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High Capacity Mode Division Multiplexing Based MIMO Enabled All-Optical Analog Millimeter-Wave Over Fiber Fronthaul Architecture for 5G and Beyond

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ABSTRACT The ever-increasing proliferation of mobile users and new technologies, and the demands for ubiquitous connectivity, high data capacity, faster data speed, low latency, and reliable services have been driven the quest for the next generation, fifth generation (5G), of the wireless networks. Cloud radio access network (C-RAN) has been identified as a promising architecture for addressing 5G requirements. However, C-RAN enforces stringent requirements on the fronthaul capacity and latency. To this end, several fronthaul solutions have been proposed in the literature, ranging from transporting digitized radio signals over fiber and functional splits to an entirely analog-radio-over fiber (A-RoF) based fronthaul. A-RoF is a highly appealing transport solution for fronthaul of 5G and beyond owing to its high bandwidth and energy efficiency, low system complexity, small footprint, cost-effectiveness, and low latency. In this paper, a high capacity multiple-input-multiple-output (MIMO) enabled all-optical analog-millimeter-wave-over fiber (A-MMWoF) fronthaul architecture is proposed for 5G and beyond of wireless networks. The proposed architecture employs photonic MMW signals generation and mode division multiplexing (MDM) along with wavelength division multiplexing (WDM) for transporting MMW MIMO signals in the optical domain. In support of the proposed architecture design, a comprehensive state-of-the-art literature review on the recent research works in high capacity A-RoF fronthaul systems and related transport technologies is presented. In addition, the corresponding potential challenges and solutions along with potential future directions are highlighted. The proposed design is flexible and scalable for achieving high capacity, high speed, and low latency fronthaul links.

INDEX TERMS 5G, fronthaul, analog-radio-over fiber (A-RoF), millimeter-wave-over fiber (MMWoF), multiple-input-multiple-output (MIMO), space division multiplexing (SDM), mode division multiplexing (MDM), cloud radio access network (C-RAN).

I. INTRODUCTION

The demand for ubiquitous connectivity, high data capacity, faster data speed, low latency, and reliable services increases day by day with the persistent growth of mobile users and new technologies. According to [1], the number of mobile users is projected to surpass 6.5 billion in 2018, and grow to over 7.2 billion by the end of 2022. Besides, the rapid evo-

lution of internet of things (IoTs) and machine-to-machine (M2M) communication is going to disrupt the existing mobile communication environment and infrastructure profoundly. It is predicted in [2] that there will be more than 15 billion connected M2M and consumer electronic devices by 2021. With such a multifold growth in the information and communication technology (ICT), the network traffic is increasing exponentially. The mobile data traffic is forecasted to increase sevenfold between 2017 and 2022, and will reach 77.5 Exabyte (EB) per month by 2022 [3]. These demands

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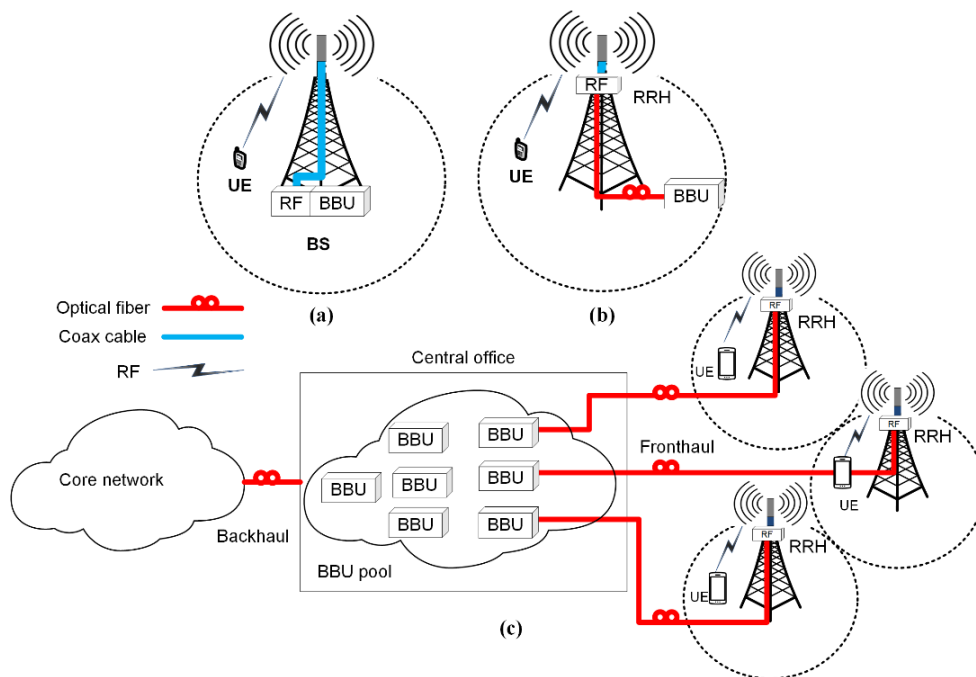


FIGURE 1. The base station architecture evolution: (a) Conventional macro base station, (b) Conventional distributed RAN, and (c) C-RAN architecture. BBU: baseband unit, UE: user equipment, RRH: remote radio head, RF: radio frequency.

have been initiated a roadmap for the next generation of wireless networks (5G), which is set to revolutionize the existing mobile communications [4].

5G networks are aimed to handle high capacity and provide faster data speed and reliable services to the mobile users ubiquitously by employing technologies, such as millimeter waves (MMW), massive multiple-input-multiple-output (M-MIMO), beamforming, coordinated multi-point (CoMP), small cells, heterogeneous networks (HetNets), full duplex, software-defined network (SDN), network functions virtualization (NFV), and cloud radio access [4]–[7]. It is reported in [7] that 5G networks are expected to bring gigabits per second experience per mobile user to reality by 2020. Thus, in order to achieve the requirements of 5G, fiber-wireless integration is inevitable. Since optical fiber offers high capacity, low latency and large transmission distance but limited mobility. On the other hand, wireless communications provide high mobility and seamless coverage but limited bandwidth and transmission distance. Therefore, seamless fiber-wireless convergence is necessary for ubiquitous and multi-gigabit wireless connectivity. Moreover, in order to achieve ultrahigh capacity and ultrahigh data rates and to overcome the wireless spectrum crunch, 5G is going to adopt heterogeneous higher frequencies from the plentiful available spectrum in the range of sub-6 GHz to MMW frequencies (30 to 300 GHz). Among them, the industry focuses on bands including 15 GHz, 18 GHz, 28 GHz, 38 GHz, 45 GHz, 60 GHz, and 72 GHz [8]. Currently, 3rd generation partnership project (3GPP) considers the evaluation of three

bands including sub-6 GHz (around 2 or 4 GHz), around 30 GHz, and around 70 GHz [9]. Such a surge in the traffic of heterogeneous wireless interfaces can be supported by deploying all-optical RoF technologies with centralized C-RAN [10], [11].

C-RAN architecture is considered cost-effective, efficient, scalable, flexible, and hence influential to exploit the full competencies of 5G [5]. The cellular network architecture has already been evolved into C-RAN and small size cells architecture. Thus the legacy distributed radio access network (D-RAN) has been replaced by C-RAN [12]. In C-RAN architecture, in contrast with the conventional macro base station as shown in Figure 1(a) and D-RAN as depicted in Figure 1(b), the base band processing units (BBUs) are moved to the central office and shared among sites in a virtualized BBU pool, whereas the remote radio heads (RRHs) remain at the cell sites, which are connected to the BBUs through a network segment called fronthaul as shown in Figure 1(c) [11]. The BBUs are further connected to the core network through backhaul network. The RRHs transmit and receive the radio frequency (RF) signals over the air interface, whereas the BBUs perform the base band and packet processing in a cloud environment as shown in Figure 1(c), hence achieves statistical multiplexing gain. However, centralization of RAN imposes stringent requirements on the fronthaul capacity and latency [5]. Therefore, the design of an efficient fronthaul for 5G and beyond is inevitable in order to achieve low latency and avoid the capacity crunch.

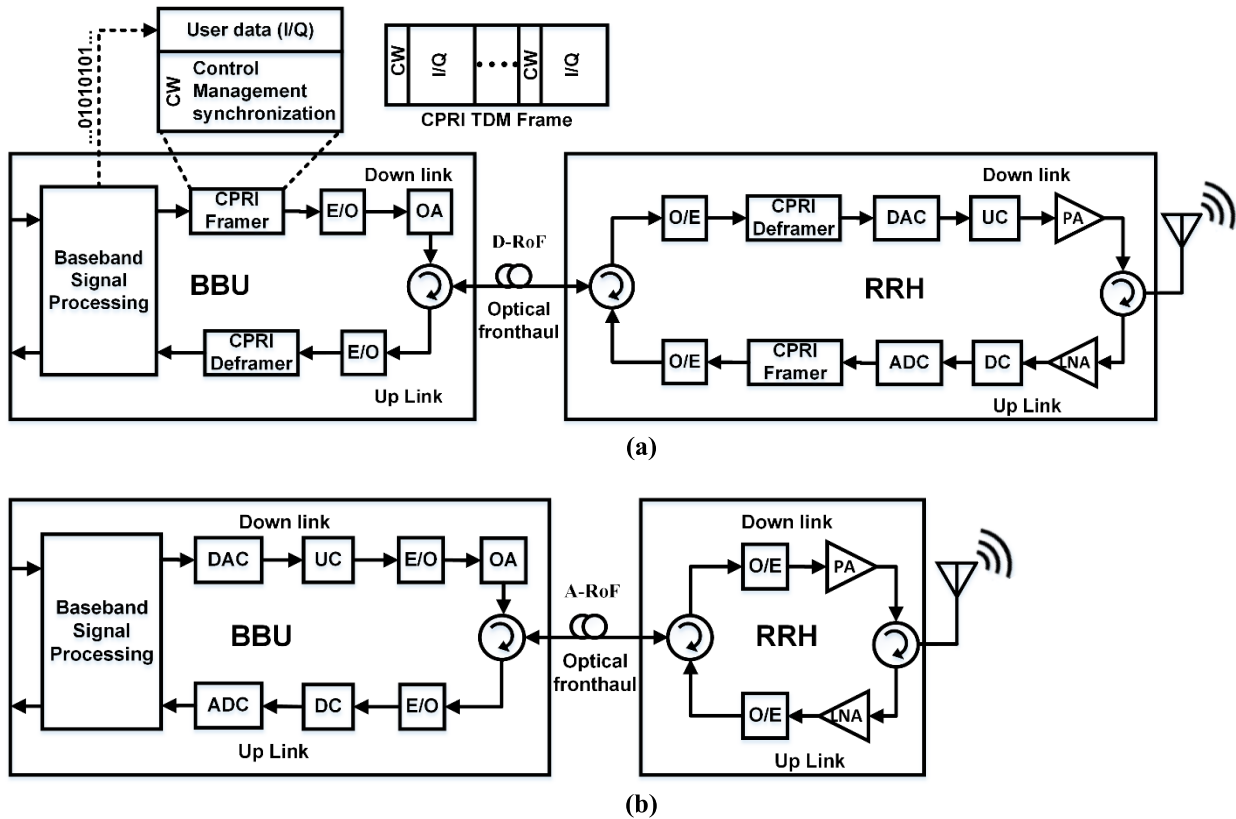


FIGURE 2. Schematic of a generic fronthaul architecture (a) D-RoF fronthaul, and (b) A-RoF fronthaul. CPRI: common public radio interface, CW: control word, I/Q: inphase/quadrature, E/O: electrical to optical, O/E: optical to electrical, TDM: time division multiplexing, PA: power amplifier, LNA: low noise amplifier, ADC: analog to digital converter, DAC: digital-to-analog converter.

A high capacity fronthaul for realizing centralized processing can be achieved by using seamless fiber-wireless integration. Gigabit wireless connectivity is also one of the drivers behind such integration. Therefore, optical fiber is used as a transport medium in the fronthaul links [13] and RoF based fronthauling has already been used in the existing wireless infrastructure, which is going to be the future of wireless communication networks as well [14]. Since such networks enable the reduction of bandwidth requirements, latency and complexity. RoF based fronthaul links can be categorized into digital RoF (D-RoF) and A-RoF as shown in Figures 2(a) and 2(b), respectively. The existing fronthaul links are based on the former category where the interface protocols such as common public radio interface (CPRI), open base station architecture initiative (OBSAI), and open radio equipment interface (ORI) have been defined by the digitization of the RF signals. Among them, CPRI is the most widely implement protocol in the fronthaul. Nevertheless, CPRI is foreseen to be impractical considering the high bandwidth requirements of the next generation fronthaul [5]. Since CPRI digitizes the wireless signals into in-phase and quadrature (I/Q) waveforms and transport them along with control words (CWs), which are used for equipment control and management and synchronization information, using time division multiplexing (TDM) and on-off keying modulation format as depicted

in Figure 2(a). This makes CPRI a bandwidth inefficient transmission standard. Consequently, CPRI interface has a constant bit rate ranging from 614.4 Mbit/s (option 1) to 24.33024 Gbit/s (option 10) over several kilometer distances between the RRHs and the BBU, which depends on the radio access technology, sampling rate, carrier bandwidth, and MIMO implementation [5], [12]. The CPRI data rate is evaluated as [12]:

$$Data\ rate = S \times M \times SR \times N \times 2(I/Q) \times CW \times C \quad (1)$$

where S , M , SR , N , $2(I/Q)$, CW , and C represent the number of sectors, the number of antennas per sector, sampling rate (sample/s/carrier), sample width (bits/sample), multiplicative factor for I and Q data, control word factor, and coding factor (10/8 for 8B/10B code or 66/64 for 64B/66B code), respectively. Moreover, the round trip fronthaul latency for CPRI is 150 - 200 microseconds [5].

Thus, besides the strict requirements of signal synchronization, jitter, latency and complexity issues, CPRI poses major challenges in terms of extremely high capacity for 5G and beyond of mobile networks. For instance, based on (1) the data rate requirement of a CPRI based fronthaul link can be as high as 590 Gbit/s, if 5G system utilizes wireless signals with aggregated bandwidth of 200 MHz, 16×16 MIMO antennas and 3 sectors [15]. Moreover, when the network is further

extended with massive MIMO systems as expected in 5G and beyond, the transmission capacities of fronthaul would scale to the range of Tb/s per cell, which questions the capability of the current CPRI based D-RoF fronthaul [16].

To overcome the aforementioned shortcomings of the current digitized mobile fronthaul, a fully A-RoF mobile fronthaul is considered to be one of the promising solutions for 5G and beyond in the literature [5], [8], [14], [16]–[18]. A-RoF fronthaul can be achieved by directly modulating the optical carrier with RF signals and transmitting them as the analog waveforms over optical link from the BBUs to RRHs, and vice versa as shown in Figure 2(b). In such systems, different types of multiple analog RF signals are directly converted to optical domain and transported simultaneously over optical fiber links while keeping the analog-to-digital converter (ADC) and digital-to-analog converter (DAC) in the BBU; hence achieving high centralization and reducing the complexity of RRH. Furthermore, with analog mobile fronthaul, the large overhead required for digitization of wireless signals to the CPRI format can be avoided, which achieves high bandwidth efficiency. For instance, if we consider the same link configuration for A-RoF fronthaul link as mentioned above for D-RoF with CPRI, the bandwidth requirement greatly reduces to around 10 GHz [15]. In addition, the extra latency that comes from the format conversion of wireless signals can also be reduced [19].

Moreover, the capacity of A-RoF fronthaul links can further be increased by incorporating space division multiplexing (SDM) technologies, such as MDM and multicore fiber (MCF). In the former case, different light propagation paths, also called linearly polarized (LP) modes, in a single core of few mode fiber (FMF) or multimode fiber (MMF) are used for simultaneous transmission of multiple RF signals [20], [21]. On the other hand, in the latter case, different cores in the same cladding of MCF are used for concurrent transmission of various RF signals using a single or multiple optical wavelengths and electrical frequencies [22]. In addition, employing MDM-RoF [20], [23], [24] and MCF-RoF [22], [25] transmissions and leveraging additional multiplexing techniques such as WDM and polarization multiplexing (PoM) can significantly enhance the capacity of fronthaul links[5]. Thus motivated by the fact that A-RoF transport solutions with SDM and WDM technologies can achieve high bandwidth and energy efficiency, high centralization, low latency and cost-effectiveness, in this paper, we propose a MIMO enabled high capacity all-optical MDM based A-MMWoF architecture for 5G and beyond of wireless networks. A list of acronyms and their definitions are provided in Table 1, which are used throughout this paper.

In the following sections, first a comprehensive literature review on the recent research trends in A-RoF based fronthaul technologies for next generation of wireless networks is presented in Section II. Section III presents the design concept of the proposed high capacity all-optical A-MMWoF architecture and its principle operation. In section IV, the corresponding challenges and potential solutions are highlighted.

TABLE 1. List of Acronyms.

Acronym	Definition
5G	Fifth Generation
C-RAN	Cloud Radio Access Network
D-RAN	Distributed Radio Access Network
A-RoF	Analog-Radio-over Fiber
D-RoF	Digital-Radio-over Fiber
A-IFoF	Analog Intermediate Frequency over Fiber
A-MMWoF	Analog Millimeter Wave over Fiber
CPRI	Common Public Radio Interface
MIMO	Multiple-Input-Multiple-Output
SISO	Single-Input-Single-Output
SDM	Space Division Multiplexing
MDM	Mode Division Multiplexing
WDM	Wavelength Division Multiplexing
PoM	Polarization Multiplexing
OFDM	Orthogonal Frequency Division Multiplexing
MMW	Millimeter Waves
RF	Radio Frequency
BBUs	Base Band Processing Units
RRHs	Remote Radio Heads
RRUs	Remote Radio Units
RAUs	Remote Antenna Units
DAS	Distributed Antenna System
SMF	Single-Mode Fiber
MCF	Multicore Fiber
FMF	Few Mode Fiber
MMF	Multimode Fiber
RFC	Ring Core Fiber
PM-ERCF	Polarization-Maintaining Elliptical Ring Core Fiber
LP	Linearly Polarized
LPV	Linearly Polarized Vector
OAM	Orbital Angular Momentum
LTE-A	Long Term Evolution Advance
EVM	Error Vector Magnitude
QAM	Quadrature Amplitude Modulation
IMD	Intermodulation Distortion
SFDR	Spurious-Free Dynamic Range
MC	Mode Converter
Mux/ DeMux	Multiplexer/ De-Multiplexer
QD	Quantum Dot

Finally, the conclusion and potential future research works are presented in the last section.

II. REVIEW OF RECENT RELATED WORKS

As it is established in the previous section that infrastructure of the current mobile fronthaul will not be able to meet the requirements of 5G and beyond, therefore, research efforts are strongly focused on the design of novel RoF technologies and systems. In the literature, several approaches have been proposed to overcome the limitations of the current D-RoF fronthaul for achieving C-RAN, ranging from CPRI compression [26] and functional splits [27], [28] to a fully A-RoF based fronthaul [8], [14], [17], [18], [23], [29]. However, A-RoF fronthaul approach has been considered one of the best potential candidates for 5G and beyond C-RAN due to its low bandwidth requirement, low latency, cost-effectiveness, and energy efficiency [5], [8], [14], [16]–[19], [23]. The bandwidth efficiency in analog mobile fronthaul is achieved by transmitting multiple RF signals simultaneously in analog

form. With this notion, an analog mobile fronthaul architecture based on low and high frequencies with different data rates is proposed for the next generation mobile networks in [8]. The low frequency is aimed to support the conventional networks while the high frequencies are envisioned for the high data rate provision and emerging small cell networks. On the other hand, an analog intermediate frequency over fiber (A-IFoF) based mobile fronthaul testbed was presented in [30], which supports two frequency association and 2×2 MIMO antennas. The real-time evaluation of this testbed is performed through demonstrating commercial mobile internet services such as Skype and YouTube video streaming over 20-km standard single-mode fiber (SMF). Similarly, the simultaneous transmission of 24 analog IF carriers of long term evolution advance (LTE-A) signals with 20-MHz bandwidth each, 2 frequency assignments, 3-sector, and 4×4 MIMO antennas was demonstrated in [31] over 20 km SMF fronthaul link. For such transmission, the error vector magnitude (EVM) value of within the 3GPP specifications was achieved. In addition, in order to investigate the effect of optical link quality on the LTE-A signal, a carrier-to-noise-ratio (CNR) requirement is derived in [31]. Similar A-IFoF scheme was also experimentally demonstrated in [32]. Besides, a spectrum efficient bidirectional mobile fronthaul architecture based on IF and DWDM was proposed in [23]. The performance of the corresponding architecture was experimentally demonstrated with the simultaneous transmission of 64-downlink carriers using 8×8 MIMO with 8-carrier assignments and 32-uplink carriers using 4×4 MIMO with 8-carrier assignments over a 25-km standard SMF achieving low EVMs. In addition, in order to realize the practicality of A-IFoF scheme, the successful transmission of 24 20-MHz LTE signals was experimentally demonstrated in [33] in a real environment over a 7.8-km deployed standard SMF link using a commercial BBU and RRH with no significant degradation in the signal quality. Furthermore, recently an analog mobile fronthaul system was presented in [34] for distributing LTE and 5G services concurrently over the same fiber link. The system was demonstrated with simultaneous transmission of seventy-five bands of LTE and 10 bands of 5G candidate waveforms over 25-km of A-IFoF link. Moreover, recently all-optical MMW fiber-wireless integrated fronthaul systems were also proposed in [35], [36], where the MMW signals are generated and distribute in the optical domain by remote heterodyning of optical beat sources.

Nevertheless, considering massive MIMO technology with large number of antennas at the RRHs or remote radio units (RRUs) and the use of over 6 GHz spectrum including MMWs that are envisaged in 5G and beyond networks, the required bandwidth in fronthaul links would scale up to an extent that would exceed the huge bandwidth provided by the single optical fiber link [21], [24]. Therefore, this expected rise in the bandwidth requirements of fronthaul optical links calls for novel multiplexing dimensions of SDM such as mode MDM in FMF [20], [24], ring core fiber (RCF) [37] and MCF [22], [25]. However, the concept of MDM application

in fronthaul of mobile networks has been recently introduced and not much research work have been devoted to its investigation. There are only few studies available in the literature that demonstrate the use of SDM for fronthaul and evaluate its performance in A-RoF links using LP modes in FMF [20], [21], [23], [38]–[42] and MMF [24], [43], linearly polarized vector (LPV) modes in polarization-maintaining elliptical ring core fiber (PM-ERCF) [44], [45], orbital angular momentum (OAM) modes in RCF [37] and free space optical links [46], and SDM in MCF [22], [25], [47]–[57]. Moreover, the feasibility of MDM for implementing RoF distributed antenna system (DAS) architectures was also reported in [58]–[62]. Thus, considering the aforementioned technologies and requirements, the design of an efficient, flexible and scalable A-RoF fronthaul for 5G and beyond of mobile networks is yet to be developed.

In order to realize the use of MDM in FMF for the next generation mobile fronthaul application, a symmetrical bidirectional system based on MDM and wavelength reuse scheme was proposed in [20], [23]. The system was experimentally demonstrated by multiplexing four 25 Gb/s downlink channels and four supplementary carriers for uplink channels using WDM and transmitting them over LP₀₁ and LP₁₁ modes of 10-km two mode FMF, respectively. In addition, to mitigate the upstream power penalty due to Rayleigh back scattering as a result of upstream and downstream spectrum overlapping, the shifting of downstream frequency is proposed. Likewise, an MDM based RoF link for W-band wireless spectrum (75-110 GHz) was proposed in [38]. The link was experimented by utilizing LP₀₁ and LP_{11a/b,x,y} modes of 30-km differential modal group delay compensated FMF. Additionally, in order to avoid the RF power fading due to mode coupling in MDM-RoF links, mode assignment and crosstalk filtering technique was proposed in [39] where RF carrier and signal components are transmitted over different LP modes using different wavelengths. In this way, the unwanted crosstalk can be filtered out before photo-mixing and wireless signal generation. The proposed technique was evaluated by transporting a carrier and signal components over LP₀₁ and LP_{11a/b,x,y} modes of 30-km FMF, respectively, with successful crosstalk suppression. However, this technique is only suitable for high bandwidth wireless signals such as MMWs (W-band). Moreover, it is shown in [40] that MDM over FMF A-RoF link can further reduce the non-linearity effects (stimulated Brillouin scattering and intermodulation distortion (IMD)) and increase the gain of the link. This is investigated through MDM of two modes, i.e., LP₀₁ and LP₁₁, over 10-km four mode FMF and it is observed that the MDM reduces the third-order IMD and improves the spurious-free dynamic range (SFDR) compared to using only any single mode of FMF or SMF. Similarly, in [24] a fully analog fronthaul was numerically investigated for massive MIMO using MDM and FDM over 10-km MMF with direct detection and all-optical passive Mux/Demux. It is numerally proven that the use of smart dynamic assignment for the mode-frequency optical resources between the radio antennas

and the mode/frequency dimensions allows to overcome the intermodal crosstalk limitations. On the other hand, the transmission of 4.46 Gb/s 2×2 MIMO orthogonal frequency division multiplexing (OFDM) with offset QAM was experimentally demonstrated in [21] over two LP modes (LP₀₁ and LP_{11a}) of 2-km elliptical three mode FMF along with 0.4 m wireless link. To overcome the problem of differential channel delay among the MIMO channels in the absence of cyclic prefix, which leads to inter-symbol interference and inter-carrier interference, a time-offset crosstalk algorithm was also presented. Additionally, in order to optically power the remote antennas units (RAUs), a system for simultaneous transmission of optical data (A-RoF) and high feed power (power-over-fiber) was designed and demonstrated in [43] over 2-km and 4-km FMF. To mitigate the modal dispersion and feed light crosstalk of the corresponding signals, center-launching and offset-launching techniques were adopted.

Moreover, for the first time in [44], [45], LPV modes in polarization-maintaining elliptical ring core fiber (PM-ERCF) were introduced for RF signals transmission. The transmission of different RF signals using 2.4 GHz and 3.3 GHz RF carriers over four LPV modes of 900-m PM-ERCF was experimentally demonstrated without the use of MIMO processing. The four modes include LPV_{11a,x}, LPV_{11b,x,y}, and LPV_{21,a,y}, where two polarization of LPV_{11b}, i.e., LPV_{11b,x,y}, are employed to analyze the polarization multiplexing property of modes. The modes are further investigated in terms of bending property of fiber, observing high loss for LPV_{21,a,y} channel compared to the other three channels.

Furthermore, OAM modes in FMF along with LP modes and RCF were also investigated. In [41], the combination of LP and OAM modes i.e., LP₀₁, LP_{11a}, LP_{11b}, OAM₊₁, and OAM₋₁, in 5-km FMF was used to analyze the performance of analog signals' transmission. It was shown that mode relative losses of different modes influence the analog transmission, and higher order modes suffer from degradation in SFDR due to high loss. However, with the same mode relative loss, all modes show similar performance. Nevertheless, FMF supports only few lower order OAM modes [63]. It was also reported in [37] that due to short length and high capacity requirements, OAM modes are suitable for fronthaul links. Since OAM are less prone to inter-modal crosstalk compared to LP modes due to their distinct propagation constants.

On the other hand, SDM in radio-over-multicore fiber has been proposed to increase the capacity, scalability and flexibility of the analog mobile fronthaul links. To this end, in [22] the simultaneous transmission of LTE-A and worldwide interoperability for microwave access (WiMAX) RF signals was demonstrated over 150-m four core MCF considering both linear and non-linear optical power regime of fiber. It was shown that by exciting the underlying Kerr non-linearity in MCF, the EVM fluctuations due to random nature of fiber can be reduced [22], [50], [51]. Similarly, MIMO and carrier aggregation over MCF for fronthaul was proposed and evaluated in [52]–[54]. Various configurations of

single-input-single-output (SISO), MIMO and carrier aggregation were investigated over 15-m of four core MCP utilizing different cores for uplink and downlink transmissions. It was shown that carrier aggregation has no effect on signal quality provided that the carriers are not overlapped in the spectrum. Besides, it was revealed that existing 3GPP MIMO algorithms can be effectively applied to MCF in fronthaul applications, which increase the data rate multiple times compared to SISO at the expense of merely few dB of power penalty [52]–[54]. To further increase the system capacity and spectral efficiency, a 4×4 MIMO radio over four cores of 20-km seven-core MCF system was demonstrated using sparse code multiple access (SCMA) and OFDM/OQAM schemes [55]. Moreover, in [25] the transmission of bidirectional two RF channels of MIMO OFDM/OQAM signals over 20-km seven-core fiber and 0.4-m wireless link was experimentally demonstrated. For the uplink colorless transmission, an optical carrier is sent into the middle core of the seven-core MCF, which is split into two optical carriers at the remote cite for the modulation of the corresponding uplink signals. In addition, the simultaneous provision of 2G, 3G and 4G services was demonstrated over a reconfigurable radio-over-multicore fiber fronthaul in [56]. The signals from different standards were fed to the remote antennas through different cores of the MCF using the same frequency band for achieving reconfigurable Ro-FMCF fronthaul. On the other hand, in [57] the radio and power over MCF transmission was also demonstrated.

Furthermore, the feasibility of MDM for implementing MIMO RoF distributed antenna system (DAS) was experimentally demonstrated in [58] using MMF. It was reported that the wireless MIMO algorithm capable of overcoming the distortion and crosstalk in both wireless and low power optical channels. Likewise, it was experimentally demonstrated in [59], [60] that the distribution of wireless MIMO signals in in-building DAS is feasible through MDM in commercially-available MMF infrastructure even under a tight fiber condition. Besides, in [61] the statistical characteristics of RF MIMO signals was studied in MDM using MMF. Similarly, in [62], an MIMO enabled DAS architecture was simulated by employing mode group division multiplexing (MGDM) in combination with WDM in plastic optical fibers (POFs) for MMW communication. It was shown that the generation of MMW 2×2 MIMO signals at the RAUs is feasible by using MGDM and WDM in POF.

The state-of-the-art literature review of analog mobile fronthaul systems reveals that A-RoF based fronthaul with SDM technologies for achieving C-RAN and seamless fiber-wireless integration cannot be avoided within the list of high gain, flexible and scalable fronthaul system designs for 5G and beyond of wireless networks. Since A-RoF transport solutions with SDM and WDM technologies can achieve high bandwidth and energy efficiency, high flexibility and scalability, high centralization, low latency and cost-effectiveness. Thus, in this paper, a high capacity MDM based MIMO enabled photonic A-MMWoF fronthal architecture

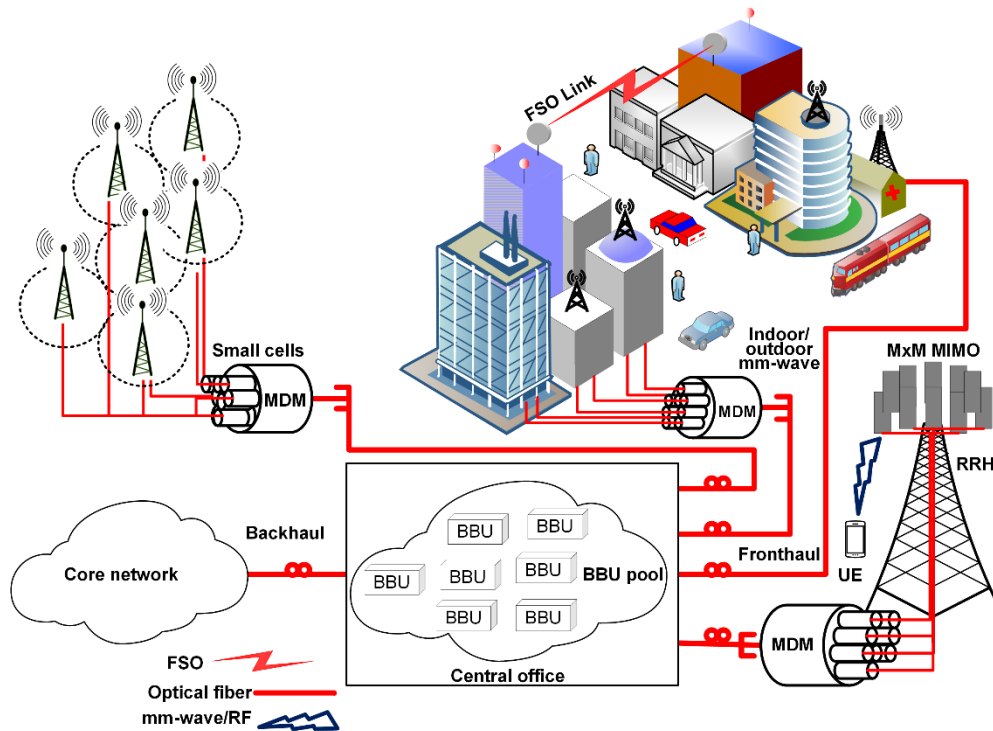


FIGURE 3. A generic MDM based MMWoF fronthaul architecture. UE: user equipment, FSO: free space optical, MDM: mode division multiplexing.

is proposed, which is discussed in details in the next section.

III. MDM BASED MIMO ENABLED ALL-OPTICAL A-MMWoF FRONTHAUL ARCHITECTURE

A general overview of the fronthaul architecture is shown in Figure 3, where BBUs in the central office are connected to the RRHs/RRUs/RAUs through optical fiber transmission links in various potential different configurations. It supports both indoor and outdoor MMW communications along with macro and small cell environments. The schematic of system design, configuration and detailed operation of the proposed wavelength reused symmetric bidirectional A-MMWoF fronthaul architecture are shown in Figure 4. To achieve high capacity gain in the fronthaul links, SDM and WDM technologies are employed in the proposed architecture design. SDM is realized through MDM using LP modes as separating multiple optical channels in a single FMF as an alternative to multiple standard SMFs. It can also be employed through OAM modes using specialized fibers, such as RCF. Since FMF supports only few lower order OAM modes [63]. It should also be noted that a large number of LP modes usually encounter more crosstalk than OAM modes as they propagate along the fiber. This is because LP modes share common eigenmodes, whereas OAM modes are constructed from distinct eigenmodes [37]. Moreover, SDM through MCF and FM-MCF can also be considered depending on the requirements.

For high capacity multiplexing gain and diversity gain in the wireless domain, MMW MxM MIMO signals are used, which are also realized here and can be adopted according to the system requirements. The MMW signals' generation is realized through optical heterodyne at the RRHs/RRUs/RAUs. Consequently, the corresponding MMW MxM MIMO signals are generated and distributed in the optical domain using MDM along with WDM. Usually RF signals are generated in electrical domain, nevertheless, considering the ultra-high speed mm-wave signals, photonic based techniques are more suitable. Because of low system complexity, low cost, high tunability, high spectral purity, and long transmission distance, they are considered advantages over their conventional electrical counterparts [64], [35]. Moreover, different techniques have been developed to generate MMW signals in the optical domain based on modulated optical signals with the MMW frequency difference. However, the most promising of them is the heterodyne beating of two optical signals, separated by the required MMW frequency, together on a high speed photodetector [65]. Since MMW signals generation through remote heterodyne methods not only overcome the problem of transmission span limitation due to optical fiber dispersion [12], but also greatly reduces system and network complexity, foot-print as well as CAPEX and OPEX. Therefore, in the design of 5G fronthaul, where massive number of RRHs are expected to be connected to the BBUs, optical distribution and remote heterodyne generation of MMW signals is considered a cost-effective

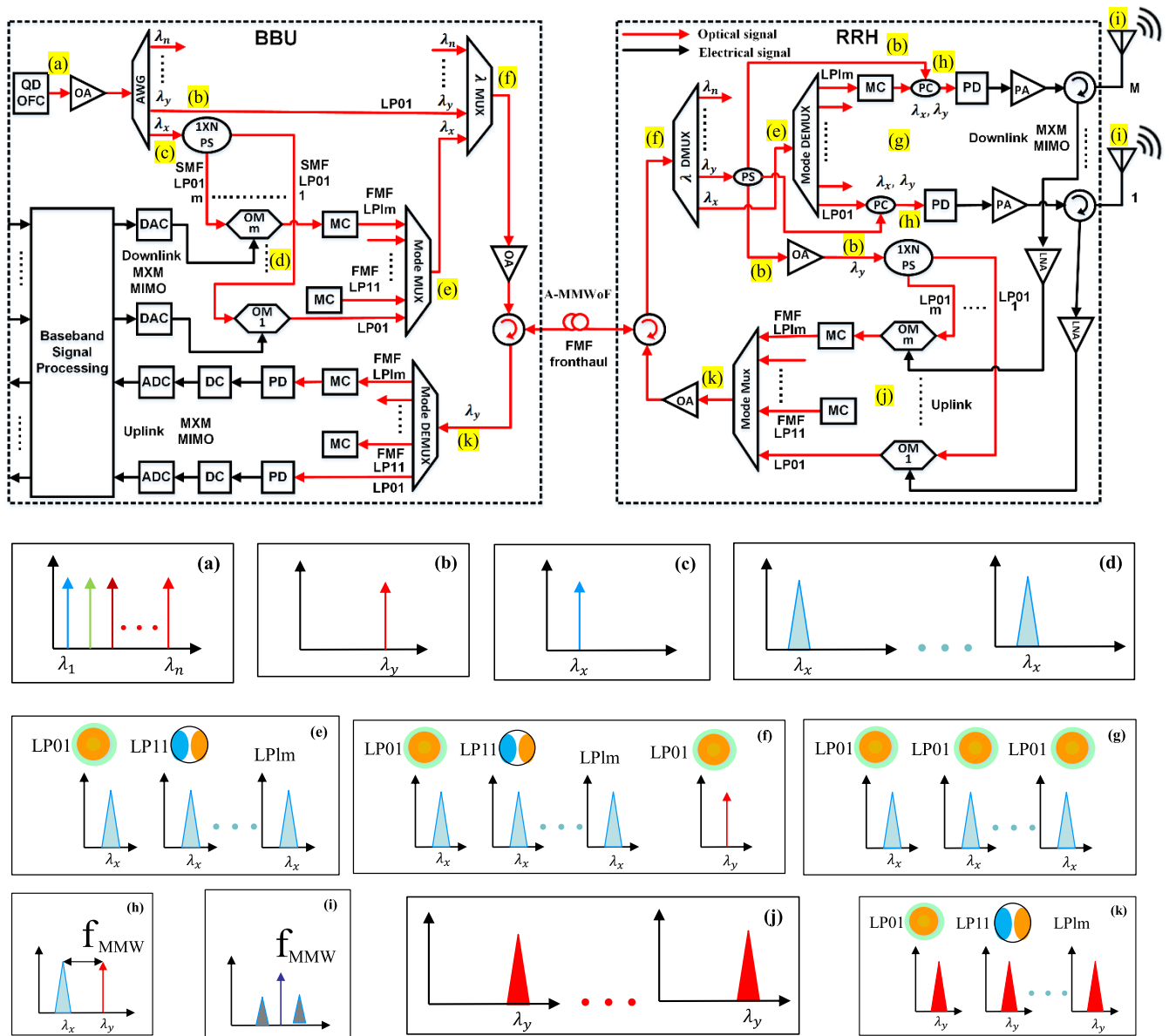


FIGURE 4. Design of symmetric bidirectional MIMO enabled all-optical A-MMWoF fronthaul system using MDM in FMF. Description of (a) - (c) optical spectrum, (d) downlink modulated signals' spectrum, (e) - (g) downlink modulated and unmodulated signals in various modes, (h) beating signals' spectrum, (i) the spectrum of corresponding MMW carrier along with modulated sidebands, and (j) - (k) uplink modulated signals and their representation in various modes. QD: quantum dot, OFC: optical frequency comb, PS: power splitter, SMF: single mode fiber, FMF: few mode fiber, MUX: multiplexer, DEMUX: de-multiplexer, OM: optical modulator, MC: mode converter, DC: down conversion, DAC: digital to analog converter, OA: optical amplifier, PD: photodetector, PA: RF power amplifier, LNA: low noise amplifier, LP1m: linearly polarized modes.

and flexible approach. However, MMW signals in optical domain are commonly generated by using commercially available single frequency laser sources, which might not achieve MMW signals with high spectral purity due to the lack of coherence and correlation between the laser sources themselves. Since their phase noise imparts to the generated MMW signals, hence degrading the system performance. Thus, the characteristics of the resultant MMW signals heavily rely on the spectral purity and stability of the laser sources used. It has been recently shown in [35] that the performance

of system with 5G candidate multicarrier modulation formats is greatly affected by the phase noise, therefore, imposes strict requirements on the uncorrelated optical sources for use in 5G heterodyne MMW communication systems. Consequently, in the proposed design, we include multi-wavelength quantum dot (QD) coherent optical frequency comb laser as an optical beat source due to their low phase noise and relative intensity noise (RIN) characteristics [66]–[68].

In the proposed design, in the BBUs, one/few (depending on system requirements) of the multiple coherent optical

carriers from QD comb source are used for downlink data transmission of MMW MxM MIMO signals over the LP modes through MDM in FMF while another optical carrier (s) is transmitted as an auxiliary carrier for use in heterodyne MMW signals generation and uplink transmission in the RRH/RRU/RAU as shown in Figure 4. The design is flexible and scalable, depending on system requirements, multiple optical carriers can be used for both downlink and uplink transmission with different combinations of spatial modes.

In a simple scenario, its principle operation at the BBU is such that two wavelengths λ_x and λ_y (where $x, y = 1, 2 \dots n$, and $x \neq y$) with the required MMW frequency difference are selected from the optical carriers of coherent QD comb source as shown in Figure 4(a) - 4(c), respectively. λ_x is intended for carrying downstream data transmission channels while λ_y is set to be used for upstream signals' modulation and heterodyne MMW signal generation at the remote unit. The light of λ_x with fundamental mode LP₀₁ is split into m paths by a 1-to- m splitter, which are modulated by potential 5G modulated RF signals using external optical modulators as depicted in Figure 4. The description of the corresponding modulated signals is shown in Figure 4 (d). The design is transparent to the modulation formats and supports all of the 5G candidate waveforms including simultaneous transmission of different multiple RF signals. In addition, optical beamforming can also be easily employed in the proposed system design. The corresponding modulated signals are converted from LP₀₁ modes to specific LP_{lm} modes of FMF by mode converter (MC) and combined by low crosstalk mode multiplexer (Mode-MUX) as shown in Figure 4 (e). Consequently, these m modulated signals and a supplementary carrier channel are multiplexed using wavelength multiplexer (λ -MUX), amplified and transmitted over FMF from BBU to RRH. The spectra of these signals are depicted in Figure 4 (f).

At the RRH, the optical carriers carrying supplementary channel and data signals are de-multiplexed using a wavelength de-multiplexer (λ -DEMUX). The corresponding data carrying optical carrier λ_x is sent to a low crosstalk mode de-multiplexer (Mode-DEMUX) followed by MCs to extract the modulated individual data signal as shown in Figure 4 (g). Then each of them is sent to the respective photodetector (PD) for MMW signals generation after combing them with the corresponding supplementary optical carrier as depicted in Figure 4 (h). On the other hand, the supplementary optical carrier λ_y is split into different paths where part of them are used in heterodyne generation of the corresponding MMW signals and the rest is amplified and further split into m paths, which are then fed to the respective optical modulators for upstream signals modulation similar to that of downstream as shown in Figure 4 (j). The corresponding generated MxM MIMO MMW signals are sent to the respective antennas for wireless propagation as shown in Figure 4 (i).

Similar to the downlink transmission, the corresponding uplink MMW modulated signals are converted onto higher order LP modes using MCs followed by mode multiplexing, amplification and transmission over FMF to the BBU as

described in Figure 4 (k). In the BBU, the uplink signals are mode-DEMUXED and down converted to the desired frequency before sending them to based band processing. Although in this example, the use of only two wavelengths are realized, nonetheless, the spectral efficiency and data rate can be further increased by using the combination of more wavelengths and more spatial modes at the expense of merely few dB of power penalties. However, this is cost-effective compared to using multiple parallel single mode fibers. In addition, in this example, we have realized MDM through LP modes, nevertheless, OAM modes can also be used. Thus, with this simple design concept, a flexible MxM MIMO enabled all optical processing based MMWoF fronthaul can be achieved for 5G and beyond of wireless networks. We believe that the proposed design is capable of achieving high speed, high capacity, low latency, and high flexibility and scalability.

IV. CHALLENGES AND POTENTIAL SOLUTIONS

The key challenges in the design of fronthaul architecture for next generation of wireless networks are to avoid the capacity bottleneck and to achieve low latency and high centralization. A-RoF technology is introduced as an enabler to overcome the capacity limitations and to simplify the fronthaul design by achieving C-RAN as highlighted in the literature review. Since A-RoF fronthaul supports simultaneous transmission of various RF signals ranging from low frequency to MMW and multiple radio access services, such as 4G, 5G, and WiMAX. Moreover, the A-RoF fronthaul will become more scalable and flexible when tailored with SDM technology, which can be achieved by leveraging MDM in FMF, MCF, RCF or the combination of them. This not only increases the capacity but also reduces the latency, cost and complexity.

However, A-RoF fronthaul is prone to various impairments such as nonlinearity impairments, chromatic dispersion and other noises, which deteriorate the performance of A-RoF transmission. With multiple higher RF signals, A-RoF link is prone to IMD due to nonlinearity caused by RF electrical and optical components in the link. Since A-RoF transmission faces non-linear characteristics, which induce power penalties and IMD; hence limiting the transmission distance. Thus, linearization is required either through the components design or other techniques, such as pre-distortion and post-distortion techniques. In the case of direct modulation, a rationally low modulation depth at the laser is required in order to gain operation in linear region. Moreover, A-RoF transmission has length depended issues for high RF signals. Since chromatic dispersion is a problem at higher RF frequencies, i.e., >10 GHz, which severely limits the propagation of high RF or MMW signals. Chromatic dispersion can be significantly reduced by using IFoF, which also relaxes the demand for very high speed optoelectronic components associated with the A-RoF link. However, this will increase the complexity of the RRU where stable local oscillators and mixers will be required for frequency translation. This can be overcome by generating and distributing the RF/MMW

signals in the optical domain. The RF/MMW signals are generated remotely through optical heterodyning. Nevertheless, generating MMW signals in the optical domain with high spectral purity is a challenging issue due to the high dependence of wireless transmission performance on the linewidth and phase noise attributes of the generated MMW signals, which in turn depend on the spectral purity and coherence of the optical sources generating them [69]. Thus, it requires optical sources with narrow spectral linewidth and low intensity noise, such as quantum dot coherent comb lasers [66].

On the other hand, the major impairments in SDM tailored A-RoF links are the inter-modal crosstalk, inter modal dispersion due to differential mode delay and other mode dependent losses due fiber bending etc., which limit the SFDR of the links. Consequently, this limits the transmission distance as well as the full spatial multiplexing capability. These impairments can be overcome by designing optimized component and specialized optical fibers, and by using digital signal processing algorithms, dispersion compensation component and optimized combinations of modes in MDM.

V. CONCLUSION AND POTENTIAL FUTURE WORK

In this paper, a high capacity MDM based MIMO enabled photonic A-MMWoF fronthaul architecture is proposed for 5G and beyond of wireless networks. The proposed architecture is supported by a comprehensive state-of-the-art literature review on the recent research trends in high capacity A-RoF fronthaul systems and related transport technologies. In addition, the challenges of current digitized fronthaul and analog fronthaul are explored and the corresponding potential solutions are highlighted. It is discovered that a high capacity fronthaul for realizing centralized processing can be achieved by fiber-wireless convergence through RoF technology. However, the current D-RoF fronthaul is foreseen to experience capacity bottleneck in the future networks. A-RoF is one of the appealing technologies that can be used to avoid capacity crunch and achieve seamless fiber-wireless conversion with high centralization in 5G and beyond of wireless networks. A-RoF approach not only increases the capacity but also reduces the, latency, cost and complexity. Moreover, the capacity of A-RoF fronthaul links can further be improved by employing SDM technologies and leveraging other multiplexing technologies such as WDM and PoIM.

As a future work, the proposed fronthaul design will be implemented and experimentally evaluated with various application scenarios using different data modulation formats, MIMO configurations and SDM schemes. Moreover, since the application of SDM in mobile fronthaul has recently been introduced and not much research work is devoted to it. It is discovered from the literature review that only few spatial modes in MDM and few cores of MCF have been investigated for A-RoF fronthaul applications over short distances. Thus, the investigation of large number of different spatial modes' combination within the same wavelength and different wavelengths over longer distances is crucial. Moreover, it is also worth researching to know the maximum number of possible

spatial modes that can be efficiently multiplexed with low inter-modal crosstalk for simultaneous transmission of analog RF/MMW signals with maximum distance. Besides, MDM in few mode multicore fiber (FM-MCF) is worth investigating for very high capacity gain in future A-MMWoF/A-RoF fronthaul links. In addition, the feasibility of MDM using OAM spatial modes can be further studied in the future mobile fronthaul links and their performance can be compared with LP spatial modes. Besides, novel optical components, such as mode converters, Mux/DeMux, modes specific optical amplifiers and specialized fibers are required for both LP and OAM modes.

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