ELKOMIKA: Jurnal Teknik Energi Elektrik, Teknik Telekomunikasi, & Teknik Elektronika

ISSN(p): 2338-8323 | ISSN(e): 2459-9638 | Vol. 11 | No. 3 | Halaman 759 - 768
DOI: http://dx.doi.org/10.26760/elkomika.v11i3.759 Juli 2023

Quality Improvement on RoF 5G Fronthaul System Design at Millimeter-wave with EDFA and FBG Techniques

CATUR APRIONO[1], SALSABILA SHITA PUTRI NUGROHO[1], YUS NATALI[2]

[1]Department of Electrical Engineering, Universitas Indonesia, Indonesia
[2]Telecommunication Engineering Program, Telkom University, Jakarta, Indonesia
Email: catur@eng.ui.ac.id

Received 5 Juni 2023 **|** *Revised* 19 Juni 2023 **|** *Accepted* 2 Juli 2023

ABSTRAK

Jaringan seluler terkini membutuhkan kapasitas tinggi dan latensi rendah di fronthaul yang dapat didukung oleh radio over fiber (RoF) dengan gelombang milimeter. Namun, dispersi merupakan salah satu masalah dalam menjaga kualitas transmisi. Penelitian ini mempelajari komponen EDFA dan FBG untuk meningkatkan kinerja transmisi pada sistem RoF gelombang milimeter menggunakan Optisystem for 5G fronthaul dengan mempertimbangkan faktor Q dan Bit Error Rate (BER). EDFA meningkatkan kinerja dengan kecepatan bit puncak 16 Gbps untuk 1 km, yang memenuhi standar fronthaul D-RAN. Peningkatan peningkatan menggunakan FBG untuk bit rate 16 Gbps memberikan kinerja yang lebih baik mulai dari jarak 4 km hingga 97,99 persen dibandingkan dengan konfigurasi tanpa FBG. Hal ini menunjukkan bahwa dispersi mempengaruhi kinerja sistem lebih dari redaman dilihat dari rata-rata perbedaan BER sebesar 6.6280e-04 ketika FBG ditambahkan dengan EDFA. Penelitian ini menunjukkan dua teknik telah meningkatkan kinerja sistem.

Kata kunci*: fiber, RoF, millimeter, fronthaul*

ABSTRACT

Advanced cellular networks need high capacity and low latency in fronthaul that can be supported by radio over fiber (RoF) with millimeter waves. However, dispersion is one problem in maintaining transmission quality. This research studies EDFA and FBG components to increase transmission performance in a millimeter wave-RoF system using Optisystem for 5G fronthaul by considering the Q factor and the Bit Error Rate (BER). EDFA improves performance with a 16 Gbps peak bit rate for 1 km, which meets D-RAN fronthaul standards. Improvement increase using FBG for a bit rate of 16 Gbps provided better performances starting from a distance of 4 km, up to 97.99 percent, compared to configurations without FBG. It shows that the dispersion influences the system performance more than the attenuation seen from the BER discrepancy average of 6.6280e-04 when the FBG is added with EDFA. This research indicates two techniques have improved the system's performance.

Keywords*: fiber, RoF, millimeter, fronthaul*

1. INTRODUCTION

Digital transformation has opened various opportunities and challenges in all sectors, including communication and data transmission. Using mobile phones not only for communication but already many services have been provided that must be conducted in a fixed and continued to become mobile, such as banking, commerce, transportation, education, entertainment, etc. Nowadays, those features mostly rely on the internet connection to cellular networks. It impacts the increasing demand for cellular networks to provide reliable mobile and broadband connection services **(Erunkulu et al., 2021)**. This condition is also driven by developments of mobile applications needing more bandwidth by applying more multimedia information that has been entering various daily activities **(Weichbroth, 2020)**.

Cellular technology has transformed from the first generation (1G) to the 5th generation (5G) since the 2020s **(Eluwole et al., 2018)**. The main purpose is to provide a reliable connection, more bandwidth, and low latency **(del Peral-Rosado et al., 2017)**. One use case of 5G, enhanced Mobile Broadband (eMBB), is anticipated to support the demand for broadband access with bandwidth up to gigabits per second with tolerable latency in a few milliseconds **(Anand et al., 2020)**. Another use case of massive machine-type communication (mMTC) offers scalability on the access of massive sensors that support the Internet of Things (IoT) **(Pokhrel et al., 2020a)**. Meanwhile, the other one-use case of ultra-reliable and low-latency communication (URLLC) intends for applications that need very low latency or very fast response applications **(Pokhrel et al., 2020b)**. This condition requires reliable infrastructure support, including transmission link connectivity to the tower, also known as fronthaul, that can either a fix or mobile cellular networks **(Kani et al., 2017)**. The transformation from 4G to 5G in terms of capacity, expected to reach up to 20 Gbps for downlink peak data rates, has also attracted attention to the behind link of a tower of its fronthaul network to comply with the access capabilities to users **(Valcarenghi et al., 2016)**. It is important to anticipate huge data transmission from aggregate traffic from all access users.

The transmission link to the tower capacity should comply with the network specifications. As the legacy link to the tower, advanced techniques have transformed coaxial cables to maintain their usefulness and compliance with existing network components **(Acatauassu et al., 2021)**. This strategy can avoid more cost than providing a new transmission link. Another promising transmission type is a link based on optical fiber that offers high bandwidth, robustness to electromagnetic interference, and low latency **(Gangwar & Sharma, 2012)**. For cellular applications, it is potential for improved performance by applying wavelength-dense multiplexing and radio over fiber (RoF) with millimeter wave **(Pandey et al., 2021; Raddo et al., 2019; Rommel et al., 2019, 2020)**

The speed and high radio frequencies of radio over fiber with millimeter wave to develop a transmission link has offered milestones in high data transmission rates **(Li et al., 2020)**. However, the previous research showed that the received power level is still above the sensitivity of optical detectors with the determined length applications of 5G fronthaul purposes; therefore, the data quality should be improved to comply with 5G standards **(Nugroho et al., 2022)**. This condition comes from the high data rates that impact higher dispersion factors. It is critical when developing a very high-speed data transmission that indicates a shorter pulse also means a very short rise period.

Based on the theoretical basis, the data quality in the bit error rate (BER) parameter can be improved by providing higher power in the signal-to-noise ratio (SNR) parameter. BER also can indicate data transmission's success, which is also related to the rise time. This condition implicitly indicates that optimizing the signal power can improve the data transmission performance. In fiber optic link, Erbium Doped Fiber Amplifier (EDFA) is the widely used optical amplifier that consists of three pumping techniques: forward, backward, or a combination of the two, called bidirectional pumping **(Hui & O'Sullivan, 2022)**. The laser pump on the EDFA can have a wavelength of 980 or 1480 nm **(Malakzadeh et al., 2020)**. EDFA is applied as an amplifier in a fiber optic system by placing the EDFA at the front (preamplifier) or the end (postamplifier) of the optical fiber transmission. The combination of the two is called symmetric use.

Another factor that should be improved is the dispersion factor. Dispersion distorts the optical signal during transmission along the optical fiber, resulting in group delay, which causes pulse widening and causes Inter-Symbol-Interference (ISI) so that the bit rate and transmission distance are limited. Therefore, it is necessary to do dispersion compensation to eliminate the dispersion effect, such as with Fiber Bragg Grating **(Chomycz, 2009)**. FBG is a single-mode fiber cable optical filter or reflector that can work as a dispersion compensation technique if the dispersion parameter used is negative so that it can eliminate the dispersion that occurs from the optical fiber. Three variables should be considered in the use of single-mode fiber (SMF), which are the dispersion of SMF (DSMF), length of SMF (LSMF), and dispersion of FBG (DFBG). DSMF is the positive dispersion value of the transmission through an optical fiber. LSMF is the transmission length of the optical fiber. DFBG is the negative dispersion value of FBG.

Based on our previous research, by considering the two main factors of power and dispersion that determine the signal and data quality, this research investigates the use of EDFA and FBG components to improve the quality of data transmission in an RoF 5G Fronthaul System Design at Millimeter-wave. The considered millimeter wave at a frequency of 64 GHz is one candidate for 5G applications **(Al-Falahy & Alani, 2017)**. Performances of the system are simulated using Optisystem and evaluated in terms of BER and Q factor parameters, then compared with the International Telecommunication Union (ITU) standard.

2. RESEARCH METHODOLOGY

2.1. Expected System Specifications

Table 1 shows the expected specifications for the RoF millimeter-wave system based on the ITU-T G.9803, 2019 International Telecommunication Union (ITU) standard. It expects the Q factor to be greater than 6 or the BER to be less than 10^{-9}. For the downstream scenario, the optical wavelength is 1550 nm, while for the upstream scenario, the optical wavelength is 1510 nm. To meet the specifications for 5G enhanced mobile broadband (eMBB) service technology, the maximum bit rate parameter for the downstream scenario is 20 Gbps. In contrast, for the upstream scenario, it is 5 to 10 Gbps **(Lashgari et al., 2022).** The distance from the radio to the fiber system to match the 5G fronthaul network for centralized RAN is 10 km or more, while for distributed RAN, it is less than 10 km.

Table 1. Target Specifications

Parameter	Value
Q Factor	>6
BER	$<10^{-9}$
Optic Wavelength	Downstream: 1550 nm Upstream: 1510 nm
Bit rate	Downstream: peak 20 Gbps Upstream: peak 5-10 Gbps
Fiber Length	C-RAN: ≥ 10 km D-RAN: < 10 km (short range)

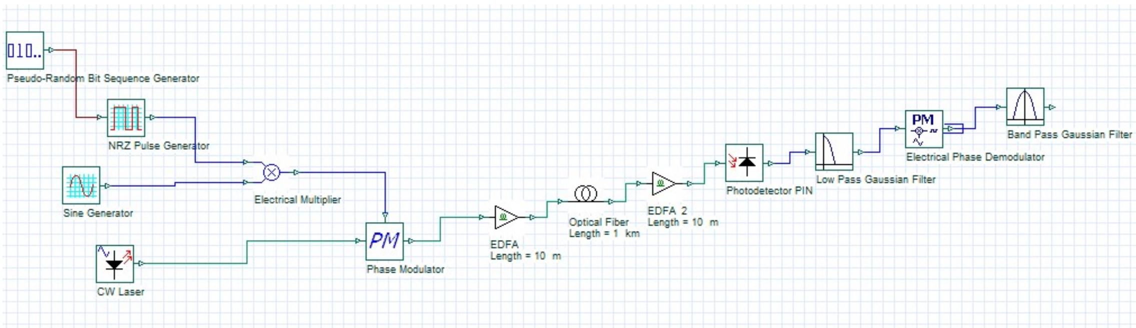

Figure 1. System schematic design with EDFA

2.2 Schematic Design with EDFA

Figure 1 shows a circuit schematic for a millimeter wave-based radio over fiber system with the addition of an EDFA Preamplifier and Post-Amplifier. EDFA Preamplifier is added to the section before signal transmission via optical fiber, while EDFA Post-Amplifier is added to the section after signal transmission via fiber optic. The goal is to increase performance by pumping power. For pumping techniques, either forward, backward, or bidirectional, 500 mW of power is used with a wavelength of 1480 nm.

2.3 Schematic Design with Dispersion Compensation FBG

Figure 2 shows a circuit schematic of a millimeter wave-based radio over fiber system with the addition of Fiber Bragg Grating dispersion compensation. The FBG component is added to the section after signal transmission via optical fiber. The purpose of adding this component is to improve performance by compensating for dispersion due to the transmission of fiber optic cables. The dispersion parameter of the FBG component is negative to compensate for the dispersion of the fiber optic cable, which is 16.75 ps/nm for every 1 km.

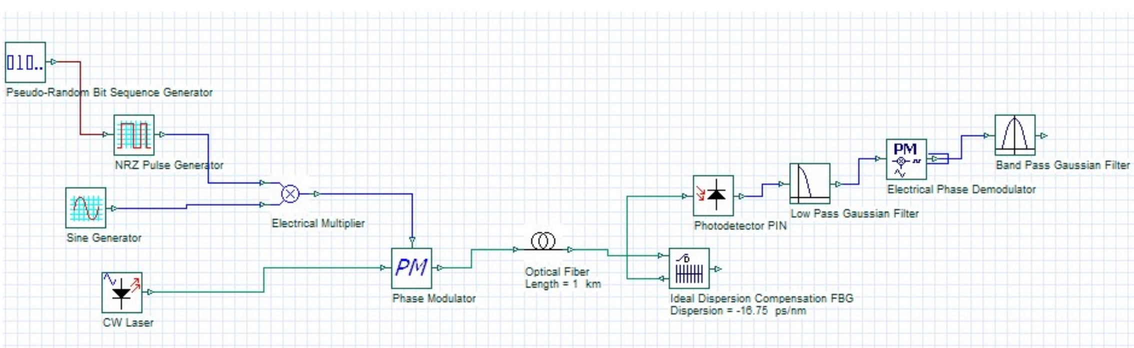

Figure 2. Schematic Design with Dispersion Compensation of FBG

3. RESULTS AND DISCUSSION

3.1 System with EDFA

This research considers the addition of EDFA aims to improve circuit performance for the downstream system scheme because the downstream has a higher data rate requirement than the downstream. The higher data rate is more suffer to decrease than the lower. Simulations were carried out by adding an EDFA Preamplifier, Post-Amplifier, and a combination of both with forward, backward and bidirectional pumping methods. This discussion presents the best results from all scenarios of adding EDFA, as are EDFA Preamplifier and Post-Amplifier with Bidirectional Pumping.

Figure 3 shows a graph of the Q Factor results for downstream simulations by adding EDFA Preamplifier and Post-Amplifier with Bidirectional Pumping. Data above the threshold line are considered values that meet the recommended ITU standards for RoF communication., i.e., Q Factor is more than 6. In the graph, it can also be seen that the higher the bit rate, the lower the Q Factor value. This condition occurs because of the emergence of dispersion on the shorter pulses as the bit rate increases. It causes higher intersymbol interference probability and increases the bit error rate value.

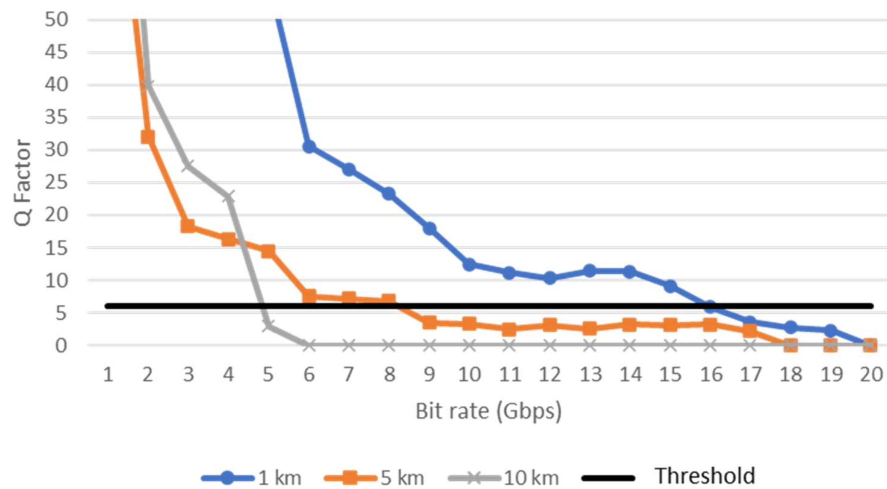

Figure 3. Q Factor results for EDFA Preamplifier and Post-Amplifier with Bidirectional Pumping Downstream

Meanwhile, three different cable lengths show different achieved data rates that comply with the minimum Q factor standard, which are 15 Gbps, 8 Gbps, and 5 Gbps for distances of 1 km, 5 km, and 10 km, respectively. These results also correspond to the received power signal detected by the optical sensors. Data transmission with further distance can be achieved if the data rate decreases simultaneously, the dispersion is higher, and the detected power decreases due to the attenuation factor.

Table 2 shows the minimum BER results for downstream simulations by adding EDFA Pre-Amplifier and Post-Amplifier with Bidirectional Pumping. The blue data in the table is considered data that is less than 10^{-9} that meet the ITU standard, while the yellow data does not meet the ITU standard. The table shows that the longer the fiber distance, the lower the maximum bit rate for data that meets ITU standards. The maximum obtained data rate is 16 Gbps at 1 km fiber length with a BER of 2.22e-09. This condition still complies with the distance of the D-RAN scenario. The maximum data rate for a fiber length of 10 km is 4 Gbps, which can meet the C-RAN distance scenario. Using the bidirectional pumping technique shows an increase in the maximum data rate compared with the previous result. However, this performance increase is insignificant, and the maximum data rate standard for the downstream 5G schemes of 20 Gbps has not been achieved.

Table 2. BER for EDFA Preamplifier and Post-Amplifier with Bidirectional Pumping Downstream

Bit Rate (Gbps)	BER Length (km) 1	5	10
1	0	0	0
2	0	0	0
3	0	9.07e-59	1.49e-147
4	8.64e-252	1.84e-41	9.50e-114
5	1.31e-208	2.22e-24	8.93e-04
6	2.42-172	4.68e-15	-
7	2.49e-129	3.38e-11	-
8	4.75e-111	5.32e-12	-
9	1.16e-57	2.88e-04	-
10	5.57e-29	8.17e-04	-
11	1.10e-22	4.59e-03	-
12	6.57e-21	1.10e-03	-
13	2.55e-21	4.32e-03	-
14	4.34e-22	6.26e-04	-
15	5.67e-19	9.15e-04	-
16	7.48e-12	7.50e-04	-
17	2.85e-05	1.47e-02	-
18	1.75e-03	-	-
19	7,80e-03	-	-
20	-	-	-

3.2 System with FBG

The previous discussion discusses the technique for increasing the Q Factor and BER parameters carried out by looking at the power side, namely by adding EDFA to add transmission signal power, have shown slight performance improvements. Therefore, a further performance parameter improvement method is carried out by looking at the dispersion side, namely the use of dispersion compensation in the circuit scheme with the addition of Fiber Bragg Grating. Simulations were carried out with a data rate of 16 Gbps starting from a distance of 1 km, which is the best condition from the previous discussion, and varying the length of the optical fiber from 1 to 10 km.

Figure 4 shows the maximum Q Factor results for downstream simulations using the FBG dispersion compensation technique. The line for the data result using EDFA tends to intersect with the line for the data result without EDFA, meaning EDFA did not significantly increase the system performance below the Q factor threshold. The Q factor decreases until it drops to zero at 6 km as the fiber length increase. The higher number is shown using FBG and FBG+EDFA than without FBG since 4 km. Using FBG and FBG+EDFA indicates comparable results, which means that the dispersion compensation by FBG is more dominant than the power compensation by EDFA. The curve shows fluctuations that may come from nonlinearities factors of the system. A significant increase is shown in fiber lengths of 6 km and above. Namely, the parameter values are getting better than the results without FBG. Although no value meets the recommended Q factor standard for the data rate of 16 Gbps, performing dispersion compensation with the Fiber Bragg Grating technique can greatly increase the network performance.

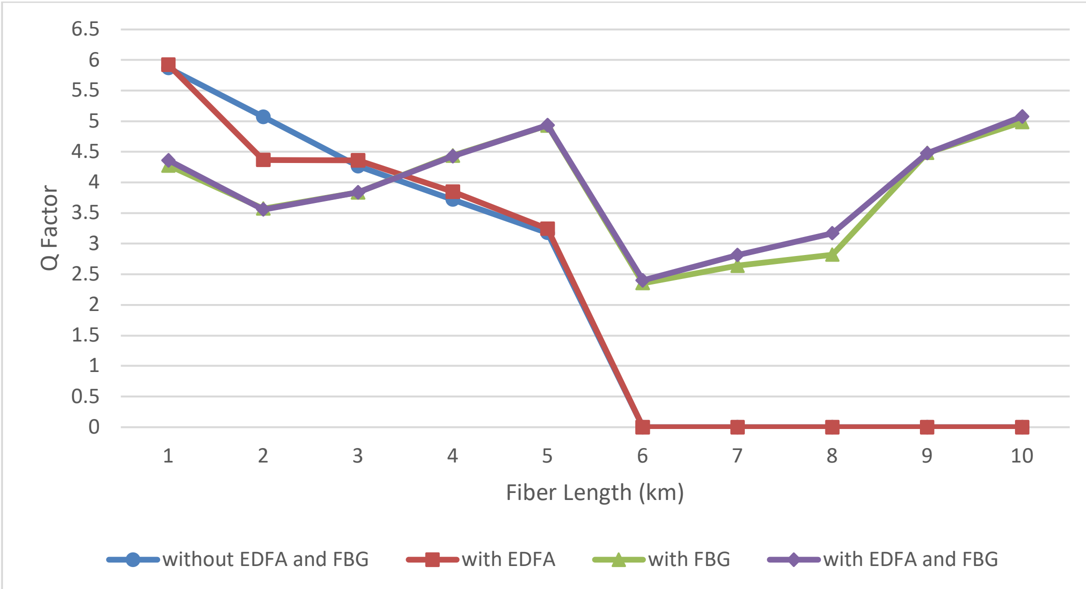

Figure 4. Q Factor for FBG Downstream

Table 3. BER for FBG Downstream

Optical Fiber Length	BER		
	Initial	**With FBG**	**With EDFA and FBG**
1	2.22e-09	8.69e-06	5.91e-06
2	2.49e-07	0.000255	0.000162
3	9.86e-06	0.000195	0.000194
4	0.000206	4.14e-06	4.4e-06
5	0.000175	3.97E-07	3.6e-07
6	-	0.008921	0.00792
7	-	0.005136	0.002198
8	-	0.002114	0.000185
9	-	3.67e-06	3.75e-06
10	-	3.01e-07	1.91e-07

Table 3 shows the BER results summary for downstream using FBG dispersion compensation with variations in optical fiber length from 1 km to 10 km and a data rate of 16 Gbps. The table compares the BER values for the initial circuit. Improvement increase using FBG for a bit rate of 16 Gbps provided better performances starting from a distance of 4 km compared to configurations without FBG, up to 97.99 percent. The table also shows an increase in performance for a series of FBG usage starting from 6 km and above; the BER value is getting better than the results without FBG. It shows that the dispersion influences the system performance more than the attenuation seen from the BER discrepancy average of 6.6280e-04 when the FBG is added with EDFA. Using dispersion compensation with the Fiber Bragg Grating technique can greatly increase system performance even though no value meets the BER threshold standard for data rates of 16 Gbps.

4. CONCLUSION

This research shows an improved millimeter wave-based Radio over Fiber 5G fronthaul system performance for downstream using EDFA to reach a maximum bit rate of 16 Gbps for 1 km fiber length that meets the D-RAN fronthaul distance standard. Improvement increase using FBG for a bit rate of 16 Gbps provided better performances starting from a distance of 4 km, up to 97.99 percent, compared to configurations without FBG. It shows that the dispersion influences the system performance more than the attenuation seen from the BER discrepancy average of 6.6280e-04 when the FBG is added with EDFA. From all results, this research indicates two techniques can improve the system's performance. However, more techniques, such as dispersion compensation fiber or other dispersion techniques, are necessary for further research to meet the recommended Q Factor and minimum BER standards for 5G Fronthaul networks.

ACKNOWLEDGMENT

Universitas Indonesia supports this research through International Indexed Publication (PUTI) Q2 Grant, 2023, number: NKB-804/UN2.RST/HKP.05.00/2023.

REFERENCES

Acatauassu, D., Licá, M., Ohashi, A., Fernandes, A. L. P., Freitas, M., Costa, J. C. W. A., Medeiros, E., Almeida, I., & Cavalcante, A. M. (2021). An Efficient Fronthaul Scheme Based on Coaxial Cables for 5G Centralized Radio Access Networks. *IEEE Transactions on Communications*, *69*(2), 1343–1357. https://doi.org/10.1109/TCOMM.2020.3039860

Al-Falahy, N., & Alani, O. Y. (2017). Technologies for 5G networks: Challenges and opportunities. *It Professional*, *19*(1), 12–20.

Anand, A., de Veciana, G., & Shakkottai, S. (2020). Joint Scheduling of URLLC and eMBB Traffic in 5G Wireless Networks. *IEEE/ACM Transactions on Networking*, *28*(2), 477–490. https://doi.org/10.1109/TNET.2020.2968373

Chomycz, B. (2009). *Planning fiber optics networks*. McGraw-Hill Education.

del Peral-Rosado, J. A., Raulefs, R., López-Salcedo, J. A., & Seco-Granados, G. (2017). Survey of cellular mobile radio localization methods: From 1G to 5G. *IEEE Communications Surveys & Tutorials*, *20*(2), 1124–1148.

Eluwole, O. T., Udoh, N., Ojo, M., Okoro, C., & Akinyoade, A. J. (2018). From 1G to 5G, what next? *IAENG International Journal of Computer Science*, *45*(3).

Erunkulu, O. O., Zungeru, A. M., Lebekwe, C. K., Mosalaosi, M., & Chuma, J. M. (2021). 5G Mobile Communication Applications: A Survey and Comparison of Use Cases. *IEEE Access*, *9*, 97251–97295. https://doi.org/10.1109/ACCESS.2021.3093213

Gangwar, A., & Sharma, B. (2012). Optical fiber: the new era of high speed communication (technology, advantages and future aspects). *International Journal of Engineering Research and Development*, *4*(2), 19–23.

Hui, R., & O'Sullivan, M. (2022). *Fiber-Optic Measurement Techniques*. Academic Press.

Kani, J., Terada, J., Suzuki, K.-I., & Otaka, A. (2017). Solutions for Future Mobile Fronthaul and Access-Network Convergence. *Journal of Lightwave Technology*, *35*(3), 527–534. https://doi.org/10.1109/JLT.2016.2608389

Lashgari, M., Tonini, F., Capacchione, M., Wosinska, L., Rigamonti, G., & Monti, P. (2022). Fiber-vs. Microwave-based 5G Transport: a Total Cost of Ownership Analysis. *European Conference and Exhibition on Optical Communication*, We1B-5.

Li, J. L., Zhao, F., & Yu, J. (2020). D-band millimeter wave generation and transmission though radio-over-fiber system. *IEEE Photonics Journal*, *12*(2), 1–8.

Malakzadeh, A., Pashaie, R., & Mansoursamaei, M. (2020). Gain and noise figure performance of an EDFA pumped at 980 nm or 1480 nm for DOFSs. *Optical and Quantum Electronics*, *52*, 1–16.

Nugroho, S. S. P., Natali, Y., & Apriono, C. (2022). Design of Millimeter-Wave based Radio over Fiber for 5G Applications. *2022 1st International Conference on Information System and Information Technology, ICISIT 2022*. https://doi.org/10.1109/ICISIT54091.2022.9872765

Pandey, G., Choudhary, A., & Dixit, A. (2021). Wavelength Division Multiplexed Radio Over Fiber Links for 5G Fronthaul Networks. *IEEE Journal on Selected Areas in Communications*, *39*(9), 2789–2803. https://doi.org/10.1109/JSAC.2021.3064654

Pokhrel, S. R., Ding, J., Park, J., Park, O.-S., & Choi, J. (2020a). Towards enabling critical mMTC: A review of URLLC within mMTC. *IEEE Access*, *8*, 131796–131813.

Pokhrel, S. R., Ding, J., Park, J., Park, O.-S., & Choi, J. (2020b). Towards Enabling Critical mMTC: A Review of URLLC Within mMTC. *IEEE Access*, *8*, 131796–131813. https://doi.org/10.1109/ACCESS.2020.3010271

Raddo, T. R., Rommel, S., Cimoli, B., & Monroy, I. T. (2019). The Optical Fiber and mmWave Wireless Convergence for 5G Fronthaul Networks. *2019 IEEE 2nd 5G World Forum (5GWF)*, (pp. 607–612). https://doi.org/10.1109/5GWF.2019.8911613

Rommel, S., Dodane, D., Grivas, E., Cimoli, B., Bourderionnet, J., Feugnet, G., Morales, A., Pikasis, E., Roeloffzen, C., van Dijk, P., Katsikis, M., Ntontin, K., Kritharidis, D., Spaleniak, I., Mitchell, P., Dubov, M., Carvalho, J. B., & Tafur Monroy, I. (2020). Towards a Scaleable 5G Fronthaul: Analog Radio-over-Fiber and Space Division Multiplexing.

Journal of Lightwave Technology, *38*(19), 5412–5422. https://doi.org/10.1109/JLT.2020.3004416

Rommel, S., Perez-Galacho, D., Fabrega, J. M., Muñoz, R., Sales, S., & Tafur Monroy, I. (2019). High-Capacity 5G Fronthaul Networks Based on Optical Space Division Multiplexing. *IEEE Transactions on Broadcasting*, *65*(2), 434–443. https://doi.org/10.1109/TBC.2019.2901412

Valcarenghi, L., Kondepu, K., Giannone, F., & Castoldi, P. (2016). Requirements for 5G fronthaul. *2016 18th International Conference on Transparent Optical Networks (ICTON)*, (pp. 1–5). https://doi.org/10.1109/ICTON.2016.7550569

Weichbroth, P. (2020). Usability of mobile applications: a systematic literature study. *IEEE Access*, *8*, 55563–55577.