Reflection-Tolerant RoF-Based Mobile Fronthaul Network for 5G Wireless Systems

Byung Gon Kim, Sung Hyun Bae, *Student Member, IEEE*, Min Sik Kim, and Yun C. Chung, *Fellow, IEEE*

***Abstract*—We propose to utilize the filtered Gaussian phase dither technique for the effective suppression of the multipath-interference (MPI) noises caused by multiple bad fiber connectors in the mobile fronthaul network (MFN) based on the radio-over-fiber (RoF) technology. We first evaluate the viable performances of the RoF-based MFN in the 5G wireless communication systems by using this technique and deduce the required bandwidth and phase modulation depth of the filtered Gaussian dither signal for the suppression of the MPI noises by numerical simulations. The results show that, by using the proposed technique, it is possible to suppress the MPI noises by ∼10 dB regardless of the number of bad fiber connectors. These simulation results are experimentally verified in the RoF link capable of transporting the 5G wireless signals (i.e., thirty-two 100-MHz orthogonal-frequency-division-multiplexed (OFDM) signals modulated in 64QAM or 256QAM format). We also evaluate the effectiveness of the proposed dither technique in a high-capacity RoF link implemented by using four wavelength-division-multiplexed channels and demonstrate the successful transmission of 128 100-MHz OFDM signals modulated in 256QAM format in the presence of multiple bad connectors.**

***Index Terms*—5G wireless communication system, high-frequency phase dither, mobile fronthaul network, multipath interference noises, radio-over-fiber.**

I. Introduction

The 5G wireless communication system is finally becoming a reality as many operators worldwide are beginning to launch their commercial 5G services [1]–[3]. However, for its prevalent deployment, it is crucial to install numerous mobile fronthaul networks (MFNs) capable of transporting 5G wireless signals everywhere. One problem associated with these MFN installations is their enormous bandwidth requirements. For example, if we utilize the conventional common public radio interface (CPRI) protocol, the transmission capacity required for the connection between the remote radio head (RRH) and baseband unit (BBU) can exceed several hundreds of Gbps [4]–[6]. To mitigate this problem, it has been proposed to change the current functional split architecture between the RRH and BBU despite some drawbacks such as the increased complexity and reduced coordination capability [5]–[7]. We would like to point out that this problem can also be mitigated by using the radio-over-fiber (RoF) technology. In fact, this technology can provide a very cost-effective solution for this problem since it can drastically reduce the immense bandwidth required for the digital transmission of the 5G wireless signals. Accordingly, there have already been many efforts to develop the RoF-based MFN for the 5G wireless systems [8]–[15]. However, it appears that the industry disregards this analog RoF technology due to the reliability issue inherent in the analog transmission system. In particular, it is well known that the RoF-based MFN is vulnerable to the dispersion-induced composite second-order (CSO) distortions and multi-path interference (MPI) noises [11], [15]. However, the CSO distortions would not cause any serious problems unless we transmit the wireless signals over the standard single-mode fiber (SSMF) by using an optical transmitter operating in the 1.5-μm region and having a large chirp (such as a directly modulated laser) [15]. In addition, even in the case of using the 1.5-μm DML transmitter, these distortions can be compensated by using a simple digital signal processing (DSP) technique [16]. Thus, the remaining issue to guarantee the performance of the RoF-based MFN is how to compensate for the MPI noises (which are caused mostly by the bad fiber connectors in the link). Recently, we have reported that the MPI noises in the RoF-based MFN can be effectively suppressed by using the high-frequency sinusoidal phase dither technique [17]. In this technique, it is necessary to optimize the dither frequency for the effective suppression of the MPI noises caused by a specific interferer (i.e., a specific set of two bad connectors in the link). Thus, it would be difficult to suppress the MPI noises by using this technique if there are multiple interferers in the RoF link.

In this paper, we propose to utilize the filtered Gaussian phase dither technique for the effective suppression of the MPI noises caused by multiple interferers in the RoF-based MFN. The operating principle of this technique is briefly described in Section II. In Section III, we evaluate the viable performances of the RoF-based MFN of the 5G wireless systems by using this technique and deduce the required parameters (such as the bandwidth and modulation depth of the filtered Gaussian dither signal) for the suppression of the MPI noises by numerical simulations. The experiments to verify these simulation results are described in Section IV. We implement an RoF link by using a 1.5-μm electro-absorption modulated laser (EML) and transmit thirty-two 100-MHz orthogonal-frequency-division-multiplexed (OFDM) signals modulated in either 64 quadrature

Manuscript received July 16, 2019; revised September 9, 2019; accepted October 4, 2019. Date of publication October 10, 2019; date of current version December 10, 2019. This work was supported by the IITP Grant funded by the Korean Government (2017-0-00702). *(Corresponding author: Yun C. Chung.)*

The authors are with the School of Electrical Engineering, Korea Advanced Institute of Science and Technology, Daejeon 34141, South Korea (e-mail: qudrhs3414@kaist.ac.kr; bsh88@kaist.ac.kr; mskim0628@kaist.ac.kr; ychung@kaist.ac.kr).

Color versions of one or more of the figures in this article are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JLT.2019.2946610

amplitude modulation (64QAM) or 256QAM format in the presence of multiple interferers. The results show that, by using the proposed technique, we can mitigate the signal-to-interference ratio (SIR) required for the transmission of the 5G signals by ∼10 dB. In addition, we implement an RoF link by using four wavelength-division-multiplexed (WDM) channels and demonstrate the successful transmission of 128 100-MHz OFDM signals modulated in 256QAM format (which has a CPRI equivalent capacity of ∼0.78 Tb/s) even in the presence of multiple interferers. Finally, this paper is summarized in Section V.

II. Theoretical Background

If the phase of the intensity-modulated optical signal is dithered with a sinusoidal wave, its electrical field and phase can be expressed as

$$E(t) = \sqrt{P_0}\sqrt{x(t)}\exp(j2\pi\nu_0 t + j\phi(t)) \quad (1)$$

$$\phi(t) = \phi_n(t) + \delta_d \cos(2\pi f_d t) \quad (2)$$

where P_0 is the average optical power, $x(t)$ is the intensity modulation of the optical signal, ν_0 is the optical frequency, and $\phi_n(t)$ is the phase noise of the optical signal. δ_d and f_d indicate the modulation depth and frequency of the sinusoidal wave used for the phase dither, respectively. In the presence of the MPI noises caused by an interferer (arising from a combination of two bad fiber connectors), the received photocurrent can be expressed as

$$i_{PD}(t) \approx R P_o \Big\{ x(t) + hx(t) + \sqrt{h}\sqrt{x(t)}\sqrt{x(t-T)} \times [\exp(j2\pi v_0 T + j\phi(t) - j\phi(t-T)) + c.c.] \Big\} \quad (3)$$

where R is the responsivity of the photodetector, h is the reciprocal of the SIR, and T is the time delay between the signal and interferer, and *c.c.* represents complex conjugate. Here, we assume that R is equal to 1. By taking the Fourier transform of the autocorrelation of this received photocurrent, we obtain its power spectral density (PSD) given by [17]

$$S_{i_{PD}}(f) = P_0^2 \Bigg[S_x(f) + h \Bigg\{ J_0^2(2\delta_d \sin(\pi f_d T)) S_N(f) + \sum_{k\neq 0} J_k^2(2\delta_d \sin(\pi f_d T)) S_N(f - kf_d) \Bigg\} \Bigg] \quad (4)$$

where $S_x(f)$ is the PSD of $x(t)$, $J_k(\cdot)$ is the Bessel function of the first kind of order k, and $S_N(f)$ is the PSD of MPI noises. This equation clearly shows that we can effectively eliminate the MPI noises by using the sinusoidal phase dither. For example, if we set the dither frequency, f_d, to be higher than twice of the bandwidth of $x(t)$, the MPI noises falling at outside of the signal bandwidth (i.e., $S_N(f-kf_d)$ term, where $k \neq 0$), can be eliminated simply by using a low-pass filter. Also, the MPI noises falling within the signal bandwidth (i.e., $J_0{}^2(2\delta_d \sin(\pi f_d T))$ term) can be suppressed completely by optimizing f_d and setting δ_d to be $\geq$1.2 (since the first root of $J_0(x)$ is ∼2.405). In this paper, we refer the $J_0{}^2(2\delta_d \sin(\pi f_d T))$ term as the noise reduction factor

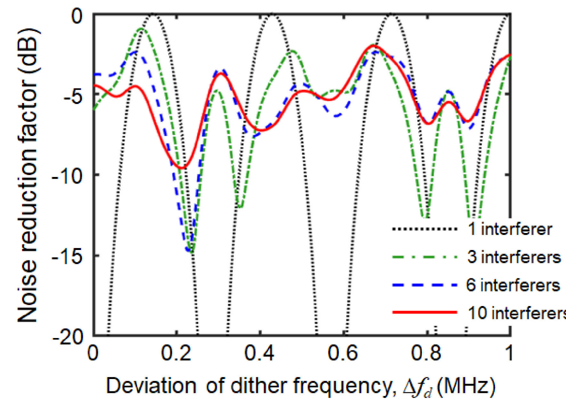

Fig. 1. Estimated NRF as a function of the dither frequency, f_d, for various number of interferers. The deviation of the dither frequency, Δf_d (= f_d − 12.5 GHz), indicates the amount of frequency separated from 12.5 GHz. In the case of 1, 3, 6, and 10 interferers, the time delays between the signal and interferers are set to be (3.5 μs), (1.9 μs, 3.5 μs, and 5.4 μs), (1.1 μs, 1.9 μs 3.0 μs, 3.5 μs, 4.6 μs, and 5.4 μs), and (0.5 μs, 1.1 μs, 1.6 μs, 1.9 μs, 2.4 μs, 3.0 μs, 3.5 μs, 4.0 μs, 4.6 μs, and 5.4 μs), respectively.

(NRF) since the MPI noises can be suppressed by reducing this term. If there are multiple interferers in the RoF link, the NRF should modified as

$$NRF = \sum_{i=1}^{N} A_i J_0^2(2\delta_d \sin(\pi f_d T_i)) \quad (5)$$

where A_i is the power ratio of the i^{th} interferer to total interferers, T_i is the time delay between the signal and the i^{th} interferer, and N is the number of interferers. Fig. 1 shows the estimated NRF as a function of the dither frequency, f_d, for various number of interferers. In this estimation, we assume that the 5G wireless signals are placed in the frequency range of <6 GHz in the RoF-based MFN. Thus, we set f_d to be ∼12.5 GHz (which is higher than twice of the signal bandwidth of 6 GHz). We also assume that the SIR, A_i, and δ_d are 20 dB, 1/N, and 1.2, respectively. The results show that, if there is only one interferer in the link, we can suppress the MPI noises completely by optimizing f_d. However, it becomes quite difficult to minimize the NRF if there are multiple interferers. For example, as the number of interferers is increased from 1 to 3, 6, and 10 (i.e., the number of bad fiber connectors in the fiber link is increased from 2 to 3, 4, and 5), the achievable value of NRF is deteriorated from −40 dB to −13 dB, −11.5 dB, and −7.9 dB, respectively, even if we optimize f_d. To overcome this problem and suppress the MPI noises regardless of the number of interferers, it would be necessary to broaden the bandwidth of the dither signal [18]. For this purpose, we propose to dither the phase of the optical signal by using the filtered Gaussian noises. In particular, if we set the bandwidth of the filtered Gaussian noises to be broader than the reciprocal of the shortest time delay between any bad connectors ($1/T_{\min}$), this technique can effectively suppress the MPI noises caused by multiple interferers as long as their time delays are longer than $T_{\min}$. Also, there is no need for the fine adjustment of f_d in this technique. When we utilize the filtered Gaussian noises for the phase dither, the electrical field of the intensity-modulated optical signal can be expressed as

$$E(t) = \sqrt{P_0}\sqrt{x(t)}\ \exp\left(j2\pi\nu_0 t + j\phi_n(t) + j\delta_d\, n(t)\ \cos(2\pi f_d t)\right) \quad (6)$$

where $n(t)$ is the filtered Gaussian noises. Then, the PSD of the received photocurrent can be expressed as

$$S_{i_{PD}}(f) = P_0^2\left[S_x(f) + h\ \exp\left(-\delta_d^2 R_n(0)\right)\ S_N(f) * \mathscr{F}\left\{\exp\left(\delta_d^2\, R_n(\tau)\ \cos(2\pi f_d \tau)\right)\right\}\right] \quad (7)$$

where the symbol $*$ and $\mathscr{F}$ denote the convolution and Fourier transform operator, respectively, and $R_n(\tau)$ represents the auto-correlation of $n(t)$. From this equation, we confirm that, by using the filtered Gaussian dither technique, the MPI noises can be suppressed regardless of the time delay between bad fiber connectors, T (i.e., $S_{i_{PD}}(f)$ is independent of T).

III. Numerical Simulations

We evaluated the effectiveness of the filtered Gaussian phase dither technique on the MPI noise suppression in the RoF-based MFN of the 5G wireless systems by numerical simulations. In particular, we investigated the bandwidth and modulation depth of the filtered Gaussian dither signal required for the effective suppression of the MPI noises, and identified its theoretically achievable performances. For this purpose, we assumed that the RoF-based MFN should be capable of transporting thirty-two 100-MHz OFDM signals for the 5G wireless systems (as specified in [6]). We also assumed that these 32 OFDM signals were placed at 2 GHz + $(i-1) \times 122.88$ MHz, where i is the channel index. Since these signals were sufficiently far away from DC (and MPI noises affected the signals located closer to DC more severely), we could achieve nearly ideal performance of the proposed technique under this condition. For the worst case analysis, we estimated the error-vector magnitude (EVM) performance of channel 1 in the presence of the MPI noises. In this EVM estimation, we assumed that the OFDM signals were modulated in quadrature phase-shift keying (QPSK) format. We also noted that one of these 32 OFDM signals could be used for the phase dither (instead of using the separately generated filtered Gaussian noises) since their amplitude statistics are exactly the same (i.e., zero-mean stationary Gaussian process) [19].

We first investigated the required bandwidth of the filtered Gaussian noises for the effective suppression of the MPI noises. For this purpose, we assumed that the shortest time delay (i.e., $T_{\min}$) of the interferer was 5 ns (which was equivalent to the path difference of 1 m). This was because the effects of the MPI noises could be neglected when the time delay was much shorter than the coherence time of the source laser (typically 0.1 μs ~ 1.0 μs) [20]. Also, we assumed that the linewidth of the source laser, modulation depth (δ_d), and SIR were set to be 4 MHz, 3.6 and 20 dB, respectively. We then evaluated the EVM performances of the OFDM channel 1 as a function of the dither frequency in the presence of an interferer having a time delay of 5 ns. The results in Fig. 2 showed that we could suppress the MPI noises with almost no dependence on the dither frequency by increasing the bandwidth of the dither signal to be broader than ~100 MHz.

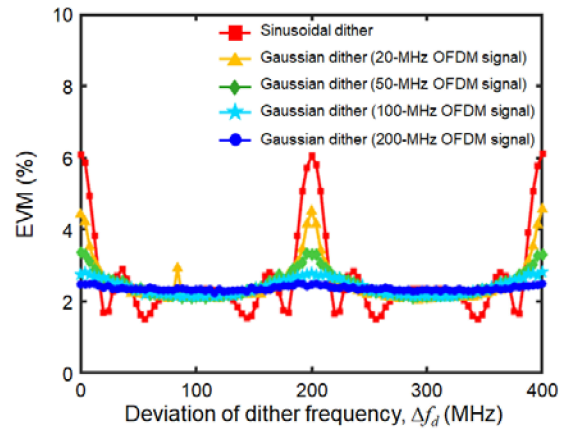

Fig. 2. Estimated EVM performance of the OFDM channel 1 as a function of the deviation of the dither frequency Δf_d $(= f_d - 12.5$ GHz) for various bandwidths of the filtered Gaussian dither signal.

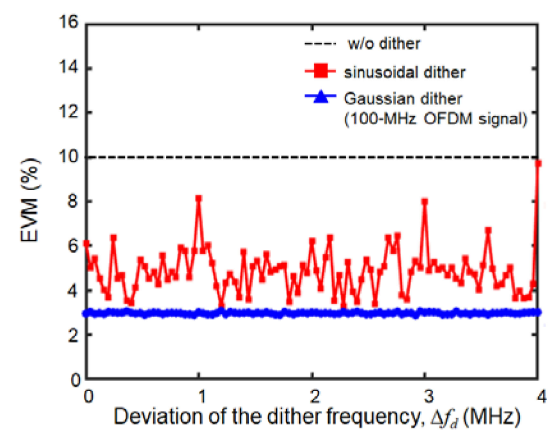

Fig. 3. Estimated EVM performances of the OFDM channel 1 as a function of the deviation of the dither frequency Δf_d $(= f_d - 12.5$ GHz) in the presence of 10 interferers in the RoF link. In this estimation, we assumed that the time delays between the signal and 10 interferers were 0.5 μs, 1.1 μs, 1.6 μs, 1.9 μs, 2.4 μs, 3.0 μs, 3.5 μs, 4.0 μs, 4.6 μs, and 5.4 μs.

For example, when we used a pure sinusoidal wave to dither the phase of the optical signal, the EVM varied between 1.8% and 6.1% depending on the dither frequency. However, when we increased the bandwidth of the filtered Gaussian dither signal to be >100 MHz, the EVM varied only in the range of 2.1% and 2.7%. From these results, we deduced that it would be possible to suppress the MPI noises caused by multiple interferers without the necessity of optimizing the dither frequency by increasing the bandwidth of the dither signal to be >100 MHz (as long as their time delays were longer than 5 ns). To verify this, we estimated the EVM performance of the OFDM channel 1 as a function of the dither frequency in the presence of 10 interferers (which could be generated by 5 bad fiber connectors). In this evaluation, we assumed that the reflected powers from these 10 interferers were the same and the bandwidth of the dither signal (centered at 12.5 GHz) was set to be 100 MHz. Fig. 3 shows the results. When we utilized the sinusoidal dither, the EVM fluctuated between 3.3% and 9.7%, depending on the dither frequency. In comparison, when we utilized the filtered Gaussian

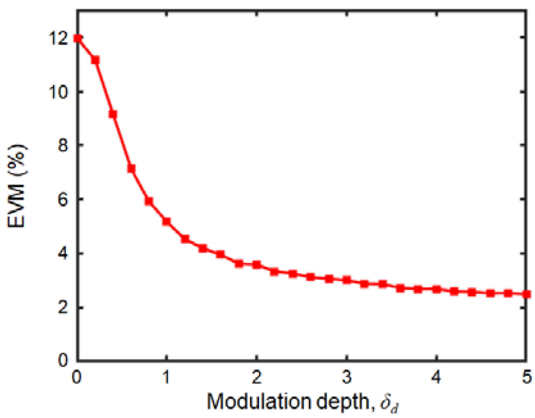

Fig. 4. Estimated EVM performance of the OFDM channel 1 as a function of the modulation depth of the filtered Gaussian dither signal when there are 10 interferers in the RoF link. In this estimation, the linewidth of the source laser, bandwidth of the filtered Gaussian dither signal (centered at 12.5 GHz), and SIR were assumed to be 4 MHz, 100 MHz, and 20 dB, respectively. The time delays between the signal and 10 interferers were 0.5 μs, 1.1 μs, 1.6 μs, 1.9 μs, 2.4 μs, 3.0 μs, 3.5 μs, 4.0 μs, 4.6 μs, and 5.4 μs.

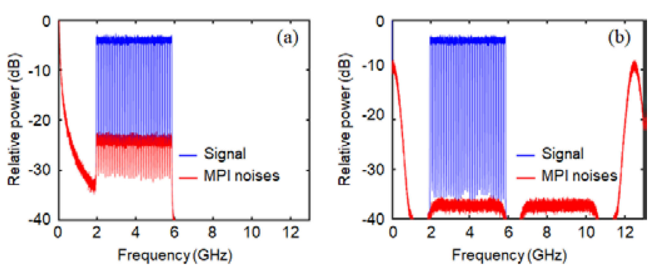

Fig. 5. Estimated RF spectra of thirty two 100-MHz OFDM signals and MPI noises when the modulation depth, δ_d, was set to be (a) 0 and (b) 3.6. In this estimation, the other parameters were set to be identical to those values used in Fig. 4.

dither, it would be possible to achieve the EVM of ~2.8% regardless of the dither frequency. These results clearly indicated the effectiveness of the proposed Gaussian dither technique for the suppression of the MPI noises caused by multiple interferers.

We also evaluated the required modulation depth of the filtered Gaussian dither signal for the effective suppression of the MPI noises caused by multiple interferers. Fig. 4 shows the estimated EVM of the OFDM channel 1 as a function of the modulation depth of the filtered Gaussian phase dither signal. As expected, the EVM performance was improved with the modulation depth. However, this improvement became quickly saturated as the phase modulation depth became larger than ~2. Thus, we determined that it would be unnecessary to increase the modulation depth to be much larger than ~4. Fig. 5 shows the RF spectra of thirty two 100-MHz OFDM signals together with MPI noises obtained with and without applying the filtered Gaussian dither signal. From these RF spectra, we confirmed that it would be possible to suppress the MPI noised by >10 dB despite the use of the limited modulation depth of 3.6.

Finally, we evaluated the achievable EVM performance of the OFDM channel 1 as a function of SIR by using the filtered Gaussian dither technique in the presence of 1~10 interferers.

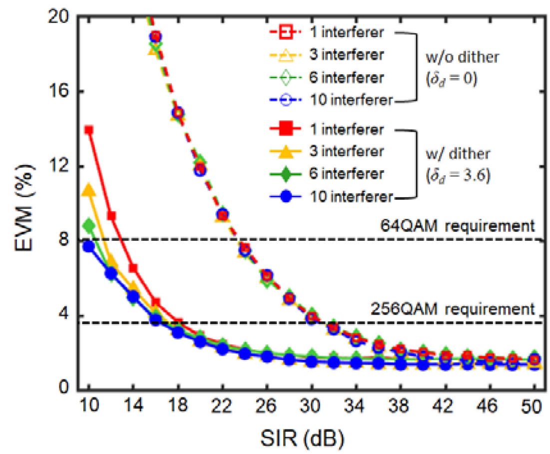

Fig. 6. Estimated EVM performances of the OFDM channel 1 as a function of the SIR in the presence of 1, 3, 6, and 10 interferers. In this estimation, the time delays were set to be the same as those used in Fig. 1.

In this evaluation, we assumed that the modulation depth was set to be 3.6. All other parameters were the same as described above. From the results in Fig. 6, we confirmed that the MPI noises could be a serious limiting factor for the RoF-based MFN. For example, when the filtered Gaussian phase dither technique was not utilized (i.e., $\delta_d = 0$), the SIR to satisfy the EVM requirement of the 256QAM signal (i.e., EVM = 3.5% [21]) was estimated to be ~30 dB. Thus, in this case, only one bad fiber connector could be allowed in the RoF-based MFN if we assumed that its reflectivity was 4% (i.e., −14 dB). However, if we utilized the filtered Gaussian phase dither technique, the necessary SIR to satisfy the EVM requirement of the 256QAM signal was reduced to be only ~18 dB. These results indicated that, without utilizing the proposed technique, the RoF-based MFN could not transport 256QAM signals if there were more than two bad connectors with 4% Fresnel reflectivity. However, in the case of utilizing the proposed technique, the RoF-based MFN could transport 256QAM signals even when there were as many as 5 bad fiber connectors with 4% reflectivity or 18 bad fiber connectors with 1% reflectivity (i.e., the SIR became to be as low as ~18 dB). From these results, we deduced that, with the help of the filtered Gaussian phase dither technique, the analog RoF link utilizing 256QAM signals could be more robust against the MPI noises than the digital transmission link utilizing 4-level pulse amplitude modulation (PAM4) signals (since the PAM4 signal could suffer from an error floor at the bit-error rate (BER) of ~10^{-3} when the SIR was degraded to 25 dB [22]).

The results in Fig. 6 also showed that the SIR to satisfy the EVM requirement of the 64QAM signal (i.e., EVM = 8% [21]) could be reduced to 10~14 dB by using the filtered Gaussian phase dither technique. However, in such a low SIR region, the interferer-interferer beat noises could no longer be neglected. Thus, the performance improvement achieved by the proposed technique became dependent on the number of interferers. For example, when there was only one interferer in the RoF link, the proposed technique could not suppress these beat noises since all these noises fell within the signal bandwidth. On the other hand, when there were multiple interferers, the proposed

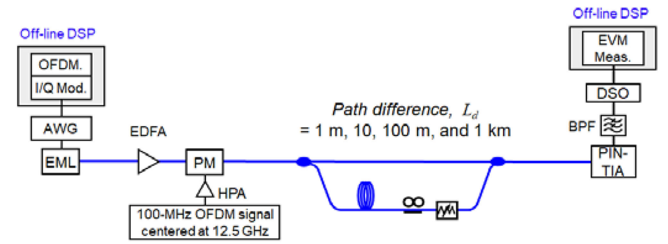

Fig. 7. Experimental setup to verify the performance of the filtered Gaussian phase dither technique.

technique could at least partially suppress these beat noises since most of them fell outside of the signal bandwidth. As a result, in the low SIR region (i.e., SIR < 15 dB), the EVM performances were estimated to be better when there were a larger number of interferers.

For the EVM estimations in Fig. 6, we set the time delays between the signal and 10 interferers to be much longer than the coherence time of the source laser. Thus, each interferer was not correlated with the signal. As a result, when we did not utilize the proposed dither technique, the EVM performances were not dependent on the number of interferers (but dependent on the SIR of the total interferers), as shown in Fig. 6.

IV. Experiments and Results

We first experimentally verified the time-delay independent performance of the filtered Gaussian dither technique, which was critical for the suppression of the MPI noises caused by multiple interferers. Fig. 7 shows the experimental setup. We generated a 100-MHz OFDM signal by taking 512 inverse fast Fourier transform (IFFT) of 340 data subcarrier and 68 pilot subcarriers modulated in QPSK format. We then up-converted this 100-MHz OFDM signal to 2 GHz. An arbitrary waveform generator (AWG) was used (vertical resolution: 8 bit, sampling rate: 64 Gsample/s) for the generation of this OFDM signal. The output of the AWG was injected to an EML operating at 1538.7 nm. The output power and linewidth of this EML were measured to be 2 dBm and 4 MHz, respectively. We dithered the output of this EML with a 100-MHz OFDM signal centered at 12.5 GHz by using a $LiNbO_3$ phase modulator. An erbium-doped fiber amplifier (EDFA) was used in front of the phase modulator to overcome the limited output power of EML. The dithered optical signal was then transmitted through a fiber link consisted of a signal's path and an interferer's path. A short SSMF (∼10 m) was used in the signal's path. In the interferer's path, we used a polarization controller and a variable attenuator to match the polarization states of the signal and interferer and adjust the SIR, respectively. We also inserted various lengths of SSMF in the range of 1 m ∼ 1 km (which corresponded to the time delay in the range of 5 ns ∼ 5 μs) to evaluate the effects of different time delays of the interferer on the performance of the filtered Gaussian dither technique. The outputs of the signal's and interferer's paths were combined by using a 3-dB coupler and sent to a PIN-TIA receiver. The detected signal was passed through a bandpass filter centered at 2 GHz (3-dB bandwidth: 500 MHz) to filter out the MPI noises caused by the optical carrier, and sampled by using a digital sampling oscilloscope (DSO) at 40 Gsample/s. We then demodulated the 100-MHz OFDM signal and measured its EVM performances. Fig. 8 shows the results. As expected from the numerical simulations, in the case of not using the proposed technique, the effect of the MPI noises on the performance of the RoF link was measured to be increased with the path difference until it became to be ∼100 m. After this length, the effect of the MPI noises became independent of the path difference. This was because the MPI noise power increased with the time delay (i.e., path difference) and reached its maximum value when the time delay became longer than the inverse of the linewidth of the source laser [20]. However, by using the filtered Gaussian dither technique, we could suppress the MPI noises by ∼10 dB regardless of the path difference. For example, the needed SIRs to satisfy the EVM requirement of the 256QAM signal were reduced from ∼32 dB to ∼22 dB (by ∼10 dB) and from ∼36 dB to ∼24 dB (by ∼12 dB) when the path differences were set to be 1 m and 1 km, respectively. In principle, if the performance of the RoF link is limited mostly by the MPI noises, this SIR could be reduced to ∼18 dB (as expected in the numerical simulations). However, we could not achieve this ideal value due to the quantization noises of the AWG and DSO. In fact, due to these quantization noises, the EVM was measured to be ∼2.7% even in the absence of the MPI noises in this experiment.

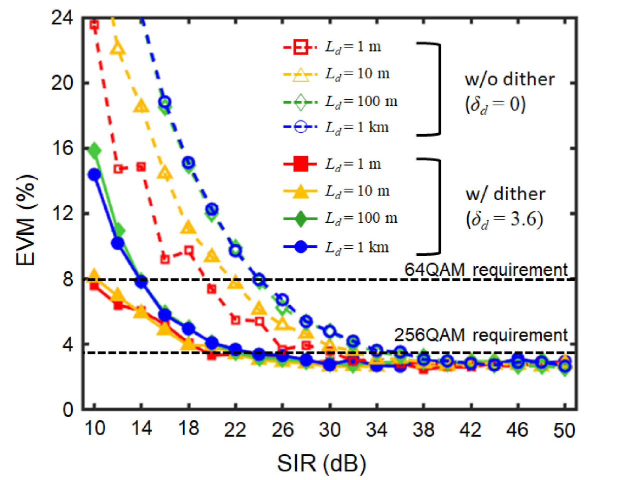

Fig. 8. Measured EVM performances of the 100-MHz OFDM signal located at 2 GHz as a function of the SIR for various path differences L_d.

Fig. 9 shows the experimental setup used to demonstrate the reflection-tolerant RoF-based MFN of the 5G wireless systems by using the filtered Gaussian dither technique. We generated thirty-two 100-MHz OFDM signals modulated in 64QAM (or 256QAM) format. The carrier frequencies of these 32 OFDM signals were set to be 700 + 122.88 × i MHz (where $i = 1 \sim 16$) and 3000 + 122.88 × (i − 16) MHz (where i = 17∼32). We utilized two output ports of the AWG for the generation of these OFDM signals to reduce the quantization noises arising from the AWG. The combined 32 OFDM signals were then applied to the EML operating at 1538.7 nm. The operating conditions of

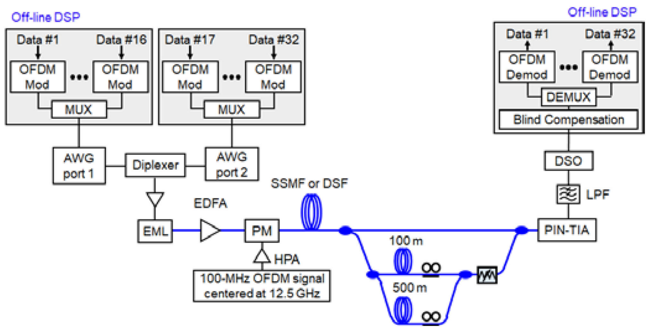

Fig. 9. Experimental setup to demonstrate the reflection-tolerant RoF-based MFN for the 5G wireless systems by using the filtered Gaussian phase dither technique.

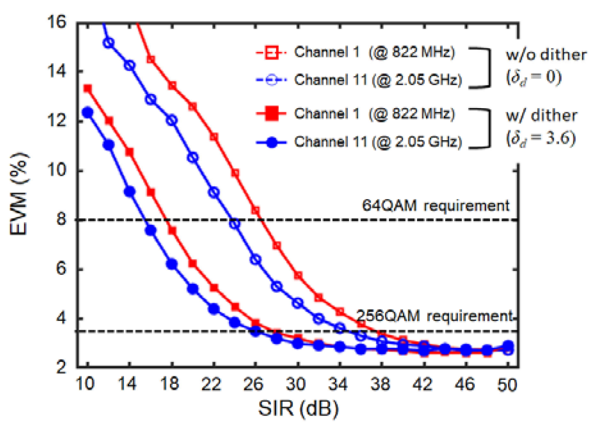

Fig. 10. Measured EVM performances of the OFDM channels 1 and 11 as a function of SIR for various modulation depths δ_d.

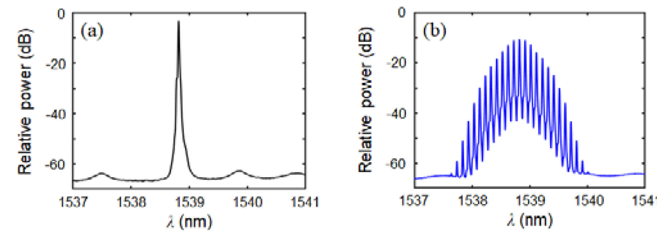

Fig. 11. Optical spectra measured when the modulation depth δ_d was set to be (a) 0 and (b) 3.6.

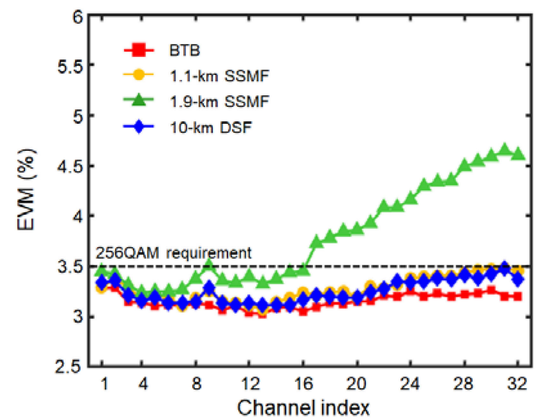

Fig. 12. Measured EVM performances of all 32 OFDM channels after the transmission over 1.1 km and 1.9 km of SSMF, and 10 km of DSF in comparison with the result obtained in the back-to-back condition (when the SIR was set to be 30 dB).

this EML were the same as described above. The output of this EML was amplified by an EDFA and sent to the $LiNbO_3$ phase modulator operated with a 100-MHz OFDM signal centered at 12.5 GHz. Thus, there was no need to generate the filtered Gaussian noises separately since we could utilize one of the 32 OFDM signals to drive the phase modulator. The output of this phase modulator was then traversed through the transmission fiber (SSMF or dispersion-shifted fiber (DSF)) and the interferometric system consisted of a signal's path and two interferer's paths having 100-m and 500-m long path differences. We utilized these two interferer's paths to emulate the MPI noises caused by multiple interferers having different time delays. The outputs of these signal's and interferer's paths were combined before being detected by a PIN-TIA receiver, and sent to the DSO operating at 40 Gsamples/s. We then applied the blind compensation technique reported in [23] for the compensation of the EML's nonlinear transfer curve, demodulated the thirty-two 100-MHz OFDM signals, and measured their EVM performances. Fig. 10 shows the measured EVM performances of the OFDM channel 1 (@ 822 MHz) and channel 11 (@ 2.05 GHz) as a function of the SIR in the back-to-back condition with and without using the filtered Gaussian dither technique. The results showed that, by using the proposed technique, we could suppress the MPI noises by ~10 dB even in the presence of multiple interferers. However, the EVM performance of channel 1 was measured to be slightly worse than that of channel 11 since the effects of the MPI noises were more severe to those channels located closer to DC. Thus, for the effective suppression of the MPI noises, it would be desirable to set the frequencies of the OFDM signals to be sufficiently high (e.g., >1.5 GHz). However, we had to set the lowest carrier frequency of the OFDM signal to be as low as 822 MHz due to the characteristics of the diplexer used in this experiment.

In Fig. 6, we showed that the phase modulation depth of the filtered Gaussian dither signal, δ_d, should be quite large (e.g., >3) for the effective suppression of the MPI noises. However, such a large modulation depth could significantly broaden the optical spectrum of the OFDM signals, as shown in Fig. 11. As a result, in the case of implementing the RoF-based MFN in the 1.5-μm region, its performance could be seriously deteriorated by the chromatic dispersion. For example, Fig. 12 shows the measured EVM performances of all 32 OFDM channels after the transmission over 1.1 km and 1.9 km of SSMF and 10 km of DSF in comparison with the results obtained in the back-to-back condition. This figure showed that, when we increased the transmission distance of the SSMF link to 1.9 km (total dispersion: ~32 ps/nm), some of the high-frequency channels could no longer satisfy the EVM requirement of the 256QAM signal mainly due to the dispersion-induced composite second-order (CSO) distortions. From this result, we estimated that,

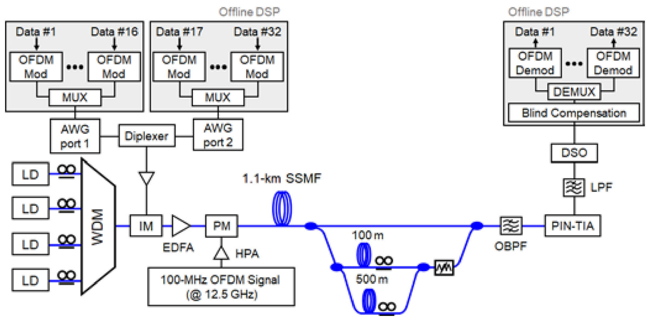

Fig. 13. Experimental setup to demonstrate the effectiveness of the filtered Gaussian phase dither technique in the WDM-type RoF-based MFN.

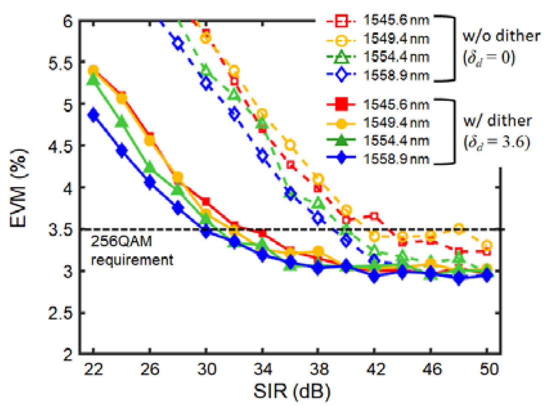

Fig. 14. Measured EVM performances of the OFDM channel 1 in all 4 WDM channels as a function of the SIR for various modulation depths δ_d.

if the modulation depth of the filtered Gaussian dither δ_d was set to be 3.6, the RoF link transporting thirty-two 100-MHz OFDM signals modulated in 256QAM format could tolerate the accumulated dispersion of ~18 ps/nm. Thus, in the case of implementing the RoF-based MFN in the 1.3-μm region, it would be possible to transport the 5G wireless signals modulated even in 256QAM format over >10 km without using any dispersion-compensation techniques (as confirmed by the results obtained in the 10-km long DSF link in this experiment).

In practice, only a few fibers are usually installed for the connection of each base station to the central office. Thus, considering the multiple sector and band antennas used in the 5G base stations, it would be indispensable to utilize multiple wavelengths in the RoF-based MFN. Thus, we evaluated the effectiveness of the filtered Gaussian dither technique in such a WDM-type RoF-based MFN. Fig. 13 shows the experimental setup. We utilized 4 lasers operating at 1545.6 nm, 1549.4 nm, 1554.4 nm, and 1558.9 nm. The outputs of these lasers were multiplexed by using fiber Bragg grating filters. A Mach- Zehnder intensity modulator was used for the generation of the 100-MHz OFDM signals modulated in 256QAM format. Fig. 14 shows the measured EVM performances of the OFDM channel 1 (@ 822 MHz) in all 4 WDM channels as a function of the SIR after the 1.1-km long SSMF transmission. The results showed that, by using the filtered Gaussian dither technique, we could effectively suppress the MPI noises in all 4 WDM

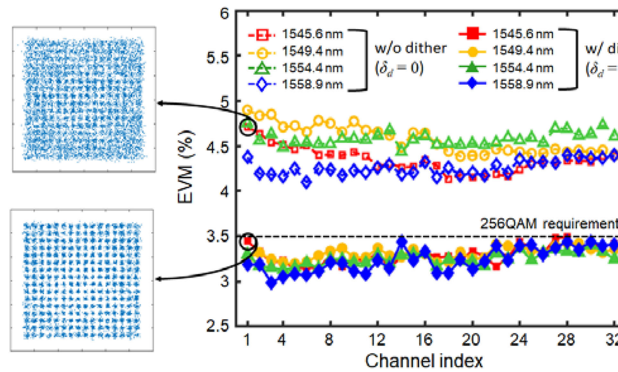

Fig. 15. Measured EVM performances of all 128 OFDM channels after the 1.1-km long SSMF transmission. In this measurement, the SIR was set to be 34 dB.

channels. As a result, the required SIR for the 256QAM signal was reduced by ~10 dB. However, despite this improvement, the achieved EVM performance was limited to be ~3% in this WDM experiment due to the signal-to-amplified spontaneous emission (ASE) beat noises as well as the quantization noises. Fig. 15 shows the measured EVM performances of all 128 OFDM channels modulated in 256QAM format after the transmission over 1.1 km of SSMF. The results showed that, by using the filtered Gaussian phase dither technique, we could effectively suppress the MPI noises in all 4 WDM channels. We also confirmed that all 128 OFDM channels could satisfy the EVM requirement of the 256QAM signal even when there were multiple interferers in the RoF link.

V. Summary

The RoF-based MFN is extremely attractive for the use in the 5G wireless systems due to its incomparably narrow bandwidth requirement. However, the industry appears to have no interest in utilizing this technology at present due to the reliability issue. In fact, it is well known that the performance of the RoF-based MFN could be seriously deteriorated by the MPI noises arising from the bad fiber connectors in the link. Recently, we have reported that the MPI noises caused by one set of bad fiber connectors could be suppressed effectively by using the high-frequency sinusoidal phase dither [17]. However, it would be difficult to suppress the MPI noises if there were more than one set of bad fiber connectors in the link. In this paper, we have proposed and demonstrated that this problem could be solved by utilizing the filtered Gaussian phase dither technique. We first evaluated the viable performances of the RoF-based MFN by using this technique through numerical simulations. In this evaluation, we assumed that the RoF-based MFN for the 5G wireless systems should be able to transport thirty-two 100-MHz OFDM signals modulated in 64QAM or 256QAM format. We also assumed that these OFDM signals were placed in the frequency range of 2.0 GHz ~ 5.8 GHz in the RoF-based MFN. The results showed that, for the effective suppression of the MPI noises caused by multiple bad connectors, the bandwidth and modulation depth of the filtered Gaussian dither signal should set to be larger than 100 MHz and ∼3.5, respectively. Under these conditions, the necessary SIR to satisfy the EVM requirement of the 256QAM signal could be reduced from 30 dB to 18 dB (which was equivalent to the SIR degraded by 5 bad fiber connectors with 4% reflectivity). From this result, we deduced that the RoF-based MFN carrying the OFDM signals modulated in 256QAM format could be more robust against the MPI noises than the digital transmission system transporting the PAM4 signals, since the PAM4 signals could suffer from an error floor (@ BER $= 10^{-3}$) when the SIR was degraded to 25 dB. We attempted to verify these simulation results experimentally. For example, we experimentally verified that, by utilizing the filtered Gaussian phase dither technique, the MPI noises could be suppressed by ∼10 dB regardless of the number of bad fiber connectors in the link. We also demonstrated a reflection- tolerant RoF-based MFN for the 5G wireless systems by using the proposed technique. For this demonstration, we transmitted thirty-two 100-MHZ OFDM signals (modulated in 64QAM or 256QAM format) over the RoF link implemented by using a 1.5-μm EML. The filtered Gaussian phase dither technique was applied by using a $LiNbO_3$ phase modulator driven with one of those 32 OFDM signals (since its amplitude statistics was identical to that of the filtered Gaussian noises). The results showed that, by using the filtered Gaussian phase dither technique, we could mitigate the SIR requirement of the 256QAM signal by ∼10 dB (from 38 dB to 28 dB). However, we could not achieve the required SIR of 18 dB (estimated by the numerical simulations) in this experiment mainly due to the quantization noises of the AWG and DSO. We would like to point out that this problem caused by the test equipment would not be an issue in the practical 5G wireless systems. We also applied the proposed technique to the WDM-type RoF link implemented with 4 wavelength channels, and demonstrated the transmission of 128 100-MHz OFDM signals modulated in 256QAM format (which had a CPRI equivalent capacity of ∼0.78 Tb/s) over 1.1 km of SSMF in the presence of multiple interferers. This transmission distance could be easily extended to >10 km by operating this RoF link in the dispersion-free 1.3-μm region. From these results, we concluded that, by using the filtered Gaussian phase dither technique, it would be possible to realize the reliable, reflection-tolerant RoF-based MFN for the 5G wireless communication systems cost-effectively.

References

[1] T. Fisher, "5G availability around the world: Most countries will have access to 5G network by 2020," *Lifewire*, Jul. 12, 2019. [Online]. Available: https://www.lifewire.com/5g-availability-world-4156244

[2] J. Wills, "5G technology: Which country will be first to adapt?" *Investopedia*, Mar. 27, 2019.

[3] S. Kinney, "5 commercial 5G launches planned for 2019," *RCR Wireless News*, Nov. 12, 2018.

[4] T. Pfeiffer, "Next generation mobile fronthaul and midhaul architectures," *J. Opt. Commun. Netw.*, vol. 7, no. 11, pp. B38–B45, Nov. 2015.

[5] ITU-T, "Transport network of IMT-2020/5G," ITU-T, Geneva, Switzerland, Tech. Rep. GSTR-TN5G, Feb. 2018.

[6] "Technical specification group radio access network: Study on new radio access technology: Radio access architecture and interfaces," 3GPP TR 38.801, v.14.0.0, Mar. 2017.

[7] J. Kani, S. Kuwano, and J. Terada, "Options for future mobile backhaul and fronthaul," *Opt. Fiber Technol.*, vol. 26, pp. 42–49, Dec. 2015.

[8] S. H. Cho, H. Park, H. S. Chung, K. H. Doo, S. Lee, and J. H. Lee, "Cost-effective next generation mobile fronthaul architecture with multi-IF carrier transmission scheme," in *Proc. Opt. Fiber Commun. Conf.*, San Francisco, CA, USA, 2014, Paper Tu2B.6.

[9] N. Shibata *et al.*, "256-QAM 8 wireless signal transmission with DSP-assisted analog RoF for mobile front-haul in LTE-B," in *Proc. OptoElectron. Commun. Conf. Aust. Conf. Opt. Fibre Technol.*, Melbourne, VIC, Australia, 2014, pp. 129–131.

[10] X. Liu, H. Zeng, N. Chand, and F. Effenberger, "Bandwidth-efficient mobile fronthaul transmission for future 5G wireless networks," in *Proc. Asia Commun. Photon. Conf.*, Hong Kong, 2015, Paper ASu3E.4.

[11] B. G. Kim, S. H. Bae, H. Kim, and Y. C. Chung, "Optical fronthaul technologies for next-generation mobile communications," in *Proc. Int. Conf. Transparent Opt. Netw.*, Trento, Italy, 2016, Paper We.D2.5.

[12] F. Lu *et al.*, "Sub-band pre-distortion for PAPR reduction in spectral efficient 5G mobile fronthaul," *IEEE Photon. Technol. Lett.*, vol. 29, no. 1, pp. 122–125, Jan. 2017.

[13] P. T. Dat, A. Kanno, N. Yamamoto, and T. Kawanishi, "190-Gb/s CPRI-equivalent rate fiber-wireless mobile fronthaul for simultaneous transmission of LTE-A and F-OFDM signals," in *Proc. Eur. Conf. Opt. Commun.*, Düsseldorf, Germany, 2018, Paper W.4.P1.SC7.72.

[14] S. Ishimura, A. Bekkali, K. Tanaka, K. Nishimura, and M. Suzuki, "1.032-Tb/s CPRI-equivalent rate IF-over-fiber transmission using a parallel IM/PM transmitter for high-capacity mobile fronthaul links," *J. Lightw. Technol.*, vol. 36, no. 8, pp. 1478–1484, Apr. 2018.

[15] B. G. Kim, S. H. Bae, and Y. C. Chung, "RoF-based mobile fronthaul networks implemented by using DML and EML for 5G wireless communication systems," *J. Lightw. Technol.*, vol. 36, no. 14, pp. 2874–2881, Jul. 2018.

[16] B. G. Kim, S. H. Bae, H. Kim, and Y. C. Chung, "DSP-based CSO cancellation technique for RoF transmission system implemented by using directly modulated laser," *Opt. Exp.*, vol. 25, no. 11, pp. 12152–12160, May 2017.

[17] B. G. Kim, S. H. Bae, and Y. C. Chung, "MPI noise reduction in RoF-based mobile fronthaul network using high-frequency phase dither," in *Proc. Eur. Conf. Opt. Commun.*, Rome, Italy, 2018, Paper Th2.61.

[18] P. Pepeljugoski and K. Lau, "Interferometric noise reduction in fiber-optic links by superposition of high frequency modulation," *J. Lightw. Technol.*, vol. 10, no. 7, pp. 957–963, Jul. 1992.

[19] T. Jiang, and G. Zhu, "Nonlinear companding transform for reducing peak-to-average power ratio of OFDM signals," *IEEE Trans. Broadcast.*, vol. 50, no. 3, pp. 342–346, Sep. 2004.

[20] R. Tkach and A. Chraplyvy, "Phase noise and linewidth in an InGaAsP DFB laser," *J. Lightw. Technol.*, vol. LT-4, no. 11, pp. 1711–1716, Nov. 1986.

[21] "Base station (BS) radio transmission and reception," 3GPP TS 38.104 version 15.5.0, Mar. 2019.

[22] S. H. Bae *et al.*, "25-Gb/s TDM optical link using EMLs for mobile fronthaul network of LTE-A system," *IEEE Photon. Technol. Lett.*, vol. 27, no. 17, pp. 1825–1828, Sep. 2015.

[23] B. G. Kim, S. H. Bae, and Y. C. Chung, "Blind compensation technique for nonlinear distortions in RoF-based mobile fronthaul implemented by using EML," *Opt. Fiber Technol.*, vol. 47, pp. 51–54, Jan. 2019.

Byung Gon Kim received the B.S. degree in electrical engineering from Hongik University, Seoul, South Korea, in 2014, and the M.S. degree in electrical engineering in 2016 from the Korea Advanced Institute of Science and Technology, Daejeon, South Korea, where he is currently working toward the Ph.D. degree in electrical engineering. His research interests are mobile fronthaul/backhaul networks and analog radio-over-fiber technology.

Sung Hyun Bae received the B.S. degree in electrical engineering from Sogang University, Seoul, South Korea, in 2013, and the M.S. degree in electrical engineering in 2015 from the Korea Advanced Institute of Science and Technology, Daejeon, South Korea, where he is currently working toward the Ph.D. degree in electrical engineering. His research interests are mobile fronthaul/backhaul networks and spatial-division multiplexing technique.

Min Sik Kim received the B.S. and M.S. degrees in electrical engineering, in 2015 and 2017, respectively, from the Korea Advanced Institute of Science and Technology, Daejeon, South Korea, where he is currently working toward the Ph.D. degree in electrical engineering. His research interest is high-speed short-haul transmission.

Yun C. Chung (F'06) is a Professor of electrical engineering with the Korea Advanced Institute of Science and Technology, Daejeon, South Korea, which he joined in 1994. From 1987 to 1994, he was with the Lightwave Systems Research Department, AT&T Bell Laboratories. From 1985 to 1987, he was with the Los Alamos National Laboratory under the AWU-DOE fellowship program. His research activities include high-capacity WDM transmission systems, optical performance monitoring techniques, WDM passive optical networks, datacenter networks, fiber-optic mobile fronthaul networks, etc. He has authored/coauthored more than 500 journal and conference papers in these areas and holds more than 90 patents. He has been General Co-Chair of OFC, OECC, and APOC, and served as the President of the Optical Society of Korea. He is a Fellow of OSA, Korean Academy of Science and Technology, and National Academy of Engineering of Korea.