularly at 40 GHz while the other parameters were remained constant. It was found that when high frequency signal transmission is involved, power fading occurred hence, limits the performance of RoF link. For the SBS fiber loop length, the output signal was at the peak which at about 16 km. The optimum fiber loop length that can be used in generating the optical signal based on the SBS technique of the model are in the range of 10 km to 25 km. In addition, at 0 dBm of input power the detected power decreased to about 34.7% when the 40 GHz signals were generated. It was observed that the higher the frequency, the lower the detected output power, the output signal is decreasing. Due to the variation of the responsivity of the p-i-n PD, it was found that as the responsivity increases, the increment rate of detected output power is decreasing. It was proven that the responsivity of a typical p-i-n PD was in the appropriate region that was between 0.6 A/W to 0.9 A/W where the trend exhibited very small increment at the detected power level. Ultimately, it is concluded that all optical signal generation based on SBS technique has been established in mm-wave band by the simulation and optimum configuration setting which was obtained from the simulation has been validated through the experimental demonstration that is not mentioned in this report. The significant of this work shown that the proposed system has simplified the BS by omitting the necessity of the LO at the BS particularly in RoF implementation.

ACKNOWLEDGEMENTS

The authors acknowledge that this work was supported by Universiti Teknologi Malaysia (UTM) and Universiti Teknologi MARA (UiTM) for the financial support through university encouragement fund (GUP) vote No. 09J82 and UTM Razak grant fund vote No. 4J283 to the main author.

REFERENCES

[1] L. BoWen, et al., “Adaptive Millimeter-Wave Radio Generation and Transmission of Phase Shift-Keying Signal Based on Radio over Fiber System”, Optical Engineering, Vol. 57, No. 8(085107), August 2018.
[2] X. Wenjing, et al., “Full Duplex Radio over Fiber System with Frequency Quadrupled Millimeter-Wave Signal Generation Based on Polarization Multiplexing”, Optics And Laser Technology, Vol. 103, 267-271, July 2018.
[3] Z. Hui, et al., “Radio-over-Fiber System with Octupole Frequency Optical Millimeter-Wave Signal Generation Using Dual-Parallel Mach-Zehnder Modulator Based on Four-Wave Mixing in Semiconductor Optical Amplifier”, Optical Engineering, Vol. 57, No. 3(036101), March 2018.
[4] Z. Huizhong, et al., “A Novel Radio-Over-Fiber System Based on Carrier Suppressed Frequency Eightfold Millimeter Wave Generation”, IEEE Photonics Journal, Vol. 9, No. 5(7203506), October 2017.
[5] J. Zacharias, et al., “Full Duplex Millimeter-Wave Radio-over-Fiber System Using Optical Heterodyning and Self-Homodyning,” in 2017 International Conference on Trends in Electronics and Informatics (ICEI), pp. 378-381, 2017.
[6] N. Mohamed, et al., “Millimeter-Wave Carrier Generation System for Radio over Fiber,” in International Symposium on High Capacity Optical Networks and Enabling Technologies (HONENT 2008), pp. 111-115, 2008.
[7] J. Yu, et al., “A Novel Radio-Over-Fiber Configuration Using Optical Phase Modulator to Generate an Optical mm-Wave and Centralized Lightwave for Uplink Connection,” IEEE Photonics Technology Letters, vol. 19, pp. 140-142, 2007.
[8] K. Kitayama, et al., “60 GHz Millimeter-Wave Generation and Transport Using Stabilized Mode-Locked Laser Diode With Optical Frequency DEMUX Switch,” in Global Telecommunications Conference (GLOBECOM 96), pp. 2162-2169, 1996.
[9] L. Jingliang, et al., “Generation and Stabilization of Millimeter-Wave Signal Employing Frequency-Quadrupling Phase-Locked Optoelectronic Oscillator”, Conference on Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications XI, San Francisco, CA, 29 January – 01 February 2018, Book Series: Proceedings of SPIE, Vol. 10531(105311Y), 2018.
[10] C. Yang, et al., “Multi-Format Signal Generation Using A Frequency-Tunable Optoelectronic Oscillator”, Optics Express, Vol. 26, No. 3, 3404-3420, 5 February 2018.
[11] Mehmood Tayyab and Ghafoor Salman, “Millimeter-wave signal generation and transmission to multiple radio access units by employing nonlinearity of the optical link”, International Journal of Communication Systems, Vol. 32, No. 1(3830), 10 January 2019.
[12] M.M.H Husaini, et al., “Optical Millimeter Wave Generation Utilizing Stimulated Brillouin Scattering For Radio Over Fiber System”, Indonesian Journal of Electrical Engineering and Computer Science (IJECS), Vol. 13, No. 2, 818 – 824, February 2019.
[13] Du Cong, et al., “Photonic generation of millimeter-wave ultra-wideband monocycle signal using up-conversion based on stimulated Brillouin scattering effect”, Optical and Quantum Electronics, Vol. 51, No. 1(25), January 2019.

All optical Millimeter-wave signal generation and transmission for... (Norliza Mohamed)
[14] W. Yue, et al., "Wideband tunable up-converting optoelectronic oscillator based on gain–loss compensation technology and stimulated Brillouin scattering", Optical and Quantum Electronics, Vol. 51, No.2(43), February 2019.

[15] N. Mohamed, et al., "Review On System Architectures For The Millimeter-Wave Generation Techniques For RoF Communication Link," in IEEE International RF and Microwave Conference, RFM 2008, 2008, pp. 326-330.

[16] D. Wake, et al., "Radio Over Fiber for Mobile Communications," in IEEE International Topical Meeting on Microwave Photonics (MWP04), pp. 157- 160, 2004.

[17] L. BoWen, et al., "Flexible photonic generation of frequency multiplication millimeter-wave vector signal based on dynamic pre-coding algorithm with dispersion compensation", Optics Communications, Vol. 435, 232-238, 15 March 2019.

[18] K. Reinhard, et al., “Output Power Enhancement in Photonic-Based RF Generation by Optical Pulse Compression With a Dispersion Managed Highly-Nonlinear Fiber”, International Topical Meeting on Microwave Photonics (MWP), Toulouse, France, 22-25 Oct 2018.

[19] J. Park, et al., “Elimination of the Fibre Chromatic Dispersion Penalty on 1550 nm Millimetre-Wave Optical Transmission,” Electronics Letters, vol. 33, pp. 512-513, 1997.

[20] G. H. Smith, et al., "Technique for Optical SSB Generation to Overcome Dispersion Penalties in Fibre-Radio Systems," Electronics Letters, vol. 33, pp. 74-75, 1997.

[21] N. Mohamed, et al., "Power Fading Effects in Millimeter-Wave Radio Over Fiber (RoF) Link," in 2nd International Conference on Communication and Computer Engineering (ICOCOE 2015), Phuket Thailand, 2015, pp. 493-503.

[22] U. Gliese, et al., "Chromatic Dispersion in Fiber-Optic Microwave and Millimeter- Wave Links," IEEE Transactions on Microwave Theory and Techniques, vol. 44, pp. 1716-1724, 1996.

[23] S. Mikroulis, et al., "Investigation of a SMF-MMF Link for a Remote Heterodyne 60-GHz OFDM RoF Based Gigabit Wireless Access Topology," Journal of Lightwave Technology, vol. 32, pp. 3645-3653, 2014.

[24] W. Zhongle, et al., "Broadband downlink stable radio frequency phase delivery exploiting fiber chromatic dispersion," in 12th International Conference on Optical Communications and Networks (ICOCN), 2013, pp. 1-3.

**BIOGRAPHIES OF AUTHORS**

Norliza Mohamed received her B. Eng. (Hons) and Master degree in Electrical Engineering from Universiti Teknologi Malaysia (UTM) in 2001 and 2003 respectively. Later she continues her study also in UTM and received her PhD degree in 2013. She currently works as a senior lecturer for Razak Faculty of Technology and Informatics, UTM Kuala Lumpur. Her expertise is in optical communication particularly in radio over fiber system. Her research interest includes millimeter-wave, optoelectronics devices, RF mixer design, frequency conversion and wireless communication for 5G technologies.

Sevia M. Idrus is Professor and faculty member of the School of Electrical Engineering UTM. She received her Bachelor in Electrical Engineering in 1998 and Master in Engineering Management in 1999, both from UTM. She obtained her Ph.D in 2004 from University of Warwick, United Kingdom in communication engineering. She has served UTM since 1998 as an academic and administrative staff. Her main research interests are optical communication system and network, IoT solution, and engineering management. Her research output have been translated into a number of publications and IPR including a high-end reference books, 'Optical Wireless Communication: IR Connectivity’ published by Taylor and Francis, 5 books published by Pearson, Springer and Novar respectively, 49 book chapters and monographs, over 150 technical papers, 5 patents granted, 35 patent filings and holds 32 UTM copyrights. She is the founder and Director of UTM spin-off company, iSmartUrus Pte Ltd which focus on commercialization University’s product. She actively involved in international collaboration project and appointed as Guest Professor at Osaka Prefecture University and Tokai University in Japan 2011 and 2014 respectively.

Azura Hamzah is a Senior Lecturer at Malaysia-Japan International Institute of Technology (MJIT), Universiti Teknologi Malaysia. In MJIT, she is a Full Member for Optical Devices and Systems Ikohza (ODESY) and an Associate Member for Disaster Preparedness and Prevention Centre (DPPC). She received her Bachelor’s degree in Communication Engineering from International Islamic University Malaysia, Malaysia in 2005 and the Master’s and PhD degree from Universiti Malaya, Malaysia in 2009 and 2012. Her research interests are in optical amplifier and laser, pulse laser, optical sensor, optical interconnect and rare-earth-doped optical devices. She is a senior member for The Institution of Electrical and Electronics Engineers. Suriani Mohd Sam received the Ph.D. degree from the Universiti Teknologi Malaysia in 2013. Currently she serves as a senior lecturer in the Advanced Informatics Department, Razak Faculty of Technology and Informatics, Universiti Teknologi Malaysia. She has been in the research
field of networking particularly in Quality-of-service (QoS) for several years. These includes in the field of data communication, wireless communication and telecommunication. She is also a member of Cyber Physical Systems Research Group at UTM and member of the IEEE society. She has authored and co-authored journals, conference articles and book chapters in the field of QoS for several types of communication networking strategies. IoT elements has become the main concern in her students projects and research.

Dr. Norulhusna Ahmad is a Senior Lecturer at Razak Faculty of Technology and Informatics, Universiti Teknologi Malaysia Kuala Lumpur. Her expertise is in the area of digital signal processing and wireless communication. Her research interests are on future communication such as 5G and cognitive radio focusing on error-correcting codes, turbo equalization, OFDM, resource allocation, network coding, and cooperative communication. She can be reached at norulhusna.kl@utm.my.

Hazilah Mad Kaidi received the B.Eng (Horns) in Electrical Engineering in Telecommunication, Universiti Teknologi Malaysia, the M.Sc. degree in Telecommunication and Information Engineering at Universiti Teknologi MARA and the Ph.D. degree from theUniversiti Teknologi Malaysia. She is currently a senior lecturer at Razak Faculty of Technology and Informatics, Universiti Teknologi Malaysia Kuala Lumpur. Her research interests include mobile and wireless communications, error control coding, relay networks, cooperative communications, Hybrid ARQ Cross Layer Design and iterative receiver, Internet of Things.

Rudzidatul Aknam Dziyauddin is a Senior Lecturer at Razak Faculty of Technology and Informatics, Universiti Teknologi Malaysia (UTM) in Kuala Lumpur, Malaysia since 2007. She received her B.Eng. in Electrical & Electronic from Universiti Sains Malaysia, Malaysia in 2000, MSc in Information Technology and Science Qualitative from Universiti Teknologi Mara, Malaysia in 2004 and PhD from University of Bristol, UK in 2012. Her research interests include resource management, intercell interference mitigation in wireless networks and smart sensors applications.