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Semi-Active Wavelength Division Multiplexing System Based on Pilot-Tone Relay Detection for 5G Centralized Front-Haul Network

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ABSTRACT A semi-active wavelength division multiplexing (WDM) system based on pilot-tone relay detection is proposed and experimentally demonstrated for 5G centralized front-haul network, which is composed of a passive WDM multiplexer at active antenna unit (AAU) side, an active WDM equipment at distributed unit (DU) side, and several WDM optical modules in AAU and DU, respectively. In this semi-active WDM scheme, WDM technology is applied as an optical transport layer to save fibers and the semi-active architecture based on pilot-tone modulation is capable of flexible deployment with lite operation, administration and maintenance (OAM) functions. The experimental results show that the sensitivity penalty is lower than 0.3 dB and the extinction ratio is still higher than 4.2 dB by using 4 % amplitude depth of pilot-tone modulation. The bit rate of the OAM signal is 1024 bps to reuse the existing micro-controller unit in the optical modules for generating and detecting OAM signals. The robustness of the pilot-tone signals is further demonstrated as the sensitivities of the 25-Gbps eCPRI signals and the 1024-bps OAM signals are −16 dBm and −23 dBm, respectively. Compared with the OAM demodulation both in upstream and downstream direction for the active WDM equipment, the number of OAM demodulation unit can be reduced by 50% and the sensitivity requirement of OAM demodulation can be improved by 11.5 dB by using only downstream OAM demodulation unit. Error-free 24-hour transmission of real-time 12-channel 25-Gbps eCPRI signals combined with 1024-bps pilot-tone OAM signals over 10-km single mode fiber is obtained.

INDEX TERMS C-RAN, front-haul transport, semi-active WDM, pilot-tone modulation, optical fiber communication.

I. INTRODUCTION

Centralized radio access network (C-RAN) architecture is a promising way for 5G RAN network [1]–[7], which is capable of decreasing power consumption, saving machine room, promoting collaborative radio, etc. Compared with the traditional distributed radio access network (D-RAN), the distributed units (DUs) are placed at one central office and the corresponding distance from active antenna unit (AAU) to DU is extended to 10 km for the main scenario of 5G C-RAN front-haul network. In this centralized scenario, wavelength division multiplexing (WDM) technology would be introduced between AAU and DU to save optical fibers [8]. Thus, with the extended transmission distance and WDM equipments, operation, administration and maintenance (OAM) functions are crucial for front-haul transport network to process the optical link failures and satisfy the reliability requirements of 5G services [9].

Several front-haul transport network schemes based on WDM technology have been proposed, including passive WDM [10], [11], active WDM [12], [13], etc. The passive WDM system is composed of WDM optical modules in AAU and DU, and a pair of passive de/multiplexer, which has the advantages of low cost, flexible deployment, etc. However, the passive equipments cannot support on-line OAM management. The potential fault points should be manually processed one by one, including optical modules, WDM multiplexer/demultiplexer, branch fibers between

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optical modules and WDM multiplexer/demultiplexer, trunk fibers between a pair of WDM multiplexer/demultiplexer, resulting in long fault detection and service disruption time. The active WDM scheme can perform powerful OAM functions, but the system cost is sharply increased and the deployment of the active equipment at AAU side is limited to power supply. As a result, the deployment of C-RAN networking for front-haul is limited in the past years. Additionally, pilot tone has been proposed to transport low-speed OAM information [14], [15]. However, it will be so complicated for front-haul transport network based on active WDM technology. For example, 2 sets of photodetectors (PDs) and OAM demodulation units in optical modules are required for each WDM channel by using pilot tone both in upstream and downstream direction and another 2 sets of optical modules are required to connect wireless equipment.

In this paper, we proposed and demonstrated a semi-active WDM system, which consists of a passive de/multiplexer at AAU side, an active WDM equipment at DU side, and several WDM optical modules in AAU and DU, respectively. We also proposed a method for performing lite OAM functions for the semi-active WDM architecture based on pilot-tone relay detection. Here, the performance of the WDM optical modules in AAU/DU and the optical fiber link can be on-line managed and monitored by using only downstream OAM demodulation unit in the active WDM equipment, such as the transmitting power, the receiving power, the temperature of the optical modules in AAU and DU, etc. The theoretical analysis show that the pilot-tone relay detection can reduce system cost and release sensitivity requirements significantly compared with the OAM demodulation both in upstream and downstream direction for the active WDM equipment. With 4 % amplitude depth of pilot-tone modulation, the sensitivity penalty is lower than 0.3 dB and the extinction ratio is still higher than 4.2 dB, demonstrating that the effect of pilot-tone modulation on the 25-Gbps enhanced common public radio interface (eCPRI) wireless services can be negligible. The sensitivities of the 25-Gbps eCPRI signals and the 1024-bps OAM signals are further measured to be −16 dBm and −23 dBm, respectively. To demonstrate the stability of the proposed semi-active system, 24-hour real-time error-free transmission of the 12-channel 25-Gbps eCPRI WDM signals combined with the 1024-bps pilot-tone OAM signals over 10 km is achieved.

II. ARCHITECTURE AND PRINCIPLE

The configuration of the proposed semi-active WDM system based on pilot-tone relay detection is shown in Fig. 1. In the upstream direction, the high-speed wireless services are firstly converted from electrical signals to optical signals in the optical modules of the AAU. Meanwhile, a low-speed OAM frame of the optical modules generated by micro-controller unit (MCU) can be combined with the high-speed service signals at the transmitter by using pilot-tone modulation. Here, WDM technology is applied as an optical transport layer to save fibers between AAU and DU. It is noted that the semi-active WDM architecture and OAM detection scheme are mainly concerned rather than the type of WDM technologies in this paper. Then, the high-speed optical signals centered at different wavelengths after pilot-tone modulation are multiplexed by a passive WDM multiplexer and launched into an optical fiber link.

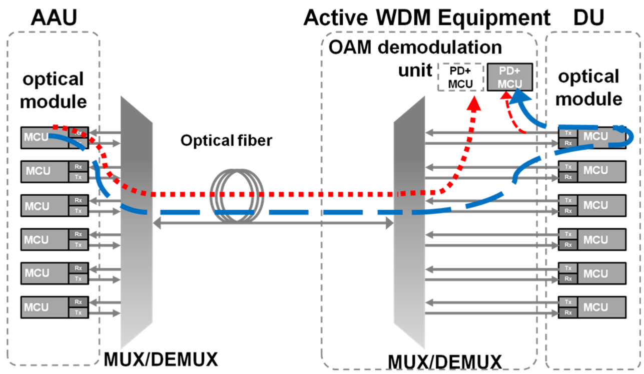

FIGURE 1. Architecture of semi-active WDM system based on pilot-tone relay detection.

At DU side, the combined signals are demultiplexed by a WDM demultiplexer in the WDM equipment. To obtain OAM information of AAU optical modules, a small part of the demultiplexed optical signal can be firstly extracted by an optical splitter and subsequently sent into an OAM demodulation unit, as shown in the red dash-line of Fig. 1, which can be presented as the conventional method. In the process of OAM demodulation, a PD is used to transfer the optical signal to electrical signal and a MCU is applied to detect the low-speed OAM electrical signal. The link penalty of the pilot-tone OAM signal in the upstream direction can be expressed as

$$Penalty_{\text{upstream in conventional method}} = IL_{\text{MUX}} + IL_{\text{DEMUX}} + Loss_{\text{fiber}} + Loss_{\text{connector}} + Loss_{\text{splitter}} \quad (1)$$

where IL_{MUX} and IL_{DEMUX} are the insertion loss of the WDM multiplexer and demultiplexer, respectively; $Loss_{\text{fiber}}$ is the loss of optical fiber; $Loss_{\text{connector}}$ is the total loss of the connectors in the link; $Loss_{\text{splitter}}$ is the loss of the optical splitter. For 12-channel 25-Gbps eCPRI WDM signals combined with the low-speed pilot-tone OAM signals over 10 km, assuming that the sum of 12-channel IL_{MUX} and IL_{DEMUX} is about 6 dB, the10-km $Loss_{\text{fiber}}$ is 3.5 dB, the $Loss_{\text{connector}}$ is 2 dB with 4 connectors, and the $Loss_{\text{splitter}}$ is 20 dB with 1% optical signal extracted by the optical splitter and launched into the OAM demodulation unit. For the splitter ratio, there is a compromise between the extracted signals for OAM demodulation and the pass-through 25-Gbps eCPRI signals to DU. The power of the extracted signals can be significantly improved by increasing the splitter ratio, but the corresponding penalty of the pass-through signals would be sharply deteriorated. In this way, the total link penalty with 10-km transmission and splitter is about 31.5 dB. To simplify the analysis, the splice loss and dispersion penalty are not considered. It means that with 1-dBm output power of optical modules in AAU, the receiving power before OAM demodulation unit would be lower than −30.5 dB, resulting high requirements for pilot-tone OAM demodulation.

In the downstream direction, a low-speed OAM frame combined with the high-speed service signals is emitted from the optical modules of the DU and then sent into the active WDM equipment at DU side. Here, another optical splitter and OAM demodulation unit are used to demodulate the low-speed pilot-tone signals. Thus, the link penalty of the pilot-tone OAM signal in the downstream direction can be described as

$$Penalty_{\text{downstream}} = Loss_{\text{fiber}} + Loss_{\text{splitter}} \tag{2}$$

where $Loss_{\text{ splitter}}$ is the loss of the optical splitter; $Loss_{\text{ fiber}}$ is the loss of the optical fiber between the DU and the active WDM equipment at DU side. As the DU and the active WDM equipment are deployed in same machine room, the $Loss_{\text{ fiber}}$ can be neglectable. In this way, the total link penalty is about 20 dB with 1% splitter ratio. As the output power of optical modules in DU is 1 dBm, the receiving power before OAM demodulation unit of the active WDM equipment is about −19 dB. It can be seen that the link penalty and receiving power of the pilot-tone OAM signal in the downstream direction are both much lower than that in the upstream direction.

Based on above analysis, pilot-tone relay detection scheme is proposed in this paper. In the upstream direction, the low-speed pilot-tone OAM signals combined with the 25-Gbps eCPRI WDM signals after the WDM demultiplexer of the active WDM equipment are directly pass-through to DU, as shown in the blue dash-line of Fig. 1. In the optical modules of the DU, the combined optical signals are transferred to electrical signal by PD and the low-speed OAM electrical signal is then detected by the MCU of the optical module. After OAM frame demodulation, the received OAM information from AAU is subsequently reframed and modulated onto the 25-Gbps eCPRI WDM signals in the downstream direction. In this pilot-tone relay detection scheme, the OAM information from AAU and DU should be alternately modulated and transmitted in the optical modules of the DU for the downstream direction. To avoid confusing the OAM process, one bit of the OAM frame is used as the flag bit to represent the original source of the OAM information. For example, the value of the flag bit will be registered as 1 to represent the OAM information from AAU while the value will be written as 0 for the OAM information from DU. Figure 2 shows the state diagram of pilot-tone relay detection. Therefore, the link penalty of the pilot-tone OAM signal in the upstream direction can be improved as

$$\begin{aligned} Penalty_{\text{upstream in pilot-tone relay method}} &= IL_{\text{MUX}} + IL_{\text{DEMUX}} \\ &\quad + Loss_{\text{fiber}} + Loss_{\text{connector}} \end{aligned} \tag{3}$$

With the assumed parameters above, the total link penalty in upstream direction with 10-km transmission is about 11.5 dB.

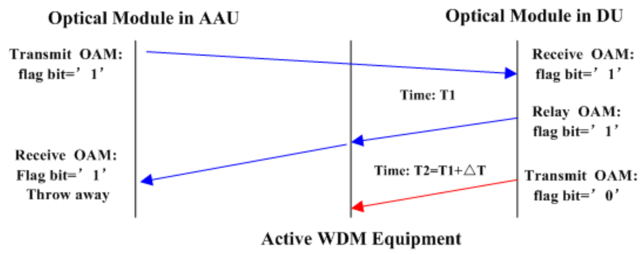

FIGURE 2. State diagram of pilot-tone relay detection.

Compared with the OAM demodulation both in upstream and downstream direction for the active WDM equipment, the sensitivity requirement of OAM demodulation can be improved from −30.5 dB to −19 dB by using pilot-tone relay detection. Additionally, the number of optical splitter and OAM demodulation unit including PD and MCU is also correspondingly reduced by 50% with an obviously improvement of system cost.

Thanks to the semi-active WDM system, the working status and information of the WDM optical modules in AAU/DU could be low-cost on-line managed and monitored. With the analysis of the pilot-tone OAM information, the fault points could be displayed in real time without changing the wireless AAU and DU equipment, such as optical module, branch fiber, trunk fiber, etc., which is benefit to the management of front-haul transport network. The OAM messages from the WDM equipment to AAU/DU can be further considered in future to perform control functions of AAU/DU modules by adding optical transceivers in the WDM equipment. However, the system cost would be correspondingly increased.

III. EXPERIMENTAL RESULTS

Corresponding experiments are performed to demonstrate the performance of the proposed semi-active WDM System. Here, 12-channel bidirectional WDM centered from 1267.5 nm to 1374.5 nm is applied as an example of the physical layer. 25-Gbps eCPRI wireless services are transformed from electrical signals to optical signals in the WDM optical modules of the AAU and DU. The 25G direct modulation laser (DML)-based transmitter and PIN-based receiver are used. The 25-Gbps eCPRI signals are generated and detected by a service analyzer. 1024-bps OAM signals are modulated onto the 25-Gbps signals simultaneously in the transceivers. The modulated optical signals at different central wavelengths are then multiplexed by a thin film filter (TFF)-based WDM multiplexer and launched into a 10-km G.652.D fiber. The split ratio of the optical splitter in the active WDM equipment is about 99:1. In this way, only 1% optical signals are extracted and detected while other 99% signals are pass-through.

The effect of the pilot-tone modulation on the performance of the 25-Gbps optical signal is firstly verified. As the low-speed OAM modulation is turned off, the sensitivities of the 25-Gbps optical signals in the receivers centered at

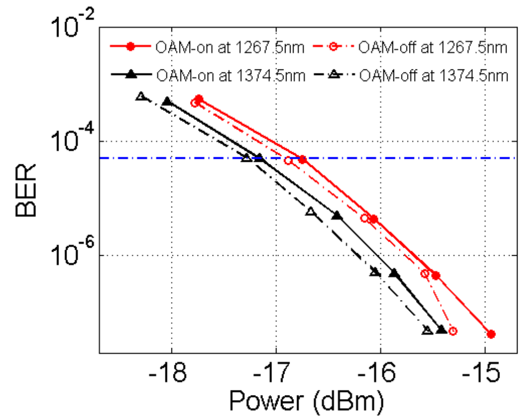

FIGURE 3. Receiving sensitivities at 1267.5 nm and 1374.5 nm as the pilot-tone OAM modulation are turned on and turned off, respectively.

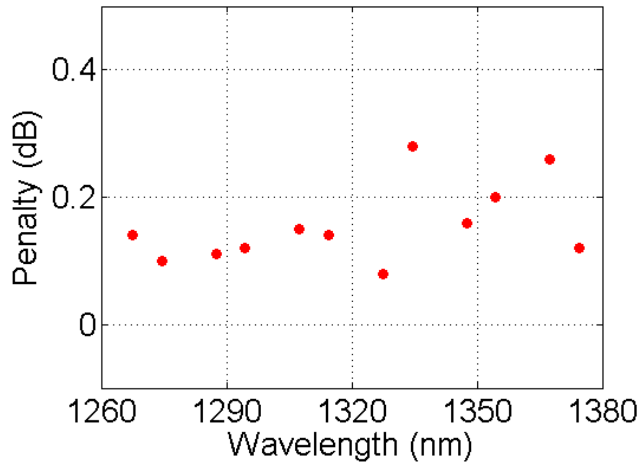

FIGURE 5. Penalty of the pilot-tone modulation for the 12-channel WDM signals.

1267.5 nm and 1374.5 nm with a bit error ratio (BER) of $5e^{-5}$ are −16.89 dBm and −17.28 dBm, respectively, which are shown in Fig. 3. It also can be seen that the corresponding sensitivities of the 25-Gbps signals combined with the 1024-bps pilot-tone OAM frame are slightly deteriorated to −16.75 dBm and −17.16 dBm, respectively.

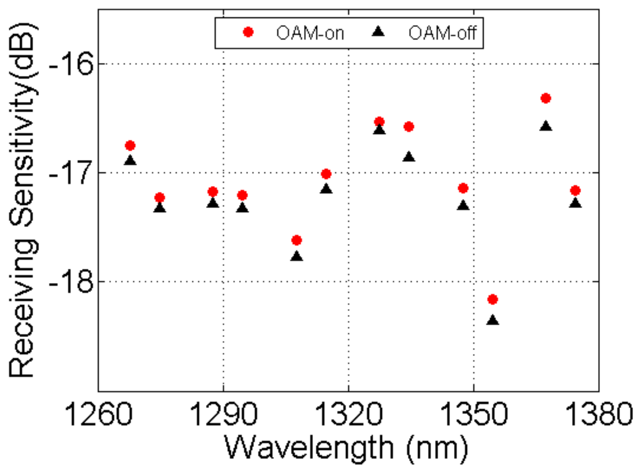

FIGURE 4. Receiving sensitivities of the 12-channel WDM signals as the pilot-tone OAM modulation are turned on and turned off, respectively.

Figure 4 shows the receiving sensitivities of the 25-Gbps 12-channel WDM optical signals as the pilot-tone OAM modulation are turned on and turned off, respectively. It can be seen that the two curves are almost overlapped. With the low modulation depth of about 4 %, the penalties introduced by pilot-tone modulation are all lower than 0.3 dB, which are shown in Fig. 5, demonstrating the practicability of pilot-tone scheme. It is noted that there is a compromise between the cost and the performance. As front-haul network is sensitive to system cost, the feasibility of the proposed semi-active scheme is firstly demonstrated based on low-cost existing elements. The physical specification of the pilot-tone such as pilot-tone frequency, modulation format and combine method are 2 KHz, ASK, and electrically method, respectively. Here, with the low frequency of 2 KHz and the simplest modulation format of ASK for pilot-tone, the existing MCU in SFP28 optical modules can be reused to generate and demodulate the pilot-tone signals in electrical domain. The Pilot-tone generation and modulation on 25GE eCPRI signals in electrical domain by adjusting the bias and driving signals of laser is a promising way for reusing the existing key components of SFP28 modules. Furthermore, the pilot-tone frequency can be significantly increased to 100 MHz, other modulation format such as FSK can be applied, and the modulation depth can be further decreased to 1% if the existing MCU is replaced by other high performance MCUs as the system cost would be correspondingly increased.

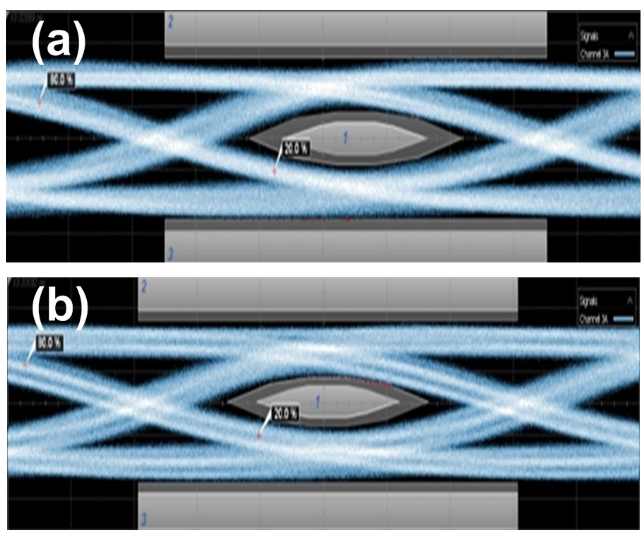

FIGURE 6. Eye-diagrams of turning on pilot-tone OAM modulation at (a) 1267.5 nm and (b) 1374.5 nm, respectively.

The high quality of the 25-Gbps signals combined with the 1024-bps OAM frame is further demonstrated. Figure 6 shows the eye-diagrams of turning on pilot-tone at 1267.5 nm

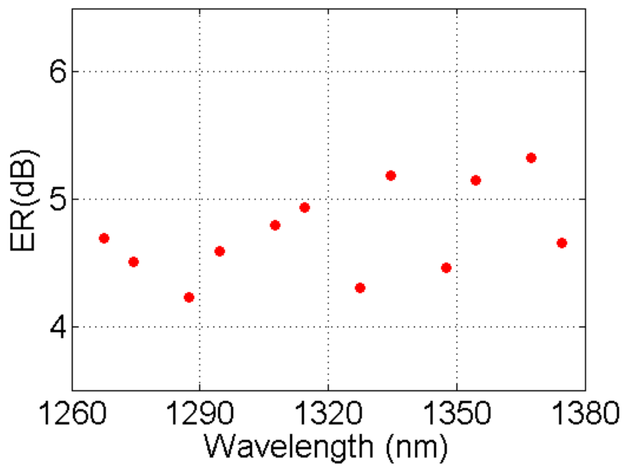

FIGURE 7. ER of the 12-channel WDM signals with the pilot-tone modulation.

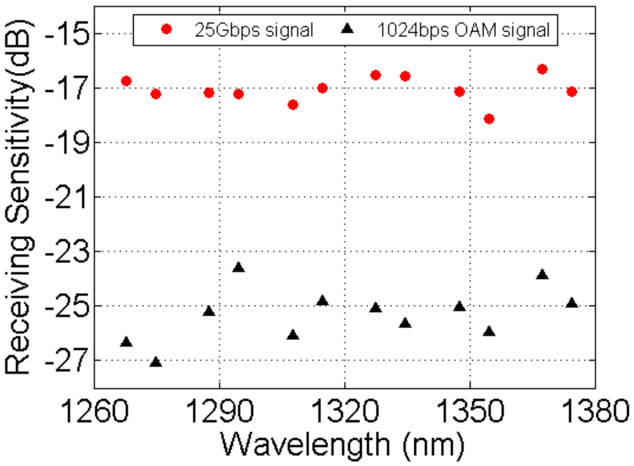

FIGURE 8. Sensitivities of the 1024-bps OAM signals and 25-Gbps WDM signals over 12 channels.

and 1374.5 nm, respectively. The extinction ratios (ERs) of the 12-channel WDM signals with pilot-tone modulation are all above 4.2 dB, which are shown in Fig. 7. The results show that the ERs of the 25-Gbps signals by turning on pilot-tone modulation can well satisfy the IEEE standards of an ER of 3.5 dB.

24-hour real-time online test is subsequently carried out. Error-free transmission of the 12-channel 25-Gbps eCPRI WDM signals combined with the 1024-bps pilot-tone OAM frame over 10 km is performed, demonstrating the stability of the proposed semi-active system based on pilot-tone relay detection.

The sensitivities of the pilot-tone signals are finally investigated. The 1024-bps OAM frames of the WDM optical modules in AAU and DU can be correctly received and detected as the receiving power of the optical module is lower than −23 dBm, meanwhile, severely bit errors of the 25-Gbps WDM signals are observed as the receiving power is lower than −16 dBm, which are shown in Fig. 8. The key information of optical modules extracted from OAM fame are shown in Table 1, including temperature, transmitting optical power, receiving optical power, etc. The results show that the pilot-tone OAM frame is more robust to the optical link budget, indicating that the proposed semi-active WDM system based on pilot-tone relay detection can management and monitoring the 5G C-RAN front-haul transport network even if the performance of the optical link is severely deteriorated.

TABLE 1. key information of optical modules extracted from OAM fame.

Item	Value	Unit
Temperature	-40 ~ +85	°C
Voltage	2.97 ~ 3.63	V
Transmitting Optical Power	2~7	dBm
Receiving Optical Power	≤ -13	dBm
Nominal Central Wavelength	1267.5 ~ 1374.5	nm
Nominal Transmission Rate	25	Gbps

IV. CONCLUSION

A semi-active WDM architecture for 5G C-RAN front-haul network is performed experimentally. With the proposed pilot-tone relay detection method, the active WDM equipment can on-line manage and monitor the performance of the WDM optical modules and optical fiber link by using only downstream OAM demodulation unit. By adjusting the modulation depth of the 1024-bps OAM signal, the penalties induced by pilot-tone modulation for 25-Gbps eCPRI signals at all WDM wavelengths are lower than 0.3 dB. In addition, the robust of the sensitivities of the pilot-tone signals is demonstrated. The results show that the semi-active system can satisfy the management and operation requirements of the 5G C-RAN front-haul network.

REFERENCES

[1] I. Chih-Lin, H. Li, J. Korhonen, J. Huang, and L. Han, "RAN revolution with NGFI (xhaul) for 5G," *J. Lightw. Technol.*, vol. 36, no. 2, pp. 541–550, Jan. 15, 2018.
[2] J. Bartelt, P. Rost, D. Wubben, J. Lessmann, B. Melis, and G. Fettweis, "Fronthaul and backhaul requirements of flexibly centralized radio access networks," *IEEE Wireless Commun.*, vol. 22, no. 5, pp. 105–111, Oct. 2015.
[3] G. O. Pérez, J. A. Hernández, and D. Larrabeiti, "Fronthaul network modeling and dimensioning meeting ultra-low latency requirements for 5G," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 10, no. 6, pp. 573–581, Jun. 2018.
[4] M. Tohidi, H. Bakhshi, and S. Parsaeefard, "Flexible function splitting and resource allocation in C-RAN for delay critical applications," *IEEE Access*, vol. 8, pp. 26150–26161, 2020.
[5] M. Masoudi, "Green mobile networks for 5G and beyond," *IEEE Access*, vol. 7, pp. 107270–107299, 2019.
[6] K. Zeb, X. Zhang, and Z. Lu, "High capacity mode division multiplexing based MIMO enabled all-optical analog millimeter-wave over fiber fronthaul architecture for 5G and beyond," *IEEE Access*, vol. 7, pp. 89522–89533, 2019.
[7] A. Udalcovs, M. Levantesi, P. Urban, D. A. A. Mello, R. Gaudino, O. Ozolins, and P. Monti, "Total cost of ownership of digital vs. Analog radio-over-fiber architectures for 5G fronthauling," *IEEE Access*, vol. 8, pp. 223562–223573, 2020.
[8] J. Zou, S. Adrian Sasu, M. Lawin, A. Dochhan, J.-P. Elbers, and M. Eiselt, "Advanced optical access technologies for next-generation (5G) mobile networks [invited]," *J. Opt. Commun. Netw.*, vol. 12, no. 10, p. D86, 2020.
[9] P. Assimakopoulos, M. K. Al-Hares, and N. J. Gomes, "Switched Ethernet fronthaul architecture for cloud-radio access networks," *J. Opt. Commun. Netw.*, vol. 8, no. 12, p. B135, 2016.

[10] J. Zou, C. Wagner, and M. Eiselt, "Optical fronthauling for 5G mobile: A perspective of passive metro WDM technology," in *Proc. Opt. Fiber Commun. Conf.*, Los Angeles, CA, USA, 2017, pp. 1–3.

[11] H. Yu, J. Zhang, Y. Ji, and M. Tornatore, "Energy-efficient dynamic lightpath adjustment in a decomposed AWGR-based passive WDM fronthaul," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 10, no. 9, pp. 749–759, Sep. 2018.

[12] Y. Ma, X. Huo, J. Li, X. Wang, and J. Yu, "Optical solutions for fronthaul application (invited)," in *Proc. 14th Int. Conf. Opt. Commun. Netw. (ICOCN)*, Nanjing, China, Jul. 2015, pp. 1–3.

[13] Z. Tayq, P. Chanclou, T. Diallo, K. Grzybowski, F. Saliou, S. Gosselin, O. Foucault, C. Aupetit, L. Bellot, T. Boukour, J. C. Plumecoq, and J. Sayed, "Performance demonstration of fiber and wireless fronthaul combination with remote powering," in *Proc. Opt. Fiber Commun. Conf.*, Anaheim, CA, USA, 2016, pp. 1–3.

[14] K. Honda, T. Kobayashi, S. Nishihara, T. Shimada, J. Terada, and A. Otaka, "Experimental analysis of LTE signals in WDM-PON managed by embedded pilot tone," *IEEE Photon. Technol. Lett.*, vol. 29, no. 5, pp. 431–434, Mar. 1, 2017.

[15] S. Pachnicke, J. Zhu, M. Lawin, M. H. Eiselt, S. Mayne, B. Quemeneur, D. Sayles, H. Schwuchow, A. Wonfor, P. Marx, M. Fellhofer, P. Neuber, M. Dietrich, M. J. Wale, R. V. Penty, I. H. White, and J.-P. Elbers, "Tunable WDM-PON system with centralized wavelength control," *J. Lightw. Technol.*, vol. 34, no. 2, pp. 812–818, Jan. 15, 2016.

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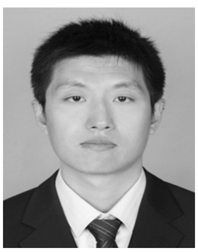

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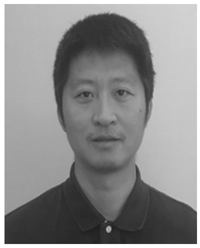

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