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Technological Trends in Open Fronthauls for Beyond 5G and 6G Networks

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Abstract

Ultra-massive interconnection composed of extremely small to minuscule networks that are significantly overloaded is required for the fifth generation (5G) and the next sixth generation (6G) networks. In order to meet the demands for network flexibility, complete coverage, and huge access, the conventional radio access network (RAN) will be completely revamped. This study focuses on the technological trends in the requirements-fulfilling Open RAN (ORAN) architecture and essential technologies in this regard. In particular, the study investigates the potential of Radio over Fibre (RoF) and Passive Optical Networks (PON) for Open Optical Front Hauls (OOFH) and trends in AI algorithms, for enhancing system performance and network intelligence simultaneously. The article showcases experimental results using OpenRAN Gym, an open-source, practical platform designed for end-to-end system design, data collection, and testing workflows aimed at intelligent control in next-generation Open RAN systems. Two xApps developed with OpenRAN Gym are demonstrated, managing a large-scale network of 10 base stations and 60 users deployed on the Colosseum testbed. Performance is assessed by analyzing transmitted packets and buffer occupancy. Additionally, an OFH system with Analog RoF is tested, using linearisation techniques to reduce the Error Vector Magnitude (EVM) to below 2%. The study also includes an experimental MIMO Fi-Wi OFH case, where a 5G new radio waveform achieves a 3% EVM, complying with the 3GPP standards.

Keywords

open radio access network; radio over fibre; fibre wireless system

1. Introduction

In Internet of Things (IoT) networks, unmanned aerial vehicles (UAVs) have emerged as a popular and practical solution to connectivity problems. The number of applications for a variety of devices found in these networks, such as smart farming sensors, smart traffic sensors, and monitoring devices, has significantly increased. Furthermore, strict requirements, such as very low latency and greatly increased bandwidth per unit area, have been imposed by the introduction of 5G and future mobile services. Due to this, base stations (BSs) must provide greater resources and guarantee higher availability. The application of unmanned aerial vehicle

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base stations (UAV-BSs) is one of the modern options that has attracted a lot of interest from the research and business communities. The goal of this strategy is to satisfy the many and constantly expanding needs in unforeseen and transient scenarios that are challenging to handle with the current infrastructure. UAV-BSs are attractive in these situations for a number of reasons.

Firstly, the mobility and agility of UAVs enable rapid deployment of flexible infrastructure for unique situations, such as one-time events or disaster-affected areas. In these cases, existing infrastructure may struggle to meet user demands due to recurring issues like power outages or an overwhelming number of users. Second, line-of-sight (LOS) communication allows UAV systems to connect with ground users in a reliable manner that surpasses the capabilities of traditional cell tower-based solutions [1]. All things considered, UAVs utilised as base stations offer practical solutions to address instability, mobility, and connectivity problems in a variety of scenarios and satisfy the evolving demands of IoT networks. To support the terrestrial network, the recently published ORAN design is utilized to create an airborne 5G O-RAN architecture, as shown in Figure 1[2]. In addition to providing 5G services, this technology enhances quality of service (QoS) and temporarily maintains the conventional network infrastructure. While O-RAN presents a plethora of new opportunities, it also presents entirely new challenges regarding network architecture, deployment, setup, optimisation, automation, and operation. Unlike typical RAN systems, O-RAN components—most notably the Open Radio Unit (O-RU), Open Distributed Unit (O-DU), and Open Centralised Unit (O-CU)—can be implemented flexibly and independently. Open interfaces are created utilizing various approaches to link these components, with certain objectives such as security and service quality being taken into consideration. Therefore, the best routing algorithms need to be used to ensure the efficient operation of this UAV-based ORAN system. The optimisation of resource allocation for task offloading with UAVBSs has been the subject of numerous studies. A game theory-based strategy was put forth in an earlier study to maximise the goals of energy, delay, and processing cost [3]. However, the authors' system only had a power constraint and ignored other crucial aspects like latency, resource constraints, and routing techniques. They also failed to take into account flexible work sharing across UAVs and edge/cloud servers. Another study, utilizing game theory and reinforcement learning, explored the application of AI in UAV data offloading within a multi-server Mobile Edge Computing system. [4] . They overlooked the routing problems and their effect on performance even though they suggested a non-cooperative game for partial data offloading. Although task transfer from UAVs to edge or cloud data centres was addressed in another method, the energy component was overlooked.[5] By reducing the strain on mobile devices with limited processing capabilities, computation offloading in the RAN improves service quality. Parallel task processing is made possible by new RAN architectures such as D-RAN, C-RAN, and V-RAN, which provide distributed computing resources through access points, base stations, edge, regional, and core cloud centres [6,7]. An effective method for organizing and scheduling offloading jobs in Fog RAN was provided by the authors in [8]. putting out a task-granularity-aware offloading technique based on C-RAN [9]. However, due to their major impact on latency and task execution delay, routing and compute resource allocation concerns need to be properly handled in order to fully realise the benefits of the emerging distributed RAN architecture. The disaggregated architecture of O-RAN, which offers resource units like OCU, O-DU, and O-RU flexibility in deployment and scaling within the system, exacerbates these difficulties even more. 5G and beyond technologies are anticipated to become more and more common in the context of computation-intensive applications including telemedicine, virtual reality, augmented reality, and online gaming. Nevertheless, user equipment's (UE) limited processing power and battery limitations present difficulties. Offloading computation to distant cloud servers has been addressed by Mobile Cloud Computing (MCC), yet performance is impacted by transmission delays resulting from the distance between cloud servers and user equipment. In order to mitigate this problem, Mobile Edge Computing (MEC) reduces computation, energy consumption, and processing delays by bringing cloud resources closer to UEs. Different techniques have been presented by researchers recently for computational offloading in MEC systems. These algorithms can be categorized as either decentralized or centralized. Decentralised algorithms let each IOT device decide how to unload itself

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autonomously, whereas centralised algorithms entail a central controller making these decisions. Prior research mostly concentrated on stationary MEC system installations. A low-complexity heuristic method and a convex optimisation technique were suggested by Tran et al. for job offloading and resource allocation in a mobile edge computing system with numerous users and servers [10]. In a cloud-based MEC system, Zhao et al. focused on maximizing system utility through cooperation for compute offloading and resource allocation optimisation, taking into account multi-user and MIMO (multiple input and multiple output) scenarios [11]. For continuous power, Chen et al. proposed a dynamic production allocation technique based on Deep Reinforcement Learning (DRL) [12]. These scenarios, however, might not work in situations where there is a sparse distribution of communication facilities or rapid natural disasters for fixed infrastructure that is provided by MEC services [13]. A framework-based approach for penalty dual decomposition optimisation was created by Hu et al. to optimise UAV trajectory, compute offloading, and user scheduling simultaneously [14]. With an emphasis on energy conservation, Diao et al. presented an optimisation approach for combined UAV trajectory and task data allocation [15]. In a UAV-based MEC system, Li et al. used a reinforcement learning approach to increase the task migration throughput of UE [16]. In a MEC system employing unmanned aerial vehicles (UAVs), Selim et al. examined Device-to-Device (D2D) communication as an extra option for compute offloading and auxiliary communication. This particular study greatly advances the field by developing a UAV trajectory and offloading task allocation system within the O-RAN framework. To the best of current knowledge, this is one of the first studies to investigate, while accounting for all the distributed components of the O-RAN system, the usage of flying base stations to assist offloading jobs in O-RAN. While prior research has focused on utilizing reinforcement learning to optimise UAV trajectories, no study has looked at how UAV systems integrate with the decentralised architecture of O-RAN. The goal of the 5G of wireless networks is to increase capacity, end-to-end latency, and energy efficiency. As BS have multiplied exponentially, the RAN has become more centralised. A centralised radio access network (C-RAN) improves scalability and lowers the requirement for network maintenance, which helps save capital costs. Fronthaul (FH) links between baseband units (BBUs) and RRHs are necessary to support C-RAN. For sophisticated 5G applications and beyond, the fronthaul link needs to offer features like high speed, ultra-low latency, traffic protection, and protected data privacy. Fronthaul is important in network operations for small and macro cells, distributed antenna systems with RAN sharing, and the move toward RAN virtualisation and openness. Managing network controllers for fronthaul access networks (FANs) and RANs is another unsolved problem. Likewise, the main fronthaul solution is optical fiber. OFH links, like RoF lines, are the foundation of OFH, as Figure 1 illustrates. This transport mode is an important choice for high-capacity wireless transmission because of its simple and affordable paradigm, which increases the network's range. This transport scheme is a significant development for very high-capacity wireless transmission because of a simple and cost-effective paradigm that expands the network's coverage. Conventional C-RAN architecture utilised for 4G and next generations networks are based on Option 8 which divides functionality between PHY and RF. The increasing data speeds in 5G render this option impracticable due to the fronthaul interface's high bandwidth requirements. This option is frequently employed with a front-haul interface based on common public radio interface (CPRI) specifications. RoF networks include channel impairments and nonlinear distortions brought on by system components, which can be fixed using linearisation methods, notwithstanding the benefits of RoF, such as reduced electromagnetic incursions, lower loss rates, and greater bandwidth [17]. In this work, the current developments and issues have been addressed in optical communication for visible light communication, optical interconnects, and front haulage. The remaining portions of the paper are separated into the following categories. The technological developments pertaining to front-haul architecture and the necessity of an Open Radio Access Network (O-RAN) will be covered in Section II. While Section IV analyses the Fibre Wireless (Fi-Wi) integration system and explains the real-time deployment of OFH and Fi-Wi with performance enhancement, Section III highlights the developments in RoF systems. The Coherent WDM-PON- Based Hybrid System will be covered in Section V, and ML opportunities in optical and visible light communication will be covered in Section VI. The paper is finally concluded in Section VII.

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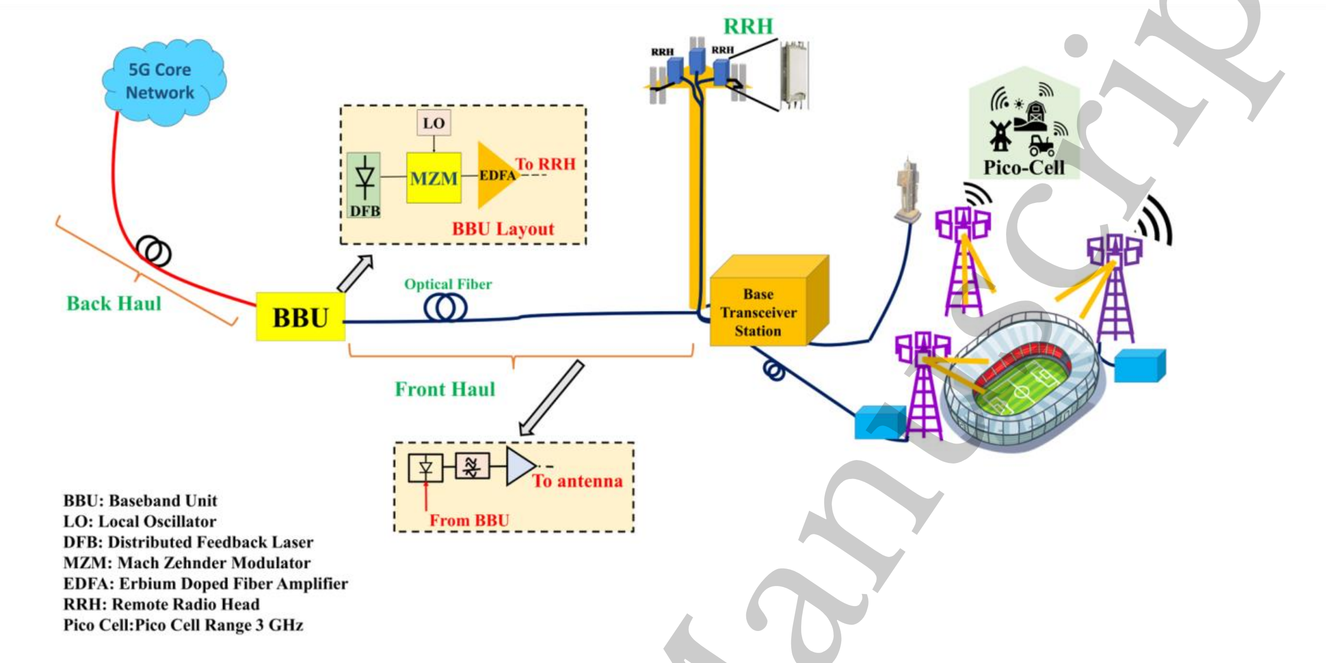

Figure 1: Block diagram explaining backhaul connection to the BBU connected to OFH and then its transmission from the transceiver station. The base station further connects it to the RRHs.

Materials and methods

2. Technological Trends Related to Fronthauls

Option 8 is the foundation of the conventional C-RAN architecture used in 4G and other future networks. It divides functions into PHY and RF layers. However, because of the fronthaul interface's high bandwidth requirements, this strategy becomes unfeasible as 5G data speeds increase. This method typically employs a fronthaul interface that complies with CPRI specifications; nevertheless, multi-vendor interoperability is difficult because to the numerous vendor-specific differences within CPRI.

To address these issues, the O-RAN Alliance is developing open fronthaul interface standards based on functional split Option 7-2x, one of the intra-PHY split options, to reduce fronthaul bandwidth requirements and enable multi-vendor interoperability. This section explores the technological trends of various functional split options for 5G fronthaul that are either under development or have been implemented (see Figure 2).

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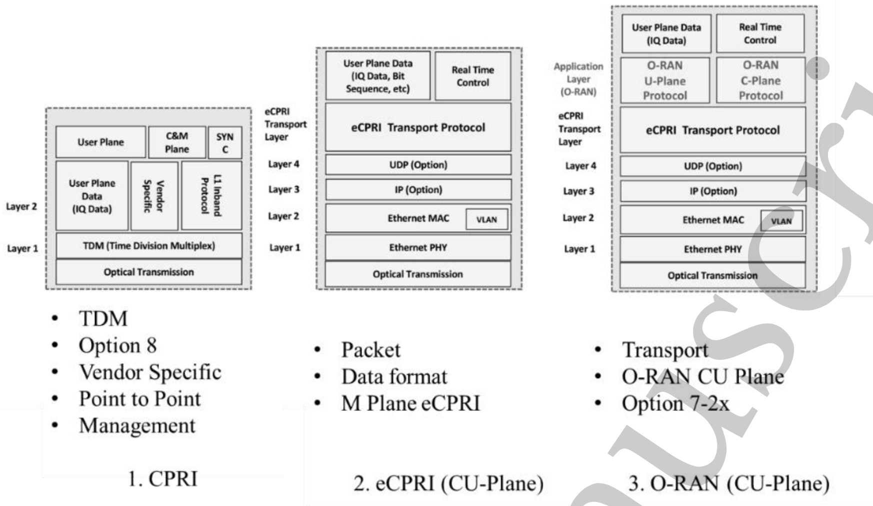

Figure 2: Comparison of protocol stacks and distinctions between fronthaul methods.

2.1 C-RAN (Centralised RAN)

The C-RAN architecture uses a fronthaul based on CPRI to separate functionality between the PHY and RF layers. To handle larger bandwidths, mmWave, massive MIMO, and backward compatibility with 4G networks, this technique is frequently used in 5G. Data transfer rates have been greatly increased utilizing Feature Split Option 8 in comparison to previous C-RAN architectures to support 5G services. Nevertheless, difficulties arise because this interface needs transfer rates of several hundred Gbps. These C-RAN fronthaul interface restrictions in providing 5G services are shown in Figure 2. For the RAN architecture, an advanced function split option beyond Option 8 is required to meet the high data rate requirements. Compatibility problems arise because of the multiple vendor-specific modifications in the CPRI specification.

2.2 CPRI

The principal signal link connecting the RU and DU is CPRI. This standard interface primarily uses Function Split Option 8 and is compatible with current 4G/5G C-RAN architectures. CPRI is a cooperatively developed network that uses point-to-point transmission and was created by firms such as Ericsson, Huawei, NEC, Nortel, Alcatel, Lucent, and Nokia. Between DU and RU, the CPRI interface facilitates the interchange of user-plane data, control and management data, and synchronisation data. Many vendor-specific components found in CPRI specifications cause compatibility issues between systems from different vendors.

2.3 eCPRI (Enhanced Common Public Radio Interface)

A packet-based fronthaul interface called eCPRI was created by the CPRI forum with help from companies like Ericsson, Huawei, NEC, and Nokia. In addition to being an O-RAN protocol, it makes advantage of packet transport networks. Compared to CPRI, the eCPRI interface offers greater flexibility by enabling user data transmission, synchronisation, control, and management. eCPRI has more options for PHY function splitting, whereas CPRI only supports Function Split Option 8. But like CPRI, eCPRI has problems with cross-vendor compatibility, and its management plane, or M-Plane, is still undefined.

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2.4 O-RAN

Future 5G and 6G network architectures will be less rigid and monolithic, with more disaggregated, adaptable, and agile designs. The requirement to support a variety of services, manage several technologies, and facilitate quick, on-demand deployments is what is driving this transition. By bringing in virtualisation, intelligence, and flexibility and creating open interfaces that encourage network innovation, the developing O-RAN framework encourages these developments. In order for O-RAN-based 5G and future 6G networks to be deployed, run, and maintained, artificial intelligence (AI) will be essential [18].

The O-RAN architecture is expected to offer cellular networks a number of services and applications, including virtual network slices and dynamic spectrum sharing. Fronthaul links geographically separated RUs to DUs in a regular or O-RAN. Due to the global deployment of 5G technology and the continuous advancement of technologies beyond 5G, fronthaul is now a crucial part of the RAN for achieving throughput, latency, reliability, and security balance. Mobile network operators and equipment suppliers have realised over the last ten years that RAN development requires a more adaptable and transparent approach, which is currently referred to as O-RAN. The phrase "O- RAN" refers to a comprehensive initiative that aims to remove obstacles to innovation and advancement while also simplifying the deployment and integration of multi-vendor mobile radio access networks. Such openness has been ensured because of the data-driven network paradigm, the specification of suitable interfaces between logical nodes, and the addition of new network elements capable of incorporating intelligence through the use of AI/ML implementation [19].

Four dimensions can be separated out of the O-RAN. Control and User Plane Separation (CUPS) make up the first dimension, which has already been completed in 5G/new radio (NR) systems, while horizontal disaggregation linked to opening interfaces is taken into consideration in the second dimension. While CUPS brings scalability and flexibility, ensuring synchronization between control and user planes, especially in dynamic and highly distributed environments, is challenging. This separation can also introduce complexities in maintaining security and managing network performance. The integration of hardware and software from multiple vendors introduces interoperability challenges, particularly when it comes to ensuring consistent performance and managing complex interactions between components. This also raises security concerns, as each additional vendor introduces potential vulnerabilities. The third dimension involves vertical disaggregation related to decoupling hardware and software. These elements have the potential to significantly impact the performance and optimisation of radio resource management (RRM). Ensuring interoperability across vendors requires stringent adherence to standards and thorough testing. In real-world deployments, variations in how vendors implement open interfaces can lead to performance inconsistencies and integration difficulties. Additionally, managing and optimizing these disaggregated components can be more complex than managing a unified system. The fourth dimension involves the disaggregation of software and data pipe through the introduction of AI/ML techniques and connectivity to external contextual data sinks. The reliance on AI/ML introduces new challenges, including the need for high-quality, real-time data to train algorithms effectively. Additionally, AI-driven decisions must be explainable, particularly in mission-critical applications where transparency is essential. Furthermore, the use of AI/ML increases the complexity of the network's control logic, and managing AI-based decisions across disaggregated components can be challenging. Security and privacy are also concerns, as AI systems can be vulnerable to data poisoning and adversarial attacks.

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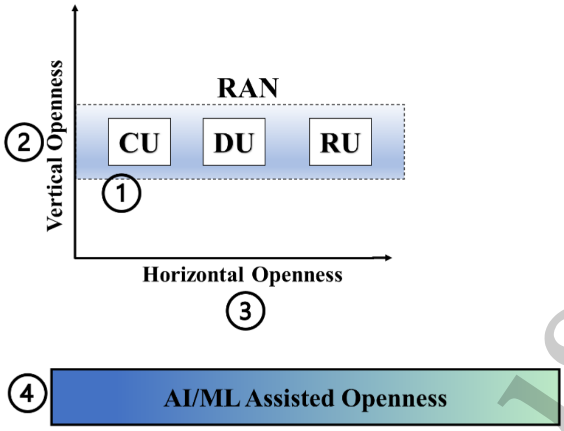

Figure 3: Openness and disaggregation along four dimensions: (1) User and Control Plane Separation; (2) Vertical Openness Enabling HW and SW Disaggregation; (3) Horizontal Openness Due to Open Interface Standardisation; and (4) ML Approach. RAN; CU; DU; RU

The main goals of the design of O-RAN fronthaul and mid-haul systems are to efficiently connect RUs to edge servers that house DUs and CUs, and to identify the best RU locations based on variables such as user distribution and long-term average throughput [20]. In C-RAN design, the best location of BBU pools for the fronthaul (split-8 only) interfaces is decided upon after users are assigned to RRHs. Consequently, unlike C-RAN, O-RAN's design is more sophisticated since it allows for more flexibility in fronthaul and mid-haul configuration as well as RU-DU-CU split option selection. By lowering the overall cost of O-RAN deployment, this strategy seeks to create a Fiber Wireless Integrated network deployment that is both economical and efficient. In the future, fronthaul bandwidth allocation optimisation will be determined by variables like user mobility, priority, or channel conditions.

An expansion of the 3GPP 7-2 split, which divides network functions among CUs, DUs, and RUs, O-RAN supports the 7-2x functional split. Lower-layer physical functionalities are handled by the RUs, and DU-RU communication is facilitated by the OFH interface. The DUs handle the higher physical and MAC layer responsibilities, while the remaining protocol stack is implemented in the CUs, which connect to the DUs via the F1 interface.

O-RAN deployments will rely mostly on self-organizing, intelligent technologies. A thorough understanding of O-RAN performance characteristics is necessary to guarantee effective operation. This section provides a basis for comprehending commercial implementations by summarizing experimental findings and lessons discovered during the deployment and use of O-RAN in real-world scenarios. The acquired knowledge can help develop sophisticated intelligence-based algorithms for the best possible system orchestration and management.

Visible Light Communication (VLC) presents a significant opportunity to enhance O-RAN, particularly as networks evolve towards 6G. By utilizing the visible light spectrum for data transmission, VLC can supplement traditional communications, especially in indoor environments such as hospitals, factories, and homes. This integration can offload traffic from congested RF bands, increasing network capacity and performance. VLC's ability to provide high data rates, leveraging existing LED lighting infrastructure, makes it a cost-effective solution for enhancing broadband access. In O-RAN architectures, VLC can be combined with fiber-wireless systems like RoF, serving as the final leg to deliver data to end-users via visible light, thereby extending coverage and reducing electromagnetic interference. VLC is also ideal for low-latency applications in O-RAN, such as industrial automation and augmented reality, where its negligible propagation delay offers a key advantage for ultra-reliable low-latency communication. Additionally, VLC's confined transmission, limited by walls and other barriers, enhances security and privacy, making it a valuable option for secure communication in environments requiring high levels of data protection. Furthermore, VLC contributes to energy

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efficiency, as it utilizes existing LED lighting systems for data transmission, aligning with O-RAN's emphasis on sustainability in 6G networks. However, challenges such as the need for line-of-sight communication and interference from ambient light remain, requiring ongoing research and development. By integrating VLC into the open and modular O-RAN framework, operators can harness this technology to meet the increasing demands for higher data rates, low-latency services, and energy-efficient communication in next-generation networks.

2.4.1 Experimental Results and Lessons Learned

A virtualised LTE system serves as the experimental platform, which is utilised to investigate O-RAN orchestration and deployment in real-world settings. It consists of two primary parts that are deployed on hardware of commercial grade: the RRHs and the Multi-access Edge Computing (MEC). The RRHs on the Software Defined Radios (SDR) platform are implemented using the Universal Software Radio Peripheral (USRP) hardware from National Instruments.

The MEC segment uses container-based virtualisation, facilitated by a Docker architecture, to manage baseband processing in a virtualized environment.. A full LTE stack implementation is achieved with Amarisoft, a commercial LTE BBU program that works with a variety of RF front-ends, including USRP devices. General Purpose Processors (GPP) can be used to run Amarisoft, which can then interact with system memory buffers to process samples. The CPU and RAM resources from the MEC pool that are assigned to the virtual LTE instances are represented by nodes, which are used by the LTE mobile stations (UEs) for communication purposes. These nodes run Ubuntu 16.04 LTS with a low-latency kernel on server-class computers with Intel Xeon CPUs. RRHs and BBUs can be connected fronthaul via 10GbE lines and a 10GbE switch. The primary experimental configurations are listed in Table 1, with a focus on O-RAN-relevant KPIs such as fronthaul performance implications, resource constraints, and CPU and RAM consumption.

Table 1. Experiment Parameters

Parameters	**Values**
Number of gNb	1 – 4
Number of UE devices	1-17
Antenna Case	MIMO
Modulation	256 QAM
UE type	USRP X310

The system under test's CPU utilisation is depicted in Figure 4(a), with usage scaled by the number of active UEs. No significant scalability issues are observed as the number of active users increases. One important discovery is that because both UL and DL signals must be simultaneously encoded and decoded, CPU use peaks in duplex mode. Furthermore, the uplink requires more processing power than the downlink, particularly when the number of devices increases. However, O-RAN systems are not significantly hampered by either CPU or memory utilisation. Based on the total LTE throughput attained, Figure 4(b) assesses the fronthaul design's influence. In virtualised RAN situations, this statistic highlights the need for a low-latency, high-efficiency fronthaul architecture.

The throughput obtained when operating the virtualised LTE system with MIMO setups across different bandwidths is shown in Figure 7(a), demonstrating that MIMO deployments result in higher performance. As seen in Figure 4(b), the performance is caused by the particular protocol and driver architecture employed in the USRP fronthaul, which introduces end-to-end latencies averaging 1 ms with peaks of up to 30 ms.

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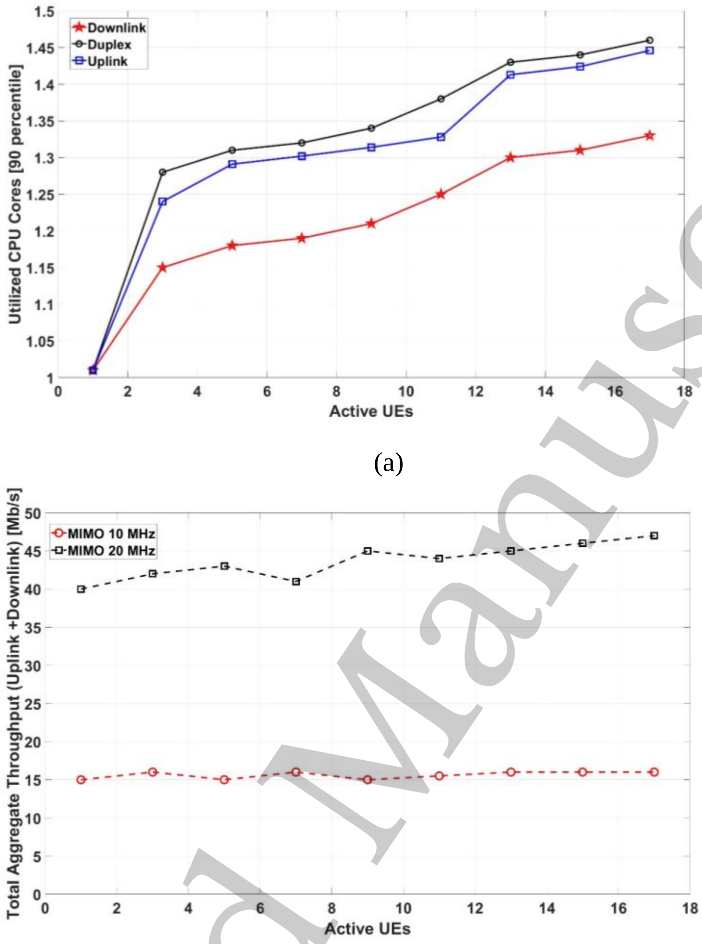

Figure 4: Number of active UEs compared to (a) Resource utilisation and (b) Total aggregate throughput (UL + DL)

Key insights from these experimental trials include:

Scalability

The results indicate that a virtualised LTE system has a minimal digital resource footprint in terms of RAM. Furthermore, because OFDMA is in place, CPU consumption does not rise appreciably as the number of users increases.

Multi-tenancy

In O-RAN virtualisation, the primary bottleneck is the capacity of the fronthaul link. While conventional servers can support many virtual eNodeBs in terms of processing and memory, accommodating the same number of eNodeBs requires very high fronthaul data rates.

Low-latency Design

The findings highlight the critical importance of a low-latency fronthaul for system performance. Ideally, the end-to-end latency between the RRH and BBUs should be an order of magnitude lower than the latency requirements of system algorithms or services. Consequently, conventional wireless systems can only be effectively virtualised and deployed at network edges, making cloud deployments impractical. Furthermore, communication protocols for data exchange between RRHs and BBUs must be swift, light-weight, and scalable.

Link Capacity

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The data rate between RRHs and BBUs is extremely high. Future research should focus on scalable methods to increase link capacity or techniques to reduce fronthaul data rates, such as compression algorithms. This issue is particularly relevant for high-bandwidth systems like LTE Carrier Aggregation and 5G.

2.4.2 Results with O-RAN Gym

We employ an efficient, open experimental toolkit called O-RAN Gym to support this research, which offers full data and design services for data collecting and testing in developing O-RAN systems [21]. Figure 5, adapted from [22], illustrates the O-RAN Gym architecture. It features: (i) one or more publicly-accessible experimental platforms for data collection and testing (e.g., Colosseum [23], Arena [24, PAWR program platforms [25]); (ii) a software RAN (e.g., implemented via srsRAN [26] or OpenAirInterface [27]); (iii) a data collection and control framework with APIs to manage cellular stacks and extract statistics (e.g., SCOPE [28]); and (iv) an O-RAN control architecture with interfaces for RAN management through AI/ML solutions (e.g., ColO-RAN [29]). O-RAN Gym's platform independence allows users to collect data, design, and train solutions in diverse environments before deploying them on production networks, enabling multiple evaluation and refinement iterations in controlled settings to ensure the final AI/ML model performs as expected. More details about this open platform can be found.

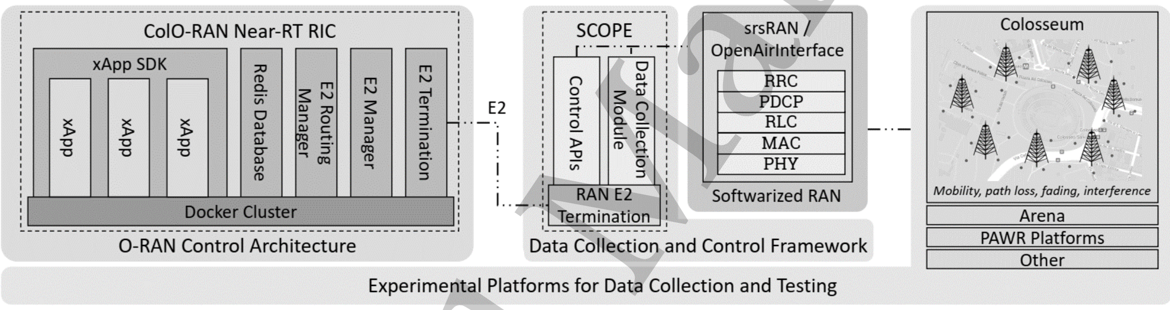

Figure 5: Architecture of O-RAN Gym

The performance analysis conducted using O-RAN Gym is now reviewed, which was used to control a cellular network with 10 base stations, 60 UEs (six a base station), and UEs that Colosseum started. To satisfy different QoS needs for the UEs, each base station provides three network slices: Machine-type Communications (MTC), Ultra-Reliable Low Latency Communications (URLLC), and Enhanced Mobile Broadband (eMBB).

As described, two xApps based on Deep Reinforcement Learning (DRL) were developed to dynamically control base station configurations using RAN Key Performance Measurements (KPMs).A dataset comprising 6 GB of RAN traces and more than 81 hours of experimental data was used to train these xApps. One xApp, called sched, is in charge of scheduling policies, and another, called sched-slicing, is in charge of allocating resources among various slices.

After these xApps are deployed on the ColO-RAN near-RT RIC to manage the network, Figure 6 shows the O-RAN's Cumulative Distribution Function (also known as the CDF). Statistics on the number of transmitted Transport Blocks (TBs) for the MTC slice and downlink buffer occupancy for the URLLC slice are shown in Figures 6a and 6b, respectively. The purpose of the xApps is to decrease the amount of time packets for URLLC traffic spend in base station queues and increase the rate at which MTC traffic is transmitted. By better controlling slice resource allocation, the sched-slicing xApp especially improves performance in terms of packet transmission and buffer occupancy.

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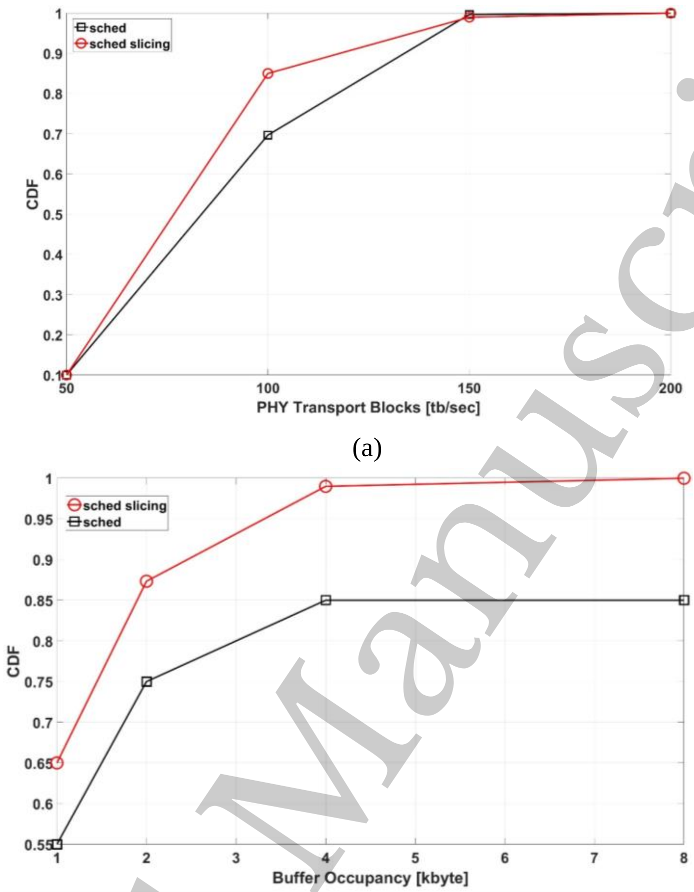

(a)

(b)

Figure 6: Statistics from the O-RAN Gym architecture on the downlink include (a) the number of transmitted Transport Blocks (TBs) for the MTC slice and (b) buffer occupancy for the URLLC slice.

3. Recent Trends in RoF as OFH

Radio over Fibre has been implemented in several different ways, including Analog Radio over Fiber (A-RoF) , Digital Radio over Fiber (D-RoF) [30-33], Sigma Delta Radio over Fiber (SD-RoF) [34–44], and other contemporary variations (see Figure 7). A-RoF links are, to some extent, the most straightforward, and cost-effective solution; nonetheless, they are hampered by nonlinearities brought on by signal imperfections and devices like laser modules, fibres, and photodiodes. The other alternatives involve using D-RoF or SD-RoF. When it comes to D-RoF systems, the process is quite expensive due to the need for analogue-to-digital conversion (ADC) and digital-to-analogue converters (DAC). In addition, CPRI limits exist because of the high data rate capacity and requirement of large bandwidth.

Addressing the nonlinearities of RoF transmission has become essential to fully maximize the system's capabilities. Many strategies have been used across all of these distinct fields to combat the pressing problems. As transmission quality declines and neighbouring channels begin to interfere, the contribution of nonlinearities from the laser and to some extent the photodiode component is crucial. However, when taking into account long-range networks, the key factor affecting signal quality is typically nonlinearities brought on by the interaction of fibre chromatic dispersion and laser frequency chirp. Recently, Vertical Cavity Surface Emitting Laser (VCSEL) nonlinearities were modelled using conventional techniques [45]. Digital Predistortion (DPD) has been the most common solution employed for these impairments. Conventional methods based on Volterra and other methods such as decomposed vector rotation [46-47], and recently machine learning solutions have given a breakthrough in performance enhancements and have opened a new avenue for technological advancements [48-51].

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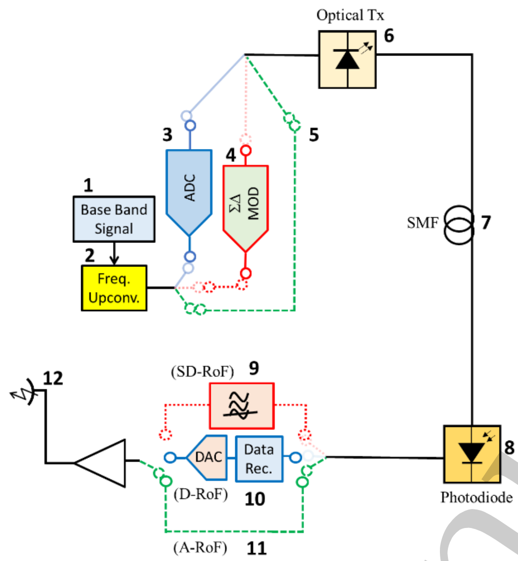

Figure 7: Types of RoF systems.

High-capacity wireless systems may efficiently generate and distribute mm-wave signals via ARoF connections based on optical heterodyning. Techniques that loosen restrictions on relative frequency drift and phase offset between the optical carriers with the least amount of added complexity are needed to facilitate the widespread implementation of these fibre-wireless systems [52-54]. In general, optical heterodyne ARoF systems using correlated lines can produce a variety of frequency-stable mm-wave carriers from a single device, resulting in a simple receiver architecture with reduced DSP requirements, though this may come at the expense of an increased optical source complexity [55-58]. The deployment of mm-wave A-RoF systems that can utilise two separate commercially available lasers is made possible by scaling up the DSP to include compensation or implementing more complex electronic receiver topologies. The precise application for which the mm-wave A-RoF system will be used will ultimately determine the optical source and signal processing combination that is employed [59-60].

When comparing the performance of the three primary optical fronthaul technologies,, ΣΔ-RoF proves to be superior to both A-RoF and D-RoF. Figure 8 illustrates this comparison. The primary advantage of A-RoF is its cost-effectiveness and widespread use, despite the fact that the other technologies generally offer better performance. This trade-off is why A-RoF is used, with its nonlinearities being managed to optimise its effectiveness.

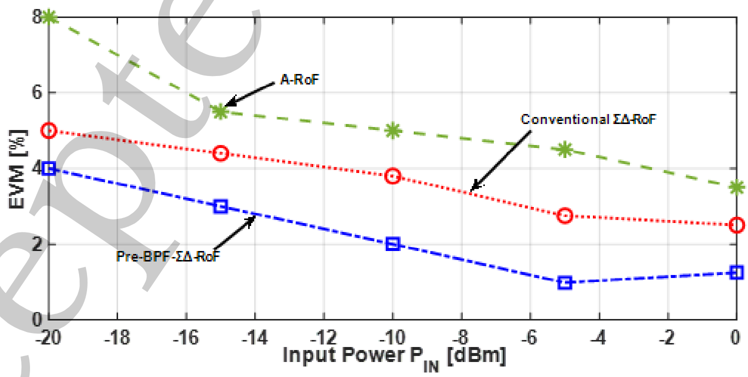

Figure 8: Performance of Different Types of OFH

3.1. Experimental Setup and Results for A-RoF OFH

To show the experimental realisation of the A-RoF OFH methodology, Figure 9 shows the proposed system that has been explored utilising an industrial use-case scenario. A supercell with a frequency of 3 GHz and an indoor femtocell with a frequency of 20 GHz are tested in the latest study as shown in Figure 9 [61].

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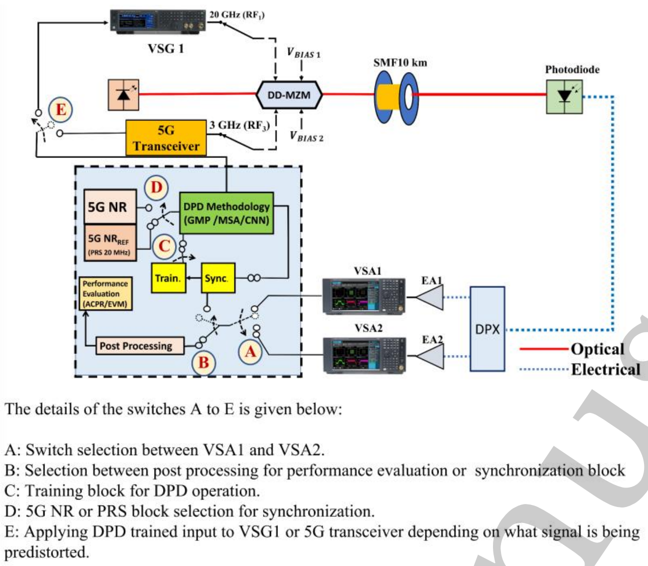
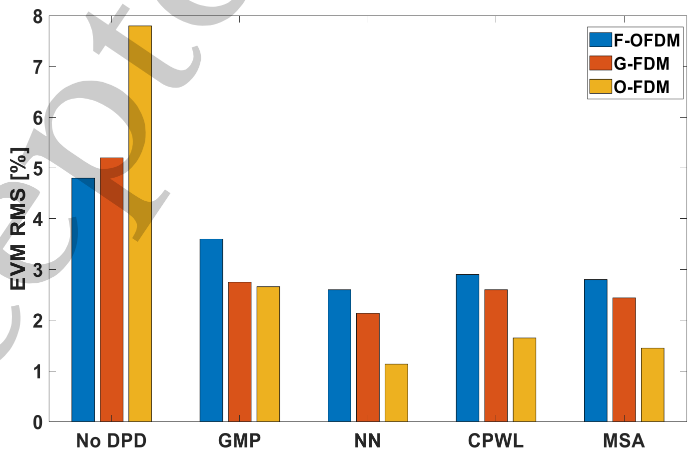


Figure 9: RoF OFH integration system was tested for 3 GHz and 20 GHz carriers. A Mach-Zehnder as an external modulator is used with a single mode fibre of 10 km deployed.

The EVM at different RF input power levels is displayed in Figure 10a. It is evident that magnitude selective affine (MSA)-based DPD reduces EVM to less than 3%, which is an improvement over the 5% EVM seen with generalised memory polynomial (GMP) approaches. While MSA-DPD provides a slight advantage over canonical piece-wise linearisation (CPWL), it is not a significant one. We expect comparable gains at a reduced complexity. Furthermore, DPD with neural networks (NN) performs 1% better than MSA-DPD. When compared to all other approaches, neural network DPD performs better than MSA between 0 and 5 dB, whereas MSA performs better between -15 and 0 dB [62–67]. EVM for various approaches applied to different flexible waveforms in the 5G NR architecture at 0 dBm RF input power is reported in Figure 10b. While less advanced than CPWL, MSA-DPD delivers comparable performance, achieving a 1% improvement over CPWL when using MSA. However, among all strategies, NN yields the best results, outperforming MSA.



(a)

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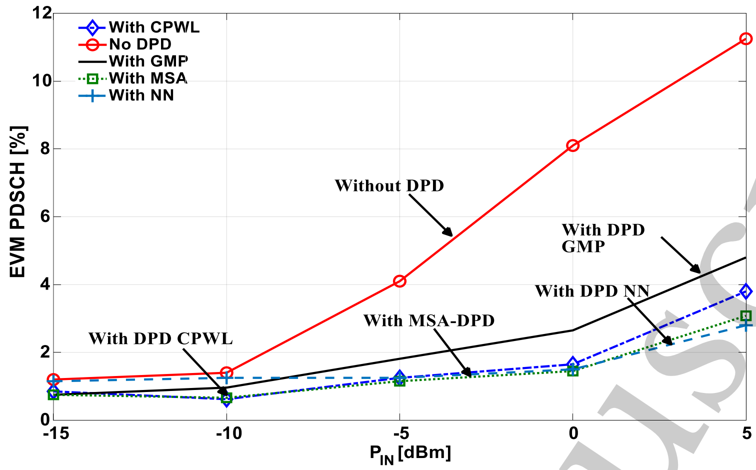

(b)

Figure 10: EVM results are shown in (a) for the DPD methods used in this study compared to the no DPD scenario, and (b) for the performance of 5G NR optical fronthaul, illustrating the effectiveness of DPD with and without its application for flexible 5G transceiver waveforms.

Power spectral density (PSD) is assessed in Figure 11 in conjunction with EVM. PSD calculates the difference between the power in adjacent bands and the power inside the useable band. Figure 11 illustrates the PSD in the no DPD situation, which is -25 dBc; the 3GPP standard places this limits at 35 dBc. Spectral regrowth is efficiently suppressed by DPD, maintaining it within the 3GPP bounds.

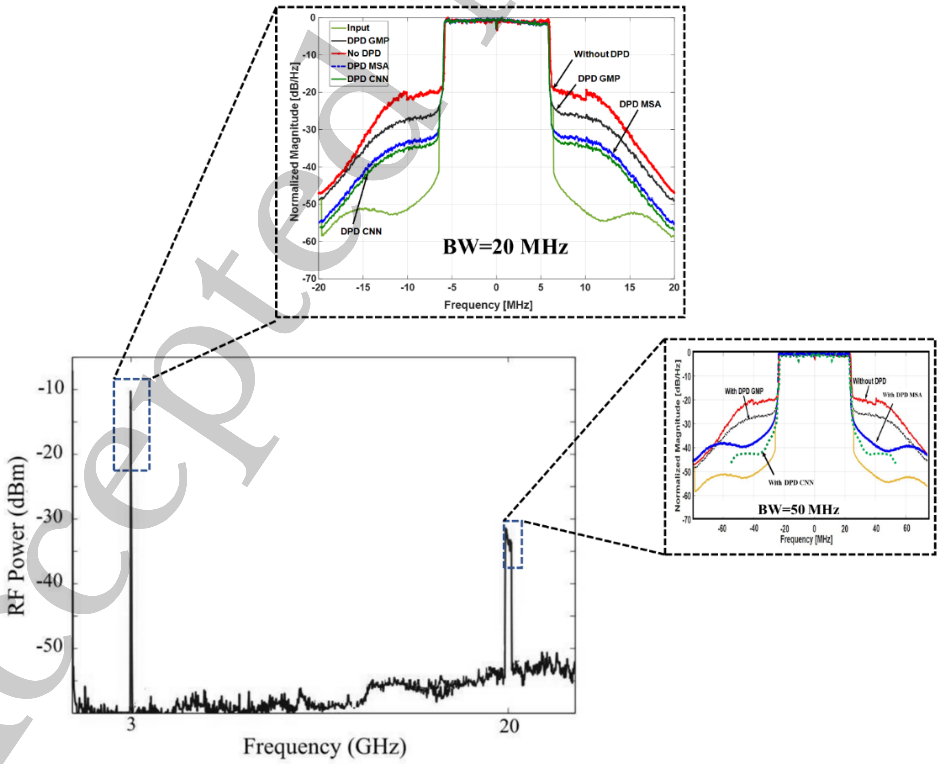

Figure 11: Comparison of spectral density performance with and without the application of DPD

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4. 5G New Radio Hybrid MIMO-Based Fi-Wi OFH System

A recent proposal introduced a hybrid Fi-Wi integration mechanism utilizing an OFH system based on RoF at its core. This integration enhances the wireless system by creating a hybrid fibre-wireless setup. After the signal is captured by the photodiode, it is duplexed and prepared for reception through wireless channels. To effectively capture and evaluate the performance of the wireless link, a 2x2 MIMO system is adequate given the dual bands of signals. In this setup, the RoF mechanism employs two RRHs, each with its own transmitter, leading to signals being received at RX1 and RX2 as follows:

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \tag{1}$$

Here, x_1 represents the first broadcast waveform, x_2 denotes the second, and n_1 and n_2 are the channel noise terms. The channel coefficient is represented by h_{11}, h_{12}, h_{21} and h_{22} respectively. The system complexity is compounded by Inter-Symbol Interference (ISI) and chromatic dispersion in the optical fiber. To address this, the Frequency Domain Equalisation (FDE) technique is applied, simplifying MIMO system complexity. Results of experiments are presented for a 5G NR MIMO Fi-Wi system. The optical power output from the electrical amplifier at the receiver is shown in Figure 12. Achieving 3GPP standards for optical levels is the aim. Interestingly, F-OFDM demonstrates a 7 dB greater range than 5G-NR, suggesting that MIMO Fi-Wi with OFH has substantial promise.

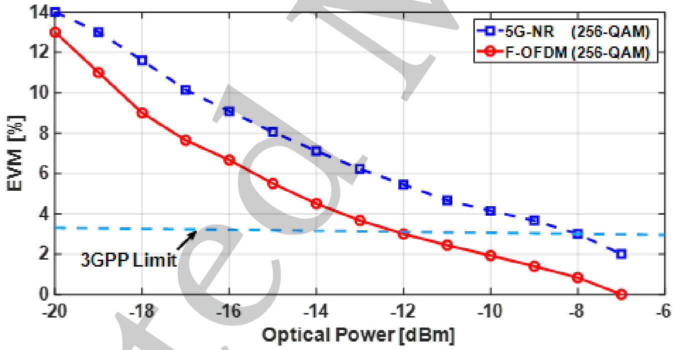

Figure 12- Optical power received at the receiver as measured by the output of electrical amplifiers, in relation to EVM.

5. Real-Time Implementation and Challenges

Receiving feedback signals from the BS to the RAU is one of the hardest tasks in the OFH connection's adaptive compensation. This is due to the possibility that the feedback link is nonlinear—possibly even more so than the adjusted RoF link. The present study is based on the assumption that the predistorter observes just those non-idealities that it needs to take into consideration. Since it is anticipated that the nonlinear feedback connection will not be compensated, the compensation's performance would be severely impaired. In short, it means that a technique is used wherein the RoF connection is compensated for using a known training signal from the RAU and a post distorter initially. Nonetheless, Figure 13 presents a tenable use of an adaptive DPD that shifts sophisticated signal processing to the Central Office/Base Transmit Station in order to simulate a possible feedback scenario (CO-BTS).

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DPD operates as a "black box," correcting system-wide nonlinearities, including those introduced by components such as the photodiode, fiber, and MZM (laser). The combined effect of fiber dispersion and laser chirp after tens of kilometres results in a significant nonlinearity problem. Thus, in this suggested configuration, the laser and maybe the photodiode are the main causes of nonlinearity, and they are reduced. To further improve linearisation, future developments might involve extending the fiber link and addressing fiber nonlinearities like the Kerr effect.

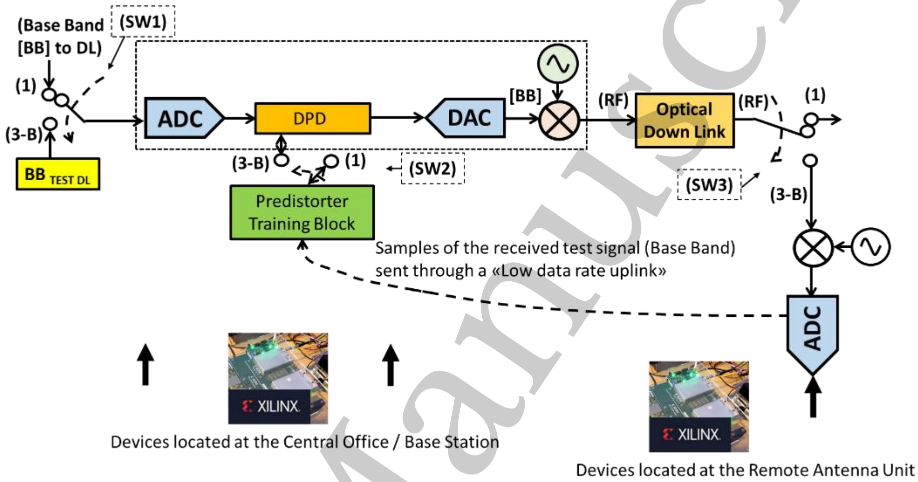

Figure 13. Conceptual Possible Realisation of an Adaptive Predistortion Scheme

In real-time implementations, complexity is an important consideration that needs to be taken into account. The MSA-DPD offers performance comparable to CPWL or GMP techniques, but with much less complexity. The coefficient calculations for the architectures under discussion are shown in Table II. 520 multiplications are needed for the MSA-DPD, which is significantly less than the 880 multiplications required for CPWL. More sophisticated variants can result from differences in nonlinearity ordering and memory depth. Therefore, when choosing a real-time implementation, careful consideration of the trade-off between performance and complexity is crucial.

Table II- Complexity comparisons

DPD Method	Coefficients	# Coefficients
GMP	$K_a(Q_a+1)+K_b(Q_b+1)R_b + K_c(Q_c+1)R_c$	84
CPWL	$(K+1)*(4M+1)*L$	880
MSA	$(K+1)*2(4M+1)*L$	520
DNN [18]	$(4+N)*K+(N-1)*K^2+6$	16966

6. Challenges and Future Prospects

The transport network architecture linking O-RAN components must address stringent and diverse requirements to support both emerging 5G services and existing 4G services. Enhanced Mobile Broadband (eMBB) demands high capacity, URLLC requires high reliability and low latency, while Massive Machine Type Communications (mMTC) involves managing numerous devices efficiently. Additionally, the integration of new radio access technologies in 5G, use of higher frequency bands, and increased antenna and access point density call for scalable, adaptable, and cost-effective transport solutions. To fulfill its potential, O-RAN must identify and implement a broad range of features and use cases across multi-vendor networks. The future of commercial deployment remains uncertain, though current market predictions suggest that O-RAN will become a significant player in the global RAN market by 2027-2028, potentially surpassing the traditional RAN market. Market forecasts estimate that the O-RAN sector will reach USD 21.371 billion in revenue by 2028, growing at a compound annual growth rate (CAGR) of 83.1% from 2020 to 2028. Factors contributing to O-RAN's market success include support from countries developing advanced domestic technologies,

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the positive impact of vertical market deployments, and new use cases. The development of mature O-RAN solutions will span several years. Initially, future work will focus on Quality of Experience (QoE), performance, and energy efficiency. In subsequent phases, O-RAN is expected to support novel applications such as Radio Resource Allocation for UAV applications, satellite communication, underwater and underground communication, RAN Slice Service Level Agreement Assurance, Machine Learning-based radio resource optimisation, and mobility management. An underwater system incorporating the discussed OFH could facilitate communications for deep-sea operations and ocean monitoring. Satellite communications present unique challenges, including smaller-scale operations and long-term cycles, which may hinder the development of an O-RAN strategy. Additionally, satellite operators' reluctance to fully adopt open standards due to their focus on technological uniqueness may be a barrier. The challenges of OFH in terms of energy efficiency and power supply are significant, particularly in the context of O-RAN architecture, where the disaggregation of components such as the Open Radio Unit, Open Distributed Unit, and Open Centralised Unit leads to increased energy consumption. Each of these distributed units requires power, and inefficient resource management can exacerbate this issue, resulting in higher overall energy demands. Ensuring a consistent and reliable power supply is also a major challenge, especially in remote or hard-to-reach locations where many OFH systems, such as UAV-based base stations, are deployed. These deployments often rely on limited-capacity power sources like solar energy or battery backups, necessitating the use of highly energy-efficient hardware and advanced power management techniques. To address energy efficiency, strategies such as sleep modes for inactive components, adaptive power control, and energy-aware scheduling algorithms are critical, allowing systems to scale power dynamically based on real-time traffic loads, thereby reducing power wastage. Moreover, the growing adoption of Mobile Edge Computing in OFH architectures, essential for reducing latency, introduces additional power challenges, as edge nodes require high-efficiency power supplies, particularly when deployed in rural or off-grid areas. Finally, integrating OFH with green energy solutions, such as solar or hybrid systems, offers a potential solution to power supply challenges, but these sources are not always reliable. Therefore, incorporating advanced energy harvesting techniques and battery technologies, alongside effective power management strategies, is essential to ensuring the sustainability and efficiency of OFH systems in 5G and beyond. Furthermore, advanced customer support and direct D2D communication at high data rates are anticipated. The integration of all types of underwater communication channels, including sensor systems, will be essential for establishing a comprehensive underwater network. To ensure accurate model training and achievement of Key Performance Indicators (KPIs), additional testing is necessary, and security issues in the multi-player O-RAN environment must be addressed. O-RAN is anticipated as a transformative technology offering significant benefits for both operators and end-users. It introduces new interfaces and nodes, enhancing commercially viable 3GPP solutions. From an operator's perspective, O-RAN must meet specific specifications before deployment. The latest technical specifications, developed by European operators, outline the areas and use cases that Open RAN should address. A large-scale roll-out of O-RAN was expected to begin in 2022, with high standards for quality and security anticipated. This includes support for both standalone (SA) and non-standalone (NSA) modes, along with compatibility with 4G and 5G radio access technologies for legacy bands. While intelligent and programmable operation capabilities are currently considered less critical and may be implemented later, specific priorities for O-RAN infrastructure, Open FH, RIC, and RAN features have been detailed by operators covered by the O-RAN Memorandum of Understanding (MoU). The benefits of the O-RAN architecture and its impact on RAN decomposition will be evaluated following commercial deployment.

The challenges and open research problems associated with Open Fronthauls in 6G are significantly more complex than those encountered in 5G, driven by the ambitious IMT-2030 service requirements [68]. Unlike 5G, which focuses on enhanced mobile broadband and reduced latency, 6G aims to support a wide range of advanced applications, such as holographic communication, tactile internet, and ultra-reliable low-latency services for critical infrastructure. These use cases require a substantial leap in connectivity, with peak data rates expected to reach 1 Tbps, ultra-low latency targets of less than 1 millisecond, and six-nines (99.9999%) reliability [69]. To meet these goals, OFH systems will need to evolve in terms of capacity, latency management, and power efficiency. While current 5G fronthaul systems rely on fixed functional splits like the 7-2x, 6G will demand dynamic and granular splits that can adapt to diverse applications. This introduces challenges in managing fronthaul capacity, optimizing signal processing, and ensuring synchronization across distributed units (O-RU, O-DU, O-CU) in real time. Energy efficiency is another critical challenge, as 6G aims to support trillions of devices with minimal environmental impact. The increased complexity of 6G networks, coupled with the high demands for low-latency and high-performance services, will necessitate advanced power management strategies and the use of energy-efficient hardware. Moreover, the integration of AI and ML into 6G fronthaul management will introduce new research problems, such as developing AI-driven orchestration algorithms for real-time optimization and addressing security vulnerabilities in an open and disaggregated network architecture [68]. The disaggregated nature of OFH in 6G also raises security concerns, as the open interfaces and multi-vendor environments increase the potential attack surface. Ensuring secure data transmission and addressing privacy issues in AI-driven systems will require robust encryption, authentication, and privacy-preserving mechanisms [70]. Additionally, 6G will need to integrate with emerging technologies like satellite and underwater communication, each of which presents unique challenges for OFH. The scalability and adaptability of fronthaul networks in these new environments will be crucial for supporting the diverse and evolving communication demands of 6G. In summary, while 5G laid the groundwork for many of the advancements in OFH, 6G brings a new set of challenges and research opportunities, particularly in terms of meeting the stringent IMT-2030 requirements for capacity, latency, energy efficiency, security, and integration with emerging technologies. Addressing these challenges will be critical to ensuring that OFH systems can support the full potential of 6G networks over the

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next decade. Table III summarises several challenges, open research problems as well as trending and enabling technologies regarding Open Fronthauls solutions within 5G and 6G.

Table III- Open Fronthauls challenges, open research problems and trends within 5G and 6G

7. Conclusions

Aspect	Challenges (5G)	Challenges (6G)	Open Research Problems (5G)	Open Research Problems (6G)	Trending and Enabling Technologies (5G)	Trending and Enabling Technologies (6G)
Data Rates	Limited to 20 Gbps, requires efficient RoF solutions	Supporting 1 Tbps for ultra-high bandwidth applications	Enhancing RoF and mmWave technologies for higher throughput	Innovating new fronthaul architectures for Tbps throughput	Radio over Fiber (RoF), mmWave, Passive Optical Networks (PON)	Hybrid RoF, THz communications, Fiber-Wireless integration
Latency	Achieving ~1 ms latency for URLLC applications	Ultra-low latency (<1 ms, microsecond-level for critical apps)	Developing reliable low-latency mechanisms for URLLC	Designing fronthaul to support microsecond-level latency	Edge computing, Mobile Edge Computing (MEC) for latency reduction	Ultra-dense networks, AI-driven latency optimization
Reliability	Maintaining 99.999% reliability in distributed networks	Ensuring 99.9999% reliability for mission-critical services	Improving fault tolerance and recovery in O-RAN networks	Optimizing reliability under extreme service demands	5G RAN reliability protocols, fault tolerance techniques	6G RAN protocols, ML-driven reliability and fault recovery
Energy Efficiency	Moderate focus on energy efficiency; optimization needed	Strict energy efficiency targets for sustainable networks	Power optimization for distributed O-RUs and O-DUs	Achieving net-zero energy networks with sustainable technologies	Sleep modes, adaptive power control for base stations	Green communications, energy harvesting, ultra-efficient hardware
AI/ML Integration	AI/ML mainly for optimization; not widely implemented	AI/ML for real-time, autonomous network orchestration	Limited research on AI/ML for predictive fronthaul management	AI/ML for dynamic, real-time control and autonomous operation	Limited AI/ML for traffic optimization and load balancing	Autonomous AI/ML orchestration, Digital Twin for network simulation
Security	Ensuring data security with basic encryption methods	Advanced security and privacy challenges in open systems	Addressing vendor interoperability and data integrity issues	Securing multi-vendor, decentralized open systems effectively	Basic encryption, authentication, vendor-specific solutions	Advanced encryption, blockchain, quantum security technologies
Emerging Technology Integration	Mainly terrestrial, UAV-based solutions	Integration of satellite, underwater, quantum technologies	Enhancing UAV-based base stations for more reliable coverage	Developing fronthaul compatible with satellite and quantum communication	UAV-based base stations, terrestrial solutions, MEC	Seamless integration of satellite, underwater, and quantum networks

This article focuses on recent trends in optical communication for 5G and 6G networks. The high-level proposed architecture and building blocks have been discussed, while summarizing the key points of the O-RAN specifications that are already accessible and demonstrating the advancements made possible by O-RAN. The article also explains the recent trends, issues and types of Radio over Fibre systems that are used as OFH. It is highlighted that Fibre Wireless integration is a way forward for increasing wireless reach. Apart from this, recent trends of coherent wavelength division multiplexing for passive optical networks and visible light communication as its test case are discussed. Furthermore, O-RAN Gym, an open-source, experimental, and practical platform that offers end-to-end design, data gathering, and testing processes for intelligent control in next-generation O-RAN systems, is utilised in the experimental outcomes. The outcomes give an example of two xApps that were created using O-RAN Gym and used to manage a big network that was set up on the Colosseum testbed with 10 base stations and 60 users. Transmission packets and buffer occupancy are used to assess performance. Furthermore, linearisation techniques are used in the experimental evaluation of OFH

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with Analog RoF in order to lower the EVM to less than 2%. Additionally, an experimental MIMO Fi-Wi OFH example has been documented, in which a 5G new radio waveform meets 3GPP limitations with an EVM of 3%.

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Conceptualisation, M.U.H. H.S; methodology, M.U.H.; software, M.U.H. N.A; validation, H.S, M.U.H.; formal analysis, H.S, M.U.H.; investigation, M.U.H.; M.W; resources, M.U.H.; data curation, M.W, N.A; writing—original draft preparation, M.U.H.; H.S; supervision, M.U.H.

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There is no conflict of interest disclosed by the author.

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