Journal of Sensor Technology, 2023, 13, 13-23
https://www.scirp.org/journal/jst
ISSN Online: 2161-1238
ISSN Print: 2161-122X

Study of Radio over Fiber Transmission with a Single Line in Ring Topology for Deployment of MIMO Antenna Access Points in a Cell-less Network

Mamadou Sarr, Dialo Diop*, Ndolane Diouf, Kharouna Talla

Solids Physics and Materials Sciences Loboratory Group, Faculty of Science and Technology, Cheikh Anta Diop University, Dakar, Senegal
Email: *dialo.diop.ucad@gmail.com

How to cite this paper: Sarr, M., Diop, D., Diouf, N. and Talla, K. (2023) Study of Radio over Fiber Transmission with a Single Line in Ring Topology for Deployment of MIMO Antenna Access Points in a Cell-less Network. *Journal of Sensor Technology*, **13**, 13-23.
https://doi.org/10.4236/jst.2023.132002

Received: May 7, 2023
Accepted: June 12, 2023
Published: June 15, 2023

Abstract

The massive growth of wireless traffic goes hand in hand with the deployment of advanced radio interfaces as well as network densification. This growth has a direct impact on the radio access architecture, which today is moving from centralized to distributed deployments through the use of a large number of access points (APs). This paper verifies the feasibility of deploying multiple APs in series on a single line in a ring topology in a cell-less network. On the one hand, this technique will further improve the communication capacity and flexibility of a Radio-over-Fiber (RoF) based mobile communication system and will reduce its construction cost. And on the other hand, this deployment topology is a solution to achieve a massive cell-free Multiple-Input Multiple-Output (MIMO) architecture and a cost-effective fronthaul solution. First, a passive optical add/drop multiplexer (OADM) is used to extract and add downlink and uplink signals from the remote access points of one kilometer. Then, a deployment model is developed with version 17 Optisystem software. The results obtained showed that the quadrature amplitude modulation (QAM) does not adapt to this multi-carrier transmission to deploy several AP in series on a single line. Thus, the performance degradation increases when the number of APs integrated on the line increases.

Keywords

RoF, Ring Topology, MIMO Antennas, Cell-less Network

1. Introduction

Wireless networks are moving away from the cell-centric paradigm, which is constrained by inter-cell interference, to the ubiquitous cell-free massive MIMO that is coherent and user-centric [1]. Radio access networks are undergoing a profound transformation by distributing access points close to end users and interconnecting them with a central processing unit (CPU). Access points are connected via front-end connections to the CPU which is responsible for coordination. The CPU receives the cumulative signals from its radio bands on the front haul and decodes them. This data will then be transmitted to the core network via the backhaul and vice versa [2]. With a large number of access points scattered throughout the expected coverage area, it is obvious that the fronthaul/backhaul burden for cell-free networks will be much heavier than that of traditional cellular systems except in the case of serial connections can be used [3].

Thus, this work studies the feasibility of deploying multiple access points on a single line in a ring topology. Indeed, it consists in deploying from the CPU, four access points on a line in a ring topology and evaluating the signal qualities of each access point. The OADM used allows the extraction of the upstream signals and adding the downstream ones of each access point integrated on the line. The remainder of this paper is organized as follows: First, the first section describes the related work, then Section 2 demonstrates the experimental deployment setup and finally, Section 3 presents results and discussion.

2. Related

A well-known Radio-over-Fiber (RoF) approach combines optical fiber and wireless communication to effectively solve the limited coverage of millimeter wave (MMW) signals. It is considered the most promising concept for this massive cell-free MIMO network [4]. To achieve a scalable massive cell-free MIMO architecture and a cost-effective fronthaul solution, Guenach *et al.* [1] consider a point-to-multipoint deployment topology where access points share a serial link. However, this tree topology causes all access points to be interrupted when switches are disconnected from the CPU. To overcome these difficulties, ring topologies are proposed as the best and most economical choice [4]. The performance of a ring network topology is studied in [5] with 13 × 15 Gbit/s channels at 30 nodes with 90 users without using dispersion-compensated fiber in the presence of an erbium-doped fiber amplifier. To reduce installation cost and wavelength reuse, Wang *et al.* [6] proposes a full-duplex fiber radio system to provide both millimeter-wave signal generation with tunable frequency multiplication factors (FMFs) and wavelength reuse for uplink data so the base station can be simplified. Pires *et al.* [7] propose the design of bidirectional 2-fiber wavelength division multiplexing (WDM) rings with optical multiplexer section protection (OMSP) to reduce the significant cost compared to the 4-fiber configuration. This led Tran *et al.* [8], to propose and demonstrate a new bidirectional optical multiplexer (BOADM) based on two six-port OCs, a single unidirectional amplifier (UOA) to achieve a bidirectional gain of more than 13 dB, and two sets of FBGs (FBG 1 and FBG 2.) For simplifying BOADM, a single-line passive insertion/extraction bidirectional optical multiplexer (SBOADM) is proposed and developed by Chang *et al.* [9] to properly accomplish a self-healing functionality in a single WDM-PON ring. Based on two FBGs and 4 three-port optical circulators (OCs), the proposed SBOADMs can remove a dedicated lightwave from the main fiber whether it is transmitted in the forward or reverse direction of the ring and can add and redirect an upstream lightwave to the central office (CO) along the reverse transmission direction of the downstream lightwave. In 2018 Chang *et al.* [10] proposed a novel SBOADM to develop a fully passive fiber optic sensor network with self-healing functionality based on two identified FBGs, two three-port optical circulators (OCs), and three four-port OCs. This SBOADM extracts the target signals and leaves a residual signal power intensity of −28.6 dB in the network to be consumed completely within the RN. To further extend the application of SBOADM, Tsai *et al.* [11] propose an SBOADM based on two FBGs, two three-port CBs and three four-port CBs by a fiber link failure detection and self-healing algorithm. To improve the wavelength utilization efficiency and obtain a colorless optical network unit, Chung-Yi Li *et al.* [12] propose a full-duplex self-recovery fiber transport system based on a novel. Bidirectional transmission over a single line can be easily realized by the SBOADM without the help of a power supply and flexible operating system by using two fiber Bragg gratings (FBGs) and five optical circulators (OCs) to compose the SBOADM. In 2021, to simplify the SBOADM, Chung-Yi Li *et al.* [13] propose a new form of SBOADM based on four 4-port optical circulators (OCs) and two fiber Bragg gratings (FBGs) to achieve the above goal. A hybrid ring topology and tree-based radio over fiber (RoF) transmission system with self-disconnect protection is proposed to support the high distribution density of base stations (BSs) in a metropolitan area and enhance the network QoS through self-disconnect protection [14] [15]. Several network scenarios are analyzed in [16] to evaluate the cost savings from the flexible use of OADMs and the WDM. Cost saving is achieved at 35% compared to the scenario with fixed capacity OADMs, and up to 45% compared to the network without OADM. However, optimization remains a complex problem with the use of OADMs.

This ring topology deployment will be proven by an optisystem simulation software to deploy 4 APs in series on a single line and evaluate the signal qualities of each antenna.

3. Experimental Configuration of the Access Point Deployment Model in a Ring Topology

3.1. Topology of the Deployment Model

This section describes our entire deployment model which is schematically illustrated in **Figure 1**. The software Optisystem version 17 devaluation is used to prove the feasibility of deploying access points serially on a ring topology. The

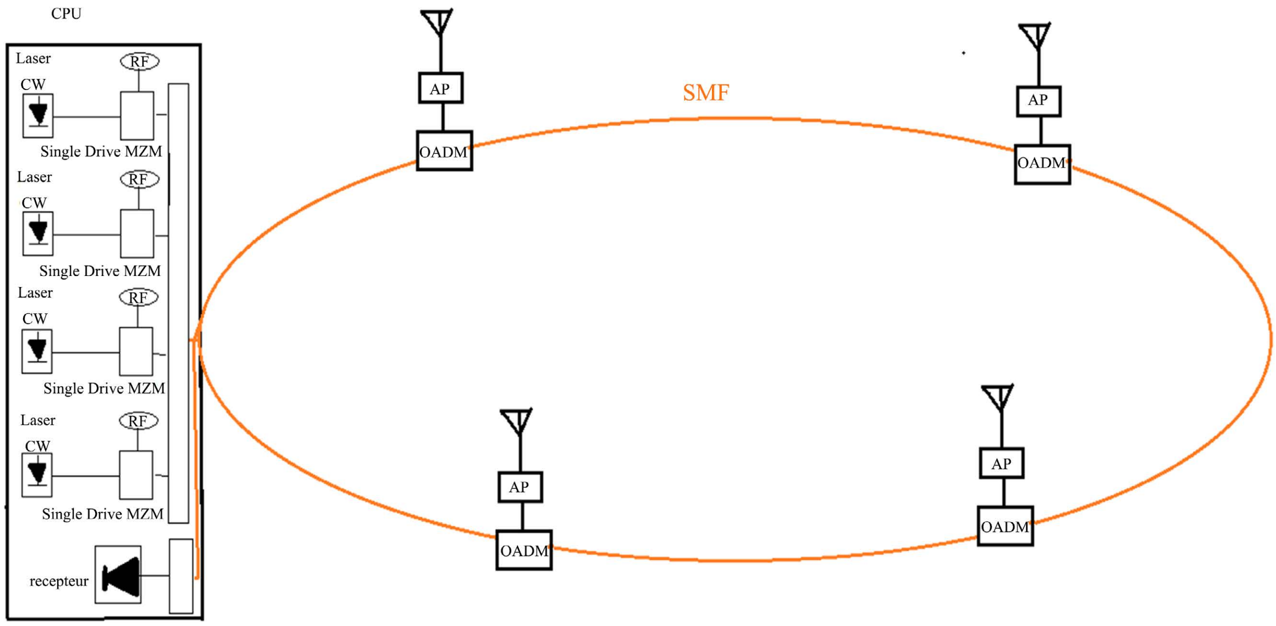

Figure 1. Schematic of the experimental model for the deployment of access points in a ring topology.

CPU sends and receives RoF signals from all APs connected to it. All optical signals downlink from the CPU to from all integrated APs on the ring topology line are combined by a wavelength division multiplexer from λ_1 to λ_N.

N: number of integrated antennas on the line.

At the CPU, each downstream optical carrier is generated by a continuous Wave laser transmitter. These four optical lasers operate at frequencies of 193.6 THz; 193.4 THz; 193.2 THz and 193.0 THz respectively. Each optical carrier modulates a 60 GHz, RF signal at a rate of 10 Gbps via a Mach-Zender modulator (MZM) before being transmitted into the optical fiber by a wavelength division multiplexer (WDM). An OADM is used every 1 km as a kind of tap on the fiber to integrate the access points. Figure 1 shows the architecture diagram of the developed model.

3.2. Structure and Operating Principle of the OADM

The AODM used in this work, consists of two passive components: two optical circulators and a Bragg filter (FBG) as shown in Figure 2. The path of the signal to be extracted from the downlink for access point 1 enters the AODM1 through the input of the OC1. This signal enters through port 1 and exits through port 2 of OC1 before being routed to FBG1. This optical signal located at the Bragg wavelength FBG1 will be reflected towards OC1 (entered from port 2 and exited from port 3) and then routed towards the Drop_1 port.

After that, the detection is performed by a photodetector (PD) to generate the radio frequency (RF) photocurrent. This 60 GHz RF signal will be filtered by a Band Pass Raised Cosine Filter to compensate for the undesirable effects of the channel before being demodulated by a quadrature demodulator to finally recover the MIMO stream. This MIMO stream is sent to the access point antenna

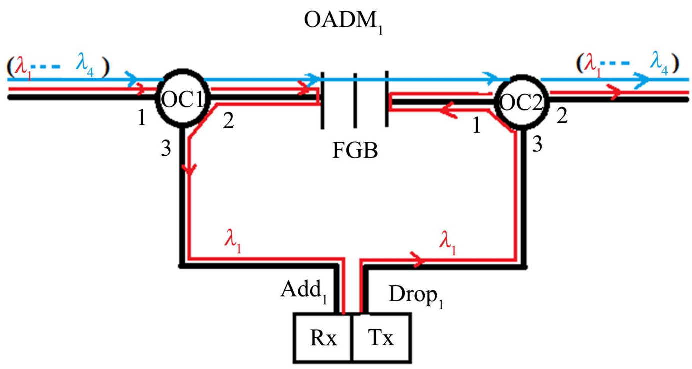

Figure 2. Structure of optical add/drop multiplexer.

for further wireless transmission to the corresponding UT. In the uplink direction, the RF signal received from the UT is processed in the TUL 1 unit and converted into the optical range with the same wavelength. This modulated optical signal enters the Add 1 insertion port of the OADM1 and will be guided via OC2 (enters through port 3 and exits through port 1), then routed to the FBG and will be reflected to OC2 (enters through port 1 and exits through port 2). This uplink signal is introduced into the multi-wavelength optical downlink signal flow outside the FBG1 Bragg wavelength range to serve the other access points and propagate through the distribution network to the CPU.

4. Results and Discussion

4.1. Optical Power Spectrum of These Different Points in the Network

Figures 3(a)-(f) show the spectra of the optical signals at different points on the transmission line: (a) transmitted to the CPU, (b) received at the first access point, (c) received at the second access point, (d) received at the third access point, (e) received at the fourth access point and (f) received at the CPU. Figure 3(a) shows that the transmitted optical signal power of each carrier is about 10 dBm on frequencies of 193.6 THz, 193.4 THz, 193.2 THz and 193.0 THz respectively at the output of the CPU. All-access points are one kilometer apart from each other. Figure 3(b) shows the optical signal from antenna 1 extracted by its OADM, the received power is about 7.59 dBm for the wavelength λ_1 and a residual of the other wavelengths up to −45 dBm. This residue shows that the OADM is imperfect. The target and non-target signals experience an insertion loss of about 2 dB and 55 dB, respectively. This results in a power variation of about 53 dB for the first access point and 35 dB for the other access points between these target and non-target signals as obtained in [13] with a power variation of about 37.13 dB. The large value of power variation will greatly reduce the unwanted interference between the target and non-target signals. This power variation between the target and non-target signal is almost the same for all access points shown in Figures 3(b)-(e). The downlink signal power from the four access points received at the CPU is about 10 dBm.

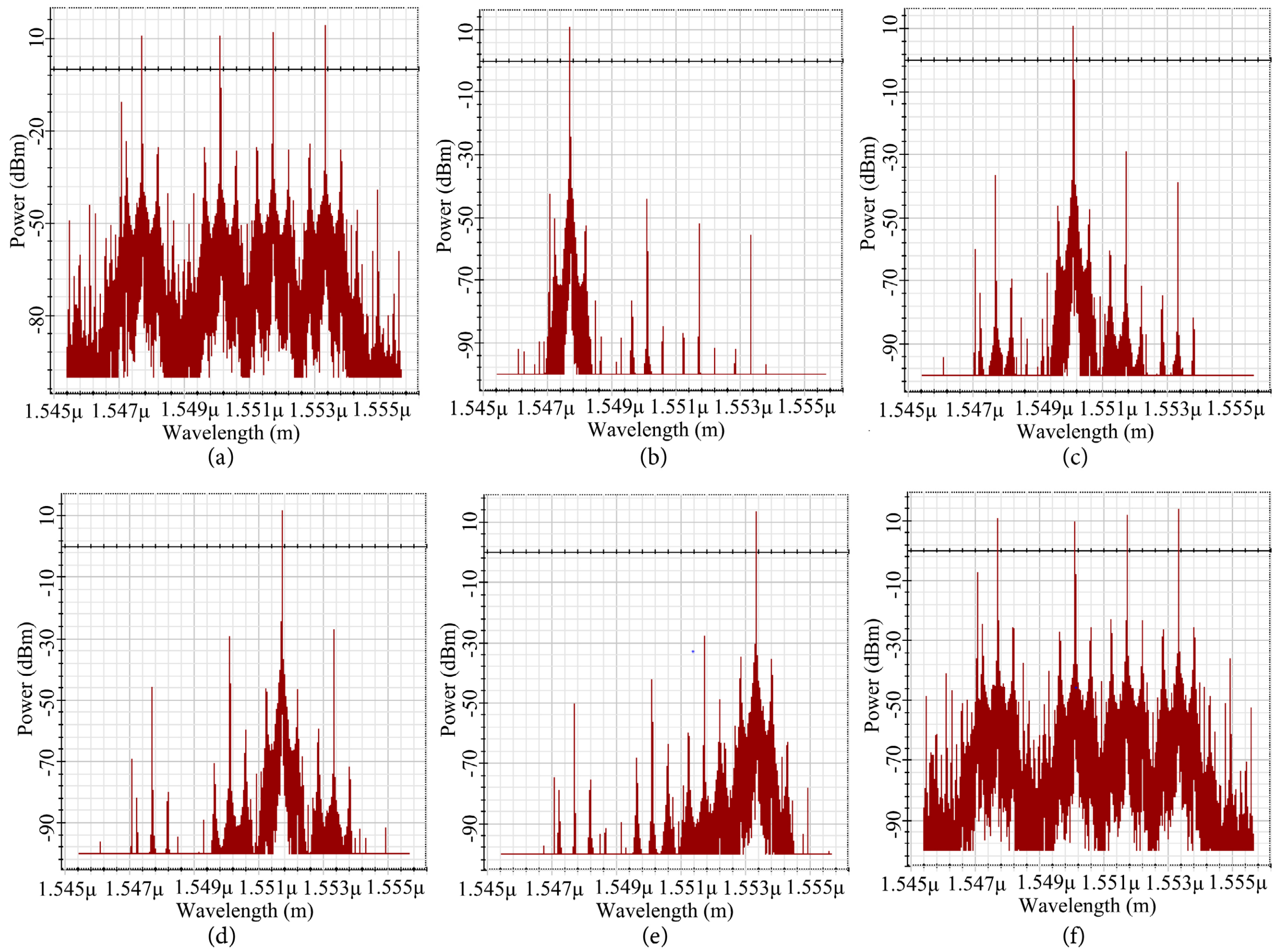

Figure 3. Optical spectrum at the different access points (a) transmitted to the CPU, (b) received at the first access point, (c) received at the second access point, (d) received at the third access point, (e) received at the fourth access point and (f) received at the CPU.

4.2. Quality of the Network Signal

The signal quality of each access point is evaluated by a constellation diagram. Compared to the constellation diagram of a single deployed antenna where all symbols are well apart and the bits of a symbol are well grouped shown in **Figure 4**.

The signal quality of the simulation model composed of four access points in series is presented by the constellation diagrams in **Figure 5**. **Figures 5(a)-(d)** represent the constellation diagrams of these 4 access points, deployed in series on a single line in a ring topology. The simulation results show that for the first 3 access points, the 16QAM symbols have moved apart but there are some scattered bits in the constellation. The dispersion of the bits of each symbol is more important when the number of access points deployed in series increases. For the fourth access point in the constellation diagram in **Figure 5(d)**, we note that the 16QAM symbols are closer together and there are a significant number of scattered bits. These results show a poor signal quality that increases when the number of antennas deployed in series increases. Beyond three access points, the transmission becomes increasingly degraded with a BER greater than or equal to 10^{-1}.

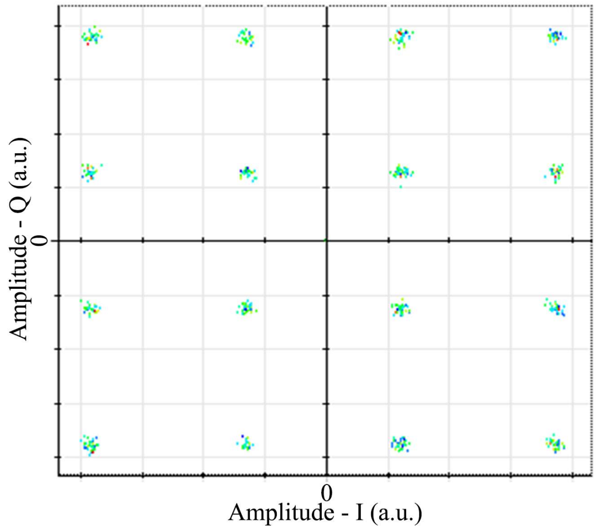

Figure 4. Constellation diagram for single access point deployment.

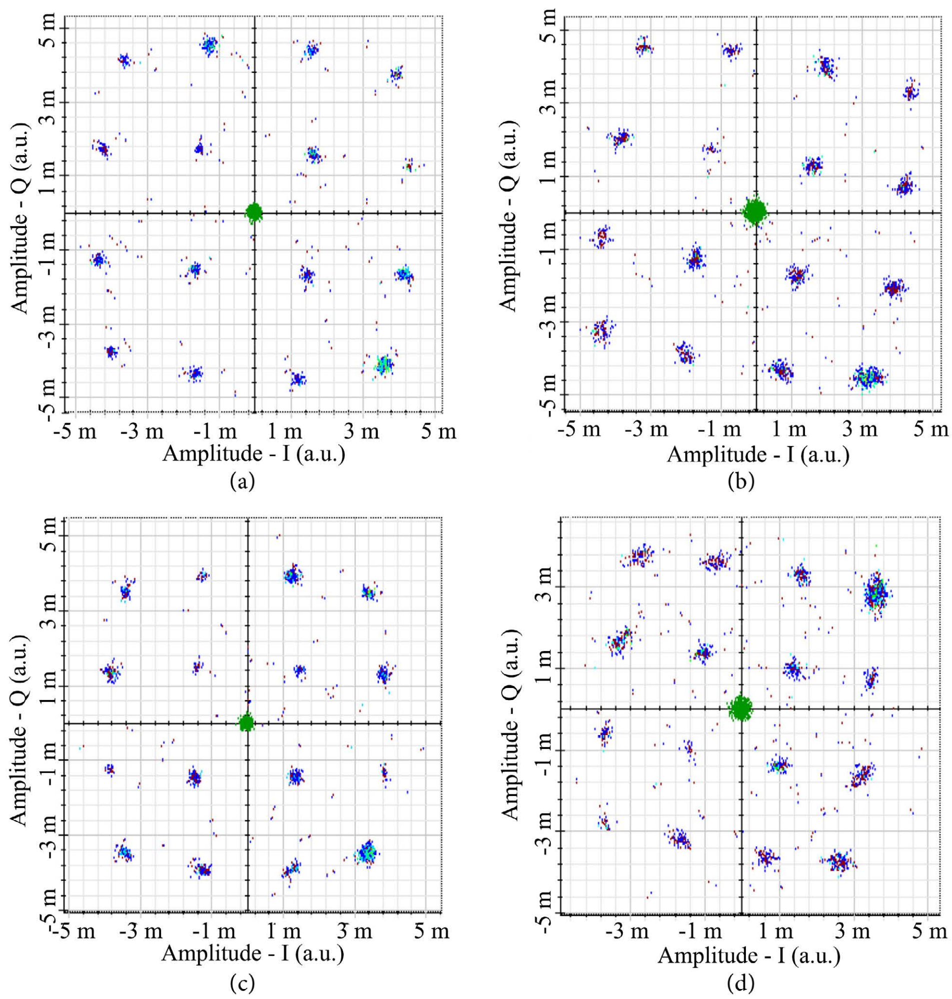

Figure 5. Constellation diagrams of the four access points deployed on a single line in a 2.5 Gbit/s ring topology. (a) Received at first access point, (b) received at second access point, (c) received at third access point, (d) received at fourth access point.

This deployment technique is also evaluated by increasing the throughput to 10 Gbps and 20 Gbps represented by **Figure 6** and **Figure 7** respectively.

When we increase the transmission rate to 10 and 20 Gbits, we obtain the constellation diagrams shown in **Figure 6** and **Figure 7** respectively. There is a large dispersion of points in the constellation diagrams, reflecting the very poor signal quality of all the access points on the line. The points are very close because of the effects of the channel, the chromatic dispersion and the effect of the cascade of several OADMs. As shown in [13] [14], OADMs are imperfect and let

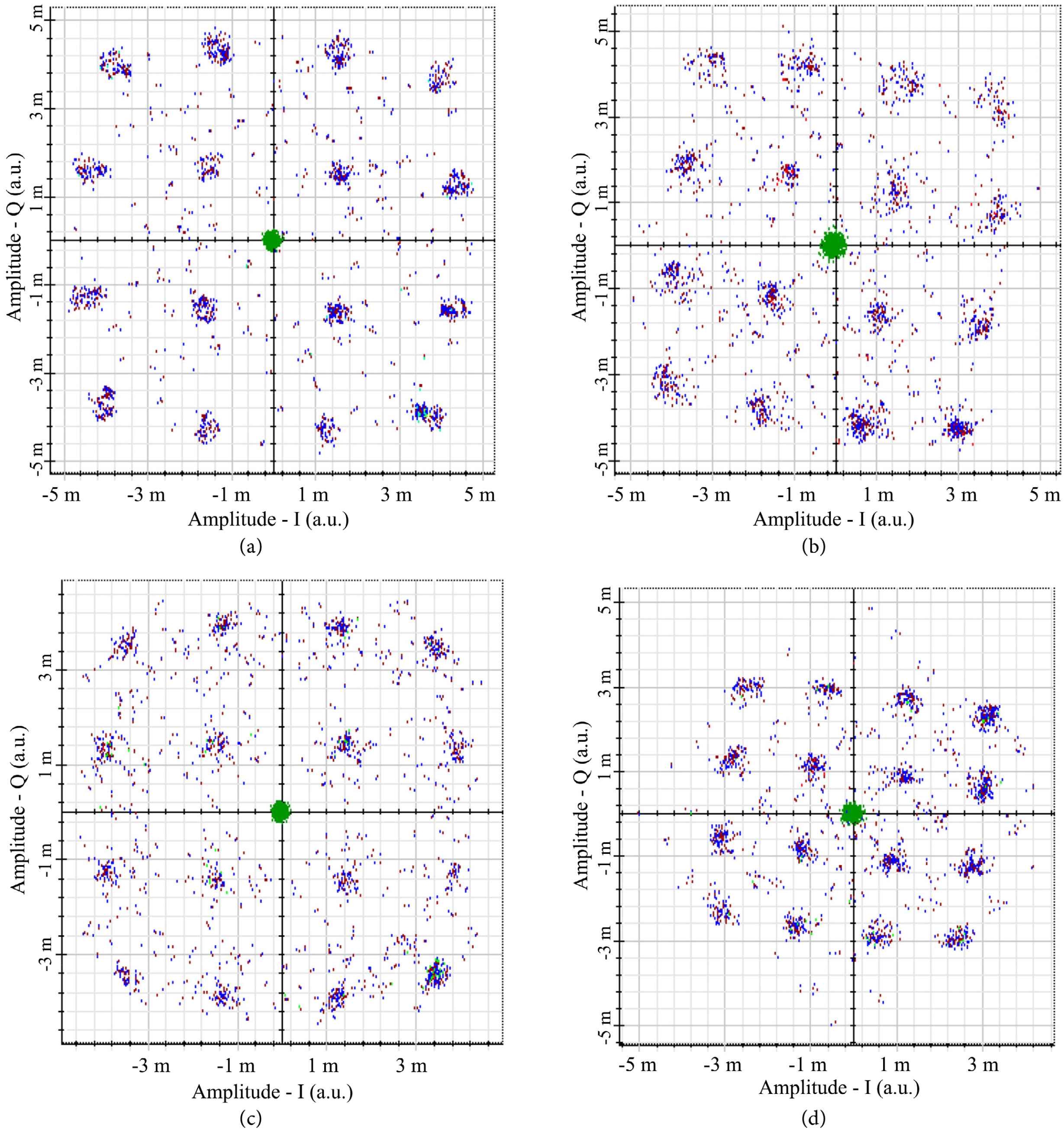

Figure 6. Constellation diagrams of the four access points deployed on a single line in 10 Gbit/s ring topology. (a) Received at first access point, (b) received at second access point, (c) received at third access point, (d) received at fourth access point.

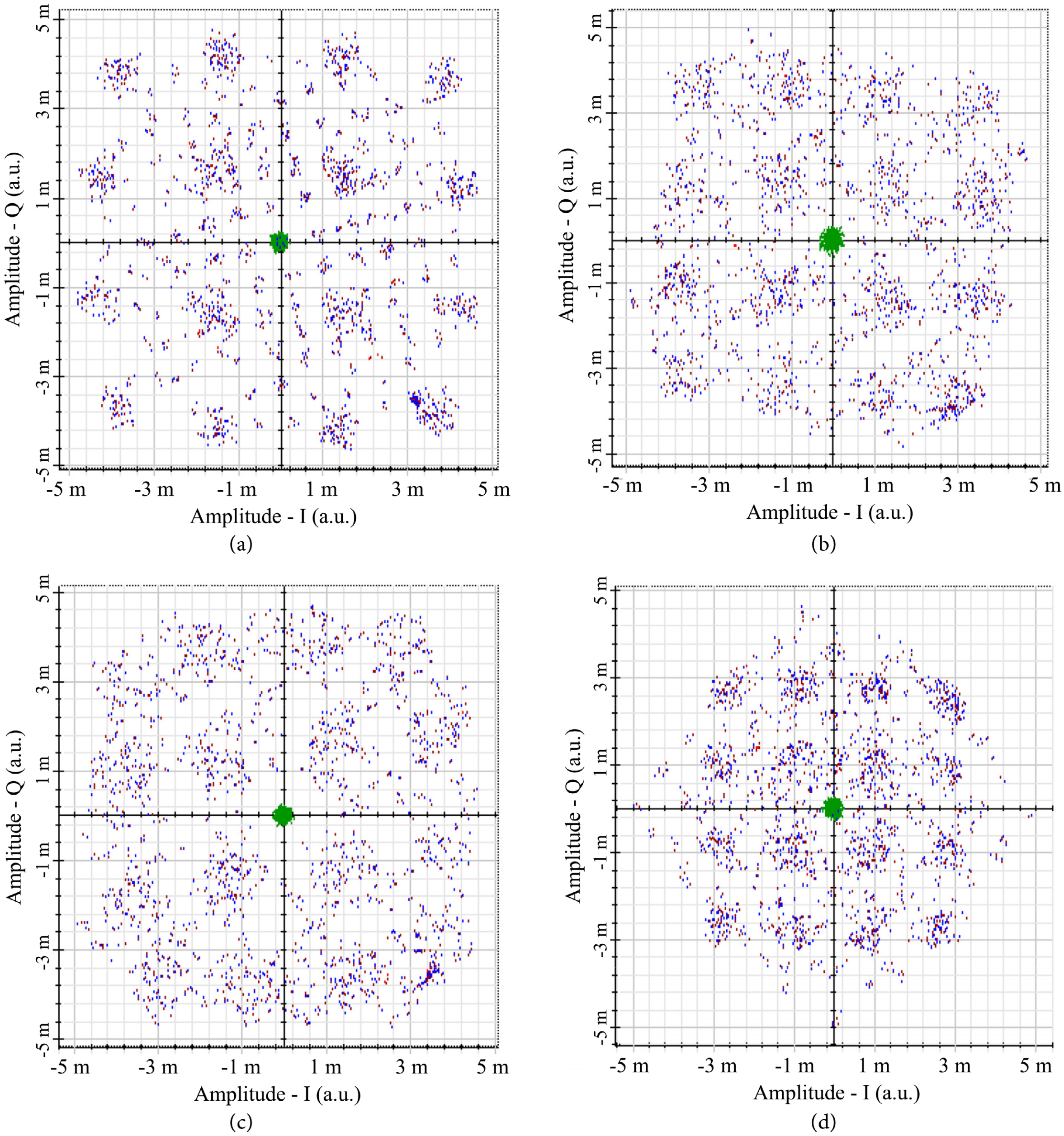

Figure 7. Constellation diagrams of the four access points deployed on a single line in 20 Gbit/s ring topology. (a) Received at the first access point, (b) received at the second access point, (c) received at the third access point, (d) received at the fourth access point.

some of the target wavelengths pass through the grating. This residue constitutes noise that increases as the number of access points on the line or the data rate increases. In addition, there are the effects of the polarization modal dispersion of the different wavelengths transmitted on the same transmission line. Thus, the results showed that QAM modulation does not adapt to multi-carrier transmissions. For each access point, the same downlink voice wavelength is reused for the uplink voice. These studies show that the main problems of OADM are bandwidth, modulation formats and wavelength reuse.

5. Conclusions

This paper studies the feasibility of deploying access points in series on a single line in a ring topology. This technique allows us to realize the dreams of access points' deployment in a cell-less network by ensuring the minimum length of fiber used. The AODM used in this work, consists of two passive components: two optical circulators and a Bragg filter (FBG) to add and extract signals from each access point. Simulation results indicate a poor signal quality visualized by constellation diagrams and a BER of 10^{-1}. This performance degradation increases when the number of access points integrated on the line increases. This is related to the QAM modulation used which does not adapt to multi-carrier transmissions and to the reuse of wavelengths.

To extend this work, it would be interesting on the one hand, to use OFDM modulation to ensure the best quality of the signal of each of the access points and on the other hand to build SBOADM for a bidirectional transmission finally to ensure the self-protection.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Guenach, M., Gorji, A.A. and Bourdoux, A. (2020) Joint Power Control and Access Point Scheduling in Fronthaul-Constrained Uplink Cell-Free Massive MIMO Systems. *IEEE Transactions on Communications*, **69**, 2709-2722. https://doi.org/10.1109/TCOMM.2020.3047801

[2] Interdonato, G., Björnson, E., Quoc Ngo, H., Frenger, P. and Larsson, E.G. (2019) Ubiquitous Cell-Free Massive MIMO Communications. *EURASIP Journal on Wireless Communications and Networking*, Article No. 197. https://doi.org/10.1186/s13638-019-1507-0

[3] Zhang, J., Björnson, E., Matthaiou, M., Ng, D.W.K., Yang, H. and Love, D.J. (2020) Prospective Multiple Antenna Technologies for Beyond 5G. *IEEE Journal on Selected Areas in Communications*, **38**, 1637-1660. https://doi.org/10.1109/JSAC.2020.3000826

[4] Belkin, M., Alyoshin, A. and Fofanov, D. (2020) Designing WDM-RoF Concept-Based Ful1-Duplex MMW Fiber Fronthaul Microcell Network. 2020 26*th Conference of Open Innovations Association* (*FRUCT*), Yaroslavl, 20-24 April 2020, 52-59. https://doi.org/10.23919/FRUCT48808.2020.9087454

[5] Singh, S. (2014) Performance Investigation on DWDM Optical Ring Network to Increase the Capacity with Acceptable Performance. *Optik*, **125**, 5750-5752. https://doi.org/10.1016/j.ijleo.2014.07.049

[6] Wang, Y., Pei, L., Li, J. and Li, Y. (2017) Full-Duplex Radio-over-Fiber System with Tunable Millimeter-Wave Signal Generation and Wavelength Reuse for Upstream Signal. *Applied Optics*, **56**, 4982-4989. https://doi.org/10.1364/AO.56.004982

[7] Pires, J.J.O. (2001) Constraints on the Design of 2-Fiber Bi-Directional WDM Rings with Optical Multiplexer Section Protection. 2001 *Digest of LEOS Summer Topical Meetings*: *Advanced Semiconductor Lasers and Applications*/ *Ultraviolet and Blue*

Lasers and Their Applications/Ultralong Haul DWDM Transmission and Networking/WDM Compo, State of Colorado, 30 July 2001-1 August 2001, 2. https://doi.org/10.1109/LEOSST.2001.941930

[8] Tran, A.V., Chae, C.J. and Tucker, R.S. (2003) A Bidirectional Optical Add-Drop Multiplexer with Gain Using Multiport Circulators, Fiber Bragg Gratings, and a Single Unidirectional Optical Amplifier. *IEEE Photonics Technology Letters*, **15**, 975-977. https://doi.org/10.1109/LPT.2003.813427

[9] Chang, C.-H., Lu, D.-Y., Yang, T.-Y. Fu, Z.-H., Liu, Q.-Q. and Zhu, Z.-M. (2017) An Optical Fiber Transport System Based on a Novel Bidirectional OADM. 2017 *Opto-Electronics and Communications Conference* (*OECC*) *and Photonics Global Conference* (*PGC*), Singapore, 31 July 2017-4 August 2017, 1-2. https://doi.org/10.1109/OECC.2017.8114801

[10] Chang, C.H., Lu, D.Y. and Lin, W.H. (2018) All-Passive Optical Fiber Sensor Network with Self-Healing Functionality. *IEEE Photonics Journal*, **10**, Article ID: 3901612. https://doi.org/10.1109/JPHOT.2018.2884448

[11] Tsai, W.S., Chang, C.H., Lin, Z.G., Lu, D.Y. and Yang, T.Y. (2019) Fiber Link Health Detection and Self-Healing Algorithm for Two-Ring-Based RoF Transport Systems. *Sensors*, **19**, Article 4201. https://doi.org/10.3390/s19194201

[12] Li, C.Y., Chang, C.H. and Lu, D.Y. (2020) Full-Duplex Self-Recovery Optical Fibre Transport System Based on a Passive Single-Line Bidirectional Optical Add/Drop Multiplexer. *IEEE Photonics Journal*, **12**, Article No. 7202310. https://doi.org/10.1109/JPHOT.2020.3022703

[13] Li, C.Y., Chang, C.H. and Lin, Z.G. (2021) Single-Line Bidirectional Optical Add/Drop Multiplexer for Ring Topology Optical Fiber Networks. *Sensors*, **21**, Article 2641. https://doi.org/10.3390/s21082641

[14] Li, C.Y., Chang, C.H. and Lin, Z.G. (2021) Hybrid Ring-and Tree-Topology RoF Transmission System with Disconnection Protection. *Photonics*, **8**, Article 515. https://doi.org/10.3390/photonics8020051

[15] Hu, X., Si, H., Mao, J. and Wang, Y. (2022) Self-Healing and Shortest Path in Optical Fiber Sensor Network. *Journal of Sensors*, **2022**, Article ID: 5717041. https://doi.org/10.1155/2022/5717041

[16] Klinkowski, M. and Jaworski, M. (2023) Cost-Aware Optimization of Optical Add-Drop Multiplexers Placement in Packet-Optical xHaul Access Networks. *Applied Sciences*, **13**, Article 4862. https://doi.org/10.3390/app13084862