Analogue Radio Over Fiber Aided Optical-Domain MIMO Signal Processing for High-Performance Low-Cost Radio Access Networks

Yichuan Li, Fasong Wang, Mohammed El-Hajjar, *Senior Member, IEEE*, Lajos Hanzo, *Fellow, IEEE*

***Abstract*—Wireless communication is facing an ever-increasing thirst for high-quality data transmission. However, this imposes high demands on the radio access networks (RAN), where optical fiber has been widely used both for the backhaul and fronthaul. However, the explosive escalation of wireless tele-traffic tests the limits of the RAN's revenue vs cost trade-off, which motivates low-cost designs. Hence, we present a cost-efficient yet high-performance radio over fiber (RoF) aided RAN concept. We commence by introducing this motivation, followed by a brief introduction to analogue RoF (A-RoF) and digitised RoF (D-RoF), as well as to wireless multiple-input-multiple-input (MIMO) techniques. Then, we present the centralised RAN (C-RAN) concept relying on A-RoF aided MIMO signal processing, where the MIMO signal is carried by fiber and it is processed optically in a central unit. Subsequently, we focus our attention on a C-RAN small-cell application followed by our performance vs cost analysis of the A-RoF system compared to that of its baseband counterparts, demonstrating that the A-RoF design is capable of reducing the RAN's total cost, whilst meeting the third generation partnership project's (3GPP) requirements.**

Index terms Optical fiber, Small Cell, Analogue radio over fiber, radio access network, C-RAN, MIMO.

I. Introduction

Our life-style has been radically changed by the information revolution [1] as exemplified by the innovative smart phones and tablets as well as the rapid evolution of artificial intelligence, paving the way for wireless futures [1]. Established to connect the terminals to the core networks, the radio access network's (RAN) evolution relies on Billions of investment funds in support of compelling, but bandwidth-thirsty new applications [1]–[3]. Therefore, it is important to carefully consider the underlying performance versus cost trade-off concerning RAN designs, where the performance is typically quantified in terms of the bit error ratio (BER), signal-to-noise ratio (SNR) or the achievable throughput. By contrast, the total cost of ownership takes into account both the Capital Expenditure (CAPEX) of the network's construction and the Operating Expenditure (OPEX) [2]. Generally, the frequency, space, time, code and polarisation domains [3] can be exploited as the available degrees of freedom that can be used for supporting a multiplicity of users at a flawless performance [3]. Although numerous techniques can be used for substantially boosting the network performance attained [3], striking an appropriate performance versus cost trade-off is always of vital importance.

In the context of the capacity-driven industry aiming for ever-increasing transmission rates, we consider the RAN design from the perspective of enhancing the performance at a low cost. Over the past three decades, three wireless generations have been rolled out, which relied on ever-smaller cells and on inceased frequency-reuse factors, with the ambitious goal of inching closer to a reuse factor of unity. This facilitated the support of more users and an increased area spectral efficiency expressed in $bits/sec/Hz/Km^2$.

As a remedy, we conceived a novel RoF aided MIMO design, which is capable of supporting a high-performance yet cost-efficient C-RAN in densely populated small-cell environments. We show that the proposed solution relying on central processing is capable of significantly reducing the OPEX of outdoor cellular systems by considering the following salient design issues:

1) **Issue 1:** A large number of base stations (BS) has to be supported in densely populated areas, which constitutes a challenge in terms of their substantial energy- and cost-requirements [4].
2) **Issue 2:** Given the limited spectrum available for mobile communications, it is essential to consider the achievable area spectral efficiency [3] as a design metric.
3) **Issue 3:** Both the inter-cell and intra-cell interferences are aggravagated by supporting more users [1]. Additionally, the inter-cell interference maybe increased by the reduced distance among BSs.

Then, considering the performance versus cost trade-off, the above-mentioned issues can be addressed by the following solutions:

1) **Issue 1** is directly related to the expenditure of deploying more BS towers designed for supporting more users. Centralised networks based on RoF mitigate the cost by splitting the functions of the traditional BS [2] between the central unit (CU) and the remote radio head (RRH). The CU hosts the baseband unit (BBU) carrying out most of the digital signal processing and carrier modulation. In the C-RAN architecture, the simplified RRH only performs radio functions, hence significantly reducing the OPEX. More explicitly, the OPEX is reduced when considering the network upgrade and management as well as site rental costs, primarily because a CU can support multiple small cell BSs. A 50% OPEX saving may be attainable compared to traditional base stations [2]. This will be further discussed in the next section.

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Yichuan Li is with Pengcheng Laboratory and Harbin Institute of Technology (Shenzhen), Shenzhen, China (e-mail: liych@pcl.ac.cn)

M. El-Hajjar, and L. Hanzo are with the School of ECS, University of Southampton, SO17 1BJ, United Kingdom (meh@ecs.soton.ac.uk; lh@ecs.soton.ac.uk).

Fasong Wang is with Zhengzhou University, Henan, China (e-mail: iefswang@zzu.edu.cn).

2) **Issue 2** and **Issue 3** are related to the spectral efficiency and to the deleterious effects of interference, which are related to the achievable throughput and system reliability. Multiple-antenna based MIMO techniques are capable of supporting beamforming as well as of providing both diversity and multiplexing gains with the aid of so-called multi-functional MIMO transceiver designs [5].

In a nutshell, multi-functional MIMOs achieve both throughput, diversity and beamforming gains, while RoF techniques assist in centralising the complex power-thirsty BS, hence resulting in reduced OPEX. Therefore, we intrinsically integrate MIMO schemes with RoF-aided centralised systems, where we aim for a high-performance yet low-cost system design by processing the MIMO signal in the optical domain, with the objective of striking a compelling performance versus cost trade-off. More explicitly, upon appropriately shaping the optical signal either by filtering or by phase-shifting, the multi-functional MIMO signal processing conventionally performed in the electronic baseband domain can be translated into the optical domain. This eliminates the electronic MIMO signal processing in the RRHs, hence potentially reducing the OPEX by beneficially exploiting the RoF's capability of centralising most of the electronic signal processing. The rest of the paper is organised as follows. In Section II, we introduce the current status of RoF. Then in Section III our optical solutions are presented, followed by our performance vs cost analysis. Finally, potential future research ideas are illustrated, followed by our conclusions.

II. Status of RoF

RoF systems convey RF signals in the optical frequency band over fiber. They can be used in numerous scenarios, such as cable television (CATV) by exploiting the wide bandwidth of the optical fiber [6]. Similarly, the ground station of satellite communication systems may invoke RoF transmissions for concentrating the signal processing in a central station, whilst flexibly positioning the antennas at the best location [6]. On a similar note, outdoor cellular networks can potentially benefit in the same way from having distributed antennas and central processing, hence, substantially reducing the OPEX of BS cooling and the overall management costs [7]. In this section, the classic D-RoF and A-RoF concepts are introduced and compared. Finally, we will opt for A-RoF for our MIMO designs, since it reduces the remote site's total power-consumption. Furthermore, in contrast to D-RoF, A-RoF systems require lower bandwidths by avoiding the sampling and digitisation [8], [9]. Quantitatively, it is shown in [9] that a 16 $\times$ 16 MIMO system using a D-RoF based 4G fronthaul requires a bandwidth of 295 GHz if using rectangular signalling pulses for digital transmissions whilst the A-RoF system having the same configuration only requires a bandwidth of 10 GHz.

A. Digitised RoF Solutions

A general D-RoF system is shown in Fig. 1, where we highlight the functions of each CU and each RRH at the right side. In the CU, the baseband-modulated symbols are up-converted by the carrier modulation of Fig. 1 [10], followed by the digitisation of the modulated RF signals using the ADC block of Fig. 1, where the RF signals are sampled and then quantified to digital signals. Finally, they are modulated and transmitted at optical wavelengths via electro-to-optical (E/O) conversion. Then, the optical signal carrying the digitised RF signals is conveyed by the optical fiber to the RRHs. In the RRH block of Fig. 1, the optical-to-electronic (O/E) conversion maps the modulated optical signal back to the digitised RF signal, prior to the digital-to-analogue conversion (DAC) of Fig. 1. The recovered RF signal will then be transmitted over the wireless channel by performing filtering and amplification for removing the unwanted out-of-band modulation products and then amplifying the attenuated signal. Again, this system avoids any sophisticated signal processing at the RRH, as depicted in Fig. 1. As a benefit, the digital optical link is capable of improving the system performance by mitigating the fiber-induced impairments with the aid of channel coding [10].

However, since D-RoF relies on the digitisation of high-frequency signals, it requires a high sampling frequency and a high-resolution ADC [7]. As a design-alternative, the A-RoF dispenses with digitisation altogether as well as with power-thirsty ADC and DAC, hence it is capable of supporting broadband services by invoking lower-bandwidth optical transmitters [11]. Therefore, in this treatise, we will rely on the A-RoF design concepts, since we aim for a low-cost RRH design. Next, we briefly describe the A-RoF solutions.

B. Analogue RoF Solutions

We also show the schematic of a general A-RoF downlink system in Fig. 1, where the ADC and DAC used for digitising/recovering the RF signal in the D-RoF architecture in Fig. 1 is removed, which we mark using dotted lines. Explicitly, as seen in Fig. 1, in the CU, the modulated RF signal is E/O-converted by using an optical transmitter before being transported over a fiber link to the RRHs. Then, in the RRH, the optically carried RF signal is photo-detected (O/E conversion), filtered by a BPF and amplified by an electronic amplifier (EA) before being directly transmitted over the wireless channel. Again, the only substantial difference between A-RoF and D-RoF is eliminating the digitisation process. Hence, by avoiding the ADC/DAC process which would increase the bandwidth requirement by a factor b, where b is the number of bits/sample after digitisation, A-RoF requires a lower-bandwidth optical transmitter in the CU and imposes a reduced power-consumption at the remote antenna site [7]. Therefore, A-RoF transmission supports the employment of low-complexity RRHs imposing a reduced cost and bandwidth requirement, which is crucial for service-oriented wireless systems requiring flexible resource allocation for high-rate data transmission. To be more explicit, the A-RoF structure may be readily integrated into small-cell systems, leading to a super-light small cell base-stations, while supporting high-bandwidth transmissions using the existing infrastructure.

However, A-RoF suffers from the limited dynamic range in terms of the optical transmit power and it is susceptible both to the fiber's nonlinearity and to its dispersion, which consequently limits the attainable fiber length to a few kilometers [7]. In particular, the fiber-link's nonlinearity including that of the four-wave mixing, cross-phase modulation and self-phase

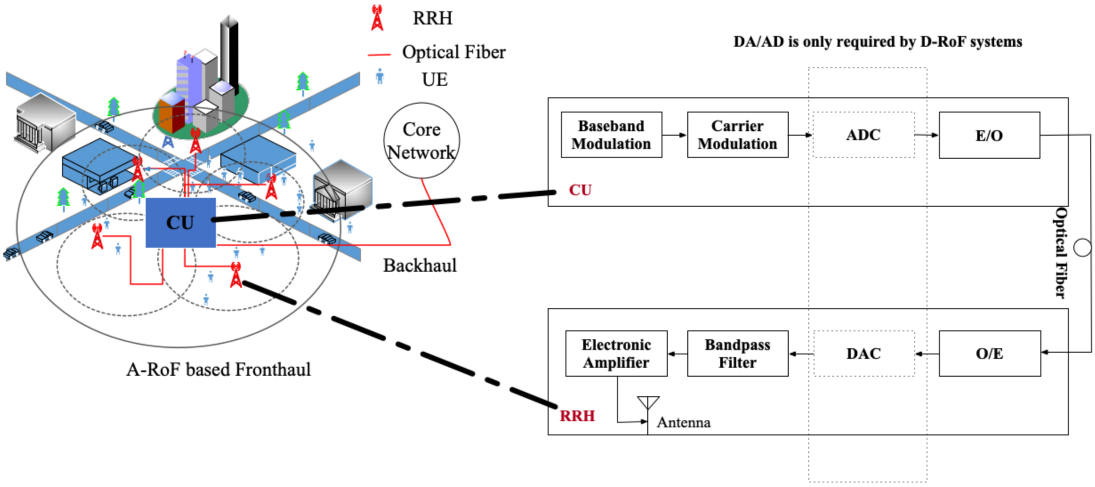

Fig. 1: RoF aided C-RAN system.

modulation as well as the optical modulation nonlinearity potentially degrade the A-RoF's performance [11]. Fortunately, nonlinearity mitigation techniques of optical injection locking and optical feed-forward linearization are capable of mitigating these impairments [11]. Therefore, A-RoF is only suitable for short-length (e.g, < 20 km) fiber-based radio access networks. Therefore, A-RoF techniques have been primarily used in millimeterWave (mmWave) [12] C-RAN systems [4] and in indoor LANs [11] for short-range transmission using plastic optical fiber [12]. But, again, A-RoF and MIMOs may be beneficially amalgamated into a cost-efficient high-performance centralised system, hence we focus our attention on A-RoF aided MIMO assisted RANs.

III. A-RoF Aided MIMO Processing for Small-Cell C-RAN Designs

In this section, we conceive a cost-efficient optical solution for densely populated A-RoF aided small-cell C-RAN systems. Observe in Fig. 2 that in our proposed small-cell C-RAN system, the CU carries out the baseband signal processing tasks of modulation, pulse shaping, digital modulation etc., while the RRH is only responsible for the low-complexity functions of filtering, amplification and transmission [2]. The C-RAN architecture is primarily deployed in densely populated areas, such as a football stadium or shopping mall. Note that we advocate all-optical MIMO signal processing, where no electronic MIMO processing is needed in the RRH of Fig. 2. More explicitly, the signals forwarded to the MIMO arrays are appropriately processed in the optical domain to avoid power-thirsty electronic devices in the RRHs. This would be exceptionally beneficial for high-bandwidth mmWave signals, since their electronic processing is challenging using the limited low-bandwidth off-the-shelf electronic components, such as ADC/DACs and RF modulators.

In this context, we briefly introduce the philosophy of optical processing aided MIMO solutions in our fiber-based C-RAN systems, as shown in Fig. 1 and Fig. 2.

In the A-RoF aided C-RAN downlink of Fig. 1, the backhaul connects the core networks and the CU, while the C-RAN fronthaul links connect the CU to the RRHs using optical fiber. Thus, a single CU is capable of supporting several RRHs with the aid of a cost-efficient, high-flexibility centralised

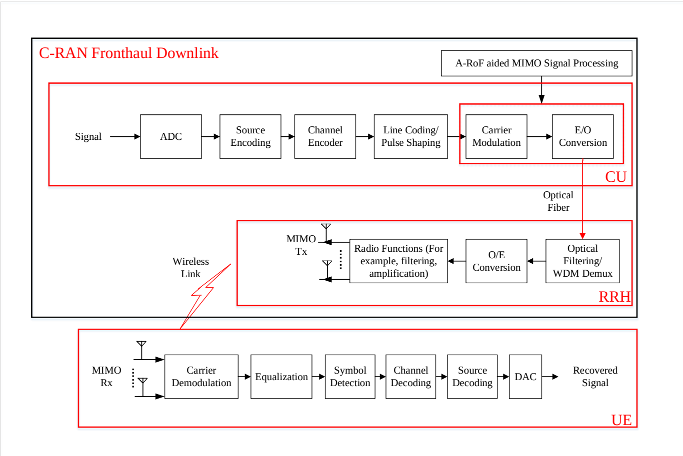

Fig. 2: A-RoF aided MIMO signal processing in the C-RAN downlink.

RoF downlink design. The detailed functional map of the A-RoF aided MIMO signal processing conceived for the C-RAN downlink is provided in Fig. 2, where we show the digital processing blocks of ADC, source coding, channel coding, line coding/pulse shaping and the RF modulation followed by E/O conversion, which are implemented within the CU. Furthermore, as shown in Fig. 2, the RRH only has to carry out the low-complexity functions of optical filtering, O/E conversion as well as RF functions, filtering and amplifications.

In Fig. 2, the optical-domain MIMO signal processing can be performed by exploiting carrier modulation and E/O conversion, where the multi-stream MIMO concept can be implemented in the optical domain either by optical side-band selection for feeding the activated antennas of the popular spatial modulation (SM) scheme [4]. Alternatively, fiber Bragg grating (FBG) may be used for true time-delay based beamforming [12] or optical filter banks may be employed for appropriately mapping the space-time-block-coding symbols to the corresponding antennas for achieving a beneficial transmit diversity gain [12]. The above-mentioned techniques are capable of totally eliminating the electronic MIMO signal processing. Explicitly, in [4], we take advantage of the optical modulator's side-band selection capability relying on a low-

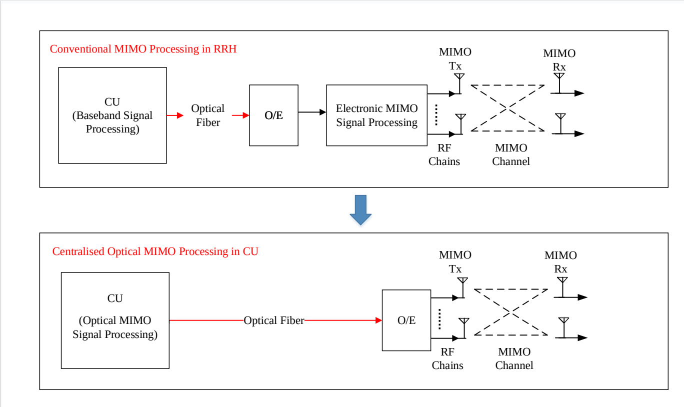

Fig. 3: Centralised A-RoF aided MIMO Processing in CU contrasted to electronic MIMO signal processing.

complexity mapping process, like for example that of classic frequency shift keying (FSK), which selects for example a single tone out of four for signalling 2 bits/symbol. Our system concept was verified by using an experimental demonstration of two optical bandpass filter of 0.114 nm 3dB bandwidth being centered at 1550.174 nm and 1550.094 nm [13]. As a design alternative, in [12], both analogue beamforming and transmit diversity gains have been achieved using the drive-frequency of E/O conversion for controlling the direction of the transmitted RF beams with the aid of the time-delay difference introduced by the FBG, hence potentially eliminating the electronic phase-shifters in the RRHs.

In a nutshell, as seen in Fig. 3, the conventional electronic MIMO scheme relies on signal processing to be carried out by the RRH, potentially increasing the RRH's complexity. By contrast, in the centralised optical MIMO processing we may completely dispense with the electronic MIMO signal processing in the RRH by invoking optical processing techniques, which simplifies the RRH design as exemplified above.

Next, we further detail our high-performance yet cost-efficient solutions.

IV. Performance vs Cost Trade-off

Let us now compare our A-RoF solution to a conventional system. Recall from Fig. 3 that the system employing the above-mentioned A-RoF aided multiple-antenna techniques including beamforming, spatial modulation and transmit diversity is much less complex and yet it exhibits an almost negligible bit error ratio (BER) degradation compared to the traditional base-station assisted MIMO downlink.

Let us now discuss the cost-efficiency of the proposed optical solutions with special emphasis on their OPEX and energy-saving, which are the most influential factors in the cost of a C-RAN [2]. In contrast to the MIMO scheme of [4], the popular spatial multiplexing (SMX) scheme based on optical signal processing is shown in the right graph of Fig. 4. Explicitly, Fig. 4 shows the traditional baseband-over-fiber RAN and our proposed A-RoF based RAN, where spatial multiplexing (SMX) relying on four transmitter streams is supported. The MIMO signal processing and RF carrier modulation of the A-RoF RAN fronthaul advocated in Fig. 4 is moved to the CU, when compared to the baseband over fiber (BBoF) RAN architecture of Fig. 4.

We list the components used for either the CU or RRH for both cases in Table I, where it is shown that in the A-RoF scenario, the power-thirsty ADC and MIMO-DSP are replaced by the passive optical components, which do not require a source of energy for their operation. As seen in Table I, the number of hardware components in the RRHs of the A-ROF RAN fronthaul is substantially reduced, namely from 20 to 13. Furthermore, a third of them are passive components, hence reducing the energy-consumption of the RRHs. This results in OPEX-savings in terms of maintenance, site-rental, network updates and cooling of the RRHs. It is estimated that 50% OPEX savings can be achieved using a C-RAN architecture compared to the conventional architecture [2]. For example, assuming a cellular system having a cluster size of 7, the number of high-complexity RRHs of the BBoF is linearly by proportional to the cluster-size of 7, hence proportionately increasing both the energy-consumption and the construction-cost. Furthermore, the power-thirsty ADC having a high sampling rate in the conventional system in the left graph of Fig. 4 dissipates an exceptionally high power according to the Texas Instrument Report [14]. Thus, the energy-consumption can be potentially further reduced by replacing both the ADC and the MIMO-DSP blocks by passive optical components, such as the WDM-Demux of the spatial multiplexing example of Fig. 4, as shown in Table I. This cost-reduction results in particular benefits for small-cell systems, which will rely on numerous RRHs in a densely populated area [2].

Hence, the primary benefit of the A-RoF over the conventional BBoF design is the employment of low-cost RRHs in the ultra-dense C-RAN systems considered. To quantify the performance of the 4×4 MIMO system proposed in Fig. 4, We portray the error vector magnitude (EVM) of the right graph of Fig. 4 in Fig. 5 for evaluating how distorted the received signal is. Explicitly, the EVM of a single channel of a 15 Gbps 64 QAM system carried by a RF of 3 GHz for meeting the high-data rate requirement of 5G and beyond is recorded in Fig. 5, where the optical central wavelength and the wavelength spacing are 1550 nm and 200 GHz, respectively, while the single mode fiber branded by Corning-28e is used. Here, we use a WDM spacing of 200 GHz and the RF of 3 GHz as a design example, where the commercial coarse WDM (CWDM) requiring 100 GHz or 50 GHz can be readily employed using the corresponding WDM components. We implemented a 15-km fiber-optic system using the Optisystem Platform, which is a popular optical research framework, where an equal laser power is measured after each LD of of the right graph of Fig. 4. Fig. 5 also shows that when the laser power ranges from -2 to 22 dBm, the EVM of the proposed A-RoF RAN solution of Fig. 4 meets the 3GPP 5G EVM requirement of 8% [8] upon transmitting the signal through a 15-km fiber link. Furthermore, we characterise the systems relying on both single-antenna and twin-antenna RRHs, which also demonstrates having an EVM level below 8% [8] for a laser power ranging from -4 to 24 dBm and from -2 to 22 dBm, hence demonstrating the robustness of our A-RoF system, although the total cost including the CAPEX and OPEX is near-linearly proportional to the number of WDM components. However, the system shows a degraded EVM exceeding 8%, when the laser power is higher than 26 dBm due to the fiber-link's non-linearity.

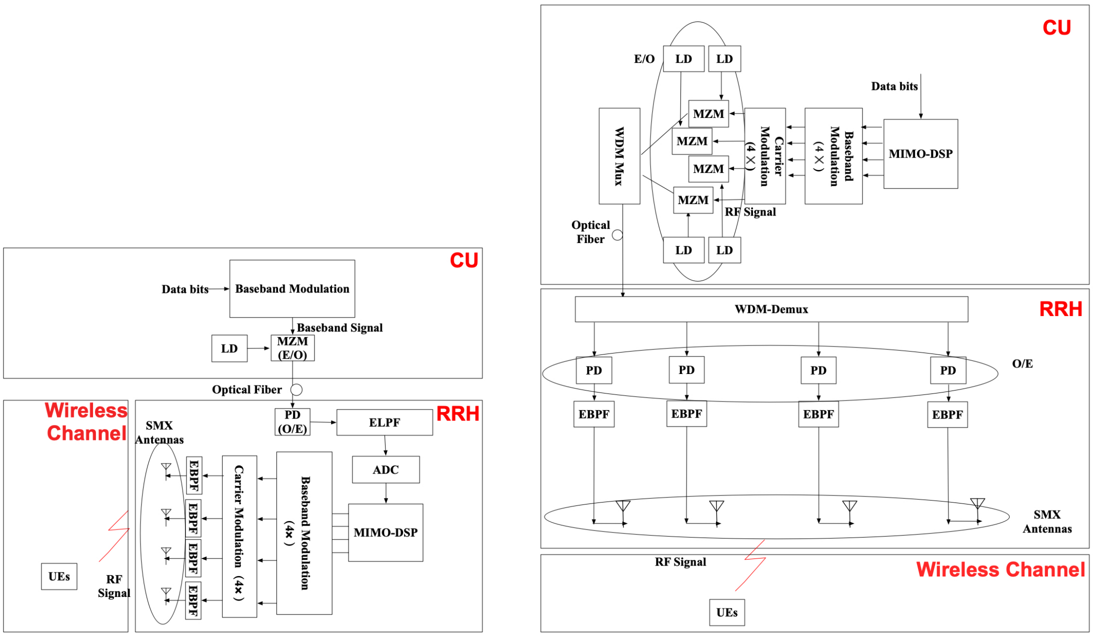

Fig. 4: Left: Spatial Multiplexing (SMX): BBoF RAN Fronthaul; Right: SMX: Our A-RoF Solution.

TABLE I Number of Components used in the BBoF and A-RoF RAN Fronthaul. MZM: Mach-Zehnder Modulator, LD: Laser Diode, LPF: Low-Pass Filter, ADC: Analogue-to-Digital Converter, MIMO-DSP: MIMO Digital Signal Processing, EBPF: Electronic Band-Pass Filter, EBPF: Electronic Low-Pass Filter, WDM-Mux: Wavelength Multiplexer, WDM-Demux: WDM Demultiplexer.

Components	Passive Components?	BBoF RAN Fronthaul		A-RoF RAN Fronthaul	
		CU	RRH	CU	RRH
Baseband Modulation	×	1	4	4	0
MZM	×	1	0	4	0
LD	×	1	0	4	0
PD	×	0	1	0	4
ADC (Symbol detection and bits demapping)	×	0	1	0	0
MIMO-DSP	×	0	1	1	0
Carrier Modulation	×	0	4	4	0
ELPF	×	0	1	0	0
EBPF	×	0	4	0	4
Antenna	×	0	4	0	4
WDM-Mux	✓	0	0	1	0
WDM-Demux	✓	0	0	0	1
Total		3	20	18	13

V. Potential Future Research

There is a paucity of information in the open literature on the performance and cost of the fiber-based RAN system. A-RoF has been to a degree renounced by the industry given its susceptibility to fiber-link impairments [10]. However, the service-oriented 5G standard requiring large bandwidth advocates an A-RoF aided MIMO solution as an explicit benefit of its cost-effective yet robust nature. Thus, in this section, we propose some future research ideas on optical MIMO signal processing:

1) **Optical processing aided beamforming by exploiting the different delays of multi-mode fiber (MMF) modes:** Explicitly, the MMF introduces different delays by the different modes and the resultant phase shifts can be exploited for generating beamforming patterns. However, the effects of mode coupling and fiber bending should be considered. More specifically, an accurate multi-mode channel model has to be conceived for the sake of characterising the associated delay and coupling behaviour. Furthermore, the feasibility of flexibly controlling the MMF's delay differences can be explored for delaying the signal fed into the antennas for analogue beamforming, hence improving both the SNR and inter-channel interference rejection.
2) **Mode division multiplexing (MDM) based MIMO-aided Analogue Radio over MMF:** MDM designed for multi-mode fiber is deemed to be the next revolutionary technique following the conception of laser, low-loss silica fiber, optical amplifiers and WDM in the optical communication history [15]. Furthermore, in the context of our A-RoF RAN system, MDM may be integrated with wireless MIMO techniques for further simplifying the RRH by avoiding components, such as the WDM Mux/Demux. Mitigating the deleterious impact of mode coupling and of mode delay are only some of the numerous impairments, which have to be considered in our future research, especially in the challenging context

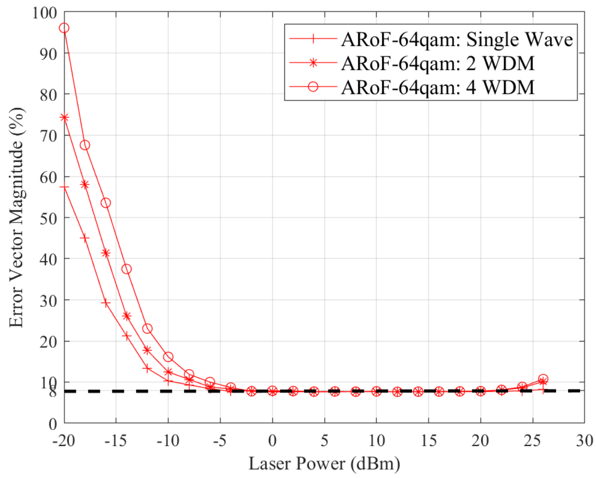

Fig. 5: The EVM performance of the proposed 4×4 A-RoF system shown in Fig. 4.

of MIMO signal processing.

VI. Conclusions

The ever-increasing demand for flawless tele-presence requires more base stations and RF chains for supporting enhanced mobile broadband services at a diminishing cost. In this article, we have provided a future RAN vision based on a high-performance yet cost-efficient optical solution, where the MIMO signal is processed centrally in a CU using A-RoF techniques. In the context of densely populated small-cell areas, we have demonstrated that the OPEX can be substantially reduced compared to the conventional BBoF RAN, while satisfying the EVM limit of 8% set out by the 3GPP 5G standards. As a further benefit, the resultant flexible central processing based design is eminently capable of supporting radically new software-defined networking functions for achieving further energy-efficiency improvements.

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Yichuan Li(liych@pcl.ac.cn) received his Ph.D degree in wireless communications from the University of Southampton, Southampton, UK. in 2019. Since May 2019, he has been working as postdoctoral researcher with Pengcheng Laboratory and also with Harbin Institute of Technology (Shenzhen), Shenzhen, China.

Fasong Wang(iefswang@zzu.edu.cn) received the Ph.D. degree in communication engineering from Xidian University in 2013. He is currently an associate professor in the School of Information Engineering, Zhengzhou University, China. From 2016 to 2017, he was a Visiting Scholar with Southampton Wireless Group at the University of Southampton. His current research interests include secrecy communication, blind signal processing, compressed sensing, sparse representation and their applications. He has published more than forty journal and conference papers on these topics.

Mohammed El-Hajjar(meh@ecs.soton.ac.uk) is an Associate Professor in the Department of Electronics and Computer Science in the University of Southampton. He received his PhD in Wireless Communications from the University of Southampton, UK in 2008. Following the PhD, he joined Imagination Technologies as a design engineer, where he worked on designing and developing Imagination's multi-standard communications platform, which resulted in several patents. He is the recipient of several academic awards and has published a Wiley-IEEE book and in excess of 80 journal and conference papers. Mohammed's research interests include the development of intelligent communications systems, energy-efficient transceiver design, MIMO, millimeter wave communications and Radio over fiber network design.

Lajos Hanzo(lh@ecs.soton.ac.uk) (http://www-mobile.ecs.soton.ac.uk) (FIEEE'04, Fellow of the Royal Academy of Engineering F(REng), of the IET and of EURASIP), received his Master degree and Doctorate in 1976 and 1983, respectively from the Technical University (TU) of Budapest. He was also awarded the Doctor of Sciences (DSc) degree by the University of Southampton (2004) and Honorary Doctorates by the TU of Budapest (2009) and by the University of Edinburgh (2015). He is a Foreign Member of the Hungarian Academy of Sciences and a former Editor-in-Chief of the IEEE Press. He has served several terms as Governor of both IEEE ComSoc and of VTS. He has published 1900+ contributions at IEEE Xplore, 19 Wiley-IEEE Press books and has helped the fast-track career of 123 PhD students. Over 40 of them are Professors at various stages of their careers in academia and many of them are leading scientists in the wireless industry.