Chapter 3
The Benefits of Convergence Through Fiber-Wireless Integration and Networking

Gee-Kung Chang and Lin Cheng

Abstract A multi-tier radio access network (RAN) combining the strength of fiber-optic and radio access technologies employing adaptive microwave photonics interfaces and radio-over-fiber (RoF) techniques is envisioned for future heterogeneous wireless communications. All-band radio access technologies (RATs) will be used to deliver wireless services with high capacity, high link speed, and low latency. The multi-tier RAN will improve the cell edge performance in an integrated heterogeneous environment enabled by fiber-wireless integration and networking for mobile fronthaul/backhaul, resource sharing, and all-layer centralization of multiple standards with different frequency bands and modulation formats. In essence, for this multi-tier radio access architecture, carrier aggregation (CA) among multiple frequency bands can be easily achieved and seamless handover can be guaranteed through coordinated multi-point (CoMP) transmission among various cells. In this way, current and future mobile network standards such as 4G and 5G can coexist with optimized and continuous cell coverage using multi-tier RoF, regardless of the underlying network topology or protocol. In terms of user's experience, the future-proof approach achieves the goals of increased system capacity and link speed, reduced latency, and continuous heterogeneous cell coverage, while overcoming the bandwidth crunch in wireless communication networks.

3.1 Introduction

Driven by video streaming, cloud computing, and Internet of Things (IoT), the overall traffic volume in wireless communication systems has grown tremendously in recent years, fueled primarily by the uptake in mobile broadband [1–3]. This trend is expected to continue into the 5G era in 2020 as predicted by the roadmap of

---

G.-K. Chang (✉) · L. Cheng
School of Electrical and Computer Engineering, Georgia Institute of Technology,
Atlanta, USA
e-mail: Geekung.chang@ece.gatech.edu

M. Tornatore et al. (eds.), *Fiber-Wireless Convergence in Next-Generation Communication Networks*, Optical Networks,
DOI 10.1007/978-3-319-42822-2_3

Table 3.1 KPIs for next-generation mobile network [5]

KPI	IMT 2020 PG values
Peak data rate per user	>10 Gb/s
Minimum data rate user	>100 Mb/s
Supported user density	>1,000,000 connections/km^2
Supported traffic density	>10 Tb/s/km^2
Latency	<1 ms
Mobility	Up to 500 km/h

3GPP [4]. Based on the predictions of several major equipment suppliers, such as Ericsson, Nokia, and Cisco, it is believed that by 2020 wireless communication systems will have to support more than 1,000 times today's traffic volume [1–3]. The key performance indices listed by the IMT-2020 promotion group in Table 3.1 foresee a tremendous growth in network performance. Extreme capacity and performance are required for the next-generation wireless access. Moreover, wireless communication trends including machine-type communication (MTC) and IoT require more features for future networks. None of the existing radio access technologies (RATs) will be able to individually provide the capabilities that effectively meet market demands. An evolution from existing and prospective technologies to support the ultimate radio access network (RAN) convergence is currently underway. Figure 3.1 gives an overall map of the various efforts to develop RANs, including raising wireless link performance, spectrum convergence, advanced multi-structure networking, and multi-RAT scenarios to fulfill the user needs for various applications.

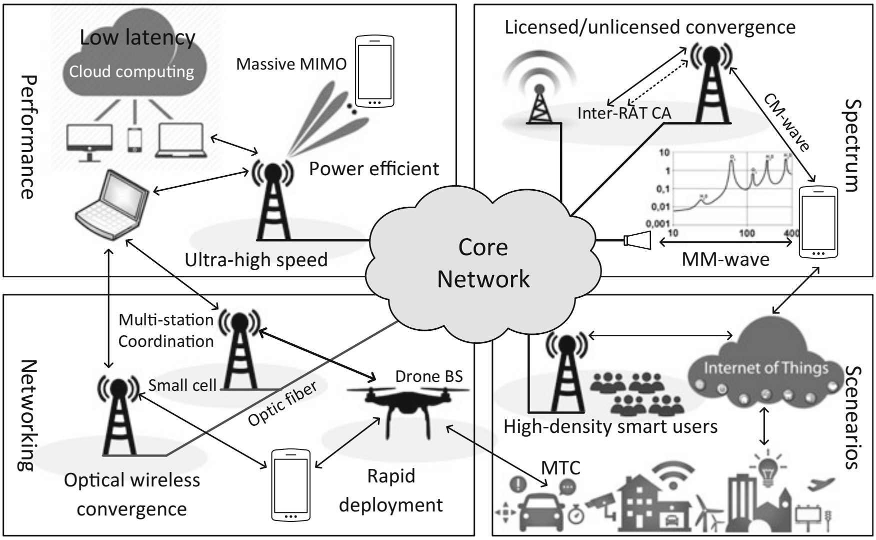


Fig. 3.1 Future mobile communication system (*BS* base station, *MTC* machine-type communication, *CA* carrier aggregation, *RAT* radio access technology)

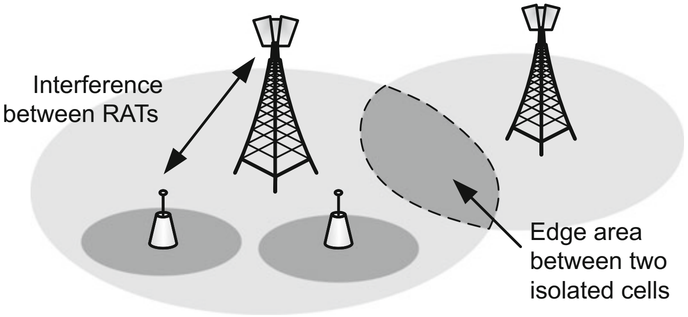
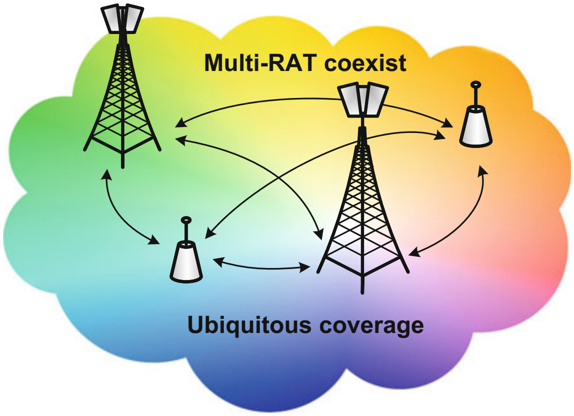


Fig. 3.2 Current RAN with "walls" between cells and services

In current 4G networks, eNB, OFDMA, IP core, etc., are the major technologies that define the advancement of LTE from previous generations. However, in all generations so far, the network coverage is still composed of almost isolated cells, as illustrated in Fig. 3.2. The "wall" between different cells creates a challenge for both the mobile user's experience and the backhauling for cell sites. Another "wall" exists among current RAT standards. Though local wireless is possible for traffic handover, users are simply served by independent RANs and unrelated RATs.

This chapter reviews how the convergence happens and what are the benefits for future mobile networks. Convergence is used to break the aforementioned "walls" and essentially merge all "isolated lanes" into a "super high-speed highway" that reaches all users in ubiquitous coverage, as shown in Fig. 3.3. It will be decided on the merits of three objective aspects: RAN architecture, backhaul and fronthaul links, and frequency bands for future mobile networks. This convergence includes fiber-wireless integration as well as multilayer centralization and resource sharing, resulting in seamless coordination among cells and services with accurate synchronization.

Fig. 3.3 Future ubiquitous coverage enabled by technology convergence



The convergence gives us a vision of future mobile networks. Multi-tier heterogeneous cells with different frequencies converge to a ubiquitous coverage in a mobile network. Carrier aggregation among various bands is arbitrary, handover between various cells is smooth, and coordination at cell edge areas is seamless. Cells from different families coexist and are merged into an optimized continuous coverage distribution when needed. Multi-service coexistence, multi-RAT support, and licensed-assisted access (LAA) allow users to wander previously disparate standards.

3.2 Convergence of Architectures

3.2.1 Centralization

In traditional architectures deployed in current macrocell RANs, as shown in Fig. 3.4, each base station (BS) can only handle traffic in its coverage area. However, the interference between cells limiting the system capacity can hardly be managed by isolated BSs. Further, the limited communication over X2 links consumes lots of capacity by adding traffic overheads. As the cell size gets reduced and the number of cells increases, it will be too expensive to build, upgrade, and operate the network, as each cell needs its own BS at the cell site. Therefore, centralization is necessary, thus eliminating the BS cost, and consequently allowing multiple heterogeneous services to share the BS [6]. In addition, local small cells can now be connected by mobile midhaul and supported by BSs [7].

Centralized radio access network (C-RAN) architectures have been proposed to extract the baseband signal processing functions from distributed BSs and colocate the baseband units (BBUs) into a pool for centralized signal processing and

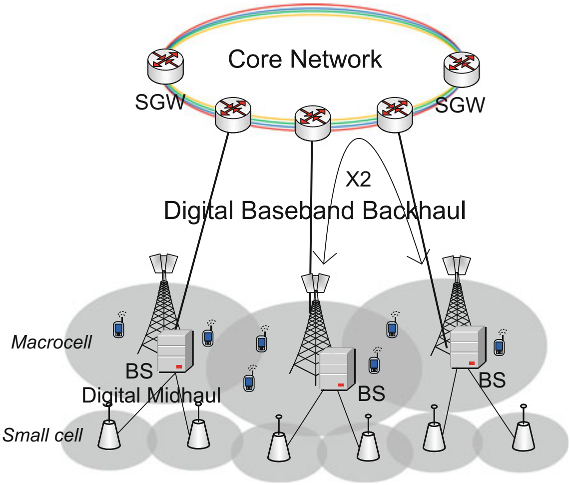


Fig. 3.4 Architecture of traditional distributed RAN (*SGW* service gateway)

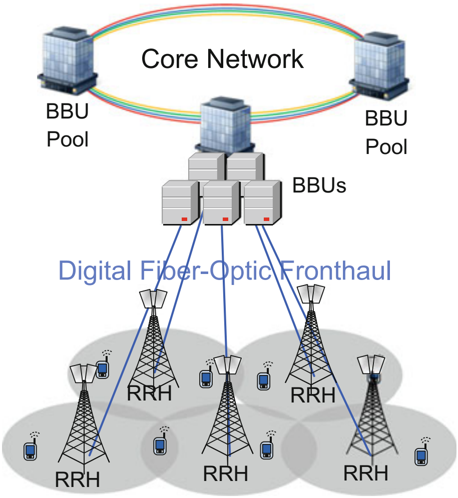


Fig. 3.5 Architecture of centralized RAN with digital fiber-optic fronthaul

management, as shown in Fig. 3.5 [8]. The centralized BBU and distributed remote radio heads (RRHs) are connected by digital fiber-optic links via standardized digital RF interfaces, such as common public radio interface (CPRI) and open base station architecture initiative (OBSAI) [9, 10]. However, only fundamental centralization is achieved by these techniques and they are limited by their implementation complexity and exceedingly low-spectrum efficiency over the digital fronthaul. Although various optimizations have been proposed to reduce the bandwidth, such as splitting-PHY processing [11], RRHs still encompass a large number of the baseband functions and all of the RF functions.

The convergence of fiber-optic and wireless communications enables radio-over-fiber (RoF) fronthaul as a new form of RAT and hence fully centralized RANs. RoFs can support both digital RoF and analog RoF, but analog RoF will benefit more in terms of convergence and centralization. In the architecture of centralized RANs based on fiber-wireless convergence, all BS functions and most of the RF functions are shifted from cell sites to the BBU pool at the central office (CO) as shown in Fig. 3.6. Different from RRHs, only O/E, E/O, and a few RF components are needed at the end of the fiber fronthaul as the radio access units (RAUs). In other words, RAU is the simplified version of RRH. The comparison between RRH and RAU and other RAN parts is shown in Fig. 3.7. In this architecture, RoF signals carrying multiple services are transmitted from the CO to the RAUs, and directly converted from optical to RF signals for downlinks, while RF signals from the UE are directly carried on light wave at the RAUs for uplinks [12].

This fully centralized RAN architecture based on fiber-wireless convergence provides a solid solution for high-throughput access systems with several advantages [12]:

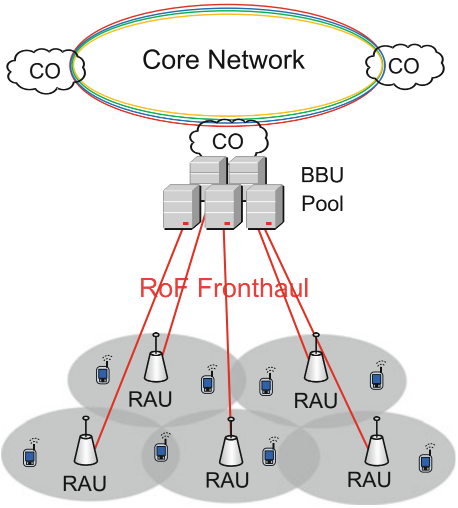


Fig. 3.6 Architecture of centralized RAN with RoF fronthaul

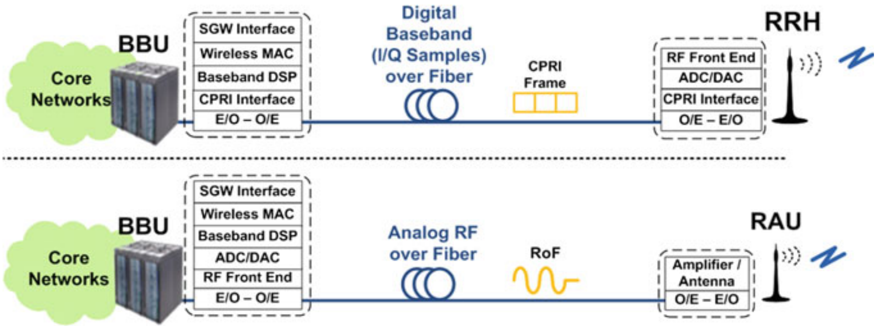


Fig. 3.7 Comparison between two centralized RAN architectures

- RAUs are highly simplified, thus the cell sites' footprint, power consumption, and demands for peripheral and technical support are considerably reduced.
- Cloud BBU pools significantly reduce the number of BSs. Each BBU can serve multiple RAUs to increase the infrastructure utilization rate.
- COs enable centralized processing and more flexible and efficient dynamic bandwidth allocation (DBA) and radio resource management (RRM). As BBUs work together, joint processing and cooperative radio to mitigate inter-cell interference (ICI) provide a higher spectral efficiency.
- Centralization and DBA make the network more adaptive to non-uniform distributed traffic resulting from the inter-cell movement of user equipment (UE).

- RoF fronthaul simplifies the generation and distribution of all frequency signals in a cost-effective way by microwave photonics (MWP) techniques, and provides a seamless integration with centralized RANs.
- The flexibility of centralization supports heterogeneous services and supplies an open platform for operations and maintenance (O&M), upgrade, and service expansion for smooth evolution.
- Most importantly, this centralized RAN architecture can maximize the resource sharing among operators and services over the entire RAN. Especially at the CO, with BBUs integrated inside the same pool, signaling, control, radio, channel state information, as well as physical infrastructures can be efficiently shared.

3.2.2 Resource Sharing

Figure 3.8 illustrates the physical resource-sharing hierarchy in centralized RANs where multiple operators and/or multiple services share the same system that includes the CO composed of high-performance BBUs and transceivers, high-bandwidth low-latency fiber links, and distributed RAUs.

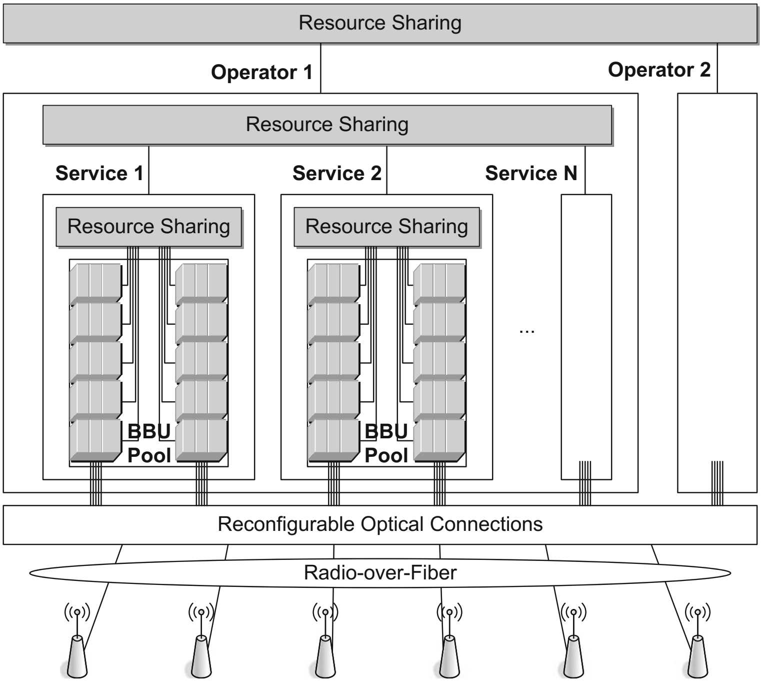


Fig. 3.8 Resource sharing occurring at different levels in a centralized RAN

Physical resources including laser sources, radio sources, and peripheral equipment can be shared among different operators that provide multiple services. Sharing at this level may include communications between operators inside the CO, thus considerably reducing the core network traffic and improving the efficiency of common services supplied by multiple operators.

For each operator, the sharing among its services involves the physical resources and the O&M. This heterogeneous sharing is especially efficient if the number of cells is high or the services share similar DBA schemes. Further, it also makes direct communication between services possible. Operators can effectively manage the communications between services from the upper layers inside the CO so that the traffic through the SGWs can be eliminated.

For each service from an operator, the sharing inside the BBU pool may occur in Layers 1–3 and also O&M. A set of BBUs and their corresponding E/O transmitters are connected to the service resource-sharing port so as to carry the data, signals, and their processing [8, 13]. Sharing reduces the complexity of each BBU and simultaneously maximizes its utilization. However, resource sharing among BBUs is not only limited to a fixed service, but can also be applied to different services or even to different operators.

Furthermore, sharing occurs not only inside the CO, but also over the entire access infrastructure. At the RAU, the RF access equipment consisting of broadband O/E, E/O converters, and RF components is shared by multiple operators and/or services from the same CO. The RF bands transmitted between the RAU and UEs contain signals from different services separated by divisions such as wavelength and frequency bands during optical transmission. On the other hand, the output from one BBU transmitter can be shared by multiple RAUs. In this case, the virtual BS from each RAU's view is identical. This can be considered as a one-on-N distributed antenna system (DAS) scenario which is likely in small-cell RANs due to the mobility and density of UEs. This infrastructure sharing regime is realized by the reconfigurable optical connections between the CO and fiber link interfaces. Each RAU is virtually connected to all the BBUs in different pools. The reconfiguration manipulated by the upper layers maintains the desired connections between BBUs and RAUs.

3.3 Convergence of Links

3.3.1 Mobile Backhaul

Mobile backhaul, midhaul, and fronthaul are the three types of connections in a RAN in terms of the location of the links. Mobile backhaul is the physical link between the core network and the BSs in a distributed architecture as shown in Fig. 3.9. Even though centralization and mobile fronthaul are going to play more and more important roles in the converged architectures, distributed systems and

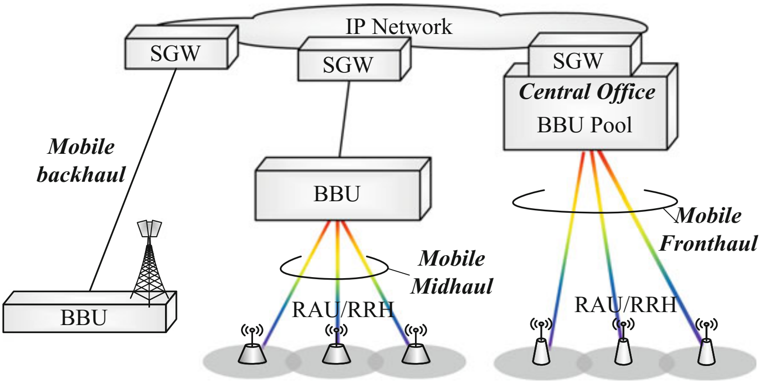


Fig. 3.9 Mobile backhaul, midhaul, and fronthaul in RANs

mobile backhaul are still necessary to provide a fundamental tier in the heterogeneous network. Further, convergence of technologies will also occur in future mobile backhaul networks.

Historically, the transition to new mobile technologies has resulted in the need for a fourfold to fivefold increase in backhaul capacity. With the advancement from 3G to 4G, RANs reached a capacity of 1–10 Gb/s per cell [14]. Future 5G RANs will increase the requirement for backhaul capacity by at least ten times considering the effective throughput for each user and multi-antenna technologies. Wavelength-division-multiplexed passive optical networks (WDM-PONs) have become a promising solution to alleviate the issue of congested backhaul data traffic [15].

In typical WDM-PON systems, as shown in Fig. 3.10a, optical network units (ONUs) at subscriber ends (BSs in this case) require distributed transmitters, receivers, and other passive components, which greatly increase the OPEX/CAPEX. To reduce the cost of a distributed system, new converged WDM-PON technologies will be adopted to simplify the BS. One of the options is to implement bidirectional transmission systems with non-overlapping downlink and uplink wavelength reuse [16]. By doing so, all the light sources for both downlink and uplink are aggregated at the optical line terminal (OLT) as shown in Fig. 3.10. Assisted by MWP technologies, the converged design enables more efficient management for all the optical sources, e.g., the traditional distributed thermal control at each ONU can be replaced by an economical centralized cooling system at the OLT. Since complexity is centralized at the OLT, the system has the potential to further increase the capacity to adapt to future high-speed WDM-PON applications. In addition, such systems can mitigate troublesome effects such as incomplete data erasing and signal back reflections of traditional reflective WDM-PONs without significantly increasing the cost.

On the other hand, to meet the needs for higher spectral efficiency and bandwidth flexibility, mobile backhaul with more advanced modulation formats will be

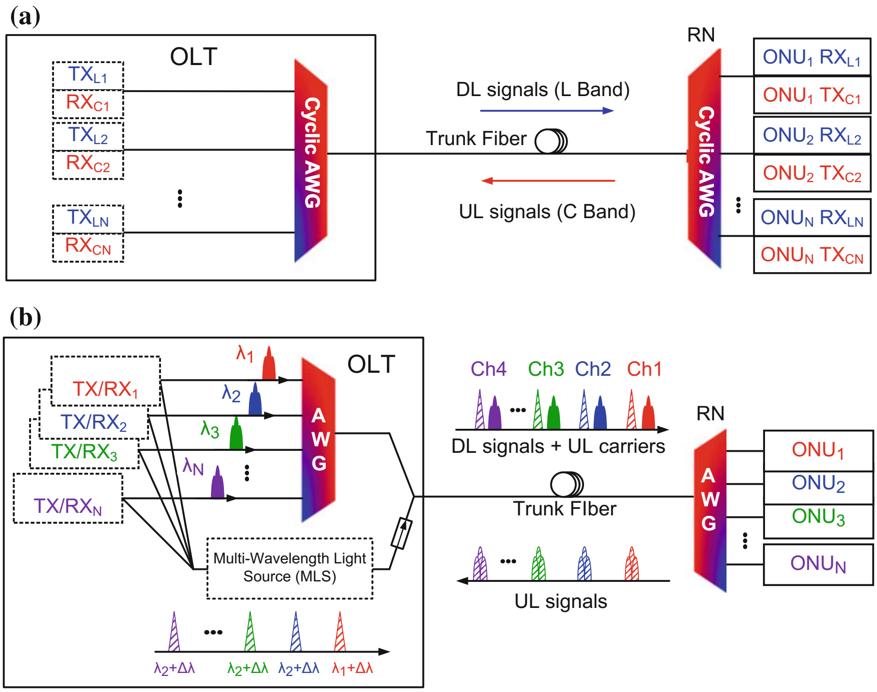


Fig. 3.10 **a** Traditional WDM-PON structure and **b** non-overlapping wavelength reuse for converged WDM-PON

developed. Currently, orthogonal frequency division multiplexing (OFDM) [17], carrier-less amplitude and phase (CAP) modulation [18], and subcarrier multiplexing (SCM) [19] have been extensively investigated. Similarly, extensive research has been performed on DSP-based modulation formats such as generalized frequency division multiplexing (GFDM), universal filtered multi-carrier (UFMC) and filter bank multi-carrier (FBMC) for high spectral efficiency. The properties for some of these techniques are listed and compared in Table 3.2 below.

Table 3.2 Advanced modulation formats

	CP-OFDM	FBMC (OQAM)	GFDM	UFMC
PAPR	High	High	Medium	High
CP for dispersion and multipaths	High	0	Reduced	0
OOB	High	Negligible	Reduced	Reduced
Time offset resiliency	Poor	Good	Good	Good
Frequency offset resiliency	Poor	Good	Good	Good
Complexity	Low	High	Medium	High
MIMO	Yes	Yes	Yes	Yes
CoMP	Yes	Excellent	Yes	Yes

In current LTE, OFDM can effectively combat multipath effect and inter-symbol interference (ISI), but it suffers from high peak-to-average power ratio (PAPR) and increases the DSP and synchronization complexities. Combined with quadrature amplitude modulation (QAM), traditional CAP and SCM techniques are more straightforward and can achieve spectral efficiencies (SE) comparable with that of OFDM. However, they still require high-speed DA/AD converters at BSs which in turn reduces the network scalability and tremendously increases the cost. Low-speed DAC/ADCs, with high resolution and reliable performance, can also be utilized to provide an inexpensive option by employing a low-cost intensity modulation/direct detection (IM/DD) scheme for future digitized optical access networks, especially at the BSs. This is now possible as a result of significant technological developments made by wireless service providers and hardware developers, enabling the low-cost and large-scale manufacture of multi-channel low-speed DAC/ADC chips, mixer arrays, and electrical oscillators by the IC industry.

3.3.2 Mobile Midhaul and Fronthaul

Mobile fronthaul is the physical link between the CO and the RRHs/RAUs in a centralized RAN. As a transient structure between backhaul and fronthaul, mobile midhaul is the link between a macroBBU and its extending RAUs. Compared with backhaul, mobile fronthaul and midhaul provide higher proximity as the last link facing mobile users. Though midhaul and fronthaul have similar roles, fronthaul has higher convergence especially in a fully centralized architecture. More and more mobile fronthaul links will coexist with traditional mobile backhaul and midhaul as the convergence occurs in RANs. The evolution and expansion of mobile fronthaul are directly driven by the exponential growth of the users' demand. A solid fronthaul design is the key approach to build efficient pipes between BBUs and users in terms of coverage, throughput, bandwidth, multi-service, quality, cost, and the compatibility to a long-term convergence. In converged RANs, as the number of cells increases and the average cell size becomes smaller, a huge number of fronthaul links are needed to distribute high-density, high-frequency, high-performance, but lightweight access units. More tiers of different types of cells will coexist in a heterogeneous form to fulfill different demands and provide ubiquitous coverage [20]. Mobile fronthaul supports new-style small cells, as well as inherits legacy cells including macrocells from 4G and small cells from WLAN networks. High-capacity, low-cost, flexible, and transparent services are the metrics for mobile fronthaul design. Furthermore, advanced technologies such as coordinated multi-point (CoMP) transmissions and multi-point carrier aggregation (CA) rely highly on fronthaul characteristics, bringing stringent synchronization and system stability requirements on mobile fronthaul designs [21].

In current RANs, digital fronthaul solutions such as CPRI and OBSAI are straightforward and robust approaches to fulfill basic LTE bandwidth needs. However, their low efficiency will require unaffordable high-speed transceivers and will limit any further bandwidth improvement when they are applied in future high-speed RANs. To fully digitize the RF signals into in-phase and quadrature components, the CPRI interface needs tremendous bandwidth, and any compression method must be developed considering the strict limitation on latency and hardware complexity. In CPRI, a 20 MHz LTE signal, as an example, takes up to 10-Gb/s fronthaul rate. When a 5-channel CA is applied, a 50-Gb/s rate will eventually consume all transceiver capacity. Moreover, in both CPRI and OBSAI, their digital interfaces cause unavoidable delay and jitter, becoming unfriendly to high-speed services that require precise synchronization.

In the next-generation 5G mobile communications, a large number of antennas are needed at the cell site in order to support antenna techniques such as massive MIMO, and each antenna needs a high-capacity stream in the CPRI scheme. Moreover, heterogeneous networks enable the seamless integration of high-frequency small cells with existing cells to support high-speed, low-latency services. As mobile fronthaul networks evolve from 4G–5G, it becomes technically challenging and cost prohibitive to accommodate multiple bands and multiple services into the conventional C-RAN network using digital interfaces.

The convergence over mobile fronthaul itself plays an important role in the universal convergence of RANs. RoF as the core technique to realize fronthaul convergence can solve most of the problems that a distributed digital system may incur. RoF technology is developed as an analog solution that avoids digital components or extra processing overhead over fronthaul. It improves optical spectrum efficiency and simplifies the RAU design. On top of a centralized RAN, RoF provides high-level centralization and minimizes complexity distribution. All baseband functions and most RF signaling are realized in a CO where resources are shared among all fronthaul links even if the links have various structures and serve different types of cells. By centralizing all DSP functions into BBU, downstream RF signals are transmitted as analog signals, where multiple bands of multiple services can be multiplexed in the frequency domain by using band mapping and CA techniques [22]. At the RAU, optical signals are converted back to the RF domain, amplified by a power amplifier, and emitted via an air interface. In addition, RoF facilitates the generation and distribution of high-frequency signals in optical approaches, as high-frequency signaling burdens fronthaul systems much more than low-frequency microwave signals [23].

A versatile multi-structure mobile fronthaul architecture based on RoF technologies and C-RAN hierarchy can converge different access technologies and can provide users proximal access in different environment, as shown in Fig. 3.11. A CO centralizes functions for both macrocells and small cells, including baseband processing as well as radio signaling. It supports both low-frequency (LF) and high-frequency (HF) bands. The LF small cells are normally in unlicensed bands (e.g., 2.4/5 GHz, LTE-U) to provide hot-spot coverage, while the HF small cells

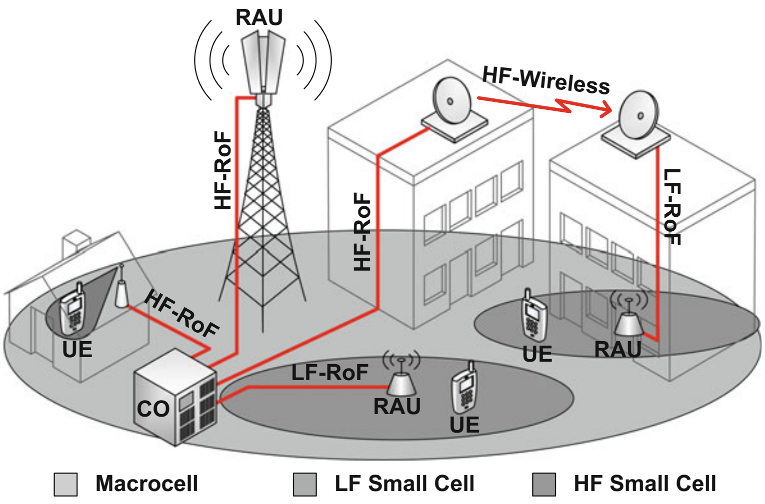


Fig. 3.11 Versatile multi-structure mobile fronthaul architecture

(e.g., 60 GHz) provide very high-throughput coverage for minor-mobility indoor users.

As a result of convergence, no baseband or digital processing exists between the CO and the UE in any fronthaul structure. Besides cost and management savings, this simplification leads to the important property that the propagation delay is only determined by the fronthaul length. For example, a user that is 1 km away from the CO and is covered by a small cell with 2-km fiber fronthaul (including 1 km of detour) has a fixed time offset of 6.7 μs without any jitter. This is a promising improvement from traditional CPRI systems where digital processing takes variable delays. Furthermore, in RoF-based fronthaul structures, all latencies are predictable, stable, and easily compensable at the CO so that advance technologies such as CoMP transmission and multi-point licensed-assisted CA can get precise synchronization.

3.4 Convergence of Bands

3.4.1 All-Band Coverage

Low-frequency bands (<6 GHz), centimeter-wave (CMW) bands (6–30 GHz), and millimeter-wave (MMW) bands (30–300 GHz) are the three main groups of serving RF bands. Existing cellular systems operating below 6 GHz frequency bands are heavily utilized. There is little space to further increase the transmission rate in these frequency bands. Thus, to reliably support multi-Gbps data rates, high-frequency bands will be exploited for high-capacity access and coverage.

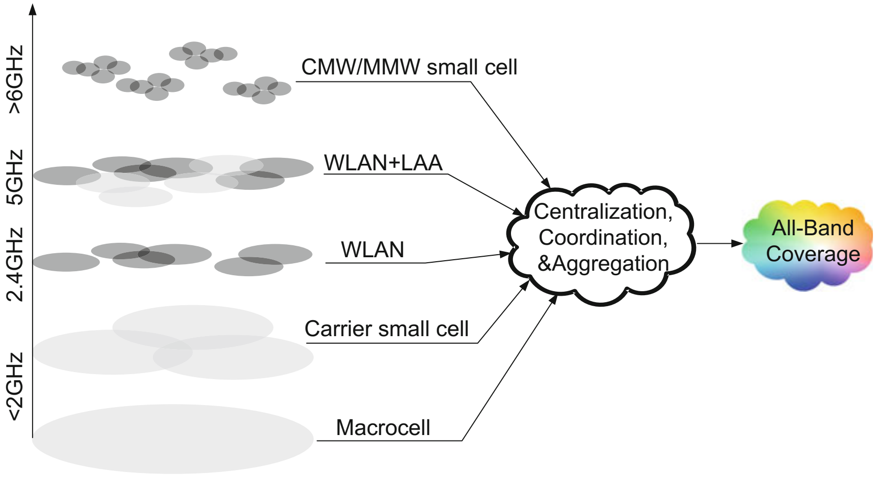


Fig. 3.12 All-band coverage and different service tiers

As shown in Fig. 3.12, on top of traditional low-frequency bands, the exploitation and convergence of CMW and MMW bands can provide potential multi-Gbps wireless links with continuous spectrum. By decoupling control and data channels, multi-RAT access over multiple available bands can boost users' throughput, while still managed by operators' networks. An example is to use WLAN and LAA to associate local unlicensed spectrum to current licensed networks so that two or more spectral channels are aggregated for a certain user. This LAA is also possible for CMW/MMW small cells with higher CA requirement.

However, although the target coverage of CMW and MMW small cells is smaller compared to low-frequency cells, there are several challenges for the deployment of these cells. First, they have to cope with unfriendly high-frequency propagation conditions such as large path loss, blocking object attenuation in real environments, and signal blockage loss due to atmospheric absorptions [24]. Second, considering the mobility of users, they should support dynamic multi-direction signal delivery [25]. Third, CMW and MMW cells should have the functionality to provide flexible support for different service coverage areas including both indoor and outdoor situations [26]. Finally, the high-carrier frequencies, and especially the ultra-wide bandwidths of MMW, have high requirements on hardware for signal generation and distribution.

To solve problems 1–3, MIMO technology is the most effective approach to overcome the inherent drawbacks of high-frequency wireless. Between CMW and MMW, the latter one, that has wide available unlicensed spectrum, is capable of potential throughout enhancement by exploiting beam-forming/steering through MIMO techniques in small cells. Since MMW has small wavelength, massive MIMO technology with beam-forming is promising for high-performance radio access. Phase antenna arrays are designed for this adaptive beam-forming in different propagation conditions, including single-user and multi-user, NLoS and LoS, static and mobile users. There is considerable research work on beam-forming schemes based on all-electronic or photonic-assisted structures. All-electrical phase-controlled antenna arrays can simultaneously change the amplitude and phase of the signal of each antenna in different RF-chain, which allows for more flexible steering. However, considering the large bandwidth of MMW requiring large numbers of high-speed ADCs and phase shifters, all-electronic control of antennas can cause significant power consumption and has high cost, high complexity, large size, and large weight. Photonic-assisted methods hold a great potential for solving these challenges and enable the use of fiber links with RAU/RRH in a long distance without much loss, as well as fast optical signal processing [27, 28]. In order to change the phase delay of each RF signal, a dispersion medium, such as fiber, fiber Bragg gratings, or other wavelength-selective modules can be used. A photonic amplitude changing module or chip is required to change the intensity of the split optical signals. After the PDs' detection, the mm-wave signals are transmitted by the antenna array with desired beam form. The independent backhauling for each antenna element is solved by the converged fiber-wireless links that conceive and maintain the amplitude and phase information of wireless signals as they are during optical transmissions. In addition, to solve the fourth problem mentioned above, microwave photonic technologies are adopted to ease the generation and distribution of MMW carriers.

In any case, high-frequency bands standing alone have inherent limitations to provide reliable control for mobile networks. By converging traditional low-frequency radio and newly deployed high-frequency radio, RANs can provide an all-band access pipe for the highest channel capacity. The multi-tier coverage for mobile users takes advantage of all the aforementioned potential frequency bands by supporting multiple types of RATs and inter-band CA.

3.4.2 MMW Links

A multi-structure mobile fronthaul provides system resilience, flexibility, and increased overall bandwidth capacity. The benefits of exploiting MMW for fronthaul transmissions include high capability of wireless data transmission, simple deployment, and adaptive environmental suitability.

To reach high spectral efficiency, advanced MMW technologies are desired for signaling, and this is realized by the supporting fiber-wireless convergence. In fact, many RoF links over MMW bands have been proposed and experimentally demonstrated in recent research efforts. Bit rates above 100 Gb/s have been attained by adopting spectrum-efficient modulation formats and digital coherent detection enabled by fiber-wireless convergence [29–31]. Different approaches for the realization of high-speed fiber-wireless integration systems as mobile backhaul/fronthaul are proposed, including optical polarization division multiplexing

(PDM) combined with MIMO reception [32, 33], advanced multi-level modulation, multi-carrier modulation [31], antenna polarization multiplexing [34, 35], MMW CoMP transmissions [36, 37], and multi-band multiplexing [38]. These approaches can effectively reduce the signal baud rate as well as the required bandwidth for optical and electrical devices. Crosstalk due to polarization rotation and MIMO transmission can be effectively solved based on advanced DSP algorithms including the classic constant modulus algorithm (CMA) [31]. Photonics-aided coordination also improves the MMW transmission stability and mitigates ICI [37].

3.5 Conclusion

In this chapter, we have discussed and reviewed the benefits of the convergence of fiber-optic-based optical access networks with radio access networks beyond the current bandwidth crunch. The convergence is used to break these legacy “walls” and merge all isolated and precious bandwidth lanes into a super-speed highway that reaches all users ubiquitously in future mobile data networks. The convergent networks will generate profound changes in RAN architectures, backhaul and fronthaul links, and the way frequency bands are used for future wireless communications. Figure 3.13 summarizes the convergent technologies and directions that will occur in the newly changed RAN architecture. The convergence originates

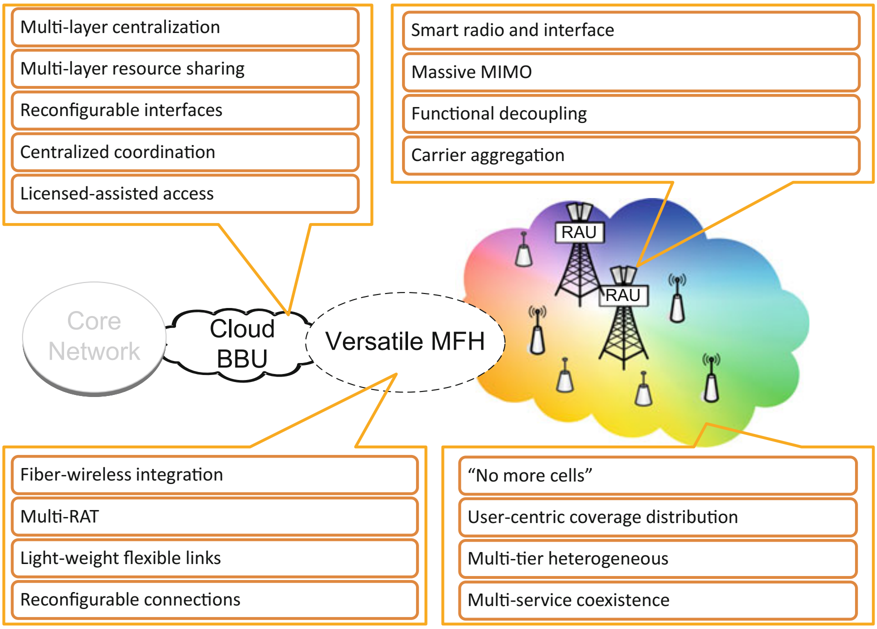


Fig. 3.13 Technology convergence occurring over the entire RAN architecture

from fiber-wireless integration to macro and small cells with multilayer centralization and resource sharing, and results in seamless coordination among cells and services with accurate synchronization in future mobile networks. The convergent networks will usher in a new era for future mobile networks, with integrated multi-tier heterogeneous cells with flexible and user-centric wireless converging to provide a ubiquitous coverage for mobile communications. In this grand unified scheme, carrier aggregation among various bands is flexible and scalable, handover between various cells is smooth, and coordination of user data throughput at cell edges is seamless. Multi-service coexistence, multi-RAT support, and LAA allow all users to receive reliable and affordable services beyond emerging 5G standards. The convergence of fiber-optic and radio access networks will ultimately benefit the future mobile users in a "no more cells" and "no more standards" environment to attain highly rich and reliable experience beyond the capacity crunch.

References

1. White paper, Cisco visual networking index: forecast and methodology, 2012–2017, Cisco VNI Report, May 2013. http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-481360.pdf
2. Rappaport TS et al (2013) Millimeter wave mobile communications for 5G cellular: it will work! IEEE Access 1:335–349
3. DOCOMO 5G White Paper, "5G Radio access: requirement, concept, and technologies". https://www.nttdocomo.co.jp/english/binary/pdf/corporate/technology/whitepaper_5g/DOCOMO_5G_White_Paper.pdf
4. Bertenyi B (2014) 3GPP system standards heading into the 5G era. EURESCOM Message. http://www.3gpp.org/news-events/3gpp-news/1614-sa_5g
5. IMT-2020 Promotion Group (2014) White Paper, 5G Vision and Requirements. http://euchina-ict.eu/wp-content/uploads/2015/03/IMT-20205GPG-WHITE-PAPER-ON-5G-VISION-AND-REQUIREMENTS_V1.0.pdf
6. Liu C, Cvijetic N, Sundaresan K, Jiang M, Rangarajan S, Wang T, Chang G-K (2013) A novel in-building small-cell backhaul architecture for cost-efficient multi-operator multi-service coexistence. In: IEEE/OSA optical fiber communication conference (OFC)
7. MEF 22.1.1, Mobile Backhaul Phase 2, Amendment 1, Jan 27, 2014
8. China Mobile, C-RAN white paper, 2011
9. Common Public Radio Interface (CPRI) specification, V6.1, June 2014
10. Open Base Station Architecture Initiative—BTS System Reference Document, V2.0, 2006
11. Miyamoto K, Kuwano S, Terada J, Otaka A (2015) Split-PHY processing architecture to realize base station coordination and transmission bandwidth reduction in mobile fronthaul. In: IEEE/OSA optical fiber communications conference (OFC), pp 22–26
12. Cheng L, Liu C, Zhu M, Wang J, Chang G-K (2013) Centralized small-cell radio access network with shared millimeter-wave radio-over-fiber resources. In: IEEE global communications conference (GLOBECOM), pp 2448–2453
13. Chang G-K, Liu C, Zhang L (2013) Architecture and applications of a versatile small-cell, multi-service cloud radio access network using radio-over-fiber technologies. In: IEEE international communications conference (ICC)

14. Oliveira RS, Frances CRL, Costa JCWA, Viana DFR, Lima M, Teixeira A (2014) Analysis of the cost-effective digital radio over fiber system in the NG-PON2 context. In: 16th international telecommunications network strategy and planning symposium (Networks), pp 1, 6, 17–19
15. Chang G-K, Chowdhury A, Jia Z, Chien H-C, Huang M-F, Yu J, Ellinas G (2009) Key technologies of WDM-PON for future converged optical broadband access networks. IEEE/OSA J Opt Commun Netw 1(4):C35–C50
16. Xu M, Wang J, Zhu M, Cheng L, Alfadhli YM, Dong Z, Chang G-K (2014) Non-overlapping downlink and uplink wavelength reuse in WDM-PON employing microwave photonic techniques. In: European conference on optical communication (ECOC), Sep. 2014, paper P. 7. 17
17. Cvijetic N (2012) OFDM for next-generation optical access networks. IEEE/OSA J Lightwave Technol 30(4):384–398
18. Zhang J, Yu J, Li F, Chi N, Dong Z, Li X (2013) 11 × 5 × 9.3 Gb/s WDM-CAP-PON based on optical single-side band multi-level multi-band carrier-less amplitude and phase modulation with direct detection. OSA Opt Exp 21(16):18842–18848
19. Buset JM, El-Sahn ZA, Plant DV (2013) Experimental demonstration of a 10 Gb/s subcarrier multiplexed WDM PON. IEEE Photon Technol Lett 25(15):1435–1438
20. Lopez-Perez D, Guvenc I, de la Roche G, Kountouris M, Quek TQS, Zhang J (2011) Enhanced intercell interference coordination challenges in heterogeneous networks. IEEE Wireless Commun 18(3):22–30
21. Irmer R, Droste H, Marsch P, Grieger M, Fettweis G, Brueck S, Mayer H-P, Thiele L, Jungnickel V (2011) Coordinated multipoint: concepts, performance, and field trial results. IEEE Commun Mag 49(2):102–111
22. Zhu M, Zhang L, Wang J, Cheng L, Liu C, Chang G-K (2013) Radio-over-fiber access architecture for integrated broadband wireless services. IEEE/OSA J Lightwave Technol 31 (23):3614–3620
23. Yu J, Jia Z, Yi L, Su Y, Chang G-K, Wang T (2006) Optical millimeter-wave generation or up-conversion using external modulators. IEEE Photon Technol Lett 18(1):265–267
24. Zhao H et al (2013) 28 GHz millimeter wave cellular communication measurements for reflection and penetration loss in and around buildings in New York City. In: IEEE international communications conference (ICC), June 2013, pp 516–567
25. Azar Y et al (2013) 28 GHz propagation measurements for outdoor cellular communications using steerable beam antennas in New York City. In: IEEE international communications conference (ICC), June 2013, pp 5143–5147
26. Dehos C, González JL, Domenico AD, Kténas D, Dussopt L (2014) Millimeter-wave access and backhauling: the solution to the exponential data traffic increase in 5G mobile communications systems? IEEE Commun Mag 52(9):88–95
27. Pasandi MEM, Sisto MM, Doucet S, Kim Y, Rusch LA, LaRochelle S (2009) Low-distortion optical null-steering beamformer for radio-over-fiber OFDM systems. IEEE/OSA J Lightwave Technol 27:5173–5182
28. Cao Z, Lu R, Wang Q, Tessema N, Jiao Y, van den Boom HPA, Tangdiongga E, Koonen AMJ (2014) Cyclic additional optical true time delay for microwave beam steering with spectral filtering. OSA Opt Lett 39:3402–3405
29. Li X, Dong Z, Yu J, Chi N, Shao Y, Chang GK (2012) Fiber-wireless transmission system of 108 Gb/s data over 80 km fiber and 2 × 2 multiple-input multiple-output wireless links at 100 GHz W-band frequency. OSA Opt Lett 37:5106–5108
30. Yu J, Li X, Chi N (2013) Faster than fiber: over 100-Gb/s signal delivery in fiber wireless integration system. OSA Opt Express 21:22885–22904
31. Zhang J, Yu J, Chi N, Dong Z, Li X, Chang G-K (2013) Multichannel 120-Gb/s data transmission over 2x2 MIMO fiber-wireless link at W-band. IEEE Photon Technol Lett 25 (8):780–783

32. Dong Z, Yu J, Li X, Chang GK, Cao Z (2013) Integration of 112-Gb/s PDM-16QAM wireline and wireless data delivery in millimeter wave RoF system. In: IEEE/OSA optical fiber communication conference (OFC) 2013, Anaheim, California, OM3D.2
33. Li F, Cao Z, Li X, Dong Z, Chen L (2013) Fiber-wireless transmission system of PDM-MIMO-OFDM at 100 GHz frequency. IEEE/OSA J Lightwave Technol 31 (14):2394–2399
34. Yu J, Zhang J, Xiao J (2014) 432-Gb/s PDM-16QAM signal wireless delivery at W-band using optical and antenna polarization multiplexing. In: European conference on optical communication (ECOC), W.3.6.6
35. Li X, Yu J, Zhang J, Dong Z, Chi N (2013) Doubling transmission capacity in optical wireless system by antenna horizontal- and vertical-polarization multiplexing. OSA Opt Lett 38 (12):2125–2127
36. Cheng L, Gul M, Ng'oma A, Lu F, Ma X, Chang G (2015) High-diversity millimeter-wave CoMP transmission based on centralized SFBC in radio-over-fiber systems. In: IEEE/OSA optical fiber communication conference (OFC), paper W3F.5
37. Cheng L, Zhu M, Gul MMU, Ma X, Chang G-K (2014) Adaptive photonics-aided coordinated multipoint transmissions for next-generation mobile fronthaul. IEEE/OSA J Lightwave Technol 32(10):1907–1914
38. Li X, Yu J, Zhang J, Dong Z, Li F, Chi N (2013) A 400G optical wireless integration delivery system. OSA Opt Express 21(16):18812–18819