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Photonics-aided 0.3-THz Wireless Transmission Based on Digital Sub-Carrier Multiplexing [Invited]

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ABSTRACT

To combine the merits of fiber communication and wireless communication, photonics-aided terahertz-wave (THz-wave) technology has become a popular technology in recent years. In this paper, a 92 Gbit/s photonics-aided 0.3-THz wireless transmission system based on digital sub-carrier multiplexing (DSCM) is proposed and simulated. In order to compensate the phase noise, both Viterbi-Viterbi and maximum likelihood (VV&ML) algorithm and decision directed digital phase lock loop (DD-PLL) method are considered and compared. According to the simulation results, DSCM based scheme can provide better performance than single carrier (SC) based scheme in the case of low received optical power (ROP) or input optical power (IOP) while there is no advantage in the case of high ROP or IOP. For SC based scheme, DD-PLL has 1 dB sensitivity gain compared with VV&ML when BER drops from 10^{-3} to 10^{-4}, while 2 dB sensitivity gain was obtained for DSCM based scheme for ROP. For SCM based scheme, DD-PLL has 1 dB sensitivity gain compared with VV&ML when BER drops from 10^{-3} to 10^{-4}. On the whole, DD-PLL outperforms VV&ML in terms of performance in high ROP case for both SC and SCM based scheme. Besides, DD-PLL has lower computation complexity than VV&ML.

Keywords: photonics-aided technology, digital-signal-processing, phase noise, digital sub-carrier multiplexing, phase lock loop, Terahertz-wave, nonlinear impairments, chromatic dispersion

1. INTRODUCTION

Future ubiquitous virtual reality/augmented reality (VR/AR), 4k/8k high-definition video, artificial intelligence, and so on will strive for larger bandwidth[1]. These application scenarios challenge the current 5G millimeter-wave (mm-wave) wireless communication system. Terahertz-band (THz-band, 0.3–10 THz) is one of the promising candidates for 6G, since it has larger available bandwidth to accommodate higher mobile data traffic and rates[2]. In recent years, the photonics-aided technology becomes popular to realize the generation, modulation, and detection of the Terahertz-wave (THz-wave) compared with bandwidth-limiting all-electric technology[3]. There are several typical techniques which can be used to realize large-capacity fiber-optic transmission, including optical polarization multiplexing, high-level quadrature-amplitude-modulation (QAM) modulation, electrical/optical multi-carrier modulation, as well as advanced transmitter-end and receiver-end digital-signal-processing (DSP) algorithms[4]. In order to make the THz-wave wireless transmission to match the large-capacity fiber-optic transmission, we can introduce the aforementioned optical communication techniques into the wireless THz-wave systems. There are three main factors limiting optical communication system: the phase noise from non-zero laser linewidth (LW), the nonlinear impairments from the nonlinear region of the electro-optical components, and linear impairments from the bandwidth constraint of the optoelectronic devices and chromatic dispersion. The impacts of these factors are serious if the symbol rate of the system is increased. To operate at low symbol rates to reduce these impacts, and also to fully utilize the bandwidth (BW) of the electrical channel to maximize the system capacity, digital sub-carrier multiplexing (DSCM) is applied by digitally multiplexing lower symbol rate sub-carriers to form a high BW signal[5]. In order to compensate the phase noise, Viterbi-Viterbi and maximum likelihood (VV&ML) algorithm and decision directed digital phase lock loop (DD-PLL) are two common methods.

In this paper, we present a systematic study on the performance of VV&ML and DD-PLL in single-carrier (SC) system and DSCM system, respectively. The algorithms are tested for a 23 GBaud 16QAM THz wireless transmission system at 0.3 THz in simulation. Note that we only consider back-to-back wireless transmission case and the number of sub-carriers is 4 in our simulation. The rest of article is organized as follows: Section 2 describes the principles of DSCM, VV&ML

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and DD-PLL methods. The simulation setup and results are given in Section 3. Finally, we summarize this work in Section 4.

2. FUNDAMENTAL PRINCIPLES

2.1 Digital sub-carrier multiplexing (DSCM)

Related studies have shown that the subcarrier granularity has great influences on the nonlinear performance of dispersion-unmanaged coherent optical (CO) transmission systems[6]. By dividing the high-baud-rate SC signal into multiple multiplexed low-baud-rate subcarriers and optimizing the number of subcarriers, the nonlinearity and chromatic dispersion (CD) tolerance of the system can be improved even though such subcarrier multiplexed (SCM) signals generally have a higher peak-to-average power ratio (PAPR) at the beginning of the transmission link[8]. The theory of four wave mixing efficiency[8] or the walk-off between subcarriers because of CD[10] can explain this improved tolerance. On the other hand, thanks to the fast development of high-speed digital-to-analog converters (DAC), SCM signals can be obtained readily by generating the required signals digitally in the transmitter DSP and loading the samples to DACs for digital-to-analog conversion. Since the multiplexing of subcarriers is achieved in the digital domain, the implementation penalty is expected to be smaller compared with the analog methods[11]. Besides, DSCM can fully utilize the BW of the electrical channel to maximize the system capacity.

Figure 1 illustrates the simulated transmitter-side spectrum of the SC signal and the SCM signals with 2 and 4 subcarriers. The total baud rate is 23 GBaud, so the baud rate of each subcarrier is 11.5 GBaud and 5.75 GBaud respectively for the two SCM signals. The modulation format of each subcarrier is 16QAM. Root raised cosine (RRC) pulse shaping with a roll-off factor of 0.1 is used. Note that no guard band is left between subcarriers in the SCM signal spectrum, so the optical bandwidth and spectral efficiency are the same for all signals.

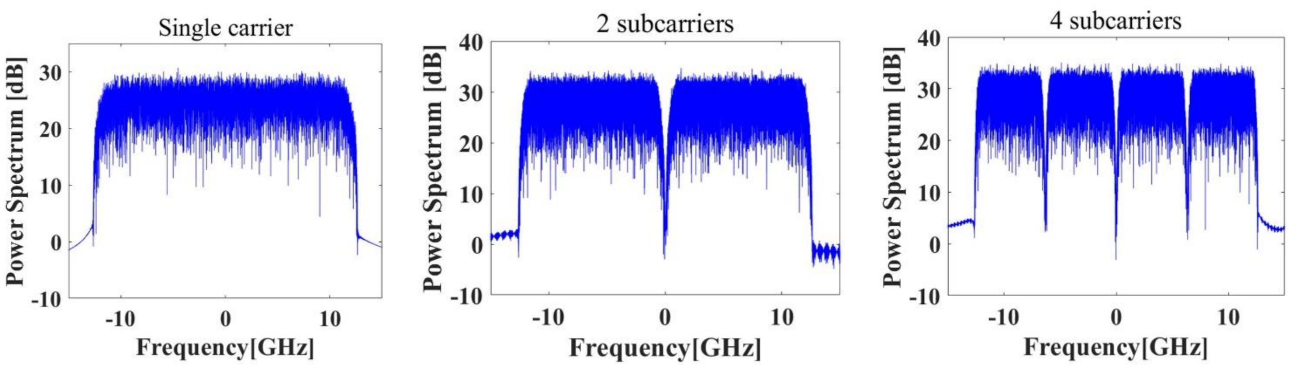

Figure 1. Power spectrum of the SC signal and SCM signals

2.2 Viterbi-Viterbi and maximum likelihood (VV&ML) algorithm

This algorithm introduces two cascaded phase recovery stages by using a coarse Viterbi-Viterbi (VV) method in the first stage and a maximum likelihood (ML) carrier phase estimate in the second stage. The block diagram of the two-stage algorithm is shown in Figure 2. For this algorithm, a coarse VV method is used in the first stage to compensate the phase noise roughly[12]. It is a classic feedforward carrier phase recovery method. According to the signal modulation format, this algorithm can eliminate the phase information after the N-th power of the signal, leaving only the frequency offset and phase noise. The frequency offset can be extracted and compensated after the correlation operation between neighboring symbols. The average of multiple symbols can reduce the effect of the amplified spontaneous emission (ASE) noise and improve the accuracy of phase noise estimation[13]. However, for 16 QAM and higher-level QAM, the simple N-th power operation cannot completely eliminate the phase modulation of the signal. A QPSK partitioning algorithm was proposed to solve this problem[14]. The decoded/decided signal based on this rough phase estimation (along with the original signal) are then fed into the second stage where a ML phase estimate is used to find a more accurate phase estimate by

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$$H_n = \sum_{n=1}^{N} R_n [\hat{Y}_n]^* \tag{1}$$

$$\varphi_{est,ML} = \tan^{-1}(\mathrm{Im}[H_n] / \mathrm{Re}[H_n]) \tag{2}$$

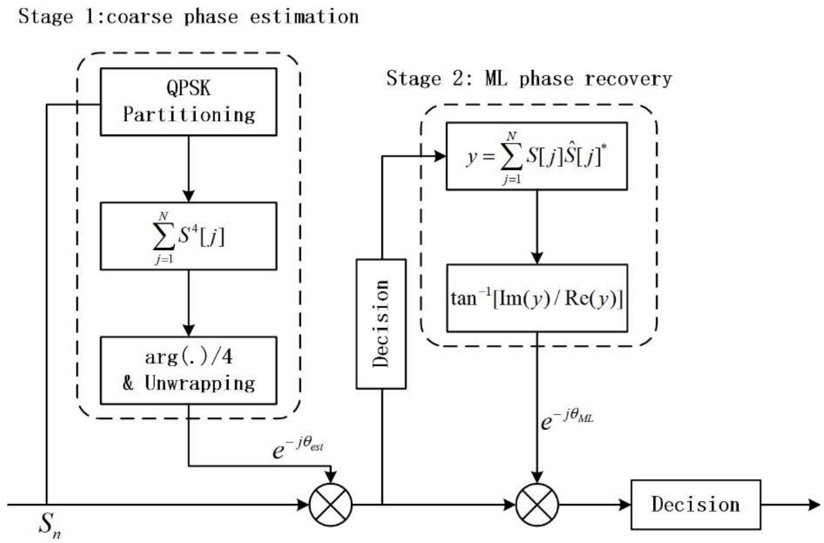

Figure 2. Illustration of the VV&ML algorithm

2.3 Decision directed digital phase lock loop (DD-PLL) method

Decision directed digital phase lock loop is another common approach to compensate phase noise[15]. The schematic diagram of DD-PLL is shown in Figure 3, including a phase detector (PD), a loop filter (LF) and a digital-controlled oscillator (DCO). The output of the phase detector is denoted as

$$p(n) = \mathrm{Im}[\frac{q(n)}{d(n)}] \tag{3}$$

Where $q(n)$ is the output of the loop, and $d(n)$ is the decision output of $q(n)$. DD-PLL estimates and compensates the phase noise by the phase error $\phi(n)$ between $q(n)$ and $d(n)$. The high frequency components and noise of $\phi(n)$ is filtered out by LF and it turns out to be $\varphi(n)$. $\varphi(n)$ drives DCO to generate modified phase $\theta(n)$ that compensates the phase of input signal at the next time. DD-PLL has good performance at high OSNR because $d(n)$ could be decided more accurately. When at low OSNR, the probability that symbol decision goes wrong is greater and $d(n)$ is not accurate. In this case, PLL is not stable and it will occur lock loss and cycle jump.

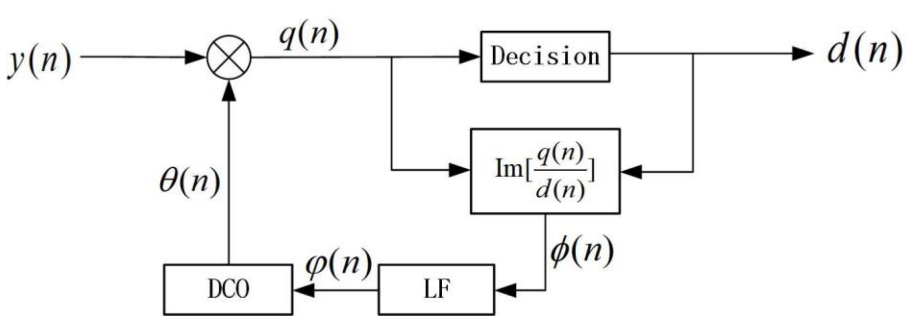

Figure 3. Schematic diagram of DD-PLL based phase noise compensation

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3. SIMULATION SETUP AND RESULTS

3.1 Simulation setup

Figure 4 shows the simulation setup. At the transmitter side DSP, the SC or SCM signals are generated offline with a total baud rate of 23 GBaud. The bit sequence is first mapped into 16-QAM symbols with a length of 2^{13}, which modulates 4 subcarriers, respectively. After two times up-sampling, a root-raised-cosine (RRC) filter with the roll-off factor 0.01 is used to realize Nyquist pulse shaping. Then, 4 subcarriers are shifted to different frequencies in the spectrum and multiplexed. The electric spectrums of SC and SCM at the transmitter side are given in Figure 4(a) and 4(b), respectively. After that, the symbol sequence is loaded to the DAC for digital to analog conversion. Two lasers with the same linewidth of 100 kHz and 0.3-THz frequency spacing are used as signal light source and local oscillator (LO) at central office and baseband unit side, respectively. The continuous wave (CW) light from external cavity laser-1 (ECL-1) is employed with the wavelength of 1553.6 nm. ECL-2 serves as a LO with an output wavelength of 1551.2 nm. One erbium doped fiber amplifier (EDFA) is used for optical signal boosting amplification before launching into the fiber. After 15 km standard single-mode fiber (SSMF) transmission, a variable optical attenuator (VOA-1) is used to control the received optical power (ROP) for sensitivity measurement. After combining with LO by an optical coupler (OC), VOA-2 is used to control the input optical power (IOP) to photodiode (PD). The PD is applied for the 0.3-THz wireless signal generation via heterodyne beating. A pair of horn antennas (HAs) is used for the wireless transmission of the signal. At the end user side, analog down conversion is performed with a 250-GHz sinusoidal RF source and a mixer. Then, the down-converted intermediate-frequency (IF) signal located at 50-GHz is boosted by another EA and captured by an oscilloscope for offline processing. The offline DSP includes down conversion, CD compensation, sub-carrier de-multiplexing, channel equalization and carrier recovery.

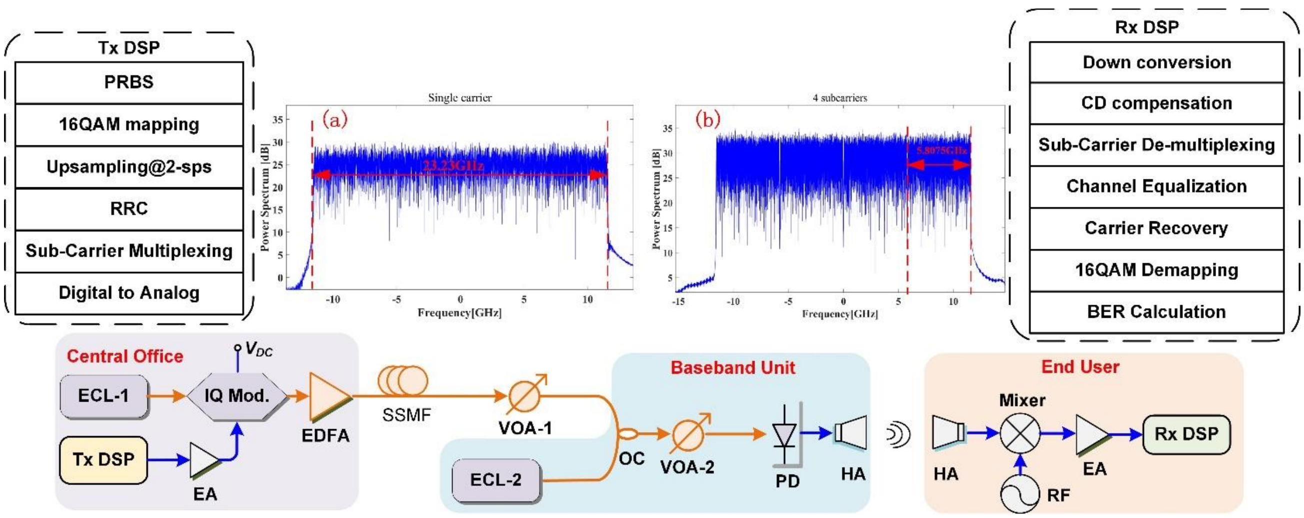

Figure 4. Simulation setup. The electric spectrum of the (a)SC (b) SCM4

3.2 Results

The algorithms are tested for a 23 GBaud 16QAM THz wireless transmission system at 0.3 THz in simulation. Note that we only consider back-to-back wireless transmission case and the number of sub-carriers is 4 in our simulation. Figure 5(a) shows the BER performance versus ROP of SC and SCM4 cases for VV&ML and DD-PLL schemes. For SC based scheme, DD-PLL has 1 dB sensitivity gain compared with VV&ML when bit error rate (BER) drops from 10^{-3} to 10^{-4}, while 2 dB sensitivity gain was obtained for DSCM based scheme in the same case. The BER versus IOP of VV&ML and DD-PLL in SC and SCM4 cases are given in Figure 4(b). For SC based scheme, the performance of VV&ML approaches that of DD-PLL. But for SCM4 based scheme, DD-PLL has 1 dB sensitivity gain compared with VV&ML when BER drops from 10^{-3} to 10^{-4}. On the whole, DD-PLL outperforms VV&ML in terms of performance in high ROP case for both SC and SCM4 based schemes. Particularly, DD-PLL has faster performance improvement than VV&ML for SCM4 based scheme and the latter encounters the flat bed of BER because DD-PLL benefits from decision feedback. On the other hand, DD-

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PLL has lower computation complexity than VV&ML because the latter uses sliding window averaging to smooth ASE noise.

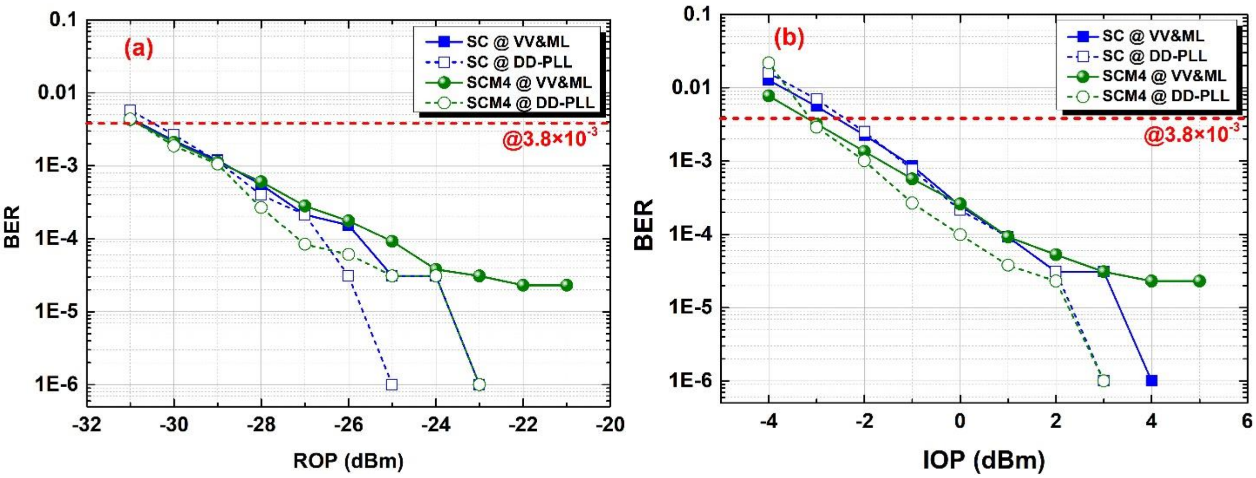

Figure 5. (a) BER versus ROP with two methods for SC and SCM4 (b) BER versus IOP with two methods for SC and SCM4

4. CONCLUSION

In this paper, we present a systematic study on the performance of VV&ML and DD-PLL in SC system and DSCM system, respectively. VV&ML and DD-PLL based schemes are considered to compensate phase noise, and the simulation results show that DSCM based scheme can provide better performance SC based scheme in the case of low ROP or IOP while there is no advantage in the case of high ROP or IOP. For SC based scheme, DD-PLL has 1 dB sensitivity gain compared with VV&ML when BER drops from 10^{-3} to 10^{-4}, while 2 dB sensitivity gain was obtained for DSCM based scheme for ROP. The performance of VV&ML approaches that of DD-PLL for IOP. But for DSCM based scheme, DD-PLL has 1 dB sensitivity gain compared with VV&ML when BER drops from 10^{-3} to 10^{-4}. On the whole, DD-PLL outperforms VV&ML in terms of performance in high ROP case for both SC and DSCM based scheme. Besides, DD-PLL has lower computation complexity than VV&ML.

ACKNOWLEDGMENT

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REFERENCES

[1] X. Li et al., "1-Tb/s Millimeter-Wave Signal Wireless Delivery at D-Band," in Journal of Lightwave Technology, vol. 37, no. 1, pp. 196-204, 1 Jan.1, 2019

[2] X. Li, J. Yu and G. Chang, "Photonics-Aided Mm-Wave Communication for 5G," 2019 Optical Fiber Communications Conference and Exhibition (OFC), 2019, pp. 1-3.

[3] X. Li et al., "120 Gb/s Wireless Terahertz-Wave Signal Delivery by 375 GHz-500 GHz Multi-Carrier in a 2 × 2 MIMO System," in Journal of Lightwave Technology, vol. 37, no. 2, pp. 606-611, 15 Jan.15, 2019

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[4] X. Li, J. Yu and G. Chang, "Photonics-Aided Millimeter-Wave Technologies for Extreme Mobile Broadband Communications in 5G," in Journal of Lightwave Technology, vol. 38, no. 2, pp. 366-378, 15 Jan.15, 2020
[5] H. Sun et al., "800G DSP ASIC Design Using Probabilistic Shaping and Digital Sub-Carrier Multiplexing," in Journal of Lightwave Technology, vol. 38, no. 17, pp. 4744-4756, 1 Sept.1, 2020
[6] L. B. Du and A. J. Lowery, "Optimizing the subcarrier granularity of coherent optical communications systems," Opt. Express 19(9), 8079–8084 (2011).
[7] A. Bononi, N. Rossi, and P. Serena, "Performance dependence on channel baud-rate of coherent single-carrier WDM systems," in Proc. ECOC (2013), paper Th.1.D.5.
[8] W. Shieh and Y. Tang, "Ultrahigh-speed signal transmission over nonlinear and dispersive fiber optic channel: the multicarrier advantage," IEEE Photon. J. 2(3), 276–283 (2010).
[9] Y. Tang, W. Shieh, and B. S. Krongold, "DFT-spread OFDM for fiber nonlinearity mitigation," IEEE Photon. Technol. Lett. 22(16), 1250–1252 (2010).
[10] Q. Zhuge, B. Chatelain, and D. Plant, "Comparison of intra-channel nonlinearity tolerance between reduced- guard-interval CO-OFDM systems and Nyquist single carrier systems," in Proc. OFC (2012), paper OTh1B.3.
[11] Y. Zhu, J. Wang, Q. Guo, Y. Cui, C. Li, F. Zhu, and Y. Bai, "Experimental comparison of terabit Nyquist superchannel transmissions based on high and low baud rates," in Proc. OFC (2013), paper JW2A.37.
[12] Xiang, Z. , and J. Yu . "Two-stage feed-forward carrier phase recovery algorithm for high-order coherent modulation formats." European Conference & Exhibition on Optical Communication IEEE, 2010.
[13] X. Li, J. Yu and G. Chang, "Photonics-Assisted Technologies for Extreme Broadband 5G Wireless Communications," in Journal of Lightwave Technology, vol. 37, no. 12, pp. 2851-2865, 15 June15, 2019
[14] I. Fatadin, D. Ives and S. J. Savory, "Carrier Phase Recovery for 16-QAM Using QPSK Partitioning and Sliding Window Averaging," in IEEE Photonics Technology Letters, vol. 26, no. 9, pp. 854-857, May1, 2014
[15] M. I. Olmedo et al., "Carrier recovery techniques for semiconductor laser frequency noise for 28 Gbd DP-16QAM," 2015 Optical Fiber Communications Conference and Exhibition (OFC), 2015, pp. 1-3.

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