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Morad Khosravi Eghbal
Mehdi Shadaram

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Morad Khosravi Eghbal* and Mehdi Shadaram

University of Texas at San Antonio, Electrical and Computer Engineering Department, San Antonio, Texas, United States

Abstract. We propose a W-band wavelength-division multiplexing (WDM)-over-optical code-division multiple access radio-over-fiber system. This system offers capacity expansion by increasing the working frequency to millimeter wave region and by introducing optical encoding and multiwavelength multiplexing. The system's functionality is investigated by software modeling, and the results are presented. The generated signals are data modulated at 10 Gb/s and optically encoded for two wavelength channels and transmitted with a 20-km length of fiber. The received signals are optically decoded and detected. Also, encoding has improved the bit error rate (BER) versus the received optical power margin for the WDM setting by about 4 dB. In addition, the eye-diagram shows that the difference between received optical power levels at the BER of 10^{-12} to 10^{-3} is about 1.3% between two encoded channels. This method of capacity improvement is significantly important for the next generation of mobile communication, where millimeter wave signals will be widely used to deliver data to small cells. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.57.1.016104](https://doi.org/10.1117/1.OE.57.1.016104)]

Keywords: millimeter wave; radio over fiber; optical code-division multiple access; wavelength-division multiplexing.

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1 Introduction

In the past few years, the introduction of bandwidth-demanding services and applications through mobile phone communication and also the wide-spread penetration of mobile phones have caused an augmentation in interest for capacity expansion of networks that can facilitate execution of such service.^{1,2} An increase in the mobile network capacity should be in a way that both backbone (fiber optic) and over-the-air transmission can support it. One method is to increase the working frequency from the current frequency region (a few gigahertz) to the millimeter wave region (>30 GHz).^{1,3,4}

This region has an inherently higher capacity and is more secure while being less occupied. Because of high frequency, antennas that transmit such signals would have a very sharp beam. In addition, at such frequencies, the attenuation (atmospheric and environmental) is more severe. These two factors contribute to the enhanced security of millimeter waves. If these high frequency [radio-frequency (RF)] signals are transmitted over the air, the propagation distance, in which these signals are severely attenuated and thus cannot be recovered, is relatively very short.² Thus, an effective method to transmit such signals is through an optical fiber link where they can be transmitted to distances much longer than over the air. The transmission of a radio frequency signal through an optical fiber link is called radio over fiber.

Another well established and widely used method to increase an optical network's capacity is to employ several parallel wavelength channels to transmit optical signals. This method is known as wavelength-division multiplexing (WDM). Depending on the number of wavelength channels, the capacity of the system will be multiplied.^{5,6}

Additionally, optical encoding will also help to further increase the capacity of the system and accommodate more channels to be transmitted simultaneously. This method assigns different optical codes to each channel that are identical and can only be decoded individually. This way, encoded data can only be decoded if it passes through a decoder with the correct optical code. This scheme is also well known and used and is called optical code-division multiple access (OCDMA).^{5,7-9}

In this paper, the optical encoding and decoding are performed with a code family called m -sequence codes. The m -sequence codes are well defined and used in the literature.⁹⁻¹³ These types of m -sequence codes that have been used in this research are unipolar codes (the phase shifts are two levels: 0 and π) with seven segments. Table 1 shows the number of shift registers and the corresponding code segments for an m -sequence code. Per Table 1, a seven-segment code can generate up to two codes with maximum orthogonality that can accommodate two individual channels. These codes are listed in Table 2.

2 Proposed System

This paper investigates a system where a millimeter wave signal is generated by help of a tandem dual-electrode Mach-Zehnder modulators (DE-MZM).^{10-12,14} There will be an unencoded and coded optical signal per channel and per code. The encoded optical signal will be transmitted to the receiver unaltered, whereas the other optical signal goes through an optical encoder [in this case, a superstructure fibre Bragg grating (SSFBG)], aggregated with the unencoded optical signal in an optical coupler and then transmitted through the fiber.¹⁰⁻¹² Each segment of the utilized seven-segment SSFBG has a length of 0.66 mm that has a period of 535.0143 nm. The difference in refractive index between two consecutive periods in one chip is $\Delta n = 5 \times 10^{-4}$, which gives a temporal chip duration of

*Address all correspondence to: Morad Khosravi Eghbal, E-mail: morad.khosravieghbal@utsa.edu

Table 1 *M*-sequence code lengths and the number of linear feed-back shift register sequences (adapted from Ref. 14).

# of shift registers (<i>n</i>)	# of code segments ($N = 2^n - 1$)	# of codes generated [$N_p(n)$]
2	3	1
3	7	2
4	15	2
5	31	6
6	63	6
7	127	18
8	255	16
9	511	48
10	1023	60

Table 2 Unipolar *m*-sequence codes for two channels.

Code#	Generated sequence	<i>M</i> -sequence code
1	0101110	0- π -0- π - π - π -0
2	1001110	π -0-0- π - π - π -0

Orthogonality distance: 2

6.4 ps. There are two lasers sources each generating optical signal at two different wavelengths, where each wavelength will generate two optical signals.

At the receiver’s side, the encoded optical signal is decoded with help of another SSFBG device that has a profile similar (but inverted) to the encoder. Then, two optical components (uncoded and decoded) are heterodyned at a photodiode to generate the millimeter wave signal. This signal could be fed to an antenna to be retransmitted over the air for a shorter distance to reach the final user.

3 Principle of Operation

Two continuous wave laser sources generated optical signals for two channels of a WDM system. The wavelength of the first laser is at $\lambda_1 = 1553.32$ nm, and the second one is at $\lambda_2 = 1550.11$ nm. The linewidth and input optical powers of both are similar: the first at 7 MHz and the second at 7.5 mW. The optical signal out of each laser is fed to individual tandem DE-MZMs that are driven by three sine wave generators as shown in Fig. 1.

The output spectrum of the second DE-MZM has components equal to the summation and subtraction of the operating frequency of each sinewave generator along with the fundamental frequencies. By changing the operating frequencies of each of those sine wave generators, a different millimeter wave frequency can be achieved at the receiver’s side. Therefore, each channel can be tuned individually to generate a millimeter wave signal at the frequency of choice. Since for both channels, the generated millimeter wave is set to be 84 GHz, the sinewave generators have the following operating frequencies: $f_1 = 21$ GHz, $f_2 = 25$ GHz, and

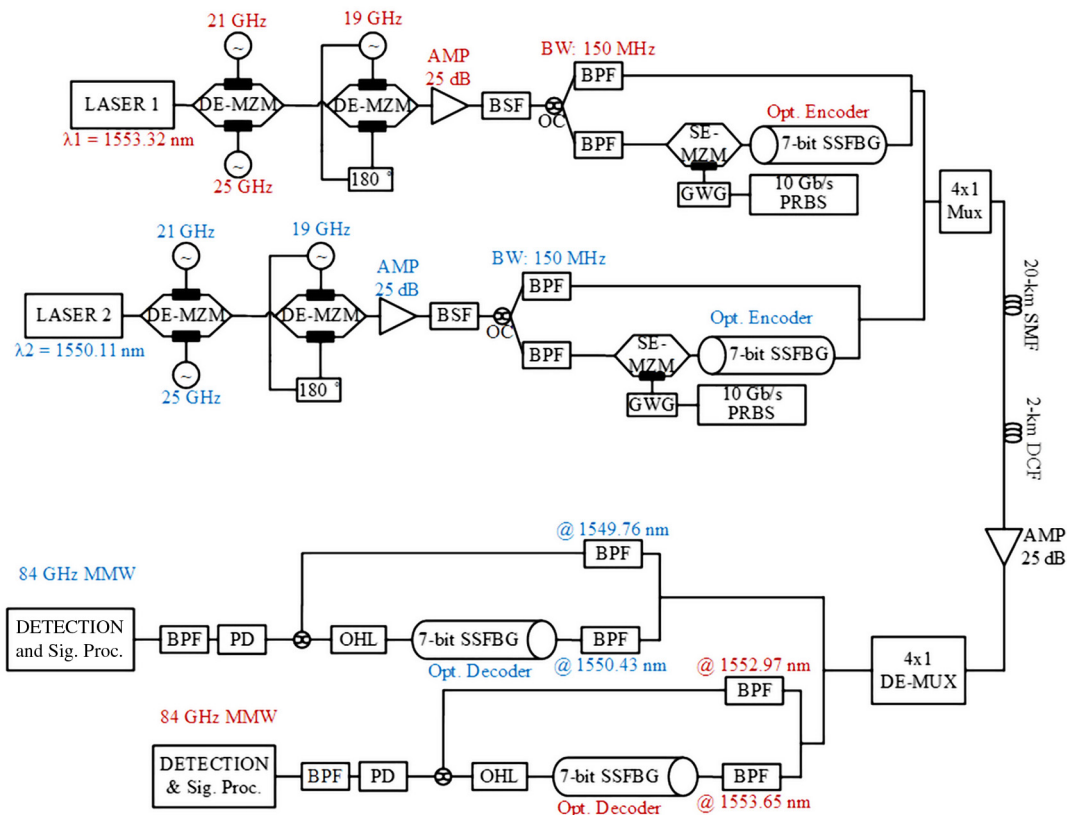


Fig. 1 Simulation setup.

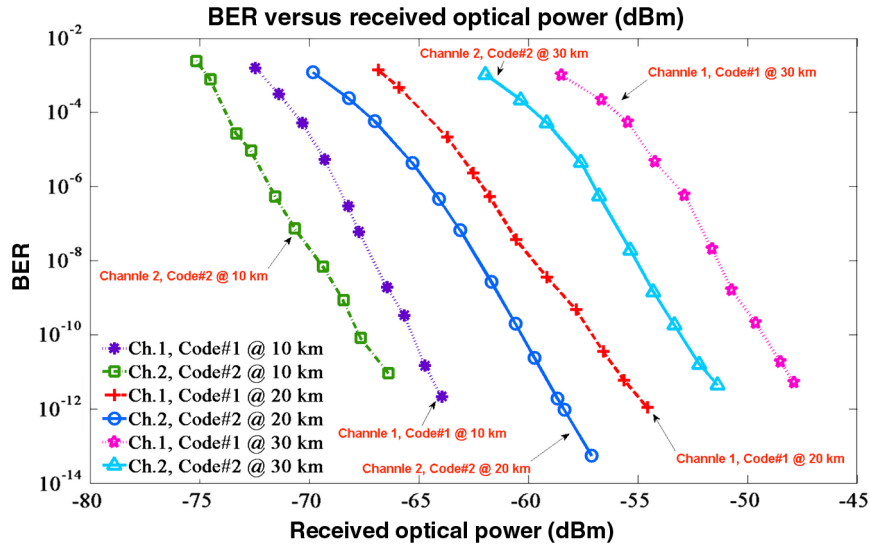


Fig. 2 BER versus received optical power (in dBm) for two optical codes at two WDM channels and fiber lengths of 10, 20, and 30 km.

$f_3 = 19$ GHz. The second DE-MZM's output spectrum has components at ± 21 , ± 25 , ± 19 , $\pm 21 \pm 19$, and $\pm 25 \pm 19$ GHz.

For the first channel, the selected uncoded and encoded components are at 1552.97 and 1553.65 nm. Also, for the second channel, the uncoded and encoded components are located at 1549.76 and 1550.43 nm, respectively. The frequency difference of each pair is 84.549 GHz. The rest of the components are filtered out with a band stop filter.

The component that is going to be encoded is passed to a single-electrode MZM (SE-MZM) to be data-modulated with a 10 Gb/s pseudorandom bit sequence generator (PRBS) operating at $2^{23} - 1$ that is shaped with a Gaussian wave generator having a full width half maximum (FWHM) of 5.2 ps. The data-modulated signal is then passed to an SSFBG device that is profiled with a unipolar seven-bit m -sequence code. The optical codes used in each channel are orthogonal. The sequence of the first channel is $0\pi 0\pi\pi 0$

and the second channel is $\pi 00\pi\pi 0$. Afterward, for each channel, the two uncoded and two encoded data-modulated signals are multiplexed and transmitted through a 20-km length of dispersion compensated fiber to the receiver.

At the receiver side, four optical signals are demultiplexed. The encoded signals are directed to another SSFBG device that has the exact same profile as the encoder except it is inverted. The output of the decoder will be a distinct peak per each "1" in the PRBS sequence and noise per each "0" of the initial data sequence. The decoded signal is then fed to an optical hard limiter device to compensate for the irregularities of the received signal and to guarantee all 1's have similar power levels.

Finally, for each channel, the uncoded and decoded components are heterodyned at a PIN photodiode to generate an electrical signal having an RF frequency equal to the frequency difference of two optical components (84.549 GHz). The output optical signal is then bandpass filtered and

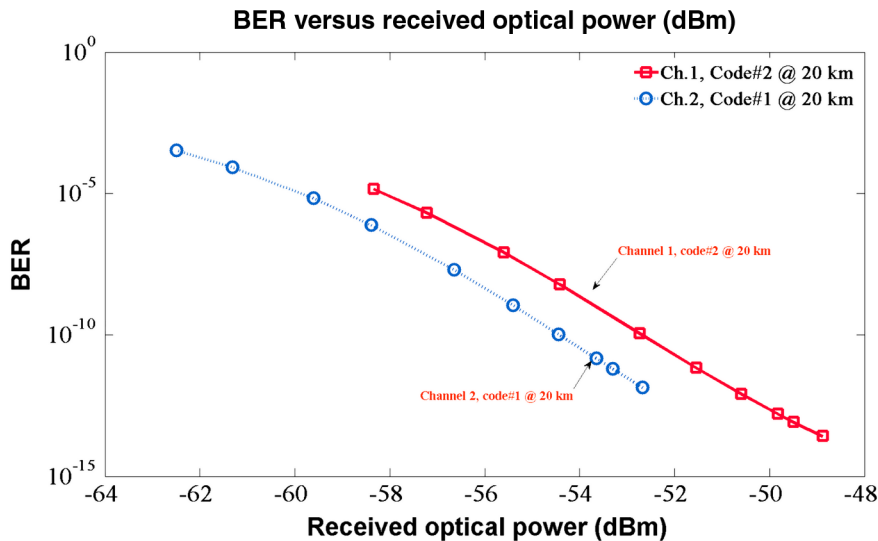


Fig. 3 BER versus received optical power (in dBm) for the reverse setting of channels and codes in Fig. 2 at 20 km.

depending on the application will be retransmitted via a millimeter wave antenna or passed on for detection to a signal processing module.

4 Simulation Results

The setup of this work, as shown in Fig. 1, has been created and simulated in VPITransmission Maker software version 9.7 from VPI Photonics. Figure 2 shows the measured bit error rate (BER) versus the received optical power (in dBm) for both codes, each at one of the WDM channels and for three lengths of optical fiber. The original fiber length for this study is 20 km. However, to better understand the effect of distance on the BER versus received optical power, fiber lengths of 10 and 30 km have been simulated too, and the results are presented. Figure 3 shows inversed channel and code configuration at 20-km length of fiber for comparison. Finally, Fig. 4 shows the eye-diagram for each channel

at three performance levels of 10^{-3} , 10^{-9} , and 10^{-12} , respectively.

5 Discussion

The two m -sequence codes that are used in this study are similar in length and in the number of 0's and π 's.

However, to verify the continuous effect of the wavelength channel on the BER, the simulation has been performed for two other optical fiber lengths (10 and 30 km), along with the target length of 20 km. The reason to include different optical fiber lengths is to check whether the length of fiber can cancel or alter the effect of wavelength channel at both longer and shorter lengths of optical fiber. Figure 2 shows three curve pair per each length of the optical fiber. It can be seen that for all three lengths, the effect of the lower wavelength channel is dominant and thus, the signal propagating in channel two, irrelevant of the code sequence

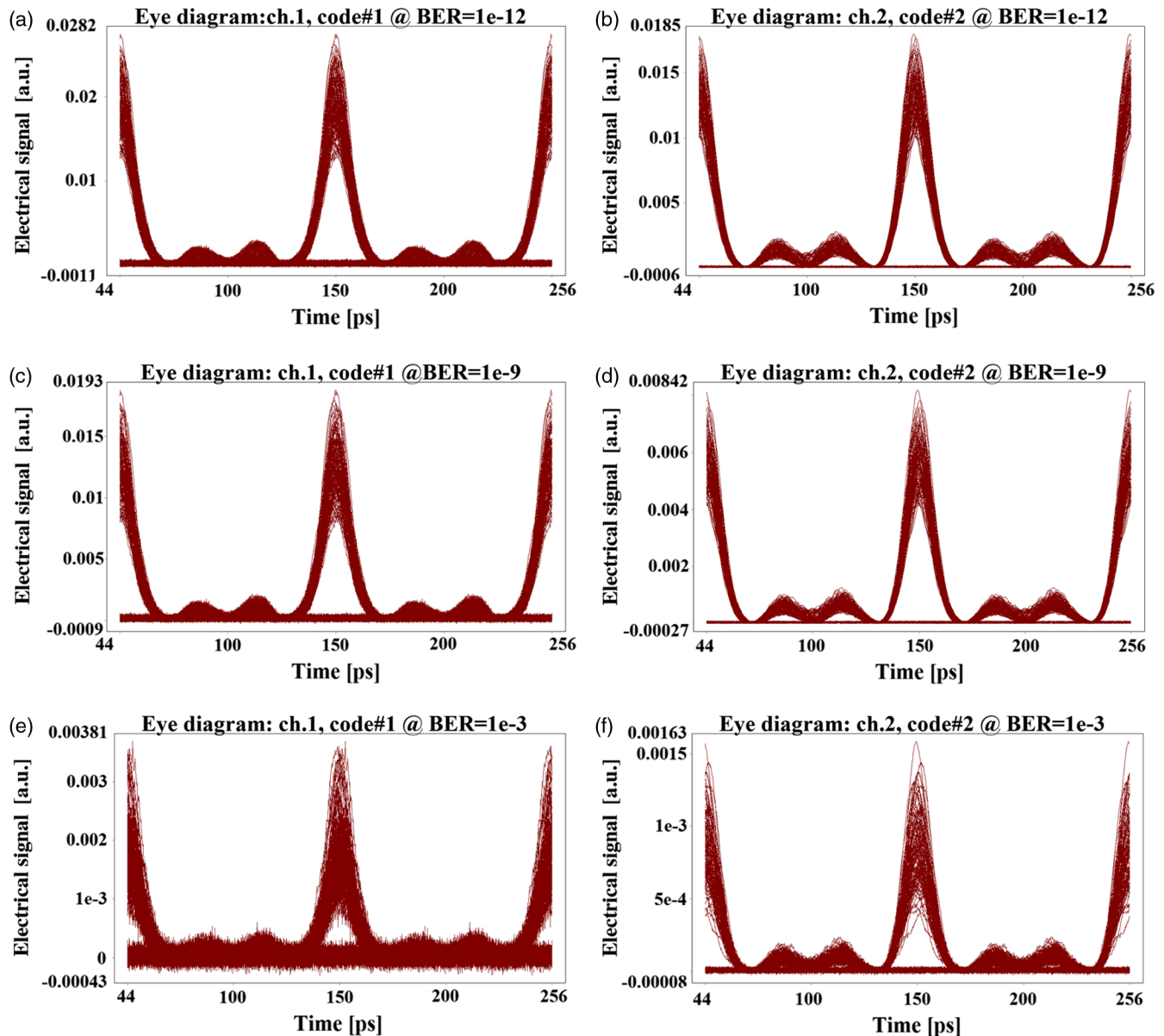


Fig. 4 Eye diagram for (a) ch.1 at BER = 10^{-3} , (b) ch.1 at BER = 10^{-9} , (c) ch.1 at BER = 10^{-12} , (d) ch.2 at BER = 10^{-3} , (e) ch.2 at BER = 10^{-9} , and (f) ch.2 at BER = 10^{-12} .

encoding the signal, shows a better BER value for the received optical power. This is also true when the codes are inverted in Fig. 3, where channel 1 carries the signal encoded with code 2 and channel 2 carries the signal encoded with code 1. Therefore, the only factor that influences the performance of two channels is the frequency difference. Here, the channel spacing is chosen to be 400 GHz to avoid using narrow filters to minimize the effect of the other component's residual bandwidth on the target signal. Thus, the traditional 100 GHz channel spacing of dense wavelength division multiplexing would require utilizing narrow filtration of each component.

The BER budget between two channels is about 4 dB for all three fiber lengths. We can see the effect of multiplexing on the BER budget for both channels. Figure 3 shows the inverse of the setup shown in Fig. 2. It can be observed that channel 1 has about 3.5-dB gain margin to channel 2. This gain difference is mainly because of the wavelength selective nature of the standard single-mode fiber optic cable used in this setup. This feature imposes higher attenuation to smaller wavelength channels. However, when transmitting encoded signals, there is ~5-dB gain difference between channel 1 encoded with code 1 and channel 1 encoded with code 2. The same measure for channel 2 is also ~5 dB. This can reveal that irrespective of the nature of the code, channel 2 experiences more attenuation. However, the BER curve for channel 2 is more promising for both setups (Figs. 2 and 3) since it has smaller received power per decrease in the BER value.

Also, eye-diagram observation reveals that the eye-opening for channel 1, the situation where BER is very small (10^{-12}) is ~94% larger than the eye opening for the erroneous BER (10^{-3}). The eye opening for channel two is ~95% between BER of 10^{-12} and 10^{-3} . The higher received optical power for channel one is also shown in Fig. 2. This means the channel with higher wavelength (channel 1's wavelength is 1553.32 nm while channel 2 is 1550.11 nm) experiences less attenuation and absorption leading to higher received optical power.

6 Conclusion

In this paper, we have demonstrated millimeter wave signal generation in a tandem DE-MZM for two optical channels, in conjunction with WDM architecture, that are optically encoded with seven-segment m -sequence unipolar codes to increase the number of users according to the OCDMA scheme. The link measures such BER and eye diagram at the receiver's side determines whether the proposed system is operable at the suggested settings (number of wavelength channels, frequency of millimeter wave signal, length and input optical power). Thus, the BER curves for the received optical power levels are compared for both channels at three different optical fiber lengths of 10, 20, and 30 km. Moreover, the effect of optical codes (from unipolar seven-bit m -sequence codes) and the effect of number of WDM channels on the performance are depicted in the figures and are therefore acknowledged.

The reach of the signal has been improved dramatically and has been compared using optical fibers with various lengths instead of wireless propagation of millimeter waves. The fiber attenuation is about 4 dB for a length of 20 km (standard single-mode fiber), whereas the over-the-air attenuation for the same distance is about 100 dB (with

antenna gain) and 152 dB (without antenna gain) more than over-the-fiber attenuation at 84 GHz. Also, the amount of BER versus the received optical power margin between two wavelength channels is about 4 dB for all three simulated fiber lengths. In addition, the eye-diagram also confirms the results obtained by BER measurement. The eye-diagram measure for channel 2 shows better opening for different BER levels.

References

1. Y. Niu et al., "A survey of millimeter wave communications (mmWave) for 5G: opportunities and challenges," *Wireless Networks* **21**(8), 2657–2676 (2015).
2. T. S. Rappaport et al., "Wideband millimeter-wave propagation measurements and channel models for future wireless communication system design," *IEEE Trans. Commun.* **63**(9), 3029–3056 (2015).
3. S. Rangan, T. S. Rappaport, and E. Erkip, "Millimeter-wave cellular wireless networks: potentials and challenges," *Proc. IEEE* **102**(3), 366–385 (2014).
4. S. A. Miraftebzadeh, P. Rad, and M. Jamshidi, "Efficient distributed algorithm for scheduling workload-aware jobs on multi-clouds," in *11th System of Systems Engineering Conf. (SoSE)*, Kongsberg, pp. 1–8 (2016).
5. T. Hamanaka et al., "Demonstration of 16-user OCDMA over 3-wavelength WDM using 511-chip, 640 Gchip/s SSFBG encoder/decoder and single light source," in *OFC/NFOEC Conf. on Optical Fiber Communication and the National Fiber Optic Engineers Conf.*, Anaheim, California, pp. 1–3 (2007).
6. W. Amaya et al., "Multi-channel en/decoding devices for WDM—coherent direct sequence OCDMA applications based on super structured fibre Bragg gratings," in *13th Int. Conf. on Transparent Optical Networks*, Stockholm, pp. 1–4 (2011).
7. R. Baños et al., "Spectral efficiency in WDM-OCDMA coherent direct sequence encoder/decoder devices based on fiber Bragg gratings," in *15th Int. Conf. on Transparent Optical Networks (ICTON)*, Cartagena, pp. 1–4 (2013).
8. K. I. Kitayama, Y. Yoshida, and R. Matsumoto, "Technology options beyond NG-PON2: IFDMA-WDM and OCDMA-WDM," in *OptoElectronics and Communication Conf. and Australian Conf. on Optical Fibre Technology*, Melbourne, pp. 286–288 (2014).
9. P. C. The et al., "Demonstration of a four-channel WDM/OCDMA system using 255-chip 320-Gchip/s quaternary phase coding gratings," *IEEE Photonics Technol. Lett.* **14**(2), 227–229 (2002).
10. M. Niknamfar and M. Shadaram, "Two sub-carriers multiplexed millimeter wave generation using Mach-Zehnder modulators," in *Int. Conf. on Transparent Optical Networks (ICTON)*, Graz, pp. 1–4 (2014).
11. M. K. Eghbal and M. Shadaram, "Tandem-modulator generated W-band OCDMA radio-over-fiber system," in *18th Int. Conf. on Transparent Optical Networks (ICTON)*, Trento, pp. 1–3 (2016).
12. M. K. Eghbal, F. Aminian, and M. Shadaram, "Effect of different optical codes on a W-band WDM-over-OCDMA system," in *19th Int. Conf. on Transparent Optical Networks (ICTON)*, Girona, pp. 1–4 (2017).
13. M. K. Eghbal and M. Shadaram, "Tandem dual-electrode Mach-Zehnder modulators generating W-band signals for an OCDMA radio-over-fiber system," in *IEEE Photonics Society Summer Topical Meeting Series (SUM)*, San Juan, pp. 213–214 (2017).
14. E. H. Dinan and B. Jabbari, "Spreading codes for direct sequence CDMA and wideband CDMA cellular networks," *IEEE Commun. Mag.* **36**(9), 48–54 (1998).

Morad Khosravi Eghbal is a PhD candidate in electrical engineering and a graduate research assistant at the Electrical and Computer Engineering Department at the University of Texas at San Antonio. He received his master's degree in photonics engineering from Chalmers University of Technology. His research focuses on capacity increase scenarios with millimeter wave radio-over-fiber communication, optical encoding techniques, and WDM optical networks for the next generation mobile networks (5G). He has published more than 10 articles in conference proceedings.

Mehdi Shadaram is the Briscoe distinguished professor and the founding director of the Center for excellence in engineering education at the University of Texas at San Antonio. His main area of research is in the broadband analog and digital fiber optic and wireless systems. He has published more than 120 articles in refereed journals and conference proceedings. He is a senior member of IEEE. He received his PhD in electrical engineering in 1984 from the University of Oklahoma.