

Toward Virtualized Optical-Wireless Heterogeneous Networks

Original

Toward Virtualized Optical-Wireless Heterogeneous Networks / Vujcic, Zoran; Santos, Maria C.; Méndez, Rodrigo; Klaiqi, Bleron; Rodriguez, Jonathan; Gelabert, Xavier; Rahman, Md Arifur; Gaudino, Roberto. - In: IEEE ACCESS. - ISSN 2169-3536. - ELETTRONICO. - 12:(2024), pp. 87776-87806. [[10.1109/access.2024.3417358](https://doi.org/10.1109/access.2024.3417358)]

Availability:

This version is available at: 11583/2991970 since: 2024-08-27T11:10:27Z

Publisher:

IEEE

Published

DOI:[10.1109/access.2024.3417358](https://doi.org/10.1109/access.2024.3417358)

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

Received 21 May 2024, accepted 15 June 2024, date of publication 20 June 2024, date of current version 28 June 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3417358

 SURVEY

Toward Virtualized Optical-Wireless Heterogeneous Networks

ZORAN VUJICIC¹, MARIA C. SANTOS², RODRIGO MÉNDEZ²,
BLERON KLAIQI³, (Member, IEEE), JONATHAN RODRIGUEZ⁴, (Senior Member, IEEE),
XAVIER GELABERT³, (Member, IEEE), MD ARIFUR RAHMAN⁵, (Member, IEEE),
AND ROBERTO GAUDINO⁶, (Senior Member, IEEE)

¹Instituto de Telecomunicações, Department of Electronics, Telecommunications, and Informatics, Universidade de Aveiro, 3810-193 Aveiro, Portugal

²Signal Theory and Communications Department, Universitat Politècnica de Catalunya, 08034 Barcelona, Spain

³Huawei Technologies Sweden AB, Stockholm Research Centre, 164 40 Kista, Sweden

⁴Faculty of Computing, Engineering and Science, University of South Wales, CF37 1DL Pontypridd, U.K.

⁵IS-Wireless, 05-500 Piaseczno, Poland

⁶Dipartimento di Elettronica e Telecomunicazioni (DET), Politecnico di Torino, 10129 Turin, Italy

Corresponding author: Zoran Vujicic (zvujicic@av.it.pt)

This work was supported by the European Union's Horizon Europe research and innovation program under the Marie Skłodowska-Curie grant agreement No. 101073265 (EWOC), and the UKRI (UK Research and Innovation) Horizon Europe Guarantee Scheme with grant no: EP/X030342/1 (EWOC). Zoran Vujicic also thanks the research and innovation program under the Marie Skłodowska-Curie grant agreement No. 872897 (EXPLOR).

ABSTRACT Towards supporting a myriad of new services and applications under highly heterogeneous operating conditions, while dynamically adapting to capacity and quality-of-service (QoS) demands, the sixth generation (6G) communication systems are required to undergo significant advances. Along with the proliferation of devices, a multitude of challenges remain towards aspired performance, versatility, security, and cost-effectiveness of next generation networks. The aim of this work is to identify said challenges and promising approaches, within the scenario of dense and complex urban deployments enabled by optical-wireless coexistence. Towards enabling such operation scenario, our 6G vision focuses on various aspects of four main innovation paradigms. First, as future systems target network capacities beyond the capabilities of current technologies, the scientific trend of pursuing radio frequencies edging towards the THz domain continues. To ensure reliable and efficient deployment and mobility under the cell densification paradigm, particularly in complex urban environments, novel approaches are required to address the challenges as latency, signal blockages, and unreliable handovers. Second, towards enabling efficient operation under the heterogeneous scenario, we highlight the cooperative coexistence paradigm as a key feature of the underlying physical layer architecture. Third, joint and holistic resource optimization is required towards dynamically optimized support of mm-wave and sub-THz operation while retaining legacy coexistence, where we consider features that may benefit from the research paths proposed within the second paradigm. Fourth, network security is identified as critical towards the market adoption of technologies proposed within the first paradigm, where we highlight aspects unique to our scenario and network vision. We provide a comprehensive overview of promising state-of-the-art approaches and identify relevant research gaps while holistically addressing the four aforementioned innovation paradigms.

INDEX TERMS 6G networks, cell densification, C-RAN, dynamic centralization, mm-Wave, optical access networks, optical Fronthaul virtualization, optical software defined transceivers, passive optical networks, stochastic geometry, ultra-dense cells.

I. INTRODUCTION

The associate editor coordinating the review of this manuscript and approving it for publication was Rentao Gu¹.

The growth rate of service versatility and subscriber count have driven mobile access standardization towards

content-centric and away from the network-centric engineering approach. In pursuit of such context and flow-driven operation, future networks are expected to envisage on-demand virtualized small cells operating at high-end mm-wave (MMW) frequency range and pursuing THz connectivity (TC) harnessing hybrid optical-wireless network (OWN) infrastructure and a dynamic cloud radio access network (C-RAN) environment for controlled centralization [1], [2], [3], [4].

Current predictions estimate the aggregate capacity handled by wireless networks by 2030 to reach up to 1Tb/s [5], [6]. The MMW roadmap is already established [4], [7], [8], due to pressing urgency for additional unlicensed spectrum and the anticipated shortcomings of presently deployed sub-6GHz small cells towards higher cell capacity targets [9]. However, current engineering paradigms exploiting multiple antenna technology and cell densification provide bounded improvement margins due to limited spectral availability. Ultra-dense cell (UDC) technology ventures beyond the 20-40 GHz band and towards higher spectral availability and cell capacity. However, cell densification leads to more complex, multi-tier interference scenarios, as well as the increased probability of spatial and temporal traffic fluctuation. Consequently, C-RAN based network centralization is identified as an attractive solution for 6G roadmap, where traffic fluctuations can be selectively addressed as per-access point, via intelligent and ubiquitous resource management and coordinated scheduling. Moreover, this approach may vastly improve spectral/energy efficiency, and lower capital/operational expenditures (CAPEX/OPEX), as compared to conventional, distributed base station (BS) architectures. Thus, 6G networks are expected to focus on low power consumption, adaptive resource allocation, and intelligent orchestration [1], [2], [3], [4]. Centralization, however, comes at the cost of stringent latency requirements and typically high front haul (FH) transmission bandwidth penalties [7], [10]. Hybrid OWN solution relating to the use of optical FH (OFH) is identified as the technology of choice towards meeting the expected lavish bandwidth demands. Namely, converged OWNs enable the best of both worlds towards 6G: high bandwidth coupled with high mobility and flexibility [1].

As of today, the commercial deployment is largely based on Passive Optical Network (PON) due to their ubiquitous use for the deployment of Fiber-to-the-Home (FTTH) in urban areas. A significant aspect of our 6G vision is thus centered on leveraging PON technology to support OWN architecture, in light of the anticipated medium- and long-term evolution of optical access networks. As of 2023, telecom operators have started commercially deploying XG-PON solutions (*i.e.*, 10Gbps downstream), while IEEE and ITU-T PON standardization is evolving towards higher bit rates: 25G and 50G recommendations have been already officially ratified (respectively by IEEE and ITU-T), while an open discussion is ongoing on the next steps towards 100G-PON [11], or even higher data rates. As market long dictates deploying next generation (NG) PON as part of a convergence solution [12],

the technology coexistence between the optical and wireless ecosystems becomes a vital point. However, OWN key open challenges lie in the native spectral availability [13], as well as the cost ramifications of bandwidth demanding RAN centralization [10]. The currently standardized and widely deployed approaches to implement fixed-mobile convergence and centralization are based on the different variants of functional split (FS), as detailed in [14]. The most common approach today is the one based on the common public radio interface (CPRI) standard, which allows to implement an ideal cloudification of baseband unit (BBU) functionalities, but at the expense of very high bit rate demands on the fronthauling fiber link. Notably, a typical LTE system with 2 antennas per-cell would require over 20Gb/s of CPRI rate [10], introducing significant penalty to the native signal bandwidth. This hinders crucial near-future concepts, such as massive multiple-input multiple-output (MIMO) implementation in wireless network segment, as per-cell bandwidth requirements may quickly become prohibitive.

To avoid the offset of the expected cost benefits of C-RAN, caused by stringent network requirements including bandwidth strain and subsequent OFH cost, facilitation of flexible function relocation (*i.e.*, FS selection) via virtualized RAN (vRAN) along with a highly adaptable, virtualized and configurable OFH architecture is required [15]. This necessity is already apparent in the growing trend of gradual migration towards the open-RAN (O-RAN), adding increased reliance on commercial off-the-shelf (COTS) equipment and vendor-neutral software-defined technologies to the traditional C-RAN concept [16]. Such approach, while centered around cloud-native virtualization techniques, enables hybrid OWNs to adapt efficiently and holistically based on usage and coverage in highly heterogeneous environments of future 6G networks. Particularly, software disaggregation and network software migration from dedicated hardware platforms and into virtualized components that are pooled and optimized in terms of FS selection, is the aspect of O-RAN that may dramatically increase network agility and flexibility, as well as promote further innovation and CAPEX/OPEX savings. In the context of this evolution, flexible orchestration of opto-electronic network elements is of high interest. Namely, holistic virtualization is poised to enhance physical layer (PHY) programmability, operational flexibility, and scalability for rapid, demand-driven operations and cost reduction. However, additional improvements are attainable by enabling cooperative features within the technology coexistence paradigm, thereby increasing the PHY configurability and resource orchestration flexibility.

A. NETWORK VISION AND SURVEY SCOPE

Fig. 1 summarizes the above-described problem statement motivating our heterogeneous network vision. The communication platform is being constantly reengineered towards content-centric systems, envisioning the end users both as content consumers and producers. As temporal and spatial

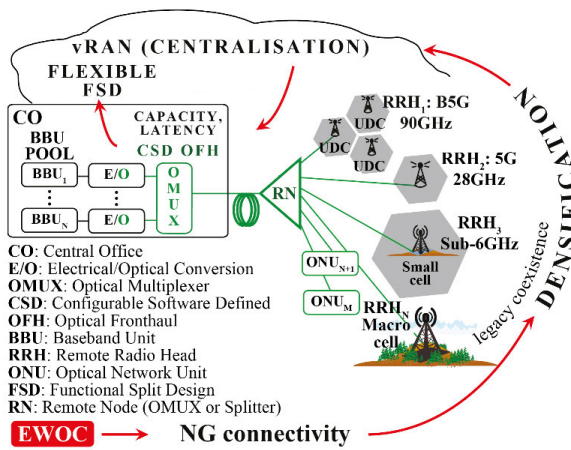


FIGURE 1. NG network paradigms driving the EWOC project vision. The central office (CO) corresponds to the central unit (CU) terminology used in 3GPP TR 38.801.

diversity of broadband services and quality requirements grows with increasing user-count, usage frequency and content diversity, network scalability needs to be addressed beyond its typical peak-provisioning and traffic approach. While a flexible OFH architecture may assist cost effective on-demand resource management in a highly heterogeneous network, vRAN with dynamically optimized FS selection provides another vehicle for increased levels of system flexibility, serving the purpose of dynamically balancing the service requirements with system constraints, thus producing positive impact on both system efficiency and cost. Moreover, the scenario of dense deployment and multi-connectivity will also expand the pool of potential entry points for security threats, raising the risk of intrusion. Thus, our vision points towards an integrated networking ecosystem, where legacy and future emerging systems all play a proactive role in establishing the highest available quality-of-service (QoS) and connection security depending on the context and the service required.

The above outlined network vision drives the main innovation paradigms explored in this paper: cell densification towards higher spectral availability, cooperative technology coexistence towards improved configurability, dynamic and holistic resource orchestration towards cost-effectiveness, and intelligent security approaches towards proactive threat mitigation. This research direction provides the impetus for novel end-to-end architectures delivering media content within a heterogeneous networking environment, where enabling protocols in the application and transport layers will be responsible for managing the connection to ensure the desired QoS; this means utilizing the available networking resources on demand, safely, flexibly and adaptively, given the various underlying networking flavors. The scope of this work covers recent innovation in pursuit of NG heterogeneous networks considering the four above outlined paradigms, with in-depth focus on the particularly challenging aspects of secure and efficient deployment and mobility in complex urban environments, cooperative

features enabling the PHY flexibility, as well as holistic and dynamic configurability. We limit the scope of our study to ultra-dense deployment in the MMW frequency spectrum, ranging from 20 GHz to 95 GHz, and extending to sub-THz bands above 95 GHz, due to its relevance to advancing 5G-Advanced and future 6G technologies, where higher frequency bands are essential for meeting the IMT 2030 performance metrics of increased capacity and reduced latency. Finally, we focus on highlighting the potential of artificial intelligence (AI) and machine learning (ML) to address specific research gaps in four key areas, rather than covering the field exhaustively or proposing broader advancements. Further research could beneficially extend into exploring lower frequency bands for UDC applications, as well as the integration with non-terrestrial networks (NTNs).

B. KEY CONTRIBUTIONS AND OUTLINE

Previous works holistically addressing heterogeneous networks predominantly focus on the generalized perspective and timeline for the 6G roadmap, the key performance indicators (KPI), and wide-ranging assessment of enabling technologies. Table 1 features recent holistic 6G surveys covering at least two of the four main paradigms addressed in this paper [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], as described in the following.

Cell densification: Opportunities and research gaps towards THz communications are addressed in the context of 6G vision enablers in most of the above mentioned works, but the focus is on general path loss considerations, band allocation and standardization progress [17], [18], [19], [20], [22], [23], [25], [27], [28], [29], [30]. Additionally, the work in [28] outlines some current limitations in terms of the bandwidth of opto-electronic devices, but it does not provide an in-depth overview of candidate transceiver architectures in the optical network segment, which is the aim of this paper. In [18] and [27], the authors recognize the need for new channel models beyond sub-6GHz communications, briefly suggesting various stochastic geometry (SG)-based implementations without addressing model types, mobility, or vertical deployment scenarios. Moreover, in [30], the authors stress the importance of SG modeling towards TC, but do not focus on a discussion on candidate approaches and current shortcomings.

Regarding specialized works focusing on ultra-dense deployments targeting high frequency bands and involving mobile users, this work contrasts with the primarily 2D (i.e. planar) focus observed in notable surveys such as [31] and [32]. As a further step, unlike the homogeneous assumptions prevalent in prior studies [31], [32], we investigate the inhomogeneous PPPs for a more realistic and nuanced view of network deployments. In addition, this approach allows for a more detailed exploration of network reliability and service quality under varied urban densities and user mobility. Our discussion intricately connects mobility management with UDC deployments, an area covered in earlier surveys [33]

TABLE 1. Research direction of recent 6G vision surveys addressing the heterogeneous networks.

Year/Ref.	Densification and Coverage	OFH PHY Configurability	OWN Dynamic Orchestration	Security	Research Focus
2021 [17]	√	×	×	√	6G KPIs, use cases, and general overview of enabling technologies and recommendations.
2021 [18]	√	×	×	√	6G trends, standardization and vision, foreseen applications and requirements, and generalized overview of enabling technologies.
2021 [19]	√	×	×	√	Generalized 6G vision, KPI and enabling technologies overview addressing the aspects of non-terrestrial coverage, spectral expansion, network security and heterogeneous operation focusing on AI and big data technologies.
2021 [20]	√	×	×	√	6G vision and motivation, KPI and enabling technologies overview. Generalized architecture discussion with no consideration on MMW OFH implementations.
2022 [21]	×	×	√	√	AI-driven holistic virtualization based on digital twins.
2022 [22]	√	×	×	√	General vision and brief discussion on 6G enabling technologies. Overview of IoT technologies and applications.
2023 [23]	√	×	×	√	Generalized 6G vision addressing the enabling technologies and architectures in broad terms.
2023 [24]	√	×	√	√	6G vision, KPI and enabling technologies overview. Generalized architecture discussion and testbed overview with limited focus on MMW OWN implementations.
2023 [25]	√	×	×	√	Generalized overview of architectures, networking, and applications towards 6G.
2023 [26]	√	×	×	√	General overview of KPIs, enabling technologies and use cases.
2024 [27]	√	×	×	√	Comprehensive overview of 6G enabling technologies, with limited focus of OFH enabling architectures and technologies.
2024 [28]	√	×	×	√	Technology integration (AI, THz, MIMO) requirements within the context of terrestrial and non-terrestrial network convergence.
This paper	√	√	√	√	The diverse aspects of cell-densification, OFH PHY-layer architecture and configurability, joint and dynamic resource orchestration and network security are analyzed, while considering their interconnectivity.

and [34]. Our survey goes beyond by linking mobility dynamics with SG modelling, offering a new view on network performance and user experience in these deployments. Our focused examination of beam management techniques in high mobility scenarios addresses the need for maintaining service continuity in NG networks utilizing MMW and THz bands. While surveys [35] and [36] briefly discuss MMW and THz operation, our more specific focus highlights the practical relevance of mobility in such challenging frequency bands.

Lastly, this paper provides a new view on how mobility management can be proactively improved by leveraging on ML and integrated sensing and communication (ISC) techniques.

OFH physical layer (PHY) design and configurability: 6G surveys outlined in Table 1 focus on visible light communications (VLC) and/or free space optics (FSO) aspects of optical-wireless convergence [17], [18], [19], [26], [27], [28], [29]. Conversely, this paper focuses on fiber-transport technologies and their configurability potential en route to heterogeneous MMW and TC. Typical limitations in practical implementations of MMW and THz networks are discussed in [20] and [24], while works in [19] and [29] cover some general PHY aspects of radio over fiber (RoF) technology. To further complement these surveys, we hereby make a comprehensive consideration of the OFH segment including cooperative features and architectures. We offer a comprehensive architecture overview, including the repercussions on the remaining network segments and the potential towards

OFH configurability. Section III of this paper focuses on surveying novel experimental demonstrations of technologies supporting flexible and configurable OFH designs towards heterogeneous TC. We consider a wide range of transport frequencies, spectral allocation schemes, data rates, and modulation formats to identify research gaps and candidate architectures.

Regarding specialized works, several surveys have examined the current technical landscape and future trajectories of transport technologies for the OFH. Some of these surveys have delved into the networking realm, pinpointing the prerequisites for the transport layer, with emphasis on O-RAN concepts and opportunities, software defined approaches and AI [37], [38]. On the other hand, surveys [39], [40], [41] have presented a descriptive analysis from the physical layer perspective, offering a comprehensive overview of operative frequency bands and latency requirements. Significantly, [39] has concentrated on PON solutions tailored for OFH, while [40] has conducted an in-depth examination of fiber technology and photonic integrated circuits, and [41] has explored antenna technology in detail. In this paper, we aim to augment the insights provided by these preceding surveys by concentrating on transport solutions for OFH at the optical transceiver architecture and design level. Specifically, we shine a spotlight on analog RoF (ARoF) implementations, which emerge as a promising option for OFH transport due to the advantages like simplification of the remote radio heads equipment, enabling cost and energy savings, flexibility,

spectral efficiency, and reduced latency. Moreover, we focus on the favorable prospects towards the MMW and THz frequency bands. Our study provides a thorough examination of experimental validations of the OFH found in recent literature, elucidating the employed frequency bands, data rates, and reach of each solution. Additionally, we explore aspects like dynamic beam steering, cooperative coexistence and configurability, further enriching the discussion. Finally, while considering the applicable fiber transport technologies, we propose the concept of cooperative component pooling towards enabling multi-purpose abstraction and augmented holistic resource management in heterogeneous networks. Building upon the identified achievements and emerging trends, we formulate a projection outlining the research directions for future progress.

Dynamic and holistic resource orchestration: Resource orchestration is only addressed in general terms of AI application in [28], with no details on current state-of-the-art on holistic approaches applicable to our network vision. In [17], [19], [20], and [25], the authors discuss the softwarization, network function virtualization and digital twin trends, but with no consideration for joint optical-wireless resource optimization. OFH technology and its virtualization is only briefly discussed in [27]. The work in [24] also does not devote particular focus on joint resource optimization in converged heterogeneous networks. The work in [26] briefly addresses the cell densification through general aspects of THz communications focusing on wireless segment only, while optical-wireless convergence is only discussed in the context of VLC. In [30], coordinated scheduling is addressed in general terms and from the aspect of joint consideration for downlink and uplink, while optical-wireless convergence is not considered. The work presented in [42], does not address the optical fiber access technology nor joint resource optimization. The main focus of the present paper is in identifying the current research gaps towards enabling the consideration of dynamic and cooperative network features. Section IV tackles joint resource orchestration procedures for dynamic balancing of system requirements and constraints considering optical, wireless, and computational resources. Moreover, we explore the system architectures enabling FS optimization using hybrid fiber transport approaches detailed in the preceding section and note the research gaps towards efficient technology convergence.

Several specialized surveys discuss resource allocation strategies for virtualized optical-wireless networks [41], [43], [44], [45]. In addition to examining the emerging trends and challenges surrounding the convergence of optical and wireless technology, the authors in [43] emphasize hybrid OWN architectures, with a focus on Quality of Service (QoS) mapping, scheduling mechanisms, and different approaches for QoS provisioning. On the other hand, [44] presents an overview of resource management strategies in converged OWN architectures, with a particular emphasis on MMW band transmission in the radio network segment. This work delivers a thorough review of the convergence between ML

and communication technologies, aimed at optimizing joint optical-wireless resource management in beyond 5G networks. The work in [45] provides a comprehensive survey of various approaches for improving energy efficiency (EE) in converged OWNs. It focuses on different network types and architectures, including RoF, while highlighting the evolution and impact on the energy consumption in telecom networks. The authors in [41] presented a survey on optical-wireless convergence, focusing on the architecture while covering a wide range of technologies, including power-over-fiber deployments, VLC, FSO, new antenna designs, and ML applications. To extend upon those surveys, this paper focuses on the evolving landscape of dense heterogeneous networks and dives deeper into the specific concepts of adaptive centralization, virtualized resource sharing, as well as holistic, intelligent, and cooperative orchestration.

Network security: As shown in Table 1, 6G security is addressed in most above considered 6G surveys, albeit with no particular focus on cell densification repercussions. Instead, these works either provide extensive overviews of various aspects of 6G security concerns and possible counter-measures [19], [20], or dominantly concentrate on a particular context of quantum computing and blockchain technology [17], [23], network virtualization [24], ML and AI [25], [27], and IoT [22]. The remaining works shown in Table 1 either do not provide state-of-the-art survey on network security [29], [30], and/or address it in broader terms [18], [26], [42], while underscoring it as a relevant research gap and a fundamental performance requirement towards the paradigms of digital twin and 6G wireless computing [21], [28]. In this paper, we focus on the security challenges stemming from our dense heterogeneous network scenario.

Regarding specialized works on network security targeting dense heterogeneous networks, previous surveys have addressed intrusion detection and the general topic of anomaly detection for network security [46]. The authors in [47] provided a comprehensive analysis of recent anomaly detection solutions for smart environments, with emphasis on multivariate time series anomaly detection in various scenarios, such as smart home, smart transport, and smart industry. The works in [48], [49], and [50] have extended these approaches based on harnessing intelligent mechanisms for autonomous detection. Outside smart scenarios, there have been works concerning vehicular ad-hoc networks [51], where the proposed intrusion detection system (IDS) framework exhibits high detection accuracy results by training the Random Forest as the classifier to label out the anomalous flow, whereas the work in [52] addressed the integrated functionality including preventive measure for Android platforms. The authors in [53] considered intrusion detection for 5G/6G technologies and device-to-device (D2D) communication, that carries various threats from attacks such as Man-in-the-middle attacks, Structured Query Language injection attacks, Dictionary attacks, Distributed Denial of Service attacks, among others, that can cause rapid battery drain increasing

the risk of D2D network failure. Nevertheless, few studies specifically address anomaly-based intrusion detection within the context of 6G and UDNs [54], where wireless networks consist of small cells and devices that are frequently limited by energy constraints, which is the aim of this paper.

The following Sections of this paper will outline the role of these enabling paradigms, and the main identified challenges, research gaps and promising approaches towards the NG network roadmap. Section II focuses on the radio segment channel modeling towards seamless mobility and reliable connectivity in complex 3D deployment scenarios. Network virtualization is addressed considering the MMW and sub-THz OFH architecture design and configurability in Section III, as well as the holistic resource orchestration in Section IV. Section V presents a discussion on network security challenges arising from our dense heterogeneous network vision. Finally, the full list of acronyms used in this paper is provided in the Appendix.

II. ULTRA-DENSE CELL TECHNOLOGY

In pursuit of new spectral opportunities, future emerging use-cases (e.g., Tactile Internet) and general “IMT 2020 beyond” data rate and latency targets, current multiple antenna technology and small-cells densification provide limited margin for improvement without migration to MMW frequencies [55]. We would first like to note that, to increase the capacity at lower cost, the World Radiocommunication Conference 2023 (WRC-23) further identified the 6GHz band for mobile communication systems as the vehicle towards the 5G-Advanced and future 6G technologies. It has been argued that further harmonization of the 3.5GHz range, as the 5G entry point in most global markets, might enable increased scale, diversity, and affordability. Additional capacity between mid-band and MMW band might be pursued in the 10GHz range, for the time being and towards 5G-advanced. However, there is still a strong scientific consensus on the urgency to pursue additional swaths of unlicensed spectrum, while recognizing the resulting cost-effectiveness as a key aspect. In fact, best candidate frequencies for use in mobile applications by service operators are already being evaluated, addressing the commercially more urgent frequencies up to 40GHz first [55]. The second phase focuses on frequencies up to 100GHz to address the key performance indicators (KPIs) outlined by IMT 2020, where 28GHz emerged as the dominant option amongst the provider prototype demonstrations [56]. Finally, the development of UDC technology based on MMW frequency range beyond 90GHz would enable a considerable bandwidth improvement over the 5G baseline [9]. Following the state-of-the-art conventions we hereby nominally classify the 20GHz-95GHz as the MMW band [57], whereas the range beyond 95GHz is henceforth referred to as the sub-THz band [58].

Towards the MMW advancements, novel research is required to address the current challenges such as frequency band selection, channel models, and densification limits towards a viable technology. The state-of-the-art

advancement under highly heterogeneous operation and distribution of users/infrastructure at high MMW frequencies requires novel wireless channel models and simulation methodologies in order to attain the desired UDC trade-off between coverage, throughput and densification limits.

Moreover, the practical deployment of UDCs also raises significant challenges, since the high frequencies will likely only support proximity wireless connectivity, limiting its applicability in terms of coverage. We thus identify the vertical deployment and mobility use-cases in the context of channel modelling as some of the most relevant state-of-the-art challenges towards enabling novel spectral availabilities.

The following subsections address the current challenges to be addressed within these use-cases, focusing on the aspects of wireless network segment, whereas the optical fronthauling aspects will be discussed in the following Section.

A. NON-PLANAR UDC DEPLOYMENT

Urban network deployments are decidedly non-planar, yet the de-facto approach from stochastic geometry (SG) treats all transceivers as living on a 2D plane [59]. SG, as a branch of applied probability, provides tractable mathematical models to analyze random events such as the behavior of wireless networks in terms of metrics like the signal-to-interference-and-noise ratio (SINR) distribution and system capacity, which depend on locations of BSs and user equipment (UE). Meanwhile, according to the United Nations (UN) study [60], urban areas are projected to grow rapidly in population and density by 2050, with two-thirds of the world's population located in urban areas by then. Concurrently, the number of wireless devices is also rapidly increasing and expected to accelerate, referred to as the internet of things (IoT) or machine-to-machine (M2M) communication devices [61].

The implications of these trends on the telecom environment will be profound: ever more devices with diverse throughput/latency requirements will be used in challenging urban environments. In this scenario, SG is a critically important tool to analyze large networks, whereby tiers of BSs are modelled as independent point processes, mostly homogeneous Poisson point process (PPP) enabling mathematical tractability [62]. PPP is a point process model whereby the number of nodes has Poisson distribution with mean value λ , denoting the node density. Homogeneous PPP exhibits no spatial correlation between nodes leading to an unrealistic model. Many of the principles of SG extend to 3 dimensions (3D) [63], but their extension to urban areas is challenging because of the non-homogeneous distribution of users and infrastructure, particularly at high-end MMW frequencies (>60 GHz) due to the sensitivity to blockages and the use of highly directional 3D beam patterns. Consequently, little is currently known about the coverage and rates achieved in vertical and dense deployments of cellular networks. Notably, [64] offers a concise overview of 3D network modeling for THz frequency towards 6G, emphasizing the use of SG as an analytical tool.

Thus, two key innovation challenges ought to be addressed in particular: the extension of the PPP process from a 3D perspective; and the exploitation of the non-PPP approaches as alternatives for transmitter modelling. The PPP technique assumes independently located wireless nodes. However, in many actual wireless networks, node locations are spatially correlated, with mutual repulsion/attraction between nodes. Therefore, we highlight the Ginibre point process (GPP), which is a determinantal point process that can be used to model random phenomena where repulsion is observed, i.e., node locations are spatially correlated and form a rather regular point pattern [65]; as well as the inhomogeneous PPP (I-PPP), where the intensity function is dependent on the distance [66], leading to unified and tractable methodology for modeling cellular networks that exhibit both spatial repulsion and/or clustering. However, I-PPPs requires a definition for the distance dependent intensity function, the choice of which is challenging. Detailed comparative investigation of these approaches is required in terms of accuracy, tractability, and practicability trade-offs to define conclusive guidelines on their definitive use. In short, 2D models are tractable and very well suited to macro cell deployment in rural and suburban areas. Nevertheless, they are inaccurate for dense urban areas. 3D network modelling provides realistic system models and differs from the 2D case due to the altitude as an additional dimension, leading to more degrees of freedom and a better ability to capture realistic scenarios.

B. UDC MOBILITY

The mobility challenge lies in the large beam steering gains required to overcome the propagation losses at MMW frequencies [19]. These gains rely on highly directional and/or adaptively tuned patterns that hold only for a small 3D angle in space. Due to its mobility, the UE must either rapidly switch beams or adapt the current beam [67], placing stringent demands on the latency and feedback requirements. In fact, the requirement for (nearly) unrestricted mobility is arguably the key feature of cellular networks. Therefore, the need to model and observe the impact of mobility is necessary in order to quantify the mobile network performance, as well as to provide a basis for designing new algorithms and protocols. In the first instance, appropriate modeling is required to emulate user mobility in small-cell deployment. Several such models have been proposed [68], [69], [70], but nearly all have significant drawbacks: they either provide reasonable accuracy or simplicity/tractability, but not both. Moreover, there is a need to analyze network metrics, such as SINR, as a function of time in order to determine quantities like connectivity or instantaneous (or average) rate. However, even a snapshot of SINR may contain dozens or hundreds of random variables, and finding a general tractable approach at any frequency or topology is challenging, even for the static case [71].

Mobility support is mostly analyzed through simulation studies, and cellular systems are still designed to

support mobility largely through iterative trial-and-error type approaches (i.e., measuring reference signals from neighboring cells and reporting back, allowing the handover decisions to be made on the “best” serving BS basis). Susceptibility to blockage of MMW and THz frequencies is one of the key challenges for 5G and beyond networks. High-frequency signal suffers from high attenuation and penetration loss leading to sudden drop in signal-to-noise ratio (SNR) when an obstacle is located between a BS and a user. In the case of blocked line-of-sight (LOS), the reliability of the network is severely affected and hence users need to be handed over to another BS with available LOS, which results in increased overhead and latency.

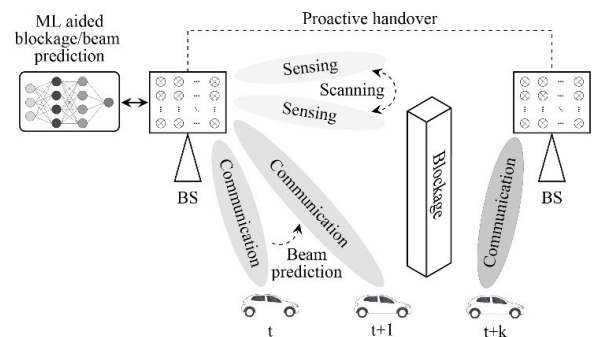


FIGURE 2. The concept of ML assisted blockage/beam prediction for proactive handover in ICS.

In this respect, cell-free architectures may aid supporting un-interrupted mobility by always providing an un-obstructed serving link from a cluster of BSs surrounding the UE. Cell-free paradigm signifies that during data transmission from UE perspective no cell boundaries exist, and BSs cooperatively serve UEs. BSs are connected via fronthaul with central processing units (CPUs), which coordinate joint transmission and reception. Cell-free massive MIMO provides macro diversity through multiple distributed BSs and interference cancellation utilizing multi-antenna techniques [72]. In addition, a recent new paradigm has emerged by harmonizing and integrating target sensing capabilities into the legacy communication system, also known as integrated communication and sensing (ICS). Communication and sensing can partially or fully share wireless resources, waveforms, and hardware. In ICS, sensing and communication are anticipated to mutually assist each other [73]. For communication-assisted sensing, the communication system is used to enhance sensing capabilities. In the framework of sensing-assisted communication, sensors could be utilized to improve the performance of wireless communication. More specifically, sensing can facilitate blockage prediction and proactive handover, which is especially useful for the latency reduction and reliability improvement of wireless networks. Furthermore, sensing enables beam prediction and significantly reduces training overhead [74].

Machine learning (ML) is a particularly promising approach for exploiting sensing-assisted communication to enable blockage and beam prediction in an effective way [75].

As depicted in Fig. 2, ML models utilize environment awareness provided by sensing to predict future LOS blockages. In this way, cellular networks can take proactive decision on handover and beam switching and hence prevent a sudden drop in wireless link quality. ML has already been applied in a number of works related to beam management for MMW [76], [77], [78], as well as for THz [79], [80], [81]. A comprehensive review on utilizing ML for MMW and THz beam management is provided in [34].

Very little is known on supporting mobility in TC networks, since TC applications have been limited to personal/local area networks or to LOS point-to-point communications. As discussed, future emerging deployment scenarios will be 3D, adding another challenging dimension to the problem. We hereby identify the necessity to develop novel frameworks and modelling approaches based on SG, and to accurately model the impact of mobility in high-end MMW cellular networks including 3D deployment scenarios. This includes mobility procedures and algorithms that utilize micro-electro-mechanical system (MEMS) components to aid mobility in narrow beam radio environments.

C. LESSONS LEARNED

Efficient and reliable UDC deployment and mobility in complex urban environments hinges on addressing the limitations of traditional channel models. Current modeling feasibility gaps and promising research directions are summarized as follows:

- 1) High-frequency MMW bands face challenges in coverage and applicability in dense urban areas due to limited range and blockage sensitivity. Vertical deployment scenarios create unique challenges that 2D-based approaches cannot address adequately.
- 2) Current wireless channel models are predominantly 2D, and thus inadequate for highly dense urban areas with non-planar deployment. Research challenges also lie in developing 3D models effectively representing the urban network complexity at high-end MMW frequencies.
- 3) Traditional homogeneous PPP approach does not accurately reflect the real-world node distribution. The GPP and inhomogeneous PPP are potential alternatives to address spatial correlations but require further exploration and validation.
- 4) Mobility in 3D deployments adds complexity and requires novel frameworks and modeling approaches. MMW and beyond frequencies require highly directional beam steering to overcome propagation losses. The need for rapid beam switching and adaptation places stringent demands on latency and feedback, creating challenges for seamless mobility. Emulating user mobility in UDC deployments while balancing accuracy and simplicity/tractability remains a challenge.
- 5) ICS offers a way to share wireless resources and hardware to improve blockage prediction and proactive

handover, leading to reduced latency and enhanced reliability. Sensing-assisted communication may facilitate blockage prediction and proactive handovers. ML-based models may then be developed to utilize environment awareness and predict future LOS blockages, enabling proactive beam switching and handover for improved stability and QoS.

III. OFH ARCHITECTURE

To ensure seamless coverage amidst the transition from the congested low-frequency radio spectrum towards MMW transmission, high cell densification becomes imperative to address the diminished wireless propagation range. As the density of cell sites per area grows, so does the need for high bandwidth and low latency fronthauling. Additionally, the enabling architecture ought to address seamless capacity upgrade, backward compatibility, and convergence with the above-discussed 6G wireless technologies. One-size-fits-all FH solution is not feasible in a highly heterogeneous scenario, and so we highlight the architecture flexibility as an essential aim, on both system and component levels.

A. FRONTHAUL TECHNOLOGY

As increased cell densification underscores the relevance of efficient network management and resource sharing, the network architecture has evolved towards centralized RAN approach. In the traditional distributed RAN model depicted in Fig. 3a, the entire baseband processing blockchain is located at the remote radio head (RRH). Although on-site processing minimizes latency issues, it is cost prohibitive under 5G scenario. The performance is also hindered by the lack of support for signal coordination across multiple sites for interference management amongst densely deployed cells. Conversely, the co-location of baseband processing functions in a centralized BBU pool, as depicted in Fig. 3b, enables its separation from the RF chain and simplification of remote equipment, vendor-agnostic architecture design, operational and maintenance cost reductions, and advanced applications via cloud-based processing. Centralized RAN architecture enables the application of advanced resource coordination and performance enhancement functionalities, such as coordinated multipoint (CoMP), multiple-input-multiple-output (MIMO), enhanced inter-cell interference cancellation (eICIC), and carrier aggregation (CA). Centralized RAN approach thus benefits both computational and network resource management efficiency, leading to increased flexibility and cost effectiveness [1], [41]. The main cost of these benefits lies in the significantly more bandwidth demanding fronthaul segment. Broadband optical access technology, offering large bandwidth with low attenuation and latency, is best suited to facilitate the fronthaul segment under centralized network scenario.

In pre-5G network era, the FH segment was CPRI-based and carried the IQ symbols ready for the RF block in the protocol stack. The FH transmission thereby entails a high-resolution digitized version of the underlying signal,

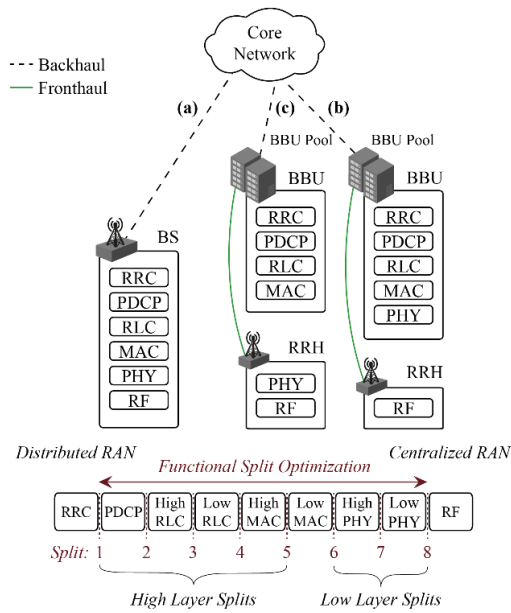


FIGURE 3. The migration from distributed to centralized network architecture model in the context of functional distribution options. The FS convention used is compatible to 3GPP TR 38.801, whereas the terminology for Central Unit (CU) and Distributed Unit (DU) segments therein correspond to BBU and RRH used in this paper, respectively.

thus highly bandwidth inefficient: the transmission requires constant data rate dependent on cell density, but irrespective of the user activity or presence. This approach does, however, carry the benefits of full centralization of baseband processing in enabling the advanced features as CA, eICIC, MIMO and CoMP. It is of note that in the context of massive MIMO systems employing hundreds of antennas, the OFH bandwidth requirement may easily scale to Tbit/s values for moderate native signal bandwidths. To illustrate the latter, Fig. 4 shows the FH bandwidth requirement in an 5G LTE system considering several values of channel bandwidth and MIMO ports. In each case, the requirement is calculated considering the worst-case resolution scenario of 16 bits/sample [82]. The results presented account for a single sector configuration, while also ignoring the line code and control overheads, the application of which would result in additional OFH bandwidth penalties [83]. Considering 100MHz of radio bandwidth (carrier aggregation of five 20MHz LTE-A mobile signals) with 3 sectors, and assuming 16 bits/sample, 8×8 MIMO antennas result in an OFH data rate requirement close to 118Gb/s. The data rate requirement increases to 157.3Gb/s when CPRI control word and 10B/8B line code overheads are considered. This highlights the importance of the FH transport technology design towards assuring bandwidth and cost-efficient operation, and clearly motivates the application of optical access technology in the FH segment (OFH). Nevertheless, such exorbitant requirements pose serious scalability and cost challenges even for the broadband optical access technology, particularly in high-end MMW scenarios. The employment of higher compression ratio is typically limited to 50%,

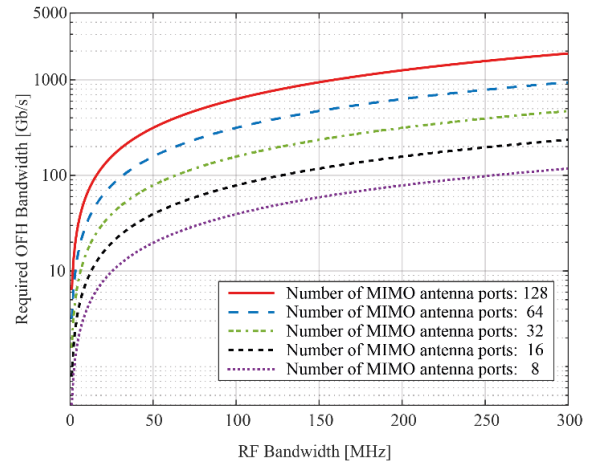


FIGURE 4. 5G LTE fronthaul bandwidth requirement for several channel bandwidth and MIMO scenarios assuming FS level 8 (i.e., traditional CPRI).

while it may have serious repercussions on the processing latency [84]. As such, the adoption of OFH architecture is accompanied by another re-engineering of the centralization paradigm involving re-distribution of baseband processing functions, as shown in Fig. 3c, this time striving to trade off a fraction of the centralization gain for more manageable OFH bandwidth requirements. Functional split (FS), referring to the point of demarcation between the centralized and distributed functions, marks the OFH link starting point and thus determines the type of data it carries. Therefore, FS selection will clearly be of great consequence to the bandwidth demand imposed upon the OFH segment, as well as its resulting reach in line with the latency requirement. For instance, functional splits in the PHY network layer imply a great deal of centralization with advanced features like MIMO and CoMP. However, this also implies stringent latency requirements due to the necessity to coordinate the PHY layer from a remote central unit (CU) which will thus be likely limited in its reach.

Given the aforementioned factors, OFH design necessitates a careful balance between link requirements and system constraints, while facilitating the simultaneous integration of advanced centralization features across all network segments. Depending on the desired degree of centralization, which dictates the type and bandwidth of data transmitted over fiber, future OFH systems present a wide range of optimization possibilities:

- 1) *The optical link topology:* ring, point-to-point, point-to-multipoint (star), as well as hybrid topologies and their multilevel variants. Apart from system cost and performance, the selection of topology also influences the feasibility of overlaying 5G signals onto existing fiber infrastructures.
- 2) *The type of fiber transport technology* facilitating the OFH connectivity. It is noteworthy that all standardized FS options to date involve transmitting a digital stream of bits over fiber. Conversely, an entirely distinct operational paradigm is involved in approaches where the

fiber carries the signal in its analog form, as elaborated upon in the following section. Furthermore, both digitized and analog approaches offer multiple frequency allocation options, resulting in various subsets of supported FSs.

- 3) *The underlying transceiver physical architecture* determines the MMW generation and detection capabilities, link capacity, level of coexistence of transport technologies, and the enabled configurability level (i.e., the range of controllable transmission characteristics, including the choice of modulation signaling and multiplexing).
- 4) *The optical transmission signaling selection* for the digital stream option: Intensity-modulation paired with direct-detection (IM-DD) technologies, as the cost-effective option; Advanced modulation formats and detection techniques (typically polarization multiplexed Quadrature Amplitude Modulation PM-QAM), as the high-performance option; Hybrid approaches amalgamating the diverse benefits of the preceding two techniques.
- 5) *The choice of optical fiber multiplexing*: Time-division multiplexing TDM in all its different variants, the most popular today being packed-based Ethernet; Wavelength-division multiplexing (WDM); Polarization-division multiplexing (PDM) and Space-division multiplexing (SDM) may be considered for additional capacity gains.

In order to support various functional splits concurrently, WDM-based connectivity may be considered in both point-to-point (PtP) and in PON point-to-multipoint (PtMP) topology scenarios. Although the most straightforward option, it is noteworthy that PtP fiber access may not be sustainable outside fiber rich areas. Depending on the MIMO and capacity limitations, high layer FS options (1-5 splits, as shown in Fig. 3) particularly may still retain the requirements manageable by cost-effective PtMP PON technologies as time-division WDM (TWDM) or coarse WDM (CWDM) PON. CWDM technology is likely to be appropriate only in scenarios of high layer FS and only several links per RRH site, due to the fixed wavelength assignment in its commercially available equipment, and its limited channel count. However, the migration towards low layer FS options (6-8 splits, Fig. 3), involving high capacity requirement and/or lower spectral efficiency of the underlying fiber transport technology, may significantly limit the coexistence with legacy PON. Dense or ultra-dense WDM (DWDM/UDWDM) technology may be employed to address these constraints, but their cost-effectiveness needs to be adequately considered against scenario-specific cell density gains. DWDM and TWDM technologies may coexist over a shared PON infrastructure, where both PtP WDM and PtMP TWDM subsystems may be concurrently fed through the same optical distribution network (ODN). Finally, another relevant question is how to handle the compatibility of any novel fronthauling solution

with the already available standards (GPON, XG-PON, XGS-PON, NG-PON2, 50G-PON in the ITU-T ecosystems, and the similar counterparts in the IEEE ecosystem).

The optimization of these factors towards the final network design is typically a matter of compromise between the system performance and cost, on per-use-case basis. Today, commercial fronthauling deployments are usually based on point-to-point, IM-DD solutions, at times coupled with CWDM. Future solutions supporting advanced 5G/6G will likely be considerably more heterogeneous and will derive from a compromise between reduced system cost (e.g., direct detection), increased spectral efficiency, power budget, and inherent channel selectivity (i.e., coherent detection) or, in the longer term, analog-based solutions. In the following, we discuss relevant OFH design aspects while focusing on PON, as by far the most commercially deployed fiber access solution worldwide.

B. WIRELESS SIGNAL TRANSPORT TECHNOLOGY

To facilitate PON architecture in the above discussed context of future MMW transmission and heterogeneous network operation, two fundamental variants of wireless signal transport over fiber may be considered, as shown in Fig. 5. Analog-radio-over-fiber (ARoF) approach is depicted through paths a and b, whereas the digitized-radio-over-fiber (DRoF) counterpart is illustrated through paths c and d. In a typical ARoF, signal processing and frequency conversion are carried out at the central office (CO, i.e., 3GPP CU), and the wireless signal is converted to the optical domain (E/O) and transmitted in its analog form using the fiber optic link. Depending on the limitations of electro-optical components, the signal may be transmitted at the final, air-interface radio frequency (RF), using a scheme often referred to as the RF over fiber (RFoF, Fig. 5a). Alternatively, in a system transmitting the intermediate frequency (IF) signal over fiber (IFoF, Fig. 5b), additional RF local oscillators (LO) and mixers are required for electrical conversion to the RF at the remote site. It is of note that the ARoF schemes may be digital signal processing (DSP)-enhanced, enabling the application of optical (pre-) compensation and more efficient channel aggregation. However, the application of DSP enhanced ARoF also requires additional high-speed digital-to-analog and analog-to-digital conversion (DAC/ADC) elements at the remote site, along with the consideration of the resulting latency and cost efficiency. Conversely, in DRoF architectures the wireless signal is digitized and transported over fiber in a serialized digital format. The transmission may also be considered at the RF or the IF (Fig. 5c and d, respectively), while signal processing may still be performed centrally, fully or partially depending on the required centralization degree and FS selection. By comparison, DRoF architecture requires additional ADC/DAC components, generally adding to the system complexity and power consumption. Note that Fig. 5 classification applies to the uplink (UL) transmission as well, where electrical up/down-conversion (EDC/EUC) rely on the same basic architecture elements.

TABLE 2. State-of-the-art on optical transport networks for wireless signals.

Year/Ref. (Fig. 5)	RoF type	IF/RF generation	RoF highest CF	Wireless RF DL/UL	Aggregate data rate	DL Reach: ODN / Wireless	Remarks
<i>Sub-6GHz band</i>							
2022 [95] (c)	DRoF	EUC	1GHz	1GHz / -	10Gb/s	4km / 1m	Delta-sigma modulation link with simplified RRHs, 10G-class optics and remote powering/seeding feature
<i>Sub-MMW band</i>							
2022 [96] (a)	ARoF	EUC	10GHz	-	0.2Gb/s	29.7km / -	Full-duplex PDM with wavelength reuse for WDM
2022 [97] (a)	ARoF	EUC	12GHz	-	10.51Tb/s (4608ch)	10.1km / -	12-SDM/16-WDM/24-SCM for high channel count link
<i>MMW band</i>							
2023 [98] (a)	ARoF	EUC	24GHz	-	1.2Gb/s	10km / -	Reconfigurable multiservice C-RAN with SiP wavelength selective switches
2022 [99] (a)	ARoF	OUC	26GHz	26GHz / 26GHz	4.03Gb/s	10km / 9m	Full-duplex TDM based on OFM (doubling) and CS DSB for DL OHD and UL EDC
2023 [100] (b)	ARoF	EUC	2GHz	27GHz / -	1.88Gb/s	5km / 165.5m	Electronic beam steering with 8 x 8 PAA
2022 [101] (a, b)	ARoF	EUC	28GHz	-	20Gb/s	20.33km / -	Dual-band RoF with concurrent 10Gb/s transmission at 3.5GHz and 28GHz using PDM
2021 [102] (a, b)	ARoF	EUC	9.1GHz	28GHz / -	34.2Gb/s	21.5km / 10m	Multi-stage SCM system: RFoF and IFoF (wide- and narrow-band). DSP based channel selection at RRH
2023 [57] (a)	ARoF	OUC	28GHz	28GHz / -	4Gb/s	50km / 2m	2-λ VCSEL DML using OCM for OHD, and novel signaling and bit loading for wired and wireless network coexistence
2023 [103] (d)	DRoF	EUC	37.5MHz	1.8GHz / -	8Gb/s	15km / -	DRoF and access PON coexistence using SiP switch and 10G-class optics
2023 [104] (a)	ARoF	OUC	42GHz	42GHz / 38GHz	0.6Gb/s	10km* / 1.1m	Full-duplex WDM/SCM. OCM and OFM (doubling)-based MMW generation for DL OHD and UL EDC *Includes a 1.1m long FSO link
2023 [105] (b)	ARoF	EUC	1.5GHz	60GHz / -	0.237Gb/s	1km / 7m	Active reconfiguration with ROADMs and VLAN tag-to-wavelength mapping. 10G-class optics
2023 [106] (b)	ARoF	EUC	3.5GHz	60GHz / -	51Gb/s (4λ WDM)	1km / 1m	Passive reconfiguration with AWGR and wavelength allocation. Electronic Beam Steering , MNO network sharing. 10G-class optics
2022 [107] (b, d)	ARoF+ DRoF	EUC	4.5GHz	60GHz / -	35Gb/s (4λ WDM)	10km / 1m	1λ-DRoF + 3λ-ARoF coexistence over a shared link using ROADM and 10G-class optics
2022 [108] (a)	ARoF	OUC	60 GHz	60 GHz / -	9.84Gb/s	10km / 1m	OHD based on dual laser OCM and analog phase noise cancellation. Flexible wavelength and radio carrier assignment.
2023 [109] (a)	ARoF	OUC	60GHz	-	10Gb/s	25km / -	OHD based on SSB and single-path dual-wavelength IQ modulator
2022 [110] (a)	ARoF	OUC	88.5GHz	88.5GHz / -	110Gb/s	100m / 4.6km	OHD relying on IQ modulator and dual-laser OCM, along with wireless PDM
<i>Sub-THz band</i>							
2022 [111] (c)	DRoF	OUC	130GHz	130GHz / -	55.8Gb/s	100m / 4.6km	Delta-sigma modulation paired with OCM and OHD
2023 [58] (a)	ARoF	OUC	150GHz	150GHz / 28GHz	60Gb/s (3λ WDM)	25km* / 0.5m	Full-duplex WDM with unidirectional wireless links. MMW-Sub-THz link using OCG, UTC PD and remote IL for UL *Includes a 500m long FSO link
2023 [112] (b)	ARoF	EUC	1GHz*	-/145GHz	6.3 Gb/s	1km/0.5m	V-band and D-band UL links over the same IFoF setup. *UL data, EUC corresponds to EDC
2023 [113] (a)	ARoF	OUC	300GHz	300GHz / -	46.7Gb/s*	1km/5m	OHD based on dual laser OCM, UTC PD and phase-insensitive receiver. *Estimated

The table focuses on downlink (DL) transmission metrics unless specifically distinguished from the uplink (UL). Each reference is associated with the RoF schemes presented in Fig. 5. **EUC**: Electrical up-conversion; **OHD**: Optical Heterodyne Detection; **OFM**: Optical frequency multiplication; **DL**: Downlink; **UL**: Uplink; **CF**: Carrier Frequency; **RF**: Radio Frequency. Key implementation features are outlined in the ‘Remarks’ column, with the identified qualitative advantages highlighted in bold text.

Candidate fronthaul fiber transport technologies must satisfy the capacity, latency, and signal fidelity requirements.

By general comparison, ARoF handles capacity requirements with higher spectral efficiency, but typically struggles to

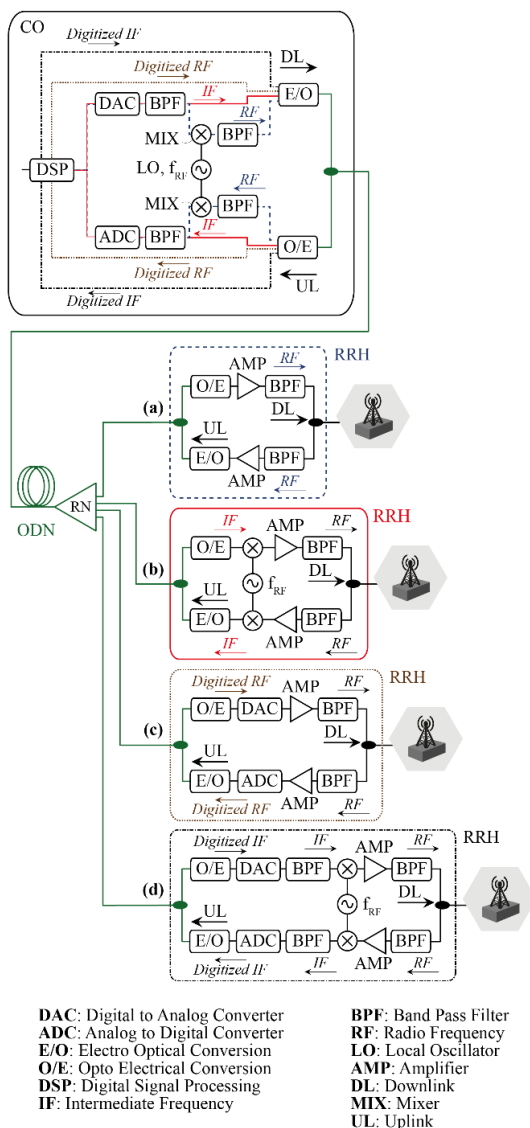


FIGURE 5. Coexistence of radio-over-fiber (RoF) transport schemes supporting various RRH types and functional splits. RF AroF (RFoF) - blue dashed, IF AroF (IFoF) - red full, RF DRoF - brown dotted, and IF DRoF - black dash-dotted, are shown in paths a-d, respectively. ODN is presented in green color. The terminology for the OFH Central Office (CO) hereby used corresponds to that of CU used in 3GPP TR 38.801.

maintain signal fidelity over longer fiber spans [85]. Two dominant reasons for this issue are high sensitivity to the intrinsic opto-electronic noise and nonlinearity, along with the fiber dispersion-induced periodic carrier fading [86]. In the context of migration to the MMW frequency transmission, the carrier fading induced penalty exacerbates, as the effect scales proportionally to the fiber length and the square of the radio carrier frequency [87]. Conversely, DRoF schemes are more immune to the mentioned impairment effects, owing to the signal digitization which effectively de-couples the radio signal from its optical representation at the E/O conversion stage. This leads to comparatively higher reach and dynamic range as the system is effectively limited by the optical segment sensitivity. However,

to maintain signal fidelity CPRI-based DRoF digitization relies on high resolution quantization, typically a 16-bit width for each radio signal I/Q sample, resulting in tremendous bandwidth requirements shown in Fig.4. Moreover, additional DAC/ADC components required in DRoF system architectures come with their own particular impairment sources and cost/complexity issues. Namely, jitter and quantization noise are critical system performance factors [88], [89], [90]. Additionally, the linear relationship between the sampling rates and power consumption makes for higher system cost compared to that of a typical AroF system, particularly under high traffic loads and/or high-end MMW transmission [91]. The bandpass sampling technique is typically employed to relax the sampling rate requirement, but it necessitates the system re-design for RF frequencies outside the originally intended frequency range [92]. By contrast, the baseband processing in AroF-schemes maintains full centralization benefit, while also simplifying the RRH architecture and enabling higher coexistence potential due to its spectral efficiency. Within the context of MMW transmission, the bandwidth required by AroF schemes relates to the sum of the signal bandwidth and the MMW frequency. When paired with MMW generation schemes such as frequency multiplication at the CO and optical heterodyning at the RRH side, the bandwidth requirement in some applications may be managed to the level of cost-effective optical transceiver technology [93], [94]. On the other hand, DRoF benefits from the generally more mature standardization compared to its analog counterpart.

Table 2 showcases how these considerations reflect on the relevant state-of-the-art developments en route to high-end MMW and sub-THz RoF feasibility in the past 3 years, as per the RoF classification introduced in Fig. 5. Namely, as both analog and digitized variants may rely on IF, we hereby keep the basic classification to AroF and DRoF for clarity. The table nominally focuses on the downlink (DL) RoF transmission metrics, unless stated otherwise, except for the column addressing the wireless RF transmission to showcase its full-duplex feature where present. Note that the discrepancy between the highest RoF carrier frequency (CF) and the wireless RF implies the RoF transmission at an IF, and the use of EUC at the RRH. The lack of reported wireless RF frequency indicates the focus on the optical segment, with no inclusion of wireless transmission, as further indicated in the wireless reach column. However, the works that do not feature wireless transmission are included provided that the RoF RF fits the band classification discussed in Section II. Namely, we hereby designate the frequencies beyond 20GHz as the MMW band, whereas the RF band beyond 95GHz is denoted as sub-THz band [58].

To assess the recent developments within the context of high-end MMW operation, we distinguish the EUC and the optically aided up-conversion (OUC), as two fundamental approaches towards RF signal spectral allocation to the desired air-interface frequency range. OUC techniques involve remotely seeded optical heterodyning (OHD),

whereby an optical carrier (i.e. pilot tone) is transmitted along with the data-carrying signal, spectrally separated by the IF/RF frequency, and serving as a LO for self-seeded up-conversion at the RRH. At the CO, the remote LO is either multiplexed using single- or dual-laser source architectures, hereby classified as the optical carrier multiplexing (OCM) schemes [57], [104], [111], and/or generated by means of optical frequency multiplication (OFM) [58], [99], [104]. OCM is mostly WDM-based, whereas SDM may be considered in full-duplex implementations aiming to minimize the bidirectional crosstalk [99]. To enable OHD with phase noise cancellation and higher laser linewidth tolerance, OCM typically involves a single-laser source for phase correlation between the signal and the LO carrier, often implemented using optical frequency comb (OFC) generators [58], [114]. Alternatively, since the use of un-correlated laser sources (i.e. dual-laser schemes) in OHD typically requires DSP along with additional ADC/DAC components at the RRH, to avoid offsetting the traditional benefits of ARoF an interesting approach may be found in the application of analog phase noise cancellation techniques [108]. Finally, OFM is often employed to make use of the modulator higher order harmonics in aid of MMW up-conversion, while pursuing lower complexity of the electronic components at the CO and RF operation beyond the modulators' native bandwidth limitation. In OFM schemes, the modulator biasing is typically optimized for carrier suppressed (CS-) double-sideband (DSB) transmission for dispersion impairment mitigation [99], [104], with the benefit of inherent frequency doubling in contrast to single-sideband (SSB) based schemes [109].

The review reveals a focus on both the 26-28GHz and 60GHz bands, with noteworthy efforts to also enable sub-THz bands [58], [111], with both ARoF and DRoF architectures featured as enabling technologies en route to future MMW transport networks. However, analog approaches are predominant, owing to the spectral efficiency and the simplicity of the RRHs processing the wireless signal in its native format, as opposed to the high-bitrate CPRI-based links. More specifically, despite requiring the EUC at the remote site, IFoF (Fig. 5b) variants of ARoF stand out in the recent literature due to the maturity of electronics and the wide availability of low-cost, often 10G-class optics [95], [103], [105], [106], [107]. Conversely, their RFoF counterparts (Fig. 5a) are predominantly OUC-based, relying on photonics-aided signal generation/detection techniques as OFM and OHD to enable high-end MMW operation at a clear advantage of lower processing complexity. The exclusion of hardware required for the EUC at the remote site, however, comes at the price of more rigorous dispersion management and increased bandwidth/complexity of the O/E conversion components. In [99] and [104], the dispersion-induced impairment is managed by using CS-DSB OFM for a 10km link transmission, while relying on a 50-GHz and a 26-GHz (3-dB bandwidth) photodetector (PD) to establish a 42GHz and a 26GHz MMW system, respectively. The THz ARoF system (OUC-based)

demonstrated in [113], relied on a uni-travelling carrier photodetector (UTC-PD). Moreover, in [58], upon the 25km fiber transmission in the 150GHz MMW (sub-THz) configuration, a 150-GHz UTC-PD was required for the O/E conversion segment at the remote site. However, the applied impairment mitigation technique was still not sufficient for a 40km transmission in multi-carrier regime, targeting the forward error correction (FEC) detection limit, including that of the 50GHz MMW carrier signal [58]. It is thus noteworthy that even when relying on high bandwidth photodetection, transmission reach in high capacity and/or MMW frequency regimes may still be a limiting factor in ARoF.

Notable examples enabling full-duplex wireless transmission are OUC RFoF schemes, based on CS-DSB and OFM [99], [104]. The main feature enabling bidirectional operation in both works is the remote seeding of the electrical LO for the purpose of UL down-conversion to IF. While in [99] the electrical LO is obtained from the electrically filtered beating of the optical tones originating from the CS-DSB signal at the PD, in [104] the LO is converted to the electrical domain using an additional PD at the RRH. The full-duplex end-to-end RoF transmission is enabled in [99] by TDM, WDM and SDM, whereas in [104] DL, UL and LO are wavelength multiplexed and share the same single mode fiber. Full-duplex WDM is also implemented in [58], although relying on decentralized deployment of dedicated laser sources for the UL fiber transmission at a separate wavelength. The architecture relies on the remote injection locking (IL) for UL impairment mitigation, which may also be considered in the DL. Other works showcasing bidirectional wireless operation do not pursue it through the cooperative convergence of the optical and radio segments. For instance, bidirectional wireless transmission is considered in [105], along with the software defined networking (SDN) capabilities, albeit without fiber transmission in the UL direction. Finally, most featured works are not full-duplex wireless transmission solutions, but rather focus on the DL direction. Nevertheless, some still provide relevant insights on current features that may be utilized in aid of bidirectional operation. In [96], a bidirectional WDM based ARoF link is achieved, with symmetrical rate of 200Mb/s and sub-MMW frequency of 10GHz. Wireless transmission is not considered, whereas the UL fiber transmission was carried out over a dedicated, short-reach fiber. However, an interesting feature employed towards organic bidirectionality is the polarization multiplexing of the DL SSB data modulation paired with self-heterodyne detection, with the optical carrier intended for the remote seeding of the UL signal. The architecture relies on the tandem operation of two dual drive MZMs, concurrently enabling the nonlinearity suppression and carrier fading mitigation, whereas the PDM enables lower bidirectional crosstalk and colorless features.

High capacity of optical channels towards MMW capabilities is mainly exploited by means of data aggregation and dense multiplexing techniques, and many implementations already support Gigabit rates. However, featured RoF

architectures with at least 1km fiber reach and beyond 10Gb/s aggregate rates while supporting MMW band transmission are mostly WDM-based [58], [106], [107]. In light of the previously discussed bandwidth requirements under densification scenario, CPRI-based DRoF has been sidelined in favor of DRoF based on enhanced-CPRI (eCPRI) and managed FS, to achieve the CPRI-equivalent data rates above 100Gb/s at the loss of some centralized resource allocation features [115]. Thus, targeting high CPRI-equivalent data rates towards deeper assessment and comparison of analog and digitized schemes is a very active field of research, albeit with little recent focus on MMW operation highlighted in Table 2. Nevertheless, the field seems to be moving towards hybrid RoF approaches, where CPRI-equivalent data rates well beyond 100Gb/s are feasible even with 10G-class optics and direct detection [116], [117]. These are promising results, however, the context of MMW operation and particularly that based on OUC RFoF, will add a significant level of complexity to the above discussed trade-off between the component/system cost and performance in terms of reach and data rate. Table 2 indicates that, for the time being, high CPRI-equivalent rates with cost-effective optics may be limited to EUC-based solutions relying on IFoF. A notable example is found in [97], where a multicore fiber based scheme (SDM) transporting multiple WDM channels paired with subcarrier multiplexing achieves the transmission of a total of 4608 OFDM channels for the aggregate rate of 10.51Tb/s. Although a proof of concept with no consideration of wireless transmission, the work in [97] suggests that systems relying on coexisting channel aggregation schemes may be considered towards 6G CPRI-equivalent data rates even when relying on an intensity modulation and direct detection (IM-DD) ARoF architecture. Namely, note that a ten-fold improvement in peak rates is expected to be necessary towards 6G networks compared to 5G, yielding the CPRI-equivalent data rate requirement likely beyond 1Tb/s [118]. Along the line of such requirement, we identify the incorporation of coherent detection (CD) systems, paired with hybrid RoF transmission schemes, as the key enabler for the shift in the CPRI-equivalent data rates beyond 1Tb/s [119], [120]. Although more cost prohibitive compared to IM-DD schemes, it is further of note that the coherent technology CAPEX and OPEX are being actively addressed and steadily decreasing [121], [122]. Finally, the above discussed approaches may also be complemented with simplified CD schemes based on optical single-sideband and twin single-sideband techniques [123], [124], [125], [126], targeting continuous multiple access, power budget gain, low-cost operation and UDWDM. An efficient use of the electrical bandwidth may be pursued by using Hilbert transforms [123], [126].

As previously noted, while the MMW generation and the fiber transport has been studied in end-to-end links, the wireless channel transmission is often entirely omitted. When included, wireless ranges up to 10m are typically achieved when relying on standard horn antennas in indoor

and regulated environments. Outdoor measurements with distances over 100m, based on a highly directive 8×8 patch phased arrayed antenna (PAA), are reported in [100], whereas a 4.6km long wireless link is obtained by relying on power amplifiers and dielectric lenses to maximize the wireless reach [110], [111]. However, in the context of MMW and sub-THz operation, dynamic radio beam steering and forming stand out as pivotal features. Practical implementations found in the researched literature incorporate standard PAA electronic beam steering functionalities [100], [106]. While these demonstrate notable progress, the advantages of converged optical-radio approaches, such as photonically aided beam steering, are becoming increasingly apparent. As opposed to phase shifters in the electronic approaches, optical beam forming networks (OBFN) often rely on true time delays (TTD) for the control of the beam direction, thus avoiding the bandwidth limitation caused by beam squint effects [127]. Centralized location of wide bandwidth TTD OBFN may enable cooperative beam direction control strategies for efficient user handover and intercell interference (ICI) mitigation [128]. Despite the anticipated gains, challenges towards practical implementation persist, but significant progress has been made through proof of concept experiments that have unveiled the potential of the technology, paving the way for future applications and further developments in the integration of OBFN within converged network environments [128], [129], [130]. Another line of research targeting the optical-wireless convergence points towards the integration of optoelectronic chips with antennas for compact low-cost remote radio-head units that may be directly connected to the OFH, with potential for dynamic beam steering and frequency reconfigurability by leveraging both the optical and the radiofrequency domain properties [131], [132], [133], [134]. Added potential is anticipated when paired with RoF schemes that make extensive use of multiplexing for carrying multiple concurrent channels with aggregate throughput of several Tb/s [97]. It is of note, however, that end-to-end convergent optical wireless network solutions that demonstrate the use of OFH are scarce.

Finally, these considerations point to the complementary merits of diverse strategies, whereby the advantages of hybrid systems may be explored through their ability to amalgamate the unique benefits of individual techniques. An interesting approach towards combining the advantages of ARoF and DRoF relies on the application of delta-sigma modulation (DSM), enabling the replacement of power-hungry DAC/ADC components with binary drivers, while matching the DRoF stability and impairment resilience [95], [111], [135]. Although steadily gaining significant traction, in some scenarios this approach will not outperform the ARoF architecture while introducing higher digital-domain complexity, which may be particularly prohibitive in the UL considerations [135]. Aside from the DSM, several other approaches have leveraged the coexistence of RoF technologies to provide enhanced functionalities to the FH. This includes enabling the coexistence of concurrent channels in low and

high frequencies in a dual-band system [101], facilitating simultaneous DRoF and ARoF operation [107], multi-vendor infrastructure sharing [106], supporting multiple radio access technologies over the same OFH [112], and allowing the resource sharing between optical networks catering to different services, such as digital data services and mobile network services [57], [103]. Both active [105] and passive [106] reconfigurability has been achieved through the tag-to-wavelength mapping using the 802.1Q virtual local area networking (VLAN) tag mechanism in thermally-controlled reconfigurable optical add-drop multiplexers (ROADM), and arrayed waveguide grating routers (AWGR) respectively, and wavelength selective switching solutions have been showcased by the works in [98] and [103]. Generally, in highly heterogeneous network operation scenarios, dynamic configurability targeting time-varying requirements rather than the a-priori commitment to any single configuration, may enable simultaneous benefits from the merits of different optical segment architectures. Namely, having the aforementioned (dis)advantages in mind, ARoF architecture may be considered the main candidate towards supporting the NG applications targeting broadband communications at low latency, such as Enhanced Mobile Broadband (EMB), Ultra Reliable Low Latency Communications (URLLC) and Massive Machine Type Communications (MMC). In some conditions, DRoF approach may be considered for MMC [136], as well as scenarios relying on longer reach, lower power requirement or higher system robustness and dynamic range.

C. OFH TRANSCEIVER CONFIGURABILITY

The concepts of dynamic FS selection and concurrent support of different RoF technologies facilitating the fronthaul connectivity are motivated by the principle of flexible coexistence and configurability, in contrast to one-size-fits-all approaches. The same principle may be applied at the level of OFH transceiver technology through its virtualization, aiming to generate a range of controllable optical transmission characteristics. This approach may be particularly beneficial towards the system cost-effectiveness, as a key challenge of PON technology implementation in a heterogeneous scenario. For instance, a large portion of the system cost of the previously described transport architectures may come from the necessity to rely on colored optics at the remote site (i.e., the use of tunable lasers and tunable filters), a scenario in which the UL data is transmitted over a dedicated wavelength. As shown in the previous section, to avoid cost ineffective application of tunable lasers at the remote site, looped-back architectures based on remote optical seeding for the UL may be used. The remote optical carriers are thereby pooled at the CO, which then centrally controls their distribution and the UL transmission wavelength. The optimization context for the remotely pooled optical carriers may then be extended to consider various MMW RoF architectures and impairment mitigation techniques.

The concept of component pooling in the electro-optical conversion segment at the CO is depicted in Fig. 6 for

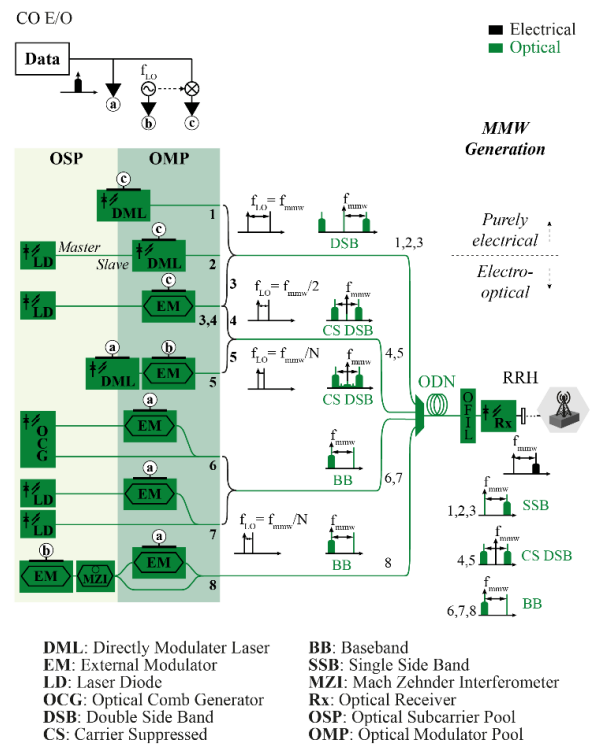


FIGURE 6. Component pooling in the electro-optical conversion segment highlighting the OSP/OMP coexistence scenario. Paths for purely electrical (paths 1-3) as well as the electro-optical (paths 4-8) MMW generation schemes are presented.

illustrative purposes, whereby the architecture is composed of the optical subcarrier and the optical modulator resource pools. The optical subcarrier pool (OSP) contains a group of optical carriers (i.e., pilot tones), which may be generated by single or multi-wavelength sources, as well as in tandem with components comprising the optical modulator pool (OMP). Within the context of previously discussed RoF options, the former may rely on single- or dual-laser OCM architecture, while the latter is compatible with the OFM based RoF schemes. The required versatility of optical modulator options available in the OMP depends on the variety of QoS characteristics that the OFH architecture must concurrently support in heterogeneous network scenarios. Said versatility pertains to the choice of modulation formats, data rates, MMW capabilities, FS optimization and latency, whereas their coordinated orchestration ought to account for the cost and the performance repercussions. Fig. 6 showcases a generalized summary of options that may be considered towards versatile, multi-purpose distribution of optical carriers for multiplexing, MMW generation, remote seeding, OFC line generation, OFM, and IL. Note that the configurations “a” and “b” denote the independent application of the baseband data and the electrical LO, respectively, while option “c” denotes their electrical mixing.

During optimized and scenario driven operation, and depending on its features, an OMP component may be used for either low-cost (paths 1,2) or high performance (path 3) scenarios, MMW generation via OFM (paths 4,5,8), as well

as for optical source correlation in OHD (path 8). Note that, in Fig. 6, N represents the sub-harmonic multiplier of the desired MMW frequency in an external modulator (EM). It is of note that all shown scenarios relying on OFM may also be considered in cascaded EM configuration mode for modular frequency multiplication. Furthermore, an OSP component may be optionally used for WDM multiplexing or UL wavelength distribution, IL-based impairment mitigation (path 2), as well as for OUC-based MMW generation in tandem with OHD technique for carrier up-conversion at the remote site (paths 6-8). Depending on the MMW signal bandwidth and transmission reach requirements, paths 1-3 may include optical baseband filtering or SSB/CS-DSB modulator biasing (path 3) for increased tolerance to chromatic dispersion related impairments. Moreover, IL may also be used for the optical SSB signal generation. Depending on the master and slave laser properties, multiple slave lasers may be injection-locked using a single master laser. Alternatively, frequency doubling may be achieved in paths 1-3 through optical interleaving rather than the carrier suppression (paths 4,5), which in turn enables remote UL seeding and wavelength re-use. In other cases, a configuration relying on carrier suppression-based frequency doubling may be preferable and lead to lower system complexity.

Such multi-purpose approaches may lead to the OSP and OMP consolidation towards reduced redundancy and cost. Aside from optimized resource distribution, all illustrated path options require careful coordination of modulator biasing and IF multiplication depending on the link and optimization requirements. To assure cost-effectiveness in a heterogeneous scenario, pooling optimization ought to be performed holistically while considering the radio network segment resources and requirements, available FS options and fiber transport technologies, as well as the CAPEX/OPEX implications of each available configuration. This scenario promotes a comprehensive consideration of the coexistence of these optical transport schemes over a flexible and configurable SDN-based framework, rather than the commitment to a singular approach [35].

In order to unlock the benefits of SDN control on the component level, the optical infrastructure framework ought to enable flexible and sliceable software defined transceiver (SDT) operation with intelligent, modular and programmable multi-rate, multi-format, multi-reach capabilities, tailored for disaggregated and cost effective OFH within the parametric requirements set by 6G UDCs. Optimized SDT design is thus crucial towards required flexibility (service versatility and granularity) with acceptable system complexity (redundancy, blueprint and CAPEX/OPEX). To fulfil the requirements of highly heterogeneous network operation, a key feature enabled by SDTs is the physical separation of control and data planes, allowing centralized control over multiple devices for context- and flow-driven operation. This paradigm requires careful consideration of physical layer attributes towards fully SDN controlled optical communication for 6G OWNs. The field of optical virtualization

has mainly been focused on network level research [137], [138], [139], with key features such as cost, complexity, scalability, and fiber-wireless integration still facing relevant technical challenges. The conceptual role of SDTs is to provide adaptability to network operating conditions, typically achieved via modulation format control facilitated through DSP [140], [141]. Such bandwidth variable software defined transceivers (BVT) are considered an attractive virtualization concept [142], [143], albeit aggregation support critical for efficient and cost-effective infrastructure sharing remains an open question. The field of SDTs has also been focusing on the upgrade to the multi-flow scheme, whereby a single BVT enables multiple traffic flows and their individual bandwidth control [144].

The above described concept of virtualized optical subcarrier and modulator pooling, allowing both resource aggregation and slicing, has been recognized as promising [142], [143]. As conceptualized in Fig. 6, following this approach implies the use of different design options for transmitter and receiver ends, where both direct and external modulation (DM/EM), as well as both direct and coherent detection (DD/CD) may be applied, for additional level of flexibility in complexity versus performance trade-off. Multicarrier modulation (MCM), based on discrete multitone (DMT) or orthogonal frequency division multiplexing (OFDM), is often employed for additional flexibility. With system cost and power consumption in mind, the utilization of DM-based transmitters such as vertical cavity surface emitting laser (VCSEL) has been explored: with the aid of advanced modulation formats using DM of VCSEL with 3-dB bandwidth limited to 15 GHz, a short-reach transmission capacity of up to 100 Gb/s is feasible [145]. Subsequently, the realization of sliceable BVTs (SBVT) relying on DM and DD is being exceedingly explored, where the ability to employ 20 GHz bandwidth tunable VCSEL technology allows up to 50 Gb/s per-flow capacity, which with the aid of photonic integration and MEMS technology supports up to 2 Tb/s capacity per single SOI chip while covering the entire C-band [146]. MCM paired with adaptive DSP is employed to enable variable bandwidth transmission [147]. Transmission reach may be significantly extended by employing simplified CD based receivers, whereas scalable aggregate capacity is further enabled by the system modularity [148]. Indeed, SDT architecture modularity is considered a key feature towards flexibility and cost effectiveness of NG converged networks targeting heterogeneous operation. Individual bandwidth slices may then be orchestrated via SDN controller according to the QoS requirements and the resource availability. However, modularity is still typically achieved by using single purpose OMP/OSP configurations, while the discussed inter-component cooperation and subsequent consolidation of the OMP and OSP have not been fully explored. Moreover, it would be highly beneficial to explore the SBVT design within the context of pursuing an increased reliance on low-cost COTS components [16], as they typically suffer from considerable bandwidth, chirp, relative intensity

noise (RIN), nonlinear impairment, and multiplexing scalability (e.g., SCM) limitations [143], [144], [149], [150]. The potential of adaptive pooling approaches targeting the NG bandwidth and latency requirements, particularly in long reach, beyond 60 GHz MMW transmission scenarios, and its interoperability with vRAN functionalities towards joint resource orchestration is still largely unexplored [7], [142], [151], [152].

The above discussed concepts and challenges of optical hardware virtualization in high cell densification and dynamic centralization scenarios highlight the necessity for deep considerations on the cost and redundancy repercussions, towards assuring that the benefits of cloud-based centralization are not prohibitively offset. In this sense, holistic approaches targeting multi-layer network optimization in both optical and radio segments concurrently are highly beneficial. Paired with multi-purpose and tandem configurations in SDT design, this direction may lead to reduced architecture redundancy and enable increased reliance on low-cost COTS components, as well as flexible and efficient optical infrastructure orchestration for multi-rate, -format, and -reach requirements of heterogeneous network operation. Although virtualization of network functions via cloud-based networking does not strictly necessitate the optical layer virtualization, joint orchestration of radio and optical transport resources facilitating the connectivity between the BBU pools and the RRUs may have a considerable impact on the overall network performance, as discussed in the following.

D. OFH VIRTUALIZATION

To extend the benefit of centralized and coordinated resource management, optical resource virtualization (ORV) and physical layer configuration of SDT-based OFH architecture ought to be streamlined with the vRAN based approach. Towards this aim, vRAN architecture is envisaged as an integrated virtualized software defined platform, that will not only include the radio access protocol stack but go beyond and include full optical resource orchestration and SDN-based optimization, foreseen as an “added-on feature”. This networking approach targets highly configurable and dynamic allocation of resources and overall system flexibility required to support legacy and backward compatibility on the one hand, and seamless evolution and convergence of technologies on the other. This direction also highlights the necessity for DSP development for scenario-centric adaptive transceiver control, where computational resources deployed for impairment compensation become a part of the joint resource management in vRAN environment. In light of the above discussed aims for UDC and OFH designs towards heterogeneous NG networks, these enablers ought to pursue simplified hardware platforms, binary modulator drivers and format-transparent DSP, allowing relaxed electrical component requirements and versatile yet simplified DSP control. Holistic network approaches are required towards establishing specific component functionalities and deriving

compensation techniques enabling enhanced bandwidth, coverage, and latency.

SDN has the potential to facilitate high optical segment flexibility and re-configurability, as it decouples the segment control and data planes enabling the abstraction of the underlying physical infrastructure and software disaggregation from dedicated and vendor-specific hardware platforms. The control and data planes communicate via open interfaces, such as OpenFlow [153], which facilitate programmability and remote control. Along with efficient integration with optical physical layer technology, these features enable higher segment and network flexibility and dynamic resource and performance control. However, extending the centralized abstraction and control into the physical network layer, beyond its conventional limitation to network Layers 2 and 3 only, necessitates software-configurable photonics often in tandem with enhanced DSP control [154], [155], [156], [157], [158], [159], [160], [161]. The benefit, however, includes the possibility for the application of scenario-specific impairment compensation control.

Unlike the dynamic nature of mobile wireless standardization in terms of adaptation of traffic requirements and physical channel parameters, ITU-T and IEEE PON standards have typically been characterized by fixed bitrates and worst-case power budget specifications (e.g., data rate and power budget) with little adaptability to the available physical channel [162]. The scientific debate on how to bridge the gap between the currently relatively static PON and the dynamic wireless networks is very active on different levels [1], [115], [137]. Towards reconfigurable and SDN-based implementation in particular, DSP-assisted techniques such as FDM aggregation have been implemented in 5G OFH architectures [163], [164], [165]. Such techniques, however, have not been addressed in the context of MT SDT architectures supporting high-end MMW and/or intermediate frequency operation and legacy coexistence. Digital orthogonal filtering (DOF) via hardware-based DSP is another approach proposed towards assuring configurable transceiver operation, while avoiding additional analog hardware [154], [155], [156], [157], [158], [159], [160], [161]. The digital filter multiple access approach, however, necessitates the application of DOF in each individual RRH/optical network unit (ONU), to enable the dynamic and adaptable access to the optical transport resources. However, the resulting DSP complexity, particularly at the UE, remains a concern being tackled in current research. Towards reducing the filtering complexity while enhancing the transmission capacity, optical OFDM based schemes have been recognized as the dominant approach [154], [158], [159], [160]. Nevertheless, due to high sensitivity to bandwidth versus complexity trade-off, the application of DOF architecture may necessitate per-use-case consideration of the radio segment design. It is also noteworthy that this approach requires careful analysis of the resulting latency and jitter ramifications [160].

In current pursuit of 100Gb/s/λ PON industry standard (IEEE 802.3ca, ITU-T SG15), the component bandwidth

limitation as well as the exploitation of advanced modulation formats and DSP are the dominant topics due to the low-cost requirement in PON [11]. Indeed, subsequent transceiver inter-symbol interference impairments mandate advanced DSP equalization, whereas high flexibility of optical virtualization hereby envisioned particularly favors DSP approaches enabling format transparent operation. With this benefit in mind, several linear/non-linear pre- and post-compensation techniques have been proposed beyond traditional implementations, such as Volterra non-linear equalization (VNLE) or artificial neural-network (ANN) equalization [166], [167], [168], [169]. However, these techniques are still prohibitively complex compared to standard DSP implemented in SDTs. Moreover, current state-of-the-art does not effectively address the high-end MMW regime within flexible FS scenario, nor does it offer comprehensive and systematic sets of architecture requirements versus the resulting computational complexity. We thus conclude that wide prospects for further investigations also lie in format-agnostic ANN equalization, as well as the further simplification of digital non-linear compensation techniques [170].

E. LESSONS LEARNED

OFH flexibility and dynamic configurability are crucial in heterogeneous network environments facilitating the coexistence of multiple applications and technologies, as well as enabling multi-vendor infrastructure sharing. This section provides a summary of identified challenges and promising research directions towards MMW and sub-THz optical fronthauling, focusing on PHY configurability and cooperative gains:

- 1) Fiber transport architectures are still dominantly focused on 26-28GHz and 60GHz bands, while the sub-THz (≥ 95 GHz) band remains largely unexplored in practical implementations. Limited focus on long-range wireless transmission constitutes a significant research gap in establishing the feasibility of hybrid networks. Wireless transmission is frequently omitted entirely, while outdoor measurements extending 100m are rare among the exceptions. Furthermore, full-duplex operation is often not addressed.
- 2) IFoF variants of ARoF are predominant, particularly in resource-constrained applications, due to spectral efficiency and the maturity of electronics and low-cost 10G-class optics. However, as the cost of high bandwidth photodetection reduces, the OUC-based RFoF may become a predominant candidate for sub-THz operation, where techniques as analog phase noise cancellation may help narrow the gaps towards the long-reach applicability.
- 3) Extensive state-of-the-art research points to complementary merits of available fiber transport technologies, and a largely unexplored potential for hybrid implementations. One-size-fits-all approaches are inadequate for heterogeneous networks, suggesting

the need for more flexible and configurable OFH architectures. Although hybrid solutions combining the benefits of ARoF and DRoF are gaining traction, the examples demonstrating successful integrations with clear performance benefits are limited.

- 4) Resource management procedures ought to be tightly related to the physical layer architecture, which in turn must enable higher level of optimization abstraction. We hereby outline the concept of cooperative component pooling for the OFH architecture, along with the applicable fiber transport technologies, enabling the multi-purpose abstraction of subcarriers and modulators towards holistic resource management in heterogeneous networks.
- 5) Converged optical-wireless solutions, focusing on integrating optoelectronic chips with antennas to create compact and low-cost RRHs, are emerging. This approach may lead to enhanced cooperative features, including dynamic beam steering, frequency configurability, and efficient data aggregation.
- 6) OBFNs employing TTD mechanisms can cooperatively control beam direction. This approach enables dynamic beam steering with relaxed bandwidth limitations compared to the electronic phase shifters. Cooperative beam steering can mitigate inter-cell interference and support efficient user handover, which is essential for MMW-based systems.
- 7) Extending SDN control into the optical network's physical layer remains challenging within dense heterogeneous scenario. Aside from highly configurable SDTs relying on cooperative gains, there is a need for scenario-centric adaptive control, requiring more streamlined holistic approaches targeting joint resource orchestration.

IV. ENABLING VIRTUALIZED RAN RESOURCE SHARING

The rapid growth of mobile traffic and the emergence of new 6G applications has led to an increasing demand for a more flexible and scalable RAN. The virtualization of RAN (vRAN) has emerged as a promising solution to address these challenges. As discussed, 6G inter-cell interference is expected to affect the UDC throughout, further motivating the system architecture design to become a basis for on-demand resource management, seamless scalability, and flexible functionality assignment for balanced system trade-offs in heterogeneous scenarios. Based on the extension of the C-RAN concept, we thus envision 6G UDCs as virtualized components and coexistent with macro- and small-cells, relying on OFH orchestrated in cooperation with ORV layer targeting dynamic resource management. This scenario calls for novel designs for the flexible FS optimization procedures, deployed on the functionality assignment level and designed to address the trade-off between the centralization benefits and the capacity strain placed on the OFH, towards assuring tangible impact on system efficiency and cost. Furthermore, the O-RAN initiative envisions

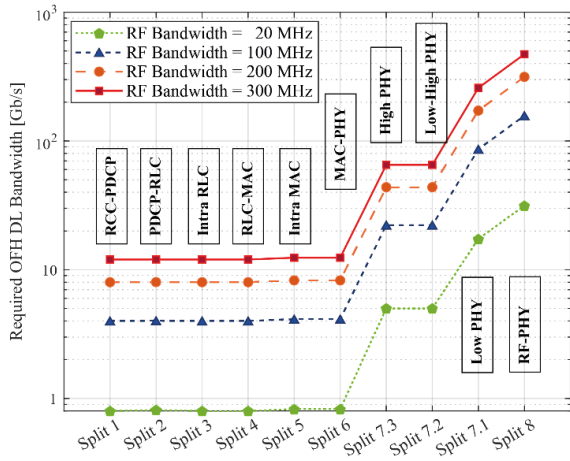


FIGURE 7. 5G LTE DL bandwidth requirement for various FS options and considering several values of channel bandwidth.

taking the vRAN based resource sharing from specialized-to general purpose-based implementation further towards the de-specialized, vendor-agnostic hardware platforms for DSP in BBUs. The end-to-end network orchestration therein poses various challenges for the allocation of optical and radio resources across the overall network architecture, stemming from the requirements of converged, heterogeneous network operation scenario. In traditional RAN, the baseband processing and the radio functions are co-located at the cell site, and the optical links are dedicated to connecting the radio units to the baseband units. In vRAN, the baseband processing is centralized, and the optical links are shared among multiple RAN sites, leading to a more complex resource allocation problem. The design of an effective optical resource management procedure for the vRAN involves various factors such as traffic demand, network topology, optical link capacity, and latency requirements. Addressing these challenges may, on the other hand, greatly complement the above discussed recommendations for the architecture design of each individual network segment.

A. ADAPTIVE CENTRALIZATION

The network architecture softwarization aims at the adaptability to instantaneous requirements while enabling software functionalities running on COTS components. Besides the separation of user and control planes enabled by the SDN technology, the benefits lie in the ability to adapt the network centralization degree to current capacity and latency requirements and thus enable deployment and operation cost reductions. In a typical system, all intelligent functions in BSs are handled by remote BBU pool [171]. In centralized RAN concept, a BBU fulfils several functions: some with strict real-time constraints implemented using dedicated DSP blocks, while others are handled with software running on conventional CPUs. Non-real-time upper layer functions may run as virtual network functions (VNFs) in a cloud outside of RAN [172]. Evidently, such approach works very well for systems of today, and industry standards such as CPRI

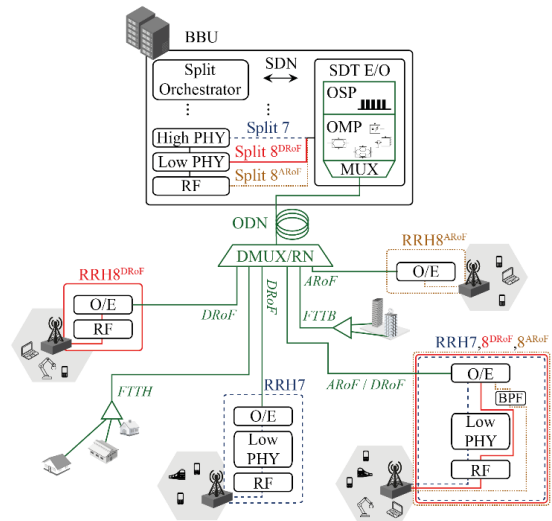


FIGURE 8. Concept of flexible OFH architecture showcasing the coexistence of optical transport schemes supporting different RRH types. DRoF-based architecture (RRH7 - blue dashed, RRH8^{DRoF} - red full), ARoF-based RRH architecture (RRH8^{ARoF} - brown dotted) and hybrid RRH architecture (RRH7,8^{DRoF},8^{ARoF}) are supported through the dynamic optimization of FS at the BBU. Options 8^{DRoF} and 8^{ARoF} indicate the same FS realized using different fiber transport technologies. ODN is presented in green color.

have evolved around them to match their requirements [115]. However, scaling this approach to support high-bandwidth cells with carrier aggregation and massive MIMO is challenging even in 5G systems, and even more so for 6G systems, where physical layer constraints limit the use of existing architectures without considerable adjustments [1].

Another significant challenge within this scenario is enabling dynamic and efficient control of the OFH bandwidth, while also considering the benefits of centralization. Fig. 7 shows the DL bandwidth requirement for each functional split in an 5G LTE system considering several values of channel bandwidth under a single sector configuration [82]. In each case, the worst-case resolution scenario of 16 bits/sample is considered [82]. The results presented do not account for line code and control overheads, nor for the worst-case scenario spectrum usage scaling and margin for upper bound estimation, for which the bandwidth requirement would be further exacerbated [83]. Nevertheless, Fig. 7 underscores the impact of functional distribution on the OFH bandwidth requirement. The OFH facilitating a typical 100 MHz system would require anywhere between 4Gb/s and 157.3Gb/s of DL bandwidth as the functional split choice edges towards the full centralization. In a 300 MHz system these values rise to 12Gb/s and 472Gb/s, respectively, demonstrating significant OFH dependence on the radio segment configuration. Hence, scenario-adaptive coordination of both optical and wireless resources is required. Moreover, as discussed, each split option has its own advantages, making the fixed FS approach suboptimal.

As a result, recent approaches have shifted towards the network-as-a-service paradigm, which involves flexible centralization of network functionalities. The FS is thus

acquired as an optimal operating point depending on the trade-off between the system requirements and resource availability. This approach supports network virtualization, resource pooling and on-demand provisioning discussed in the previous sections. Namely, it has been demonstrated that most of the functions allocated across candidate functional splits outlined in [173] are suitable for softwarization [83], [174]. This makes flexible FS optimization an appealing approach for joint virtual resource management and application-oriented optimization in NG networks [136]. As shown in Fig. 8, this approach supports the coexistence of several OFH configurations targeting specific traffic conditions while considering resource availability. In Fig. 8, superscripts “a” and “b” indicate the same FS realized with two distinct RoF architectures. Accordingly, various variants of RRH architecture offer unique benefits tailored to specific scenarios: low-end power consumption at the cost of high computational load at the BBU may be favored in a particular scenario (e.g., RRH8^{ARoF}), whereas other scenarios may benefit from offloading BBU processing to an optimized degree to target varying latency and bandwidth demands at a reasonable cost (e.g., RRH7 versus RRH8^{DRoF}). FS optimization, however, must simultaneously account for numerous factors, such as UDC deployment, bandwidth, wireless transmission frequency, and latency requirements, OFH pooling optimization, computational load, and ultimately, the CAPEX/OPEX implications.

As illustrated, RRHs designed for different optical transport technologies and supporting FS options 7 and 8 concurrently may also be integrated (RRH7,8^{DRoF},8^{ARoF}). The downside of such implementation may lie in the fact that it necessitates the deployment of hardware for hosting the network functionalities on both network sides to concurrently support different FS mappings. Thus, efficient and comprehensive network resource management in such scenarios is crucial to enable the multipurpose utilization of these resources for other profitable network services to the greatest extent possible [174].

Novel BBU processing offloading routines are required to enable the above discussed network operation. Non-real-time layer 2 and 3 functions may run as VNFs, however, real-time layer 1 functions (real time digital RF processing, alarms and error handling, error correction) are still challenging to virtualize and typically run on DSPs that are physically located at the RRH. To effectively handle the evolving computation demands in a genuine vRAN fashion, it is essential to assure optimal, future-proof physical resource allocation with satisfactory upgradability features. Moreover, the framework must account for latency and capacity constraints of OFH and NFV cloud towards assuring improved support for NG network evolution while remaining cost-effective for legacy systems.

B. INTELLIGENT AND COOPERATIVE ORCHESTRATION

In addition to dynamic FS optimization, the scenario under consideration requires innovative techniques to minimize

scheduling complexity within a coexistence paradigm. This entails accounting for the UDC deployment requirements, OFH SDT architecture optimization, and efficient allocation of computational resources driven by DSP. Full-duplex vRAN functionalities ought to incorporate OFH local resource status information obtained from the optical virtualization layer, facilitating efficient convergence. Furthermore, with beamforming gaining significance at MMW frequencies, the effective management of schedules across numerous RRUs within a BBU pool becomes challenging, as it involves not only controlling power but also direction on both the BS and UE sides. As scheduling is one of the most stringent tasks in enhanced node BS (eNB) logic, new efforts are required to enable its scaling into 6G in a cost- and energy-efficient manner.

Resource scheduling encompasses a set of techniques for efficient allocation based on traffic requirements and available resources, where SDN facilitates centralized control and optimization. Efficient resource management in OWNs can be complex and requires a comprehensive approach. Namely, resource scheduling must consider optical, radio, and computational resources simultaneously to meet Quality of Service (QoS) requirements based on KPIs such as latency, reliability, and throughput, which are extensively covered in the literature [17], [18], [19], [22], [23], [24], [26], [28]. In heterogeneous scenarios, coordination across optical, wireless, and computational domains must address the diverse QoS requirements of end-users with varied traffic priorities while ensuring consistent QoS prioritization. As outlined in Section III, cost-effective one-size-fits-all OFH architectures designed to support various traffic types may not be suitable when addressing a wide range of QoS requirements, highlighting the need for flexible FS orchestration. Thus, several key factors need to be considered towards designing joint resource orchestration in converged, heterogeneous vRAN architectures. The typical initial step is to estimate the number of users and the amount of data traffic in the network, as well as the peak and average traffic loads. This assessment informs the trade-off between the required optical link capacity in a converged vRAN architecture and the supported degree of centralization. In turn, the selection of FS, PON architecture and deployment topology affects the latency, bandwidth, and cooperative gain limitations. For instance, a mesh topology may provide redundancy and resilience, whereas a star topology may enable simpler management and control [175]. Resource allocation algorithms ought to consider such factors holistically while minimizing the network cost and power consumption and addressing a wide range of QoS requirements.

State-of-the-art approaches for resource scheduling procedures in optical and radio converged vRAN architectures include dynamic bandwidth allocation and QoS-based allocation algorithms [137], [174], [176], [177], [178], [179]. Works considering FS flexibility typically focus on the selection of the highest available centralization degree, while considering data rate and latency as QoS requirements with

significant impact on the required OFH bandwidth and power consumption. In [174], a FS selection scheme in an SDN-based OWN is proposed to maximize the centralization degree considering OFH bandwidth constraints. The work in [176] proposes an annealing-based dynamic resource allocation scheme to jointly optimize the grade-of-service and power consumption. In [177], a resource allocation optimization method is proposed for the elastic OFH segment, incorporating dynamic FS selection to examine the power consumption and FH loads of the overall system architecture. The optimization problem is solved by a modified stochastic Lyapunov method to overcome the queuing delay that provides a constructive cooperation between the optical and radio network segments. The cooperation amongst radio and optical networks proposed by the authors considerably minimized the power consumption compared to traditional cloud native RAN. An efficient resource management scheme for joint resource optimization towards enhancing the energy efficiency considering all resource types, including radio, optical, and computational resources, is presented in [137]. The proposed methods demonstrate the ability to dynamically assign resources while reducing the energy consumption. However, additional optimization factors still needed to be investigated towards a converged vRAN architecture: topology and cooperative configurability awareness in the optical domain, UDC deployment and TC throughput, traffic load variation for resource allocation decision, optical PHY virtualization through SDN, and scalability of the resource allocation methods. In [178], the authors propose a dynamic bandwidth allocation scheme for slicing-based TDM-PON, focusing on the uplink direction and satisfying the requirements of each connected sub-network. Similarly, multi-access dynamic bandwidth allocation for future PON is studied in [179], considering both orthogonal and non-orthogonal multiple access for resource allocation towards improved network throughput. A multi-dimensional resource schedule scheme designed for joint resource optimization while maximizing the CoMP gain has been proposed in [180]. However, the consideration of the OFH cooperative gains discussed in Section III has not yet been investigated within this context.

Proactive, ML-based strategies, such as the prediction of LOS blockages described in Section II, may also be applied to addressing resource orchestration challenges. Several researchers have leveraged ML algorithms to enhance the system configurability and proactively tackle resource allocation issues within virtualized OWNs [181], [182], [183], [184]. In [181], the authors proposed a cooperative dynamic bandwidth allocation scheme, relying on long short-term memory neural network, for traffic prediction in an SDN-based TDM-PON. Based on traffic prediction, the proposed solution considers a priority weighted proportional bandwidth allocation algorithm to minimize latency. In [182], the authors proposed an efficient resource allocation scheme with edge-cloud collaborative traffic prediction, relying on ML to maximize resource utilization in integrated OWNs.

Similarly, the authors in [183] used SDN to offer reconfigurable optical x-haul connections based on user requests, involving amplified ROADM transmission system. In [184], a resource allocation challenge was addressed with a proximal policy optimization (PPO)-based deep reinforcement learning (DRL) solution, which aims to maximize resource efficiency by optimizing policies. The problem was framed as a Markov decision process (MDP). This study underlines the importance of a robust dataset for training neural networks when using ML to solve resource allocation problems [41]. Reinforcement learning, however, does not require a pre-existing dataset, as it is trained on-the-fly to solve resource allocation issues in virtualized optical-wireless communication networks. The application of ML may also be an attractive approach towards reducing the complexity of scheduling virtualized resources shared by BBUs to match the offered load [185]. As such, an exceptionally complex scheduling task may be, over time and with sufficient training input, solved in real time even with modest processing capability. To enable such learning, however, information would have to be shared between network nodes and aggregated effectively, such that scheduling policies could be devised and applied. In addition, the online ML would have to be considered as the network configuration ought to respond to changes in deployment, settings, and environment. An extension to the above approach based on utilization of co-located infrastructure may also be considered, whereby co-located 5G and 6G systems may be leveraged to improve one-another's performance. For instance, MMW 6G signal may provide better position estimate, improving 5G interference planning, whereas 5G may provide faster BS discovery. While advantages of doing so have been considered in the literature, very little practical work was done towards enabling such cooperative functionalities in the system architecture.

C. LESSONS LEARNED

Virtualized RAN architectures enable increased flexibility and scalability towards NG network applications, optimized resource allocation, and cost reductions. This section provides a summary of identified challenges and promising research directions towards dynamic and holistic resource orchestration in dense heterogeneous networks:

- 1) Cell densification and heterogeneity raise the risk of inter-cell interference, requiring adaptive resource management. The shift to vRAN complicates resource allocation due to shared optical links among sites and varying traffic demands. Current centralized RAN approaches face scalability issues with high-bandwidth demand and massive MIMO systems.
- 2) Optimized centralization via flexible FS enables balancing the system requirements with its constraints. Within this context, the power consumption and latency of real-time processing ought to be considered along with the UDC and OFH architectures. Novel methods are required to address the adaptable FS jointly

facilitating flexible allocation of all three resource types: optical, wireless, and computational.

- 3) Some recent works address the orchestration of all three resource types, but most do not account for dynamic network behavior, or relevant factors such as the topology and cooperative coexistence awareness in the optical segment, traffic load variation for resource allocation decision, and scalability of the resource allocation methods. Generally, the extension of joint resource optimization to include the cooperative functionalities in coexisting architectures is largely unexplored.
- 4) Efficient orchestration in virtualized environments is challenging due to the need for adaptive resource management in heterogeneous scenarios. ML approaches show great potential for proactive traffic prediction, as well as to provide real-time solutions to complex scheduling problems. However, insufficient practical work has been done towards considering configurability and cooperative features of a converged system architecture.

V. NETWORK SECURITY

Network security, addressing the development of intelligent intrusion detection mechanisms, is identified as one of the key challenges towards the market adoption of the proposed UDC technology, and is of particularly high importance for applications such as connected robotics and autonomous systems (CRAS) and multisensory extended reality (XR), among others. This section details the network security implications and potential mitigation strategies arising from the architectural shift towards small cell and UDC technology envisioned in this paper.

A. THREAT SURFACE

Denser deployment of cells, mesh networks, multi-connectivity, and D2D communications will become the standard, increasing the threat surface of the 6G UDC networks [186], [187]. Nevertheless, while trustworthiness stands as one of the fundamental values that NG networks must address to ensure cyber-resilience, privacy, and trust, it will face threats and challenges in a variety of novel ways. For instance, the trustworthiness will be jeopardized by the connection of potentially billions of endpoints and millions of subnetworks that are typically untrusted, the presence of open interfaces and architectural disaggregation, the existence of heterogeneous cloud environments, and a combination of open-source and multi-vendor software [188], [189], [190]. Beyond the communication architecture and devices, 6G builds on 5G systems to include connected “intelligence” and “hyper-connected cloudification”, in synergy with “distributed and automated service provisioning”. This places stringent requirements on the security approach. The end-to-end automation of network services requires proactive threat discovery, intelligent mitigation techniques, and self-sustaining networks.

Holistically, our network vision may be perceived as an integrated intelligent communication architecture that poses diverse security threats and attacks on different logical layers. This can range from data privacy issues due to automation and the absence of machine ethics at the “application layer”, to attacks on SDN controllers, denial of service (DoS) attacks on network slices on the “control layer”, man-in-the-middle attacks in mobile edge computing (MEC) on the “edge layer”, to eavesdropping, jamming, and data theft from “IoT devices”. Moreover, an intelligent architecture is also exposed to AI and ML based attacks, such as data poisoning attacks, data injection and manipulation, logic corruption, model invasion and inversion, mode extraction, and membership inference. Moreover, a prominent characteristic in 6G networks are resource constrained devices (for e.g. sensors, smart objects, or smart devices) that have limited processing, memory, and power resources [191]. Often, these devices have limited security features with a lack of resources to handle complex security functions. Hence, there is an immediate requirement for novel security and privacy provisioning approaches in 6G that is able to provide robust security solutions, even harnessing devices with limited resource capability. Addressing these aspects is critical to earn the trust of all relevant stakeholders and unlock the full 6G market potential from 2030 onwards.

B. MITIGATION APPROACHES

An effective approach to addressing security challenges in 6G involves adopting anomaly-based intrusion detection systems (IDS) [51], which show promise for enhancing network security and preserving privacy. Namely, this technology can be network-based and is typically deployed at specific points within a network to monitor traffic and scan for potential threats. If the network anomaly matches a known threat in the repository, the packet isn’t allowed to transverse the network.

We propose building upon the concepts of collaborative and anomaly-based intrusion detection and towards investigating the adoption of privacy-preserving technologies relevant to the 6G-era exploiting energy constrained devices. These include federated learning, multi-party computation, homomorphic encryption, and differential privacy - not only towards building a holistic view and detecting intrusions with low false positive and false negative rates, but also to efficiently maintain data privacy [192], [193], [194], [195]. Furthermore, we recognize a great potential in making use of the emerging paradigm of Tiny-ML, facilitating embedded-ML applications with low computational cost, for performing local training and detection [196], [197].

C. LESSONS LEARNED

Dense heterogeneous networks with holistic resource orchestration face novel intrusion mechanisms, posing a relevant challenge towards their practical deployment, as summarized:

- 1) Cell densification and heterogeneity create a broader attack surface, exacerbated by more connections to

untrusted endpoints, open interfaces, and architectural disaggregation.

- 2) Many NG network devices will have limited capacity for complex security functions. This limitation necessitates security solutions tailored for resource-constrained devices and should be factored into the holistic resource orchestration.
- 3) The rise of AI and ML introduces novel security threats, requiring sophisticated mitigation strategies that current technologies may struggle to address.
- 4) As a network-based technology that can be deployed at key points to detect threats in real-time, IDS may play a vital role; Tiny-ML is a feasible approach to perform local training and detection on resource-constrained devices.
- 5) Federated learning, multi-party computation, homomorphic encryption, and differential privacy enable cooperative security approaches without compromising sensitive data.

VI. CONCLUSION

The NG network vision is heading towards an integrated, context- and service-driven networking, where legacy and emerging systems actively coexist. Cell densification, cooperative coexistence of technologies, adaptive holistic orchestration and network security paradigms are identified as the enablers of interest towards the next piece in the NG network puzzle. We have outlined viable technology options across various network segments to facilitate such network vision and discussed their comparative strengths and weaknesses.

Emerging wireless communication technologies face significant challenges due to the migration to MMW and sub-THz frequencies and the complexity of dense urban environments. Novel modeling approaches are required to capture the non-planar, heterogeneous nature of 3D deployments in urban settings. Iterative trial-and-error methods for mobility support are inefficient, and most small-cell deployment models either offer accuracy or tractability. Further research is necessary to develop robust mobility procedures and algorithms that ensure seamless connectivity in dynamic and complex environments. We underscore the ICS technology as a proactive approach in managing the LOS blockages, reducing latency, and improving reliability. ML offers further possibilities, enabling effective blockage and beam prediction, which may enhance network performance.

To facilitate the connectivity under the adopted scenario, a flexible infrastructure enabled by service centric, configurable, and cost-effective OFH is envisioned. An overview of novel experimental demonstrations illustrates the potential of various strategies for flexible OFH, incorporating a wide range of transport frequencies, spectral allocation schemes, data rates, and modulation formats. Experimental implementations of RoF are primarily focused on frequency bands below 90 GHz, with a general lack of focus on cost-effectiveness, bidirectionality and long-range wireless transmission. We argue that addressing these limitations

TABLE 3. List of acronyms.

3D	3-Dimensional
6G	Sixth Generation
ADC	Analog-to-Digital Conversion
AI	Artificial Intelligence
ANN	Artificial Neural-Network
ARoF	Analog-Radio-over-Fiber
AWGR	Arrayed Waveguide Grating Routers
BBU	Baseband Unit
BS	Base Station
BVT	Bandwidth Variable Transceivers
CA	Carrier Aggregation
CAPEX	Capital Expenditures
CD	Coherent Detection
CF	Carrier Frequency
CO	Central Office
CoMP	Coordinated Multipoint
COTS	Commercial off-the-Shelf
CPRI	Common Public Radio Interface
CPUs	Central Processing Units
C-RAN	Cloud Radio Access Network
CRAS	Connected Robotics and Autonomous Systems
CS	Carrier Suppressed
CU	Central Unit
CWDM	Coarse WDM
D2D	Device-to-Device
DAC	Digital-to-Analog Conversion
DD	Direct-Detection
DL	Downlink
DM	Direct Modulation
DMT	Discrete Multitone
DOF	Digital Orthogonal Filtering
DoS	Denial of Service
DRL	Deep Reinforcement Learning
DRoF	Digitized-Radio-over-Fiber
DSB	Double-Sideband
DSM	Delta-Sigma Modulation
DSP	Digital Signal Processing
DU	Distributed Unit
DWDM	Dense WDM
E/O	Electro/Optic
eCPRI	enhanced-CPRI
EDC	Electrical Down-Conversion
EE	Energy Efficiency
eICIC	enhanced Inter-Cell Interference Cancellation
EM	External Modulator
EMB	Enhanced Mobile Broadband
eNB	enhanced Node BS
EUC	Electrical Up-Conversion
FEC	Forward Error Correction
FH	Fronthaul
FS	Functional Split
FSO	Free Space Optics
FTTH	Fiber-to-the-Home
GPP	Ginibre Point Process
ICI	Inter-Cell Interference
ICS	Integrated Communication and Sensing
IDS	Intrusion Detection Systems
IF	Intermediate Frequency
IFoF	IF-over-Fiber
IL	Injection Locking
IM	Intensity-Modulation
IoT	Internet of Things
I-PPP	Inhomogeneous PPP
KPI	Key Performance Indicator
LO	Local Oscillators
LOS	Line-of-Sight
M2M	Machine-to-Machine

TABLE 3. (Continued.) List of acronyms.

MCM	Multicarrier Modulation
MDP	Markov Decision Process
MEC	Mobile Edge Computing
MEMS	Micro-Electro-Mechanical System
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
MMC	Massive Machine type Communications
MMW	mm-Wave
MNO	Mobile Network Operator
MZM	Mach-Zehnder Modulators
NG	Next Generation
NTN	Non-terrestrial Networks
OBFN	Optical Beam Forming Networks
OCM	Optical Carrier Multiplexing
ODN	Optical Distribution Network
OFC	Optical Frequency Comb
OFDM	Orthogonal Frequency Division Multiplexing
OFH	Optical Fronthaul
OFM	Optical Frequency Multiplication
OHD	Optical Heterodyning
OMP	Optical Modulator Pool
ONU	Optical Network Unit
OPEX	Operational Expenditures
O-RAN	Open-RAN
ORV	Optical Resource Virtualization
OSP	Optical Subcarrier Pool
OUC	Optically-aided Up-Conversion
OWN	Optical-Wireless Network
PAA	Phased Arrayed Antenna
PD	Photodetector
PDM	Polarization-Division Multiplexing
PHY	Physical Layer
PM-QAM	Polarization Multiplexed Quadrature Amplitude Modulation
PON	Passive Optical Network
PPO	Proximal Policy Optimization
PPP	Poisson Point Process
PtMP	Point-to-Multipoint
PtP	Point-to-Point
QoE	Quality-of-Experience
QoS	Quality-of-Service
RF	Radio Frequency
RFoF	RF-over-Fiber
RIN	Relative Intensity Noise
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RoF	Radio-over-Fiber
RRH	Remote Radio Head
SBVT	Sliceable BVT
SCM	Subcarrier Multiplexing
SDM	Space-Division Multiplexing
SDN	Software Defined Networking
SDT	Software Defined Transceiver
SG	Stochastic Geometry
SINR	Signal-to-Interference-and-Noise Ratio
SNR	Signal-to-Noise Ratio
SSB	Single-Sideband
TC	THz connectivity
TDM	Time-Division Multiplexing
TTD	True Time Delays
TWDM	Time-Division WDM
UDC	Ultra-Dense Cell
UDWDM	Ultra-Dense WDM
UE	User Equipment
UL	Uplink
UN	United Nations
URLLC	Ultra Reliable Low Latency Communications
UTC-PD	Uni-Travelling Carrier Photodetector
VCSEL	Vertical Cavity Surface Emitting Laser

TABLE 3. (Continued.) List of acronyms.

VLAN	Virtual Local Area Networking
VLC	Visible Light Communications
VNF	Virtual Network Functions
VNLE	Volterra Non-Linear Equalization
vRAN	Virtualized RAN
WDM	Wavelength-Division Multiplexing
WRC-23	World Radiocommunication Conference 2023
XR	Extended Reality

hinges not only on further research to overcome the intrinsic bandwidth and complexity constraints, but also on pursuing holistic approaches focusing on cooperative flexibility. The survey validates that the commitment to a single configuration, with over-provisioned resources geared towards the worst-case traffic conditions, may result in suboptimal performance in diverse operations and that dynamic configurability is an essential design aim in both radio and optical segments towards addressing time-varying requirements and coexisting scenarios. However, ensuring convergence and support for legacy technologies requires more advanced and adaptive transceiver designs. We thus underscore the necessity for novel SDT designs towards enabling augmented configurability of PON channels and technology selection. On the system level, OFH ought to enable a successful compromise between the system cost and required bandwidth, latency, spectral efficiency, and power budget. On the component level, versatile transceiver technology capable of flexible configuration to a wide range of optical transmission parameters, in support of dynamic high-end MMW operation, holds the key to deriving simultaneous benefits from the complementary merits of multiple optical transport schemes.

The efficacy of network configurability features hinges on the development of novel holistic approaches for joint optical-wireless resource orchestration, herein envisioned as an “added on feature” for the dynamic vRAN architecture supporting heterogeneous network operation. To enable such operation, the centralization degree ought to be considered as a dynamic parameter via flexible allocation of VNFs, whereby network softwarization enables dynamic trade-offs between coordinated resource management on the one hand, and the stringent physical and computational constraints on the other. Thus, a well-coordinated allocation of tasks ought to concurrently consider all network segments, while targeting approaches that enable reduced complexity.

While NG heterogeneous networks offer increased connectivity and intelligence, they also introduce novel security gaps and challenges. The presence of numerous untrusted endpoints, diverse environments, new advanced threat forms, and resource-constrained devices further complicates the network security landscape. Addressing these issues may involve adopting anomaly-based IDS, collaborative security approaches, and Tiny-ML for resource-constrained devices, but these solutions must navigate complex integration, scalability, and performance constraints.

APPENDIX

For the full list of acronyms see Table 3.

ACKNOWLEDGMENT

This work was supported by the European Union's Horizon Europe research and innovation program under the Marie Skłodowska-Curie grant agreement No. 101073265 (EWOC—'Enabling virtualized Wireless and Optical Coexistence for 5G and beyond'), and the UKRI (UK Research and Innovation) Horizon Europe Guarantee Scheme with grant no: EP/X030342/1 (EWOC). Zoran Vujicic also thanks the research and innovation program under the Marie Skłodowska-Curie grant agreement No. 872897 (EXPLOR—'EXperimentation and simulation based PLatform for beyond 5G Optical-wireless network Research and development'). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the EU. The EU cannot be held responsible for them.

REFERENCES

- [1] A. Dogra, R. K. Jha, and S. Jain, "A survey on beyond 5G network with the advent of 6G: Architecture and emerging technologies," *IEEE Access*, vol. 9, pp. 67512–67547, 2021, doi: [10.1109/access.2020.3031234](https://doi.org/10.1109/access.2020.3031234).
- [2] T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Madanayake, S. Mandal, A. Alkhateeb, and G. C. Trichopoulos, "Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond," *IEEE Access*, vol. 7, pp. 78729–78757, 2019, doi: [10.1109/ACCESS.2019.2921522](https://doi.org/10.1109/ACCESS.2019.2921522).
- [3] S. Dang, O. Amin, B. Shihada, and M.-S. Alouini, "What should 6G be?" *Nature Electron.*, vol. 3, no. 1, pp. 20–29, Jan. 2020, doi: [10.1038/s41928-019-0355-6](https://doi.org/10.1038/s41928-019-0355-6).
- [4] G. Gui, M. Liu, F. Tang, N. Kato, and F. Adachi, "6G: Opening new horizons for integration of comfort, security, and intelligence," *IEEE Wireless Commun.*, vol. 27, no. 5, pp. 126–132, Oct. 2020, doi: [10.1109/MWC.001.1900516](https://doi.org/10.1109/MWC.001.1900516).
- [5] Y. Yuan, Y. Zhao, B. Zong, and S. Parolari, "Potential key technologies for 6G mobile communications," *Sci. China Inf. Sci.*, vol. 63, no. 8, Aug. 2020, Art. no. 183301, doi: [10.1007/s11432-019-2789-y](https://doi.org/10.1007/s11432-019-2789-y).
- [6] Z. Allam and D. S. Jones, "Future (post-COVID) digital, smart and sustainable cities in the wake of 6G: Digital twins, immersive realities and new urban economies," *Land Use Policy*, vol. 101, Feb. 2021, Art. no. 105201, doi: [10.1016/j.landusepol.2020.105201](https://doi.org/10.1016/j.landusepol.2020.105201).
- [7] J. K. Chaudhary, A. Kumar, J. Bartelt, and G. Fettweis, "C-RAN employing xRAN functional split: Complexity analysis for 5G NR remote radio unit," in *Proc. Eur. Conf. Netw. Commun. (EuCNC)*. Spain: IEEE, Jun. 2019, pp. 580–585, doi: [10.1109/EUCNC.2019.8801953](https://doi.org/10.1109/EUCNC.2019.8801953).
- [8] *Study on Scenarios and Requirements for Next Generation Access Technologies*, Standard TR 38.913, V16.0.0, 3GPP, 2020.
- [9] (2020). *Detailed Specifications of the Radio Interfaces of IMT-2020*. [Online]. Available: <http://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Pages/default.aspx>
- [10] N. Cvijetic and T. Wang, "Systems challenges for SDN in fiber wireless networks," in *Optical Networks*. Cham, Switzerland: Springer, 2017, pp. 189–209.
- [11] *100G-EPON Task Force*, Standard IEEE 802.3ca-2020, 2020.
- [12] J. Liu, H. Guo, H. Nishiyama, H. Ujikawa, K. Suzuki, and N. Kato, "New perspectives on future smart FiWi networks: Scalability, reliability, and energy efficiency," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 2, pp. 1045–1072, 2nd Quart., 2016, doi: [10.1109/COMST.2015.2500960](https://doi.org/10.1109/COMST.2015.2500960).
- [13] A. Shahpari, R. M. Ferreira, R. S. Luis, Z. Vujicic, F. P. Guiomar, J. D. Reis, and A. L. Teixeira, "Coherent access: A review," *J. Lightw. Technol.*, vol. 35, no. 4, pp. 1050–1058, Feb. 4, 2017, doi: [10.1109/JLT.2016.2623793](https://doi.org/10.1109/JLT.2016.2623793).
- [14] J. Pérez-Romero, O. Sallent, A. Gelonch, X. Gelabert, B. Klaiqi, M. Kahn, and D. Campoy, "A tutorial on the characterisation and modelling of low layer functional splits for flexible radio access networks in 5G and beyond," *IEEE Commun. Surveys Tuts.*, vol. 25, no. 4, pp. 2791–2833, 1st Quart., 2023, doi: [10.1109/COMST.2023.3296821](https://doi.org/10.1109/COMST.2023.3296821).
- [15] L. Diez, C. Hervella, and R. Agüero, "Understanding the performance of flexible functional split in 5G vRAN controllers: A Markov chain-based model," *IEEE Trans. Netw. Service Manage.*, vol. 18, no. 1, pp. 456–468, Mar. 2021, doi: [10.1109/TNSM.2020.3045968](https://doi.org/10.1109/TNSM.2020.3045968).
- [16] *O-RAN Minimum Viable Plan and Acceleration Towards Commercialization*. O-RAN Alliance, Alfter, Germany, Jun. 29, 2021.
- [17] J. R. Bhat and S. A. Alqahtani, "6G ecosystem: Current status and future perspective," *IEEE Access*, vol. 9, pp. 43134–43167, 2021, doi: [10.1109/ACCESS.2021.3054833](https://doi.org/10.1109/ACCESS.2021.3054833).
- [18] C. D. Alwis, A. Kalla, Q.-V. Pham, P. Kumar, K. Dev, W.-J. Hwang, and M. Liyanage, "Survey on 6G frontiers: Trends, applications, requirements, technologies and future research," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 836–886, 2021, doi: [10.1109/OJCOMS.2021.3071496](https://doi.org/10.1109/OJCOMS.2021.3071496).
- [19] X. You et al., "Towards 6G wireless communication networks: Vision, enabling technologies, and new paradigm shifts," *Sci. China Inf. Sci.*, vol. 64, no. 1, Jan. 2021, Art. no. 110301, doi: [10.1007/s11432-020-2955-6](https://doi.org/10.1007/s11432-020-2955-6).
- [20] W. Jiang, B. Han, M. A. Habibi, and H. D. Schotten, "The road towards 6G: A comprehensive survey," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 334–366, 2021, doi: [10.1109/OJCOMS.2021.3057679](https://doi.org/10.1109/OJCOMS.2021.3057679).
- [21] X. Shen, J. Gao, W. Wu, M. Li, C. Zhou, and W. Zhuang, "Holistic network virtualization and pervasive network intelligence for 6G," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 1, pp. 1–30, 1st Quart., 2022, doi: [10.1109/COMST.2021.3135829](https://doi.org/10.1109/COMST.2021.3135829).
- [22] D. C. Nguyen, M. Ding, P. N. Pathirana, A. Seneviratne, J. Li, D. Niyato, O. Dobre, and H. V. Poor, "6G Internet of Things: A comprehensive survey," *IEEE Internet Things J.*, vol. 9, no. 1, pp. 359–383, Jan. 2022, doi: [10.1109/JIOT.2021.3103320](https://doi.org/10.1109/JIOT.2021.3103320).
- [23] V. K. Quy, A. Chehri, N. M. Quy, N. D. Han, and N. T. Ban, "Innovative trends in the 6G era: A comprehensive survey of architecture, applications, technologies, and challenges," *IEEE Access*, vol. 11, pp. 39824–39844, 2023, doi: [10.1109/ACCESS.2023.3269297](https://doi.org/10.1109/ACCESS.2023.3269297).
- [24] C.-X. Wang, X. You, X. Gao, X. Zhu, Z. Li, C. Zhang, H. Wang, Y. Huang, Y. Chen, H. Haas, J. S. Thompson, E. G. Larsson, M. D. Renzo, W. Tong, P. Zhu, X. Shen, H. V. Poor, and L. Hanzo, "On the road to 6G: Visions, requirements, key technologies and testbeds," *IEEE Commun. Surveys Tuts.*, vol. 25, no. 2, pp. 905–974, 2nd Quart., 2023, doi: [10.1109/COMST.2023.3249835](https://doi.org/10.1109/COMST.2023.3249835).
- [25] L.-H. Shen, K.-T. Feng, and L. Hanzo, "Five facets of 6G: Research challenges and opportunities," *ACM Comput. Surveys*, vol. 55, no. 11, pp. 1–39, Nov. 2023, doi: [10.1145/3571072](https://doi.org/10.1145/3571072).
- [26] M. Banafaa, I. Shayea, J. Din, M. Hadri Azmi, A. Alashbi, Y. Ibrahim Daradkeh, and A. Alhammedi, "6G mobile communication technology: Requirements, targets, applications, challenges, advantages, and opportunities," *Alexandria Eng. J.*, vol. 64, pp. 245–274, Feb. 2023, doi: [10.1016/j.aej.2022.08.017](https://doi.org/10.1016/j.aej.2022.08.017).
- [27] M. Shafi, R. K. Jha, and S. Jain, "6G: Technology evolution in future wireless networks," *IEEE Access*, vol. 12, pp. 57548–57573, 2024, doi: [10.1109/access.2024.3385230](https://doi.org/10.1109/access.2024.3385230).
- [28] N. A. Alhaj, M. F. Jamlos, S. A. Manap, S. Abdelsalam, A. A. Bakhit, R. Mamat, M. A. Jamlos, M. S. M. Gismalla, and M. Hamdan, "Integration of hybrid networks, AI, ultra massive-MIMO, THz frequency, and FBMC modulation toward 6G requirements: A review," *IEEE Access*, vol. 12, pp. 483–513, 2024, doi: [10.1109/ACCESS.2023.3345453](https://doi.org/10.1109/ACCESS.2023.3345453).
- [29] H. Tataria, M. Shafi, A. F. Molisch, M. Dohler, H. Sjöland, and F. Tufvesson, "6G wireless systems: Vision, requirements, challenges, insights, and opportunities," *Proc. IEEE*, vol. 109, no. 7, pp. 1166–1199, Jul. 2021, doi: [10.1109/JPROC.2021.3061701](https://doi.org/10.1109/JPROC.2021.3061701).
- [30] Z. Wang et al., "Vision, application scenarios, and key technology trends for 6G mobile communications," *Sci. China Inf. Sci.*, vol. 65, no. 5, May 2022, Art. no. 151301, doi: [10.1007/s11432-021-3351-5](https://doi.org/10.1007/s11432-021-3351-5).
- [31] M. Kamel, W. Hamouda, and A. Youssef, "Ultra-dense networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 4, pp. 2522–2545, 4th Quart., 2016, doi: [10.1109/COMST.2016.2571730](https://doi.org/10.1109/COMST.2016.2571730).
- [32] A. A. Salem, S. El-Rabaie, and M. Shokair, "Survey on ultra-dense networks (UDNs) and applied stochastic geometry," *Wireless Pers. Commun.*, vol. 119, no. 3, pp. 2345–2404, Aug. 2021, doi: [10.1007/s11277-021-08334-1](https://doi.org/10.1007/s11277-021-08334-1).
- [33] S. Muhammad Asad Zaidi, M. Manalastas, H. Farooq, and A. Imran, "Mobility management in emerging ultra-dense cellular networks: A survey, outlook, and future research directions," 2020, *arXiv:2009.13922*.
- [34] M. Quratulain Khan, A. Gaber, P. Schulz, and G. Fettweis, "Machine learning for millimeter wave and terahertz beam management: A survey and open challenges," *IEEE Access*, vol. 11, pp. 11880–11902, 2023, doi: [10.1109/ACCESS.2023.3242582](https://doi.org/10.1109/ACCESS.2023.3242582).

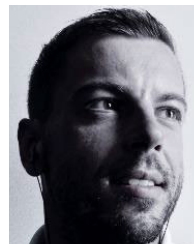
- [35] M. Tayyab, X. Gelabert, and R. Jäntti, "A survey on handover management: From LTE to NR," *IEEE Access*, vol. 7, pp. 118907–118930, 2019, doi: [10.1109/ACCESS.2019.2937405](https://doi.org/10.1109/ACCESS.2019.2937405).
- [36] W. Yu, H. Xu, H. Zhang, D. Griffith, and N. Golmie, "Ultra-dense networks: Survey of state of the art and future directions," in *Proc. 25th Int. Conf. Comput. Commun. Netw. (ICCCN)*, HI, USA: IEEE, Aug. 2016, pp. 1–10, doi: [10.1109/ICCCN.2016.7568592](https://doi.org/10.1109/ICCCN.2016.7568592).
- [37] C. Ranaweera, C. Lim, Y. Tao, S. Edirisinghe, T. Song, L. Wosinska, and A. Nirmalathas, "Design and deployment of optical x-haul for 5G, 6G, and beyond: Progress and challenges [Invited]," *J. Opt. Commun. Netw.*, vol. 15, no. 9, p. D56, Sep. 2023, doi: [10.1364/jocn.492334](https://doi.org/10.1364/jocn.492334).
- [38] P. Chanclou, G. Simon, F. Saliou, M. Wang, and A. Bollore, "Optical access solutions in support of 5G and beyond [Invited]," *J. Opt. Commun. Netw.*, vol. 15, no. 7, pp. C48–C53, Jul. 2023, doi: [10.1364/JOCN.480580](https://doi.org/10.1364/JOCN.480580).
- [39] T. R. Raddo, S. Rommel, B. Cimoli, C. Vagionas, D. Perez-Galacho, E. Pikasis, E. Grivas, K. Ntontin, M. Katsikis, D. Kritharidis, E. Ruggeri, I. Spaleniak, M. Dubov, D. Klonidis, G. Kalfas, S. Sales, N. Pleros, and I. T. Monroy, "Transition technologies towards 6G networks," *EURASIP J. Wireless Commun. Netw.*, vol. 2021, no. 1, p. 100, Dec. 2021, doi: [10.1186/s13638-021-01973-9](https://doi.org/10.1186/s13638-021-01973-9).
- [40] T. Sizer, D. Samardzija, H. Viswanathan, S. Thai Le, S. Bidkar, P. Dom, E. Harstead, and T. Pfeiffer, "Integrated solutions for deployment of 6G mobile networks," *J. Lightw. Technol.*, vol. 40, no. 2, pp. 346–357, Jan. 14, 2022, doi: [10.1109/JLT.2021.3110436](https://doi.org/10.1109/JLT.2021.3110436).
- [41] H. R. D. Filgueiras, E. S. Lima, M. S. B. Cunha, C. H. De Souza Lopes, L. C. De Souza, R. M. Borges, L. Augusto Melo Pereira, T. Henrique Brandão, T. P. V. Andrade, L. C. Alexandre, G. Neto, A. Linhares, L. L. Mendes, M. A. Romero, and A. Cerqueira S., "Wireless and optical convergent access technologies toward 6G," *IEEE Access*, vol. 11, pp. 9232–9259, 2023, doi: [10.1109/ACCESS.2023.3239807](https://doi.org/10.1109/ACCESS.2023.3239807).
- [42] S. Marinova and A. Leon-Garcia, "Intelligent O-RAN beyond 5G: Architecture, use cases, challenges, and opportunities," *IEEE Access*, vol. 12, pp. 27088–27114, 2024, doi: [10.1109/ACCESS.2024.3367289](https://doi.org/10.1109/ACCESS.2024.3367289).
- [43] A. G. Sarigiannidis, M. Iloridou, P. Nicopolitidis, G. Papadimitriou, F.-N. Pavlidou, P. G. Sarigiannidis, M. D. Louta, and V. Vitsas, "Architectures and bandwidth allocation schemes for hybrid wireless-optical networks," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 427–468, 1st Quart., 2015, doi: [10.1109/COMST.2014.2356640](https://doi.org/10.1109/COMST.2014.2356640).
- [44] D. Sahinel, S. Rommel, and I. T. Monroy, "Resource management in converged optical and millimeter wave radio networks: A review," *Appl. Sci.*, vol. 12, no. 1, p. 221, Dec. 2021, doi: [10.3390/app12010221](https://doi.org/10.3390/app12010221).
- [45] J. Lorincz, Z. Klarin, and D. Begusic, "Advances in improving energy efficiency of fiber–wireless access networks: A comprehensive overview," *Sensors*, vol. 23, no. 4, p. 2239, Feb. 2023, doi: [10.3390/s23042239](https://doi.org/10.3390/s23042239).
- [46] R. Samrin and D. Vasumathi, "Review on anomaly based network intrusion detection system," in *Proc. Int. Conf. Electr., Electron., Commun., Comput., Optim. Techn.*, Dec. 2017, pp. 141–147, doi: [10.1109/ICEEC-COT.2017.8284655](https://doi.org/10.1109/ICEEC-COT.2017.8284655).
- [47] D. Fährmann, L. Martín, L. Sánchez, and N. Damer, "Anomaly detection in smart environments: A comprehensive survey," *IEEE Access*, vol. 12, pp. 64006–64049, 2024, doi: [10.1109/ACCESS.2024.3395051](https://doi.org/10.1109/ACCESS.2024.3395051).
- [48] Y. Meidan, D. Avraham, H. Libhaber, and A. Shabtai, "CADESH: Collaborative anomaly detection for smart homes," *IEEE Internet Things J.*, vol. 10, no. 10, pp. 8514–8532, May 2023, doi: [10.1109/JIOT.2022.3194813](https://doi.org/10.1109/JIOT.2022.3194813).
- [49] A. Patil, D. Machale, D. Goswami, P. Muley, and P. Rajarapollu, "Anomaly-based intrusion detection system for IoT environment using machine learning," in *Proc. IEEE Int. Carnahan Conf. Secur. Technol. (ICCSST)*, Oct. 2023, pp. 1–4, doi: [10.1109/iccsst59048.2023.10474238](https://doi.org/10.1109/iccsst59048.2023.10474238).
- [50] N. Sarwar, I. S. Bajwa, M. Z. Hussain, M. Ibrahim, and K. Saleem, "IoT network anomaly detection in smart homes using machine learning," *IEEE Access*, vol. 11, pp. 119462–119480, 2023, doi: [10.1109/ACCESS.2023.3325929](https://doi.org/10.1109/ACCESS.2023.3325929).
- [51] K. Soares and A. A. Shinde, "Intrusion detection systems in VANET: A review on implementation techniques and datasets," in *Proc. 5th Int. Conf. Intell. Commun. Technol. Virtual Mobile Netw. (ICICV)*, India: IEEE, Mar. 2024, pp. 897–905, doi: [10.1109/icicv62344.2024.00148](https://doi.org/10.1109/icicv62344.2024.00148).
- [52] J. Ribeiro, F. B. Saghezchi, G. Mantas, J. Rodriguez, and R. A. Abd-Alhameed, "HIDROID: Prototyping a behavioral host-based intrusion detection and prevention system for Android," *IEEE Access*, vol. 8, pp. 23154–23168, 2020, doi: [10.1109/ACCESS.2020.2969626](https://doi.org/10.1109/ACCESS.2020.2969626).
- [53] S. V. J. Rani, I. I. Ioannou, P. Nagaradjane, C. Christophorou, V. Vassiliou, H. Yarramsetti, S. Shridhar, L. M. Balaji, and A. Pitsillides, "A novel deep hierarchical machine learning approach for identification of known and unknown multiple security attacks in a D2D communications network," *IEEE Access*, vol. 11, pp. 95161–95194, 2023, doi: [10.1109/ACCESS.2023.3308036](https://doi.org/10.1109/ACCESS.2023.3308036).
- [54] J. Rodriguez, G. P. Koudouridis, X. Gelabert, M. Tayyab, R. Bassoli, F. H. P. Fitzek, R. Torre, R. Abd-Alhameed, M. Sajedin, I. Elfergani, S. Irum, G. Schulte, P. Diogo, F. Marzouk, M. De Ree, G. Mantas, and I. Politis, "Secure virtual mobile small cells: A stepping stone toward 6G," *IEEE Commun. Standards Mag.*, vol. 5, no. 2, pp. 28–36, Jun. 2021, doi: [10.1109/MCOMSTD.001.2000019](https://doi.org/10.1109/MCOMSTD.001.2000019).
- [55] T. Nagatsuma, "Advances in terahertz communications accelerated by photonics technologies," in *Proc. 24th OptoElectronics Commun. Conf.*, Jul. 2019, pp. 1–3, doi: [10.23919/PS.2019.8818026](https://doi.org/10.23919/PS.2019.8818026).
- [56] Nat. Instrum. (2022). *mmWave: The Battle of the Bands*. Accessed: Nov. 30, 2022. [Online]. Available: <https://www.ni.com/en/shop/wireless-design-test/what-is-mmwave-transceiver-system/mmwave-the-battle-of-the-bands.html>
- [57] H.-Y. Wang, C.-H. Cheng, B. Su, and G.-R. Lin, "Ultrahigh capacity MMWoF link using 2- λ VCSEL front-haul transmitter encoded with broadband generalized FDM data stream," *J. Lightw. Technol.*, vol. 41, no. 10, pp. 3007–3016, May 1, 2023, doi: [10.1109/JLT.2023.3241272](https://doi.org/10.1109/JLT.2023.3241272).
- [58] H.-H. Lu, C.-Y. Li, W.-S. Tsai, Y.-E. Peng, W.-C. Fan, C.-J. Lin, Y.-S. Tang, Y.-X. Chen, and Y.-S. Lin, "Two-way 5G NR fiber-wireless systems using single-carrier optical modulation for downstream and phase modulation scheme for upstream," *J. Lightw. Technol.*, vol. 41, no. 6, pp. 1749–1758, Mar. 4, 2023, doi: [10.1109/JLT.2022.3230375](https://doi.org/10.1109/JLT.2022.3230375).
- [59] T. Huang, L. Ma, X. Hu, S. Huang, and S. Liu, "2D autoregressive model-based dynamic correlated massive MU-MIMO channel simulator," *Electron. Lett.*, vol. 53, no. 17, pp. 1228–1230, Aug. 2017, doi: [10.1049/el.2017.1768](https://doi.org/10.1049/el.2017.1768).
- [60] United Nations. (2018). *World Urbanization Prospects: The 2018 Revision*. [Online]. Available: <https://esa.un.org/unpd/wup/>
- [61] C. Zhang, "Intelligent Internet of Things service based on artificial intelligence technology," in *Proc. IEEE 2nd Int. Conf. Big Data, Artif. Intell. Internet Things Eng. (ICBAIE)*, Mar. 2021, pp. 731–734, doi: [10.1109/ICBAIE52039.2021.9390061](https://doi.org/10.1109/ICBAIE52039.2021.9390061).
- [62] H. Nassar et al., "Remarks on a stochastic geometric model for interference-limited cellular communications," *IEEECS*, vol. 34, no. 2, p. 1376, May 2024, doi: [10.11591/ijeecs.v34.i2.pp1376-1388](https://doi.org/10.11591/ijeecs.v34.i2.pp1376-1388).
- [63] Y. Zhang, L. Pang, G. Ren, F. Gong, X. Liang, J. Dou, and J. Li, "3-D MIMO parametric stochastic channel model for urban macrocell scenario," *IEEE Trans. Wireless Commun.*, vol. 16, no. 7, pp. 4246–4260, Jul. 2017, doi: [10.1109/TWC.2017.2695188](https://doi.org/10.1109/TWC.2017.2695188).
- [64] K. M. S. Huq, J. Rodriguez, and I. E. Otung, "3D network modeling for THz-enabled ultra-fast dense networks: A 6G perspective," *IEEE Commun. Standards Mag.*, vol. 5, no. 2, pp. 84–90, Jun. 2021, doi: [10.1109/MCOMSTD.001.2000048](https://doi.org/10.1109/MCOMSTD.001.2000048).
- [65] N. Deng, W. Zhou, and M. Haenggi, "The Ginibre point process as a model for wireless networks with repulsion," *IEEE Trans. Wireless Commun.*, vol. 14, no. 1, pp. 107–121, Jan. 2015, doi: [10.1109/TWC.2014.2332335](https://doi.org/10.1109/TWC.2014.2332335).
- [66] M. Di Renzo, S. Wang, and X. Xi, "Inhomogeneous double thinning—Modeling and analysis of cellular networks by using inhomogeneous Poisson point processes," *IEEE Trans. Wireless Commun.*, vol. 17, no. 8, pp. 5162–5182, Aug. 2018, doi: [10.1109/TWC.2018.2838597](https://doi.org/10.1109/TWC.2018.2838597).
- [67] I. F. Akyildiz, A. Kak, and S. Nie, "6G and beyond: The future of wireless communications systems," *IEEE Access*, vol. 8, pp. 133995–134030, 2020, doi: [10.1109/ACCESS.2020.3010896](https://doi.org/10.1109/ACCESS.2020.3010896).
- [68] D. Zhang, A. Li, M. Shirvanimoghaddam, P. Cheng, Y. Li, and B. Vucetic, "Fast beam tracking for millimeter-wave systems under high mobility," in *Proc. IEEE Int. Conf. Commun. (ICC)*, China: IEEE, May 2019, pp. 1–6, doi: [10.1109/ICC.2019.8761896](https://doi.org/10.1109/ICC.2019.8761896).
- [69] S. Shaham, M. Kokshoorn, M. Ding, Z. Lin, and M. Shirvanimoghaddam, "Extended Kalman filter beam tracking for millimeter wave vehicular communications," in *Proc. IEEE Int. Conf. Commun. Workshops*, Jun. 2020, pp. 1–6, doi: [10.1109/iccworkshops49005.2020.9145366](https://doi.org/10.1109/iccworkshops49005.2020.9145366).
- [70] X. Gao, L. Dai, Y. Zhang, T. Xie, X. Dai, and Z. Wang, "Fast channel tracking for terahertz beamspace massive MIMO systems," *IEEE Trans. Veh. Technol.*, vol. 66, no. 7, pp. 5689–5696, Jul. 2017, doi: [10.1109/TVT.2016.2614994](https://doi.org/10.1109/TVT.2016.2614994).
- [71] Y. Hmamouche, M. Benjillali, S. Saoudi, H. Yanikomeroğlu, and M. D. Renzo, "New trends in stochastic geometry for wireless networks: A tutorial and survey," *Proc. IEEE*, vol. 109, no. 7, pp. 1200–1252, Jul. 2021.

- [72] G. Interdonato, E. Björnson, H. Quoc Ngo, P. Frenger, and E. G. Larsson, "Ubiquitous cell-free massive MIMO communications," *EURASIP J. Wireless Commun. Netw.*, vol. 2019, no. 1, p. 197, Dec. 2019, doi: 10.1186/s13638-019-1507-0.
- [73] F. Liu, Y. Cui, C. Masouros, J. Xu, T. X. Han, Y. C. Eldar, and S. Buzzi, "Integrated sensing and communications: Toward dual-functional wireless networks for 6G and beyond," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1728–1767, Jun. 2022, doi: 10.1109/JSAC.2022.3156632.
- [74] U. Demirhan and A. Alkhateeb, "Radar aided 6G beam prediction: Deep learning algorithms and real-world demonstration," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, TX, USA: IEEE, Apr. 2022, pp. 2655–2660, doi: 10.1109/WCNC51071.2022.9771564.
- [75] U. Demirhan and A. Alkhateeb, "Integrated sensing and communication for 6G: Ten key machine learning roles," *IEEE Commun. Mag.*, vol. 61, no. 5, pp. 113–119, May 2023, doi: 10.1109/MCOM.006.2200480.
- [76] A. Alkhateeb, S. Alex, P. Varkey, Y. Li, Q. Qu, and D. Tujkovic, "Deep learning coordinated beamforming for highly-mobile millimeter wave systems," *IEEE Access*, vol. 6, pp. 37328–37348, 2018, doi: 10.1109/ACCESS.2018.2850226.
- [77] M. S. Sim, Y.-G. Lim, S. H. Park, L. Dai, and C.-B. Chae, "Deep learning-based mmWave beam selection for 5G NR/6G with sub-6 GHz channel information: Algorithms and prototype validation," *IEEE Access*, vol. 8, pp. 51634–51646, 2020, doi: 10.1109/ACCESS.2020.2980285.
- [78] H. Echigo, Y. Cao, M. Bouazizi, and T. Ohtsuki, "A deep learning-based low overhead beam selection in mmWave communications," *IEEE Trans. Veh. Technol.*, vol. 70, no. 1, pp. 682–691, Jan. 2021, doi: 10.1109/TVT.2021.3049380.
- [79] Y. Wu, J. Koch, M. Vossiek, and W. Gerstacker, "Hierarchical beam alignment in single-user MIMO single-carrier frequency division multiple access terahertz communication systems," in *Proc. IEEE Int. Conf. Commun. Workshops*, Jun. 2021, pp. 1–7, doi: 10.1109/ICCWorkshops50388.2021.9473531.
- [80] Y. Ahn, J. Kim, S. Kim, K. Shim, J. Kim, S. Kim, and B. Shim, "Towards intelligent millimeter and terahertz communication for 6G: Computer vision-aided beamforming," *IEEE Wireless Commun.*, vol. 30, no. 5, pp. 1–18, Oct. 2022, doi: 10.1109/MWC.007.2200155.
- [81] Y. Zhang, M. Alrabeiah, and A. Alkhateeb, "Reinforcement learning of beam codebooks in millimeter wave and terahertz MIMO systems," *IEEE Trans. Commun.*, vol. 70, no. 2, pp. 904–919, Feb. 2022, doi: 10.1109/TCOMM.2021.3126856.
- [82] *CU-DU Split: Refinement for Annex A*, Standard R3-162102, 3GPP, 2016.
- [83] *Study on CU-DU Lower Layer Split for NR*, Standard TR38.816, V15.0.0, 3GPP, 2017.
- [84] K. Miyamoto, S. Kuwano, J. Terada, and A. Otaka, "Analysis of mobile fronthaul bandwidth and wireless transmission performance in split-PHY processing architecture," *Opt. Exp.*, vol. 24, no. 2, p. 1261, Jan. 2016, doi: 10.1364/oe.24.001261.
- [85] H. Ji, C. Sun, and W. Shieh, "Spectral efficiency comparison between analog and digital RoF for mobile fronthaul transmission link," *J. Lightw. Technol.*, vol. 38, no. 20, pp. 5617–5623, Oct. 10, 2020, doi: 10.1109/JLT.2020.3003123.
- [86] W. Zhai, A. Wen, and D. Shan, "Multidimensional optimization of a radio-over-fiber link," *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 1, pp. 210–221, Jan. 2021, doi: 10.1109/TMTT.2020.3021095.
- [87] G. H. Smith, D. Novak, and Z. Ahmed, "Overcoming chromatic-dispersion effects in fiber-wireless systems incorporating external modulators," *IEEE Trans. Microwave Theory Techn.*, vol. 45, no. 8, pp. 1410–1415, Aug. 1997, doi: 10.1109/22.618444.
- [88] Y. Yang, A. Nirmalathas, and C. Lim, "Digitized RF-over-fiber as a cost-effective and energy-efficient backhaul option for wireless communications," *Ann. Telecommun. Annales Des Telecommun.*, vol. 68, nos. 1–2, pp. 23–39, Feb. 2013, doi: 10.1007/s12243-012-0319-6.
- [89] J. Wang, Z. Yu, K. Ying, J. Zhang, F. Lu, M. Xu, L. Cheng, X. Ma, and G.-K. Chang, "Digital mobile fronthaul based on delta-sigma modulation for 32 LTE carrier aggregation and FBMC signals," *J. Opt. Commun. Netw.*, vol. 9, no. 2, pp. A233–A244, Feb. 2017, doi: 10.1364/JOCN.9.00A233.
- [90] M. Xu, F. Lu, J. Wang, L. Cheng, D. Guidotti, and G.-K. Chang, "Key technologies for next-generation digital RoF mobile fronthaul with statistical data compression and multiband modulation," *J. Lightw. Technol.*, vol. 35, no. 17, pp. 3671–3679, Sep. 25, 2017, doi: 10.1109/JLT.2017.2715003.
- [91] A. Haddad and M. Gagnaire, "Radio-over-Fiber (RoF) for mobile backhauling: A technical and economic comparison between analog and digitized RoF," in *Proc. Int. Conf. Opt. Netw. Design Model.*, May 2014, pp. 132–137.
- [92] Y. Yang, C. Lim, and A. Nirmalathas, "Multichannel digitized RF-over-fiber transmission based on bandpass sampling and FPGA," *IEEE Trans. Microwave Theory Techn.*, vol. 58, no. 11, pp. 3181–3188, Nov. 2010, doi: 10.1109/TMTT.2010.2075450.
- [93] C. Mitsolidou, C. Vagionas, A. Mesodiakaki, P. Maniotis, G. Kalfas, C. G. H. Roeloffzen, P. W. L. van Dijk, R. M. Oldenbeuving, A. Miliou, and N. Pleros, "A 5G C-RAN optical fronthaul architecture for hotspot areas using OFDM-based analog IFoF waveforms," *Appl. Sci.*, vol. 9, no. 19, p. 4059, Sep. 2019, doi: 10.3390/app9194059.
- [94] S. Rommel, D. Dodane, E. Grivas, B. Cimoli, J. Bourderionnet, G. Feugnet, A. Morales, E. Pikasis, C. Roeloffzen, P. van Dijk, M. Katsikis, K. Ntontin, D. Kritharidis, I. Spaleniak, P. Mitchell, M. Dubov, J. B. Carvalho, and I. T. Monroy, "Towards a scaleable 5G fronthaul: Analog Radio-over-Fiber and space division multiplexing," *J. Lightw. Technol.*, vol. 38, no. 19, pp. 5412–5422, Oct. 4, 2020, doi: 10.1109/JLT.2020.3004416.
- [95] L. Zhong, Y. Zou, X. Chang, H. Yang, X. Dai, C. Liu, M. Cheng, S. Fu, L. Deng, Q. Yang, and D. Liu, "An optically-powered cost-efficient fiber-wireless mobile fronthaul system based on delta-sigma modulation," in *Proc. Asia Commun. Photon. Conf. (ACP)*, Nov. 2022, pp. 457–461, doi: 10.1109/ACP55869.2022.10088603.
- [96] R. Wang, Y. Fan, S. Qin, J. Tan, X. Wang, Q. Tan, W. Zhai, and Y. Gao, "Bidirectional colorless WDM-PON RoF system with large spurious free dynamic range," *J. Opt. Commun. Netw.*, vol. 14, no. 5, pp. 389–397, May 2022, doi: 10.1364/JOCN.442968.
- [97] K. Tanaka, S. Nimura, S. Ishimura, K. Nishimura, R. Inohara, T. Tsuritani, and M. Suzuki, "10.51-Tbit/s IF-over-Fibre mobile fronthaul link using SDM/WDM/SCM for accommodating ultra high-density antennas in beyond-5G mobile communication systems," in *Proc. Eur. Conf. Opt. Commun. (ECOC)*, Sep. 2022, pp. 1–4.
- [98] D. Dass, L. Yuan Dai, K. Bergman, X. Ouyang, P. Townsend, C. Roeloffzen, and C. Browning, "Low noise ultra-flexible SiP switching platform for mmWave OCDM & multi-band OFDM ARoF fronthaul," *IEEE Photon. Technol. Lett.*, vol. 35, no. 12, pp. 653–656, Jun. 4, 2023, doi: 10.1109/LPT.2023.3269901.
- [99] J. P. Santacruz, G. Nazarikov, S. Rommel, A. Jurado-Navas, and I. T. Monroy, "Bidirectional ARoF fronthaul over multicore fiber for beyond 5G mm-Wave communications," *Opt. Commun.*, vol. 521, Oct. 2022, Art. no. 128591, doi: 10.1016/j.optcom.2022.128591.
- [100] J. Pérez Santacruz, E. Meyer, R. X. F. Budé, C. Stan, A. Jurado-Navas, U. Johannsen, I. Tafur Monroy, and S. Rommel, "Outdoor mm-Wave 5G/6G transmission with adaptive analog beamforming and IFoF fronthaul," *Sci. Rep.*, vol. 13, no. 1, p. 13945, Aug. 2023, doi: 10.1038/s41598-023-40112-w.
- [101] F. Shi, Y. Fan, X. Wang, W. Zhang, and Y. Gao, "High-performance dual-band radio-over-fiber link for future 5G radio access applications," *J. Opt. Commun. Netw.*, vol. 14, no. 4, pp. 267–277, Apr. 2022, doi: 10.1364/JOCN.440530.
- [102] H.-Y. Kao, S. Ishimura, K. Tanaka, K. Nishimura, and R. Inohara, "End-to-end demonstration of fiber-wireless fronthaul networks using a hybrid multi-if-over-fiber and radio-over-fiber system," *IEEE Photon. J.*, vol. 13, no. 4, pp. 1–6, Aug. 2021, doi: 10.1109/JPHOT.2021.3106706.
- [103] J. Xia, T. Li, Q. Cheng, M. Glick, M. Crisp, K. Bergman, and R. Penty, "A future proof reconfigurable wireless and fixed converged optical fronthaul network using silicon photonic switching strategies," *J. Lightw. Technol.*, vol. 41, no. 6, pp. 1610–1618, Mar. 9, 2023, doi: 10.1109/JLT.2022.3188773.
- [104] L. Vallejo, J. Bohata, J. Mora, S. Zvanovec, and B. Ortega, "Remote mmW photonic local oscillator delivery for uplink down-conversion in DML-based optical hybrid C-RAN fronthaul," *J. Opt. Commun. Netw.*, vol. 15, no. 6, pp. 357–366, Jun. 2023, doi: 10.1364/JOCN.482085.
- [105] C. Vagionas et al., "End-to-end real-time service provisioning over a SDN-controllable analog mmWave fiber-wireless 5G X-haul network," *J. Lightw. Technol.*, vol. 41, no. 4, pp. 1104–1113, Feb. 9, 2023, doi: 10.1109/JLT.2023.3234365.
- [106] R. Maximidis, C. Vagionas, G. Kalfas, Y. Leiba, A. Miliou, and N. Pleros, "A 51 Gb/s reconfigurable mmWave fiber-wireless C-RAN supporting 5G/6G MNO network sharing," *J. Lightw. Technol.*, vol. 41, no. 14, pp. 1–8, Jul. 15, 2023, doi: 10.1109/JLT.2023.3246597.
- [107] E. Ruggeri, C. Vagionas, R. Maximidis, G. Kalfas, D. Spasopoulos, N. Terzenidis, R. M. Oldenbeuving, P. W. L. van Dijk, C. G. H. Roeloffzen, N. Pleros, and A. Miliou, "Reconfigurable fiber wireless fronthaul with A-RoF and D-RoF co-existence through a Si₃N₄ ROADM for heterogeneous mmWave 5G C-RANs," *J. Lightw. Technol.*, vol. 40, no. 16, pp. 5514–5521, Aug. 4, 2022, doi: 10.1109/JLT.2022.3179636.

- [108] D. Dass, A. Delmado, L. Barry, C. G. H. Roeloffzen, D. Geuzebroek, and C. Browning, "Wavelength & mm-Wave flexible converged optical fronthaul with a low noise Si-based integrated dual laser source," *J. Lightw. Technol.*, vol. 40, no. 10, pp. 3307–3315, May 7, 2022, doi: [10.1109/JLT.2022.3169446](https://doi.org/10.1109/JLT.2022.3169446).
- [109] L. Gonzalez-Guerrero, A. Delmado, D. Dass, C. Browning, L. Barry, F. Smyth, H. Lamela, and G. Carpintero, "Dual-Wavelength-Modulation mm-Wave and THz systems: Analysis and experimental demonstration at 60 GHz with a gain-switched laser," *J. Lightw. Technol.*, vol. 41, no. 23, pp. 7276–7284, Dec. 4, 2023, doi: [10.1109/jlt.2023.3322908](https://doi.org/10.1109/jlt.2023.3322908).
- [110] F. Wang, J. Yu, Y. Wang, W. Li, B. Zhu, J. Ding, K. Wang, C. Liu, C. Wang, M. Kong, L. Zhao, F. Zhao, and W. Zhou, "Delivery of polarization-division-multiplexing wireless millimeter-Wave signal over 4.6-km at W-band," *J. Lightw. Technol.*, vol. 40, no. 19, pp. 6339–6346, Oct. 5, 2022, doi: [10.1109/JLT.2022.3195542](https://doi.org/10.1109/JLT.2022.3195542).
- [111] M. Wang, J. Yu, X. Zhao, W. Li, Y. Wei, X. Yang, J. Shi, C. Bian, T. Xie, F. Zhao, J. Yu, W. Zhou, and K. Wang, "SNR improved digital-delta-sigma-modulation radio-over-fiber scheme for D-band 4.6-km photonics-aided wireless fronthaul," *Opt. Lett.*, vol. 48, no. 15, p. 3997, Aug. 2023, doi: [10.1364/ol.498450](https://doi.org/10.1364/ol.498450).
- [112] C. Vagionas, R. Maximidis, K. Kanta, P. Toumasis, G. Giannoulis, D. Apostolopoulos, G. Kalfas, M. Gatzianas, A. Mesodiakaki, H. Avramopoulos, A. Miliou, and N. Pleros, "Multi-RAT fiber-wireless technologies towards 6G networks," in *Proc. 23rd Int. Conf. Transparent Opt. Netw. (ICTON)*, Jul. 2023, pp. 1–4, doi: [10.1109/icton59386.2023.10207366](https://doi.org/10.1109/icton59386.2023.10207366).
- [113] M. Sung, S. Kim, E.-S. Kim, S.-R. Moon, M. Kim, I.-M. Lee, K. H. Park, J. K. Lee, and S.-H. Cho, "Photonic THz communications based on radio-over-fiber technology for 6G mobile network: Design and opportunity," *IEEE J. Sel. Topics Quantum Electron.*, vol. 29, no. 5, pp. 1–11, Sep. 2023, doi: [10.1109/JSTQE.2023.3308899](https://doi.org/10.1109/JSTQE.2023.3308899).
- [114] E. S. Lima, R. M. Borges, N. Andrioli, E. Conforti, G. Contestabile, and A. C. Sodré, "Integrated optical frequency comb for 5G NR xhuals," *Sci. Rep.*, vol. 12, no. 1, Sep. 2022, Art. no. 1, doi: [10.1038/s41598-022-20553-5](https://doi.org/10.1038/s41598-022-20553-5).
- [115] (2019). *ECPRI Specification*. [Online]. Available: <http://www.cpri.info>
- [116] X. Liu, "Hybrid digital-analog Radio-over-Fiber (DA-RoF) modulation and demodulation achieving a SNR gain over analog RoF of >10 dB at halved spectral efficiency," in *Proc. Opt. Fiber Commun. Conf. Exhibition*, Jun. 2021, pp. 1–3.
- [117] X. Liu, H. Zeng, N. Chand, and F. Effenberger, "CPRI-compatible efficient mobile fronthaul transmission via equalized TDMA achieving 256 Gb/s CPRI-equivalent data rate in a single 10-GHz-bandwidth IM-DD channel," in *Proc. Opt. Fiber Commun. Conf. Exhibition (OFC)*, Mar. 2016, pp. 1–3.
- [118] S. Chen, Y.-C. Liang, S. Sun, S. Kang, W. Cheng, and M. Peng, "Vision, requirements, and technology trend of 6G: How to tackle the challenges of system coverage, capacity, user data-rate and movement speed," *IEEE Wireless Commun.*, vol. 27, no. 2, pp. 218–228, Apr. 2020, doi: [10.1109/MWC.001.1900333](https://doi.org/10.1109/MWC.001.1900333).
- [119] Y. Xu, Q. Zhuge, Y. Fan, M. Fu, Y. Zhu, X. Zeng, H. Jiang, L. Yi, W. Hu, and X. Liu, "Coherent digital-analog radio-over-fiber (DA-RoF) system with a CPRI-equivalent data rate beyond 1 Tb/s for fronthaul," *Opt. Exp.*, vol. 30, no. 16, p. 29409, Aug. 2022, doi: [10.1364/oe.457586](https://doi.org/10.1364/oe.457586).
- [120] S. Ishimura, A. Bekkali, K. Tanaka, K. Nishimura, and M. Suzuki, "1.032-Tb/s CPRI-equivalent rate IF-over-fiber transmission using a parallel IM/PM transmitter for high-capacity mobile fronthaul links," *J. Lightw. Technol.*, vol. 36, no. 8, pp. 1478–1484, Apr. 8, 2018, doi: [10.1109/JLT.2017.2787151](https://doi.org/10.1109/JLT.2017.2787151).
- [121] Y. Zhu, L. Yi, B. Yang, X. Huang, J. S. Wey, Z. Ma, and W. Hu, "Comparative study of cost-effective coherent and direct detection schemes for 100Gb/s/λ PON," *J. Opt. Commun. Netw.*, vol. 12, no. 9, pp. D36–D47, Sep. 2020, doi: [10.1364/JOCN.390911](https://doi.org/10.1364/JOCN.390911).
- [122] X. Zhou, R. Urata, and H. Liu, "Beyond 1 Tb/s intra-data center interconnect technology: IM-DD OR coherent?" *J. Lightw. Technol.*, vol. 38, no. 2, pp. 475–484, Jan. 9, 2020, doi: [10.1109/JLT.2019.2956779](https://doi.org/10.1109/JLT.2019.2956779).
- [123] M. Masanas, J. Tabares, I. Cano, and J. Prat, "Demonstration of continuous multiple access with homodyne and image-rejection heterodyne coherent receivers using directly modulated laser transmitters," *J. Opt. Commun. Netw.*, vol. 15, no. 7, pp. C108–C119, Jul. 2023, doi: [10.1364/JOCN.481793](https://doi.org/10.1364/JOCN.481793).
- [124] M. Masanas, V. Polo, and J. Prat, "Simple single-laser coherent transceiver based on low-cost D-EML for edge networks," *IEEE Photon. Technol. Lett.*, vol. 35, no. 6, pp. 337–340, Mar. 4, 2023, doi: [10.1109/LPT.2023.3243689](https://doi.org/10.1109/LPT.2023.3243689).
- [125] M. Masanas, V. Polo, and J. Prat, "Single sideband techniques for next generation low-cost UD-WDM coherent PONs," in *Proc. 13th Int. Symp. Commun. Syst. Netw. Digit. Signal Process. (CSNDSP)*, Jul. 2022, pp. 558–561, doi: [10.1109/CSNDSP54353.2022.9908037](https://doi.org/10.1109/CSNDSP54353.2022.9908037).
- [126] J. Tabares and J. Prat, "Low-complexity phase-and-polarization-diversity coherent receiver with high spectral efficiency for UDWDM," in *Proc. Opt. Fiber Commun. Conf. Exhibition (OFC)*, Jun. 2021, pp. 1–3.
- [127] F. Duan, Y. Guo, Z. Gu, Y. Yin, Y. Wu, and T. Chen, "Optical beamforming networks for millimeter-Wave wireless communications," *Appl. Sci.*, vol. 13, no. 14, p. 8346, Jul. 2023, doi: [10.3390/app13148346](https://doi.org/10.3390/app13148346).
- [128] J. P. Santacruz, S. Rommel, C. G. H. Roeloffzen, R. B. Timens, P. W. L. van Dijk, A. Jurado-Navas, and I. T. Monroy, "Incoherent optical beamformer for AroF fronthaul in mm-Wave 5G/6G networks," *J. Lightw. Technol.*, vol. 41, no. 5, pp. 1325–1334, Mar. 6, 2023, doi: [10.1109/JLT.2022.3221861](https://doi.org/10.1109/JLT.2022.3221861).
- [129] D. Milovancev, N. Vokic, D. Loschenbrand, T. Zemen, and B. Schrenk, "Analog coherent-optical mobile fronthaul with integrated photonic beamforming," *IEEE J. Sel. Areas Commun.*, vol. 39, no. 9, pp. 2827–2837, Sep. 2021, doi: [10.1109/JSAC.2021.3064640](https://doi.org/10.1109/JSAC.2021.3064640).
- [130] A. V. Martí, D. Löschenbrand, M. Hofer, T. Zemen, and B. Schrenk, "Photonic delay processing with centralized etalon cascade for radio beamsteering in simplified 2 × 5 phased-array radio heads," *J. Lightw. Technol.*, vol. 40, no. 20, pp. 6929–6938, Oct. 6, 2022, doi: [10.1109/JLT.2022.3188355](https://doi.org/10.1109/JLT.2022.3188355).
- [131] C. Ballesteros, M. Maestre, M. C. Santos, J. Romeu, and L. Jofre, "A 3D printed lens antenna for 5G applications," in *Proc. IEEE Int. Symp. Antennas Propag. USNC-URSI Radio Sci. Meeting*, GA, USA: IEEE, Jul. 2019, pp. 1985–1986, doi: [10.1109/APUSNCURSINRSM.2019.8889092](https://doi.org/10.1109/APUSNCURSINRSM.2019.8889092).
- [132] C. Ballesteros, M. Maestre, M. C. Santos, J. Romeu, and L. Jofre, "An architecture analysis for millimeter-wave optically steerable antenna array," in *Proc. 13th Eur. Conf. Antennas Propag.*, Krakow, Poland, Mar. 2019, pp. 1–5.
- [133] C. Ballesteros, S. Vega, M. C. Santos, and L. Jofre-Roca, "Short asymmetrical inductive dipole antenna for direct matching to high-Q chips," *IEEE Antennas Wireless Propag. Lett.*, vol. 22, pp. 149–153, 2023, doi: [10.1109/LAWP.2022.3204841](https://doi.org/10.1109/LAWP.2022.3204841).
- [134] S. Vega, C. Ballesteros, C. Caillaud, D. Lanteri, K. Mekhazni, M. C. Santos, L. Pradell, and L. Jofre-Roca, "Direct connection of uni-traveling-carrier photodiodes to antennas for frequency reconfigurable fiber-radio transmission in the ka band," *Opt. Laser Technol.*, vol. 174, Jul. 2024, Art. no. 110637, doi: [10.1016/j.optlastec.2024.110637](https://doi.org/10.1016/j.optlastec.2024.110637).
- [135] L. Breynne, G. Torfs, X. Yin, P. Demeester, and J. Bauwelinck, "Comparison between analog radio-over-fiber and sigma delta modulated radio-over-fiber," *IEEE Photon. Technol. Lett.*, vol. 29, no. 21, pp. 1808–1811, Nov. 28, 2017, doi: [10.1109/LPT.2017.2752284](https://doi.org/10.1109/LPT.2017.2752284).
- [136] Y. Alfidhli, M. Xu, S. Liu, F. Lu, P.-C. Peng, and G.-K. Chang, "Real-time demonstration of adaptive functional split in 5G flexible mobile fronthaul networks," in *Proc. Opt. Fiber Commun. Conf. Expo. (OFC)*, Mar. 2018, pp. 1–3.
- [137] T. Lagkas, D. Klonidis, P. Sarigiannidis, and I. Tomkos, "Optimized joint allocation of radio, optical, and MEC resources for the 5G and beyond fronthaul," *IEEE Trans. Netw. Service Manage.*, vol. 18, no. 4, pp. 4639–4653, Dec. 2021, doi: [10.1109/TNSM.2021.3094789](https://doi.org/10.1109/TNSM.2021.3094789).
- [138] K. Walkowiak, R. Goscienc, P. Lechowicz, and A. Wlodarczyk, "Comparison of various sharing approaches in survivable translucent optical networks," in *Proc. Int. Conf. Comput. Commun. Netw. (ICCCN)*, Greece: IEEE, Jul. 2021, pp. 1–6, doi: [10.1109/ICCCN52240.2021.9522298](https://doi.org/10.1109/ICCCN52240.2021.9522298).
- [139] M. Klinkowski, P. Lechowicz, and K. Walkowiak, "Survey of resource allocation schemes and algorithms in spectrally-spatially flexible optical networking," *Opt. Switching Netw.*, vol. 27, pp. 58–78, Jan. 2018, doi: [10.1016/j.osn.2017.08.003](https://doi.org/10.1016/j.osn.2017.08.003).
- [140] A. P. T. Lau, Y. Gao, Q. Sui, D. Wang, Q. Zhuge, M. H. Morsy-Osman, M. Chagnon, X. Xu, C. Lu, and D. V. Plant, "Advanced DSP techniques enabling high spectral efficiency and flexible transmissions: Toward elastic optical networks," *IEEE Signal Process. Mag.*, vol. 31, no. 2, pp. 82–92, Mar. 2014, doi: [10.1109/MSP.2013.2287021](https://doi.org/10.1109/MSP.2013.2287021).
- [141] N. Yoshimoto, J.-I. Kani, S.-Y. Kim, N. Iiyama, and J. Terada, "DSP-based optical access approaches for enhancing NG-PON2 systems," *IEEE Commun. Mag.*, vol. 51, no. 3, pp. 58–64, Mar. 2013, doi: [10.1109/MCOM.2013.6476866](https://doi.org/10.1109/MCOM.2013.6476866).

- [142] I. Alimi, R. Patel, N. Silva, C. Sun, H. Ji, W. Shieh, A. Pinto, and N. Muga, "A review of self-coherent optical transceivers: Fundamental issues, recent advances, and research directions," *Appl. Sci.*, vol. 11, no. 16, p. 7554, Aug. 2021, doi: [10.3390/app11167554](https://doi.org/10.3390/app11167554).
- [143] Y. Ou, S. Yan, A. Hammad, B. Guo, S. Peng, R. Nejabati, and D. Simeonidou, "Demonstration of virtualizeable and software-defined optical transceiver," *J. Lightw. Technol.*, vol. 34, no. 8, pp. 1916–1924, Apr. 6, 2016, doi: [10.1109/JLT.2015.2510819](https://doi.org/10.1109/JLT.2015.2510819).
- [144] A. S. Thyagaturu, A. Mercian, M. P. McGarry, M. Reisslein, and W. Kellerer, "Software defined optical networks (SDONs): A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 4, pp. 2738–2786, 4th Quart., 2016, doi: [10.1109/COMST.2016.2586999](https://doi.org/10.1109/COMST.2016.2586999).
- [145] C. Xie, P. Dong, S. Randel, D. Pileri, P. Winzer, S. Spiga, B. Kögel, C. Neumeyr, and M.-C. Amann, "Single-VCSEL 100-Gb/s short-reach system using discrete multi-tone modulation and direct detection," in *Proc. Opt. Fiber Commun. Conf. Exhibition (OFC)*, Mar. 2015, pp. 1–3.
- [146] M. S. Moreolo, J. A. Hernandez, A. Gatto, P. Parolari, P. Boffi, M. S. Moreolo, J. M. Fabrega, L. Nadal, R. Martinez, V. Lopez, J.-P. Fernandez-Palacios, G. Otero, and D. Larrabeiti, "All-optical aggregation and distribution of traffic in large metropolitan area networks using multi-Tb/s S-BVTs," *J. Opt. Commun. Netw.*, vol. 14, no. 5, pp. 316–326, May 2022, doi: [10.1364/JOCN.448115](https://doi.org/10.1364/JOCN.448115).
- [147] M. S. Moreolo et al., "Spectrum/Space switching and multi-terabit transmission in agile optical metro networks," in *Proc. 24th OptoElectronics Commun. Conf.*, Jul. 2019, pp. 1–3, doi: [10.23919/PS.2019.8818018](https://doi.org/10.23919/PS.2019.8818018).
- [148] M. S. Moreolo, L. Nadal, J. M. Fabrega, F. J. Vilchez, C. Neumeyr, A. Gatto, P. Parolari, and P. Boffi, "Multi-Tb/s photonic transceivers for metro optical network connectivity evolution," in *Metro and Data Center Optical Networks and Short-Reach Links IV*. Bellingham, WA, USA: SPIE, Mar. 2021, doi: [10.1117/12.2577521](https://doi.org/10.1117/12.2577521).
- [149] Z. Vujcic, A. Shahpari, B. Neto, N. Pavlovic, A. Almeida, A. Tavares, M. Ribeiro, S. Ziaie, R. Ferreira, R. Bastos, and A. Teixeira, "Considerations on performance, cost and power consumption of candidate 100G EPON architectures," in *Proc. 18th Int. Conf. Transparent Opt. Netw. (ICTON)*, Jul. 2016, pp. 1–6, doi: [10.1109/ICTON.2016.7550683](https://doi.org/10.1109/ICTON.2016.7550683).
- [150] V. Cristofori, F. Da Ros, O. Ozolins, M. E. Chaibi, L. Bramerie, Y. Ding, X. Pang, A. Shen, A. Gallet, G.-H. Duan, K. Hassan, S. Olivier, S. Popov, G. Jacobsen, L. K. Oxenlwe, and C. Peucheret, "25-Gb/s transmission over 2.5-km SSMF by silicon MRR enhanced 1.55- μm III-V/SOI DML," in *Proc. IEEE Photon. Conf. (IPC)*, Oct. 2017, pp. 357–360, doi: [10.1109/IPCON.2017.8116138](https://doi.org/10.1109/IPCON.2017.8116138).
- [151] A. Nag, Y. Zhang, L. A. DaSilva, L. Doyle, and M. Ruffini, "Integrating wireless BBUs with optical OFDM flexible-grid transponders in a C-RAN architecture," in *Proc. Opt. Fiber Commun. Conf. Exhibition (OFC)*, Mar. 2017, pp. 1–3.
- [152] D. Larrabeiti, G. Otero, J. A. Hernández, P. Reviriego, J. Fernández-Palacios, V. López, M. S. Moreolo, R. Martínez, and J. M. Fabrega, "Tradeoffs in optical packet and circuit transport of fronthaul traffic: The time for SBVT?" in *Proc. Int. Conf. Opt. Netw. Design Model. (ONDM)*. Spain: IEEE, May 2020, pp. 1–5, doi: [10.23919/ONDM48393.2020.9133009](https://doi.org/10.23919/ONDM48393.2020.9133009).
- [153] N. Cvijetic, A. Tanaka, P. N. Ji, S. Murakami, K. Sethuraman, and T. Wang, "First OpenFlow-based software-defined λ -flow architecture for flex-grid OFDMA mobile backhaul over passive optical networks with filterless direct detection ONUs," in *Proc. Opt. Fiber Commun. Conf. Expo. Nat. Fiber Optic Eng. Conf. (OFC/NFOEC)*, Mar. 2013, pp. 1–3.
- [154] T. Tyagi, R. P. Giddings, and J. M. Tang, "Real-time demonstration of concurrent upstream and inter-ONU communications in hybrid OFDM DFMA PONs," *IEEE Photon. Technol. Lett.*, vol. 35, no. 3, pp. 148–151, Feb. 3, 2023, doi: [10.1109/LPT.2022.3227369](https://doi.org/10.1109/LPT.2022.3227369).
- [155] M. Kumari, V. Arya, and H. M. R. Al-Khafaji, "Simulation investigation of symmetric 8×25 Gbps hybrid TWDM-DFMA PON for long-reach applications," *IEEE Access*, vol. 11, pp. 43360–43369, 2023, doi: [10.1109/ACCESS.2023.3272293](https://doi.org/10.1109/ACCESS.2023.3272293).
- [156] W. Jin, Z. Q. Zhong, S. Jiang, J. X. He, D. Chang, Y. H. Hong, R. P. Giddings, X. Q. Jin, M. O'Sullivan, T. Durrant, J. Trewern, G. Mariani, and J. M. Tang, "Rectangular orthogonal digital filter banks based on extended Gaussian functions," *J. Lightw. Technol.*, vol. 40, no. 12, pp. 3709–3722, Jun. 6, 2022, doi: [10.1109/JLT.2022.3153589](https://doi.org/10.1109/JLT.2022.3153589).
- [157] A. F. Pakpahan and I.-S. Hwang, "Flexible access network multi-tenancy using NFV/SDN in TWDM-PON," *IEEE Access*, vol. 11, pp. 42937–42948, 2023, doi: [10.1109/ACCESS.2023.3271142](https://doi.org/10.1109/ACCESS.2023.3271142).
- [158] Z. Q. Zhong, W. Jin, S. Jiang, J. X. He, D. Chang, Y. H. Hong, R. P. Giddings, X. Q. Jin, M. O'Sullivan, T. Durrant, J. Trewern, G. Mariani, and J. M. Tang, "Concurrent inter-ONU communications for next generation mobile fronthauls based on IMDD hybrid SSB OFDM-DFMA PONs," *J. Lightw. Technol.*, vol. 39, no. 23, pp. 7360–7369, Dec. 9, 2021, doi: [10.1109/JLT.2021.3115573](https://doi.org/10.1109/JLT.2021.3115573).
- [159] Y. Dong, X. Gao, A. Yi, X. Deng, H. Yang, L. Jiang, X. Zou, and L. Yan, "Virtual carrier assisted optical SSB direct detection for digital filter multiplexed OFDM transmission," in *Proc. Asia Commun. Photon. Conf. (ACP)*, Oct. 2021, pp. 1–3.
- [160] O. F. A. Gonem, R. P. Giddings, and J. Tang, "Timing jitter analysis and mitigation in hybrid OFDM-DFMA PONs," *IEEE Photon. J.*, vol. 13, no. 6, pp. 1–13, Dec. 2021, doi: [10.1109/JPHOT.2021.3121168](https://doi.org/10.1109/JPHOT.2021.3121168).
- [161] H. Bao, X. Gong, Q. Zhang, T. Hu, R. Li, and W. Hou, "Performance investigations of DFMA-PON systems using a parallel IM/PM transmitter for dispersion compensation," in *Proc. 9th Int. Conf. Intell. Comput. Wireless Opt. Commun. (ICWOC)*. China: IEEE, Jun. 2021, pp. 28–32, doi: [10.1109/ICWOC52624.2021.9530214](https://doi.org/10.1109/ICWOC52624.2021.9530214).
- [162] F. J. Effenberger, "Industrial trends and roadmap of access," *J. Lightw. Technol.*, vol. 35, no. 5, pp. 1142–1146, Mar. 3, 2017, doi: [10.1109/JLT.2016.2636246](https://doi.org/10.1109/JLT.2016.2636246).
- [163] P. Torres-Ferrera, S. Straullu, S. Abrate, and R. Gaudino, "Upstream and downstream analysis of an optical fronthaul system based on DSP-assisted channel aggregation," *J. Opt. Commun. Netw.*, vol. 9, no. 12, pp. 1191–1201, Dec. 2017, doi: [10.1364/JOCN.9.001191](https://doi.org/10.1364/JOCN.9.001191).
- [164] I. Correa, B. Dortschy, and A. Klautau, "SNR-based pre-emphasis for transmission of frequency-multiplexed radio signals in fronthaul," *IEEE Commun. Lett.*, vol. 24, no. 9, pp. 2034–2037, Sep. 2020, doi: [10.1109/LCOMM.2020.2994767](https://doi.org/10.1109/LCOMM.2020.2994767).
- [165] S. Noor, P. Assimakopoulos, and N. J. Gomes, "A flexible subcarrier multiplexing system with analog transport and digital processing for 5G (and beyond) fronthaul," *J. Lightw. Technol.*, vol. 37, no. 14, pp. 3689–3700, Jul. 6, 2019, doi: [10.1109/JLT.2019.2918215](https://doi.org/10.1109/JLT.2019.2918215).
- [166] J. Zhang, C. Guo, J. Liu, X. Wu, A. P. T. Lau, C. Lu, and S. Yu, "Decision-feedback frequency-domain Volterra nonlinear equalizer for IM/DD OFDM long-reach PON," *J. Lightw. Technol.*, vol. 37, no. 13, pp. 3333–3342, Jul. 9, 2019, doi: [10.1109/JLT.2019.2915329](https://doi.org/10.1109/JLT.2019.2915329).
- [167] J. Zhang, J. Liu, Z. Lin, J. Liu, L. Shen, and S. Yu, "Nonlinearity-aware adaptive bit and power loading DMT transmission over low-crosstalk ring-core fiber with mode group multiplexing," *J. Lightw. Technol.*, vol. 38, no. 21, pp. 5875–5882, Nov. 29, 2020, doi: [10.1109/JLT.2020.3004560](https://doi.org/10.1109/JLT.2020.3004560).
- [168] V. Houtsma, E. Chou, and D. van Veen, "92 and 50 Gbps TDM-PON using neural network enabled receiver equalization specialized for PON," in *Proc. Opt. Fiber Commun. Conf. Exhibition (OFC)*, Mar. 2019, pp. 1–3.
- [169] L. Yi, T. Liao, L. Huang, L. Xue, P. Li, and W. Hu, "Machine learning for 100 Gb/s/ λ passive optical network," *J. Lightw. Technol.*, vol. 37, no. 6, pp. 1621–1630, Mar. 6, 2019, doi: [10.1109/JLT.2018.2888547](https://doi.org/10.1109/JLT.2018.2888547).
- [170] H. Wang, P. Torres-Ferrera, G. Rizzelli, V. Ferrero, and R. Gaudino, "100 Gbps/ λ C-band CD digital pre-compensated and direct-detection links with simple non-linear compensation," *IEEE Photon. J.*, vol. 13, no. 4, pp. 1–8, Aug. 2021, doi: [10.1109/JPHOT.2021.3107487](https://doi.org/10.1109/JPHOT.2021.3107487).
- [171] N. S. Saad, W. N. S. F. W. Ariffin, J. Nordin, A. S. M. Zain, and L. I. M. Asri, "A literature survey on cloud-RAN architecture toward 5G green wireless communication systems," *J. Phys., Conf. Ser.*, vol. 1962, no. 1, Jul. 2021, Art. no. 012036, doi: [10.1088/1742-6596/1962/1/012036](https://doi.org/10.1088/1742-6596/1962/1/012036).
- [172] Y. Rouault, *The Path To 5G Requires a Strong Optical Network*, 2017. [Online]. Available: https://www.exfo.com/contentassets/293462850d1d4c9dae245e8f9faf899f/exfo_wpaper073_path-5g-requires-strong-optical-network_en.pdf
- [173] *Transport Network Support of IMT-2020/5G*, Standard GSTR-TN5G, 2020.
- [174] A. Marotta, D. Cassioli, K. Kondepu, C. Antonelli, and L. Valcarenghi, "Exploiting flexible functional split in converged software defined access networks," *J. Opt. Commun. Netw.*, vol. 11, no. 11, pp. 536–546, Nov. 2019, doi: [10.1364/JOCN.11.000536](https://doi.org/10.1364/JOCN.11.000536).
- [175] S. Das, F. Slyne, A. Kaszubowska, and M. Ruffini, "Virtualized EAST-WEST PON architecture supporting low-latency communication for mobile functional split based on multiaccess edge computing," *J. Opt. Commun. Netw.*, vol. 12, no. 10, pp. D109–D119, Oct. 2020, doi: [10.1364/JOCN.391929](https://doi.org/10.1364/JOCN.391929).

- [176] E. Datsika, J. S. Vardakas, K. Ramantas, P.-V. Mekikis, I. T. Monroy, L. A. Neto, and C. Verikoukis, "SDN-enabled resource management for converged Fi-Wi 5G fronthaul," *IEEE J. Sel. Areas Commun.*, vol. 39, no. 9, pp. 2772–2788, Sep. 2021, doi: [10.1109/JSAC.2021.3064651](https://doi.org/10.1109/JSAC.2021.3064651).
- [177] F. S. Vajid, M. Hadi, C. Bhar, M. R. Pakravan, and E. Agrell, "Dynamic joint functional split and resource allocation optimization in elastic optical fronthaul," *IEEE Trans. Netw. Service Manage.*, vol. 19, no. 4, pp. 4505–4515, Dec. 2022, doi: [10.1109/TNSM.2022.3166100](https://doi.org/10.1109/TNSM.2022.3166100).
- [178] H. Uzawa, K. Honda, H. Nakamura, Y. Hirano, K.-I. Nakura, S. Kozaki, and J. Terada, "Dynamic bandwidth allocation scheme for network-slicing-based TDM-PON toward the beyond-5G era," *J. Opt. Commun. Netw.*, vol. 12, no. 2, pp. A135–A143, Feb. 2020, doi: [10.1364/JOCN.12.00A135](https://doi.org/10.1364/JOCN.12.00A135).
- [179] E. Inaty, R. Raad, and M. Maier, "Generalized multi-access dynamic bandwidth allocation scheme for future generation PONs: A solution for beyond 5G delay/jitter sensitive systems," *J. Lightw. Technol.*, vol. 40, no. 2, pp. 452–461, Jan. 6, 2022, doi: [10.1109/JLT.2021.3098106](https://doi.org/10.1109/JLT.2021.3098106).
- [180] P. Yang, L. Chen, H. Zhang, J. Yang, R. Wang, and Z. Li, "Joint optical and wireless resource allocation for cooperative transmission in C-RAN," *Sensors*, vol. 21, no. 1, p. 217, Dec. 2020, doi: [10.3390/s21010217](https://doi.org/10.3390/s21010217).
- [181] X. Liang, Q. Tian, F. Wang, W. Yu, and X. Xin, "A dynamic resource allocation based on network traffic prediction for sliced passive optical network," in *Proc. 19th Int. Conf. Opt. Commun. Netw. (ICOCN)*, Aug. 2021, pp. 1–3, doi: [10.1109/ICOCN53177.2021.9563790](https://doi.org/10.1109/ICOCN53177.2021.9563790).
- [182] B. Bao, H. Yang, Q. Yao, L. Guan, J. Zhang, and M. Cheriet, "Resource allocation with edge-cloud collaborative traffic prediction in integrated radio and optical networks," *IEEE Access*, vol. 11, pp. 7067–7077, 2023, doi: [10.1109/ACCESS.2023.3237257](https://doi.org/10.1109/ACCESS.2023.3237257).
- [183] T. Chen, J. Yu, A. Minakhmetov, C. Gutterman, M. Sherman, S. Zhu, S. Santaniello, A. Biswas, I. Seskar, G. Zussman, and D. Kilper, "A software-defined programmable testbed for beyond 5G optical-wireless experimentation at city-scale," *IEEE Netw.*, vol. 36, no. 2, pp. 90–99, Mar. 2022, doi: [10.1109/MNET.006.2100605](https://doi.org/10.1109/MNET.006.2100605).
- [184] J. Su, S. Nair, and L. Popokh, "Optimal resource allocation in SDN/NFV-enabled networks via deep reinforcement learning," in *Proc. IEEE 9th Int. Conf. Commun. Netw.*, Nov. 2022, pp. 1–7, doi: [10.1109/ComNet55492.2022.9998475](https://doi.org/10.1109/ComNet55492.2022.9998475).
- [185] J. A. Hatem, A. R. Dhaini, and S. Elbassuoni, "Deep learning-based dynamic bandwidth allocation for future optical access networks," *IEEE Access*, vol. 7, pp. 97307–97318, 2019, doi: [10.1109/ACCESS.2019.2929480](https://doi.org/10.1109/ACCESS.2019.2929480).
- [186] W. Saad, M. Bennis, and M. Chen, "A vision of 6G wireless systems: Applications, trends, technologies, and open research problems," *IEEE Netw.*, vol. 34, no. 3, pp. 134–142, May 2020, doi: [10.1109/MNET.001.1900287](https://doi.org/10.1109/MNET.001.1900287).
- [187] Y. Siriwardhana, P. Porabage, M. Liyanage, and M. Ylianttila, "AI and 6G security: Opportunities and challenges," in *Proc. Joint Eur. Conf. Netw. Commun. 6G Summit (EuCNC/6G Summit)*, Jun. 2021, pp. 616–621, doi: [10.1109/EuCNC/6GSummit51104.2021.9482503](https://doi.org/10.1109/EuCNC/6GSummit51104.2021.9482503).
- [188] M. A. Uusitalo, P. Rugeland, M. R. Boldi, E. C. Strinati, P. Demestichas, M. Ericson, G. P. Fettweis, M. C. Filippou, A. Gati, M.-H. Hamon, M. Hoffmann, M. Latva-Aho, A. Pärssinen, B. Richerzhagen, H. Schotten, T. Svensson, G. Wikström, H. Wymeersch, V. Ziegler, and Y. Zou, "6G vision, value, use cases and technologies from European 6G flagship project Hexa-X," *IEEE Access*, vol. 9, pp. 160004–160020, 2021, doi: [10.1109/ACCESS.2021.3130030](https://doi.org/10.1109/ACCESS.2021.3130030).
- [189] V. Ziegler, P. Schneider, H. Viswanathan, M. Montag, S. Kanugovi, and A. Rezaki, "Security and trust in the 6G era," *IEEE Access*, vol. 9, pp. 142314–142327, 2021, doi: [10.1109/ACCESS.2021.3120143](https://doi.org/10.1109/ACCESS.2021.3120143).
- [190] V. Ziegler, H. Viswanathan, H. Flinck, M. Hoffmann, V. Räisänen, and K. Hätönen, "6G architecture to connect the worlds," *IEEE Access*, vol. 8, pp. 173508–173520, 2020, doi: [10.1109/ACCESS.2020.3025032](https://doi.org/10.1109/ACCESS.2020.3025032).
- [191] J. Rodríguez, *Enabling 6G Mobile Networks*. Cham, Switzerland: Springer, 2022.
- [192] V. Mothukuri, P. Khare, R. M. Parizi, S. Pouriyeh, A. Dehghantaha, and G. Srivastava, "Federated-learning-based anomaly detection for IoT security attacks," *IEEE Internet Things J.*, vol. 9, no. 4, pp. 2545–2554, Feb. 2022, doi: [10.1109/JIOT.2021.3077803](https://doi.org/10.1109/JIOT.2021.3077803).
- [193] Y. Sun, J. Liu, J. Wang, Y. Cao, and N. Kato, "When machine learning meets privacy in 6G: A survey," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 4, pp. 2694–2724, 4th Quart., 2020, doi: [10.1109/COMST.2020.3011561](https://doi.org/10.1109/COMST.2020.3011561).
- [194] J. Li, X. Kuang, S. Lin, X. Ma, and Y. Tang, "Privacy preservation for machine learning training and classification based on homomorphic encryption schemes," *Inf. Sci.*, vol. 526, pp. 166–179, Jul. 2020, doi: [10.1016/j.ins.2020.03.041](https://doi.org/10.1016/j.ins.2020.03.041).
- [195] T. Zhang, T. Zhu, P. Xiong, H. Huo, Z. Tari, and W. Zhou, "Correlated differential privacy: Feature selection in machine learning," *IEEE Trans. Ind. Informat.*, vol. 16, no. 3, pp. 2115–2124, Mar. 2020, doi: [10.1109/TII.2019.2936825](https://doi.org/10.1109/TII.2019.2936825).
- [196] D. L. Dutta and S. Bharali, "TinyML meets IoT: A comprehensive survey," *Internet Things*, vol. 16, Dec. 2021, Art. no. 100461, doi: [10.1016/j.iot.2021.100461](https://doi.org/10.1016/j.iot.2021.100461).
- [197] R. Sanchez-Iborra and A. F. Skarmeta, "TinyML-enabled frugal smart objects: Challenges and opportunities," *IEEE Circuits Syst. Mag.*, vol. 20, no. 3, pp. 4–18, Aug. 2020, doi: [10.1109/MCAS.2020.3005467](https://doi.org/10.1109/MCAS.2020.3005467).



ZORAN VUJICIC received the M.Sc. degree in electrical engineering from the University of Belgrade, Serbia, in 2008, and the Ph.D. degree in electrical engineering from the University of Aveiro, Portugal, in 2015.

Since 2015, he has been with the Instituto de Telecomunicações, Aveiro, with various roles, including that of a Principal Researcher. He is currently a Senior Researcher and a Project Coordinator with the Instituto de Telecomunicações,

Aveiro. He is the Project Coordinator of European 6G project EWOC. His current research interests include the enabling technologies for low cost, high performance PON systems, and coexistence with legacy and wireless technologies. He has authored and helped develop several national and European projects. He is actively involved as a reviewer of various peer-reviewed journals.



MARIA C. SANTOS received the degree in telecommunication engineering from Barcelona Tech (UPC), Barcelona, in 1993, and the Ph.D. degree from the Signal Theory and Communications Department, UPC, in 1998.

She is currently an Associate Professor with the Signal Theory and Communications Department, UPC, where she has been teaching graduate and undergraduate courses in a broad variety of disciplines ranging from microwave engineering

to basic electromagnetism, fiber optics, nonlinear optics, and microwave photonics, since 1993. She is also with the CommSensLab Research Group which has been recognized with the María de Maeztu Excellence Award, in 2016, and the Premi Nacional de Comunicacions, in 2003. Her research interests include microwave photonics for communications and space applications, terahertz communications and imaging, and converged fiber mobile access networks, a topic she has helped develop through several European Consortium projects, such as SARDANA, EUROFOS, ACCORDANCE, and COCONUT.



RODRIGO MÉNDEZ received the B.S. degree in electronic engineering from the Universidad de San Carlos de Guatemala, in 2019, and the joint Erasmus master's degree in innovative microwave electronics and optics from the University of Limoges, the University of Brescia, and the Basque Country University, in 2022. He is currently pursuing the Ph.D. degree with the Signal Theory and Communications Department, Universitat Politècnica de Catalunya.

He is currently researching optical analog links for communication systems and their deployment on beyond 5G Fronthaul networks.



BLERON KLAIQI (Member, IEEE) received the Dipl. Ing. (M.Sc.) degree in electrical engineering and information technology from RWTH Aachen University, Germany, and the Ph.D. degree in electronic and electrical engineering from The University of Sheffield, U.K.

From 2006 to 2012, he was a Senior Engineer in UMTS/HSPA Layer1 and interworking between multiple RATs with Intel Corporation, Nuremberg, Germany. During the Ph.D. degree, he was a Marie-Curie Experienced Researcher for EU H2020 Decade and is 3DMIMO Projects. He is currently with Huawei, Kista, Sweden, working as a 5G/6G Baseband Research Engineer. His main research interests include massive MIMO and beyond, application of AI/ML in baseband (L1/L2), reconfigurable intelligent surfaces, and joint communication and sensing. He served as a reviewer for several major IEEE journals and conferences.



JONATHAN RODRIGUEZ (Senior Member, IEEE) received the Ph.D. degree from the University of Surrey, U.K., in 2004, and the D.Sc. degree from the University of South Wales, U.K., in 2022.

In 2005, he became a Researcher with the Instituto de Telecomunicações, Portugal, and a Senior Researcher, in 2008. He is currently a Full Professor in mobile communications with the University of South Wales, U.K. He has served as a Project Coordinator for major international research projects (Eureka LOOP, FP7 C2POWER, and H2020-MSCA-SECRET), whilst acting as the Technical Manager for FP7 COGEU and FP7 SALUS. He is currently the Project Director of the PHYSEC Project funded under the NATO Science for PEACE and Security Program. He is the author of more than 700 published works on mobile communication architectures. He serving as an Associate Editor for IEEE Access and IET Communications journal. His professional affiliations include C.Eng. (2013), FIET (2015), and SFHEA (2022).



XAVIER GELABERT (Member, IEEE) received the M.S. degree in electrical engineering from the Royal Institute of Technology, in 2003, and the M.S. degree in telecommunication engineering and the Ph.D. degree from the Technical University of Catalonia (UPC), in 2004 and 2010, respectively.

Since 2012, he has been a Researcher with Huawei's Stockholm Research Centre. He has more than 20 years of research experience across academia (UPC, GATech, and KCL), a non-profit research institute (iTEAM), a Telco Operator (Orange Labs), and an equipment vendor (Huawei). He actively contributed to 3GPP NR in RAN1 and RAN2 and holds several related patents. His research interests include radio, spectrum and compute resource management, self-organized networks, and more recently, baseband systems implementation, and architecture design.



MD ARIFUR RAHMAN (Member, IEEE) received the M.Sc. degree in electronics and communications from Teesside University, Middlesbrough, U.K., in 2012, and the Ph.D. degree in electrical engineering from the University of Ulsan, South Korea, in 2019.

Currently, he is a Senior Research and Development Engineer with IS-Wireless, Piaseczno, Poland, focusing on leading the research process and developing the research roadmap for the company. Prior to joining IS-Wireless, he was a Postdoctoral Researcher with Centrale Supélec, Campus of Rennes, France. He contributed in an ANR funded Enhanced Physical Layer for Cellular IoT (EPHYL) Project and developed radio resource management algorithm for multi-cell NB-IoT network scenario. He was a co-supervisor of master's students in the area of cooperative relaying in NOMA techniques with 2 years of experience during the Ph.D. program. His current research interests include cell-free mMIMO, cloud computing in 5G networks, multi-access edge computing, virtual radio access networks, AI application in wireless communications, digital twins, and emerging technologies in wireless communications.



ROBERTO GAUDINO (Senior Member, IEEE) received the Ph.D. degree in electronic engineering from the Politecnico di Torino, Turin, Italy, in 1998.

He is currently a Full Professor with the Politecnico di Torino. His current main research interests include modeling of optical communication systems and in the experimental implementation of optical networks, with specific focus on access networks. He is the coauthor of about 300 articles in these fields. In last years, he focused his activity on next-generation passive optical access networks (PON) and on ultra-high-capacity systems for short reach links. Previously, he worked extensively on fiber modeling, optical modulation formats (such as duo-binary, polarization, or phase modulation), coherent optical detection, plastic optical fibers, and on the experimental demonstration of packet switched optical networks.

...