Architecture and Applications of a Versatile Small-Cell, Multi-Service Cloud Radio Access Network Using Radio-over-Fiber Technologies

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***Abstract*— Small-cell systems based on cloud radio access network (cloud-RAN) architecture have been proposed as promising solutions to meet the ever-increasing capacity demand of the next-generation wireless access networks. By centralizing the processing power to reduce the complexity of conventional cell sites, the cloud-RAN architecture is ideal for large-scale small-cell system at reduced capital and operational expenses. However, high-speed, flexible, and scalable backhaul links between the centralized baseband processing unit (BBU) and the remote antenna units (RAUs) are required to support the high throughput of the small-cell cloud-RANs, and the conventional approaches are based on digital baseband signal transmission in the backhaul links.**

In this paper, we propose a novel multi-service small-cell wireless access architecture based on radio-over-fiber (RoF) technologies. By utilizing analog radio frequency (RF) signal transmission in the optical backhaul links, the design of RAUs can be further simplified. In addition, by combing RoF with optical wavelength division multiplexing (WDM) techniques, multiple bands, multiple services and multiple operators can coexist in a shared optical infrastructure without interference. To demonstrate the proposed system, two-operator coexistence in a shared small-cell cloud-RoF access network is implemented in an in-building testbed by using off-the-shelf optoelectronic components and commercialized WiMAX base stations and clients. In addition, the feasibility of delivering both conventional wireless services and future-proof high-RF-band services (millimeter-wave band) is also demonstrated in the proposed multi-service small-cell cloud-RoF access systems.

Keywords—wireless access network; small cell; cloud-RAN; radio-over-fiber

I. INTRODUCTION AND MOTIVATION

Mobile data traffic growth due to proliferation of smart mobile devices is accelerating the evolution of wireless access networks from 3G to 4G and beyond. Small-cell deployment and exploration of higher RF band are the two main directions for the next-generation wireless access networks. By reducing the cell size, limited spectral resources can be reused among the small cells more frequently, thus enhancing the total system capacity. On the other hand, by exploiting higher RF bands, e.g., millimeter-wave bands, much more spectrum are available that can easily support multi-gigabit wireless transmission without requiring time-consuming and complicated coding and modulation schemes. Due to the limited transmission range at higher RF bands, small-cell architecture is a natural choice for the exploitation of high RF bands. The small cells are likely to be deployed in traffic 'hot-spots' and 'not-spots', and to complement existing macrocell systems to form a heterogeneous network [1]. To support the small-cell systems, optical fibers are considered as ideal backhaul media to provide sufficient bandwidth as well as future-proof capacity upgrade. Therefore, optical-wireless integrated technologies for the next-generation small-cell wireless access networks become important topic and require strong interdisciplinary research efforts.

Recently, Cloud-based radio access network (cloud-RAN) of small cells was proposed in this direction and has been advocated by both operators (e.g., NTT, KT, France Telecom/Orange, Telefonica, SoftBank/Sprint, and China Mobile [2]) as well as service providers (e.g., Alcatel-Lucent LightRadio [3], Nokia-Siemens Liquid Radio [4]). The basic concept of cloud-RAN is to separate the digital baseband processing units (BBUs) of conventional cell sites, from the largely analog radio access units/ remote antenna units (RAUs), and move the BBUs to the "cloud" (BBU pool) for centralized signal processing and management. By centralizing the processing power, conventional complicated cell sites can be simplified to cost-effective and power-efficient RAUs, which is very important for the deployment of large-scale small-cell systems. In addition, the centralized processing power enables more advanced and efficient network coordination and management. For example, the coordination among several cell sites (or RAUs) enables inter-cell interference cancellation for cell-edge users and enhances their throughput in the concept of network multiple-input and multiple-output (network-MIMO) [5]. This inter-cell coordination can be achieved more efficiently in the cloud-RAN system with centralized processing power. Therefore, cloud-RAN architecture provides flexible and powerful network management in a cost-effective and power-efficient way for small-cell wireless access systems. However, the design of optical backhaul networks to connect BBU pool with

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Liang Zhang is currently with the State Key Lab of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai, China 200240 many small-cell RAUs and support high-speed data transmission in between is very critical for cloud-RAN systems. The small-cell backhaul is at an early stage of development, with a wide range of solutions being proposed and considered. The most prevailing method is to transmit digital baseband oversampled I/Q streams in the backhaul link based on Common Public Radio Interface (CPRI) or Open Base Station Architecture Initiative (OBSAI). However, due to I/Q streams are oversampled and multiple streams are needed to support multiple antenna for intra-cell MIMO application, this approach puts a high requirement for the throughput and capacity of the backhaul networks. In addition, by separating MAC and PHY layer functions at BBU and RAU, latency and jitter are big issues for cloud-RAN backhaul networks.

On the other hand, the exploration of higher RF bands, especially at the millimeter-wave (mm-wave) band (30GHz – 300GHz), has attracted huge attention of both industries and academia. Within the mm-wave band, 60GHz band with 7GHz license-free bandwidth is the hot topic. Many organizations have been working on the standardization of 60GHz band for all kinds of high-speed communication applications. For example, WirelessHD Consortium is targeted on very-high-speed wireless HD video transmission over the wireless video area network (WVAN) [6]. The IEEE 802.11ad task group [7] and the WiGig Alliance [8] are working on expanding Wi-Fi to the 60GHz band for wireless local area network (WLAN), while the IEEE 802.15.3c group specializes in the applications of 60GHz wireless personal area networks (WPAN) [9]. But the study of mm-wave band for mobile access network is still at preliminary stage due to the difficulties in mobility management, inter-cell interference management, and the cost. However, small-cell cloud-RAN architecture provides a good platform to exploit the bandwidth advantage at higher RF bands while minimizing the cost related to mobility and inter-cell interference management.

Therefore, in this paper, evolving from the concept of small-cell cloud-RAN with centralized processing, we propose a novel multi-service small-cell wireless access architecture by using radio-over-fiber (RoF) technologies. By transmitting analog RF signals over fiber-optic backhaul, the functions of RAUs can be further simplified. More importantly, different from the conventional digital-baseband-transmission approach that only supports one service at a time, the analog-RF-over-fiber method enables multi-service multi-operator coexistence in a shared infrastructure without interference. In addition, the seamless integration with optical wavelength division multiplexing (WDM) techniques provides more versatility and flexibility to the backhaul network. Therefore, a hierarchical coexistence can be achieved in the proposed small-cell cloud-RoF system. Firstly, multiple operators can co-exist in a shared small-cell infrastructure by using different WDM wavelengths without interference. Secondly, within each operator, different wireless services (including existing wireless services carried on lower RF bands as well as the future-proof higher-RF-band services) can co-propagate in the RoF backhaul in a simplified way. Thirdly, within each wireless service, multiple MIMO streams and multiple sub-bands (e.g. cognitive radio uses multiple RF sub-bands adaptively) can also coexist in the RoF link without incurring undesirable interference that hamper the high-bit-rate data services. Finally, different operators, different services, and different wireless techniques can share the small-cell infrastructure while maintaining independent configurability through the centralized management.

To demonstrate the proposed multi-service small-cell cloud-RoF access system, a two-operator coexistence testbed is implemented in an in-building small-cell environment by using off-the-shelf optoelectronic components and commercialized WiMAX base stations / mobile clients for real-time throughput measurement. WDM techniques are used to provide independent and flexible configurability of the two operators. Additionally, the feasibility of delivering conventional wireless services (WiFi/WiMAX) together with future-proof high-RF-band services (mm-wave band) is also demonstrated in the proposed multi-service small-cell cloud-RoF access system.

The rest of this paper is organized as follows: first in Section II, the architecture of proposed small-cell cloud-RoF access system is illustrated and compared with existing macrocell systems and conventional digital-baseband cloud-RAN systems. In Section III, an in-building WiMAX testbed of two-operator coexistence with independent configurability is demonstrated. Section IV shows the experimental setup and results for WiFi/WiMAX and future-proof 60GHz mm-wave services coexistence in a shared cloud-RoF backhaul. The conclusions are given in Section V.

II. Cloud Radio-over-Fiber Access System

The overall architectures of conventional macrocell systems and proposed small-cell cloud-RoF systems are illustrated in Fig. 1, and their main differences are summarized in Table I.

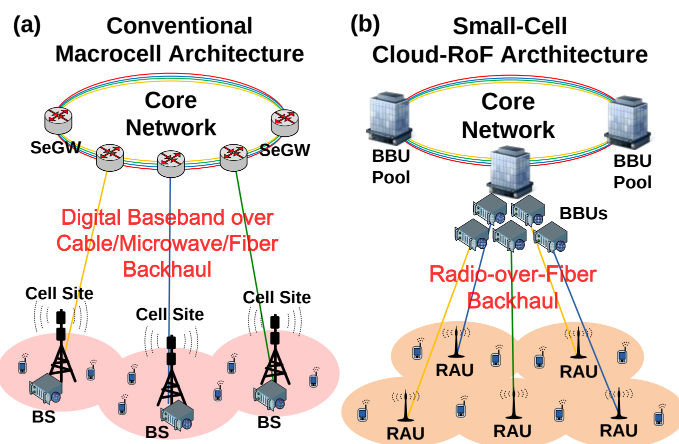

Fig. 1 Architectures of conventional macrocell system (a), and the proposed small-cell cloud-RoF system (b).

TABLE I. Comparison of Macrocell and Small-Cell Cloud-RoF Systems

	Macrocell	**Small-Cell Cloud-RoF**
Cell Size (radius)	1km~10km	10m~500m
Radio Frequency	700MHz ~ 5GHz	Microwave/Mm-wave bands
Cell Site Functions	Baseband Processing / RF Frontend	Simplified to RAU
Backhaul Media	Microwave/Cable/Fiber	Optical Fiber
Signal Format in Backhaul Link	Digital Baseband	Analog RF

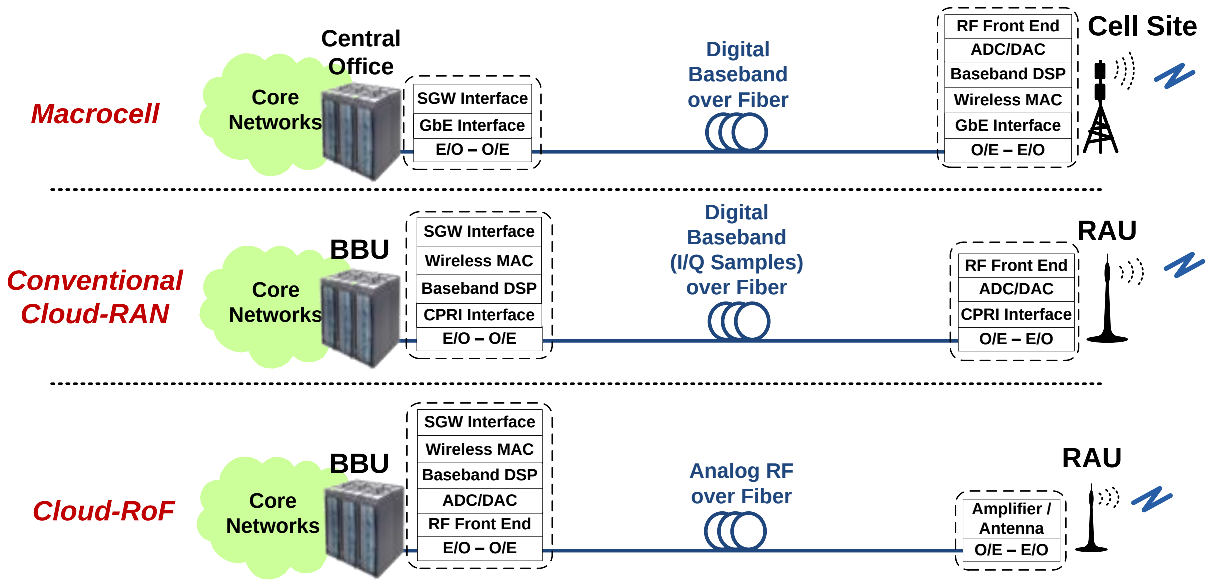

Fig. 2 Functions of central-office/cell-site (or BBU/RAU) for macrocell, conventional cloud-RAN, and the proposed cloud-RoF systems.

First of all, the radius of cells is reduced from 1km~10km of conventional macrocells to less than 500m. The radio frequency of the small cells can be either conventional low-RF microwave bands (700MHz ~ 5GHz) as well as future-proof mm-wave bands. Notice that for the mm-wave small cells, the cell size is limited to the scale of 10 meters due to the high propagation loss, which makes them more likely to be deployed for in-building environments. Due to radio-over-fiber techniques are used in the cloud-RoF systems, optical fibers are exclusively used as the backhaul media, which is different from the conventional macrocell system with all types of backhaul media.

The key differences of cloud-RoF small cell from macrocell (including the conventional cloud-RAN) are the central-office/cell-site (or BBU/RAU) functions and associated signal transmission formats in the backhaul link. The detailed comparisons are illustrated in Fig. 2. Comparing cloud-RAN with macrocell, the complicated cell site is simplified to radio access unit (RAU) by shifting the MAC layer functions and baseband processing to the central office/BBU, and digital I/Q samples are transmitted in the backhaul link. However, for cloud-RoF system, the function of RAU is further simplified by shifting ADC and RF frontend functions to BBU. Therefore, only O/E and E/O conversions, and RF antenna are needed in the remote antenna unit (RAU). Since RF front-end is shifted to BBU, analog RF signals are transmitted in the backhaul, which enables multiple radios (multi-band/multi-service/multi-operator) coexistence in the optical fiber backhaul. This multi-service coexistence feature further reduces the cost related to the small-cell deployment, and provides versatility to the small-cell access system.

III. Two-Operator Coexistence Test

To demonstrate multi-service multi-operator coexistence in the proposed cloud-RoF access system and show the feasibility of incorporating WDM techniques to provide independent and flexible configurability to the backhaul, an in-building two-operator testbed is conducted, and a two-operator two-service example is shown in Fig. 3[10].

At the BBU pool, where the centralized digital processing power is located, the baseband data traffic from core networks is processed and up-converted to radio frequency (RF) via base station (BS) units. Since different operators and/or wireless services occupy different RF spectral bands, f_1, f_2, and f_3 represent the RF carrier frequencies of signals from different

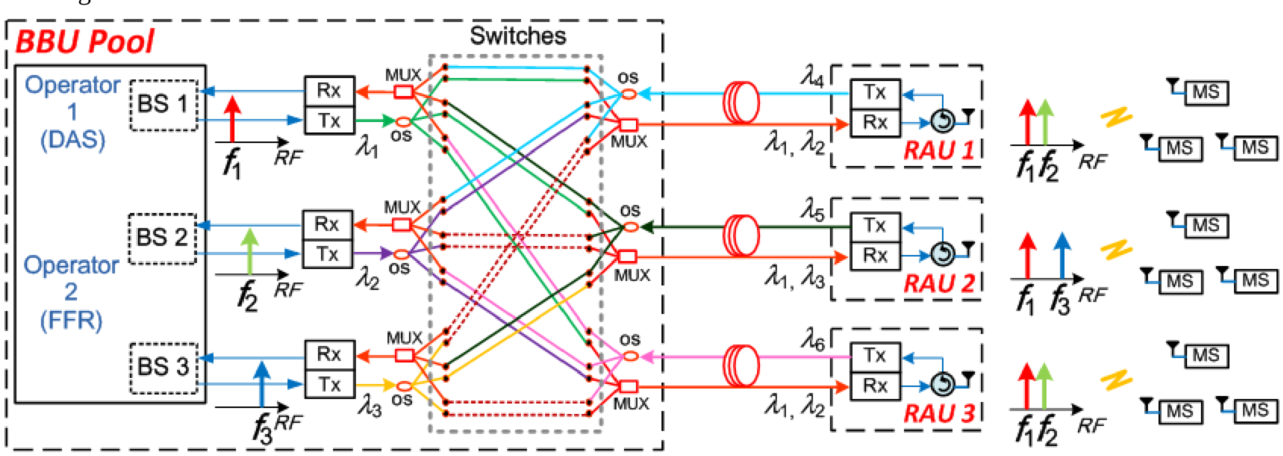

Fig. 3 Reconfigurable small-cell cloud-RoF architecture for multi-service, multi-operator coexistence.

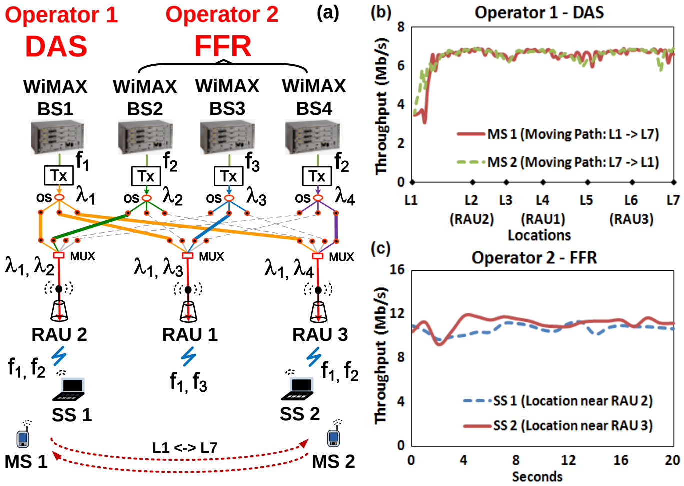

Fig. 4 (a) System configuration of in-building small-cell cloud-RoF testbed; (b) measured downlink throughput of mobile users of Operator 1 at different locations and (c) measured downlink throughput of static users of Operator 2.

BSs. Each downstream RF signal is then intensity modulated onto a different CWDM optical wavelength, λ_1, λ_2, λ_3, respectively, using integrated off-the-shelf transceivers (Tx/Rx in Fig. 3) for bi-directional intensity modulation and direct photodetection. Optical splitters (OS) and CWDM multiplexers (MUX) are used at the BBU pool to split and multiplex the downlink and uplink signals. An off-the-shelf optical switch with built-in independent on-off sub-switches is used to establish reconfigurable fiber-optic connections between the centralized BS units and distributed RAUs. Two system configurations are considered for two operators independently: distributed antenna system (DAS) and fractional frequency reuse (FFR). In the DAS scenario, the same signal is distributed to all RAUs to extend coverage especially for mobile users, while in the FFR scenario, different signals are transmitted to different RAUs to exploit spectral reuse and increase total system capacity especially for static users. By properly configuring the optical on-off switches in Fig. 3, the signal from BS1 on f_1 and λ_1 (from Operator 1) can be distributed to all three RAUs, as in a DAS scenario. To simultaneously emulate FFR scheme with a spectral re-use factor of 2 for Operator 2, the optical switches can be configured to distribute the signal from BS2 on f_2 and λ_2 to RAU1 and RAU3, while the signal from BS3 on f_3 and λ_3 is distributed to RAU2. After the optical switch, downstream signals are CWDM-multiplexed and delivered to several in-building RAUs via optical fiber links. In the cloud-RoF architecture, multiple wavelengths carrying multiple RF signals from different operators are all detected simultaneously by a single photodetector (PD) at each RAU, yet without interference. The theoretical analysis can be found in [10].

Based on this architecture, an in-building small-cell cloud-RoF testbed was set up as shown in Fig. 4(a). In this case, two operators with totally 4 WiMAX BSs were centralized at the BBU pool. 1 WiMAX BS (f_1 = 2.57GHz) is used in the DAS configuration to serve 2 mobile users MS1 and MS2 along a moving path denoted by checkpoints L1— L7. The remaining WiMAX BSs are used in the FFR configuration (f_2 = 2.61GHz, f_3 = 2.59GHz; reuse f_2 for BS2 and BS4), serving two static users (SS1 and SS2.) Both DAS and FFR configurations were thus running simultaneously. The output RF signals of four BSs are carried on four CWDM wavelengths ($\lambda_1, \lambda_2, \lambda_3, \lambda_4$) = (1490nm, 1510nm, 1530nm, 1550nm), respectively. The measured downlink throughputs for the DAS and FFR scenarios are shown in Fig. 4(b) and (c), respectively. For Operator 1, since the DAS configuration is used, the mobile users experience no degradation in the steady 6Mb/s throughput while moving across three small cells (L1 to L7, and back), even at the cell edges, highlighting the key coverage benefits of DAS. For Operator 2, since FFR with a reuse coefficient of 2 was exploited for static users, the system throughput is doubled to 12Mb/s for each user, which demonstrates the capacity benefits of this scheme. Therefore, the small-cell cloud-RoF architecture enables both operators to simultaneously run different backhaul scenarios by sharing the in-building optical infrastructure, without interference.

IV. Coexistence with Mm-Wave Services

A proof-of-concept experiment was conducted to demonstrate the feasibility of delivering conventional wireless services (WiFi/WiMAX) together with future-proof mm-wave services through the shared cloud-RoF system. The experimental setup is shown in Fig. 5.

At the BBU pool, a continual wave (CW) tunable laser at wavelength λ_1 of 1553.50nm is fed into a single-drive Mach-Zenhder modulator (MZM) for data modulation. Data 1 and Data 2 are 400Mb/s 16QAM-OFDM signals generated by an arbitrary waveform generator (AWG), and they are mixed with 2.5GHz and 5.6GHz sinusoidal RF clocks to emulate the WiFi and WiMAX services, respectively. The output of the

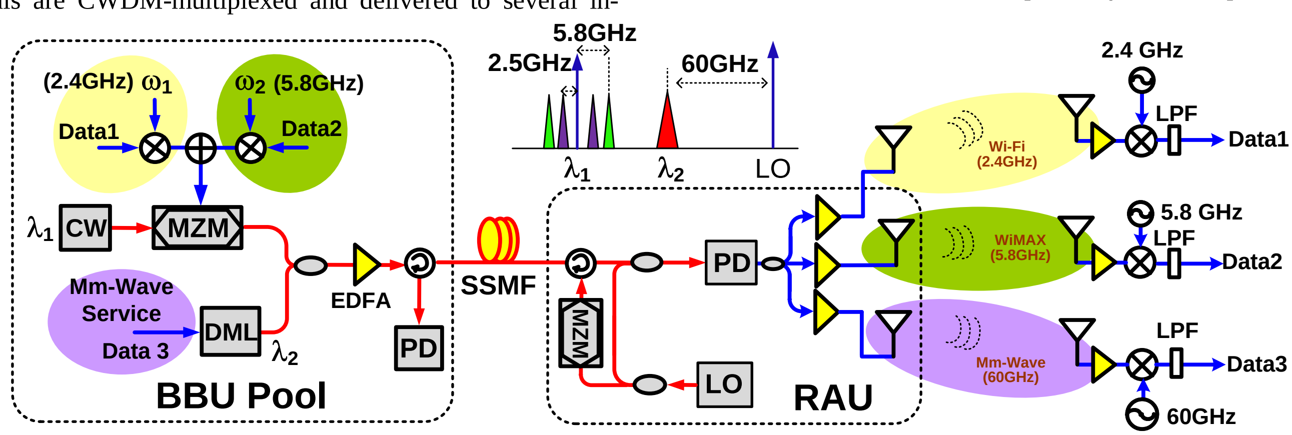

Fig. 5 Experimental setup of conventional wireless services (WiFi/WiMAX) and mm-wave service coexistence in cloud-RoF backhaul.

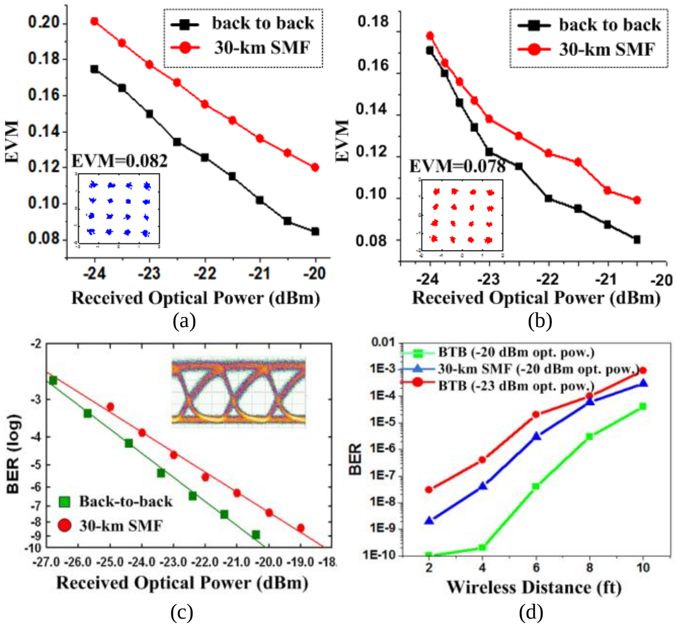

Fig. 6 Measured EVM value vs. received optical power for 16QAM-OFDM WiFi signals carried on 2.4GHz (a) and 16QAM-OFDM WiMAX signals carried on 5.8GHz (b). Measured BER vs. received optical power (c) and vs. wireless transmission distance (d) for OOK data carried on 60GHz mm-wave radio.

mixer are combined and amplified to drive the MZM. Data 3 of 1Gb/s on-off keying (OOK) signal is used to emulate the high-speed data service carried on mm-wave radio. Optical mm-wave generation scheme is adopted in this experiment to reduce the requirement on high-speed optical modulator for direct mm-wave modulation. The OOK data is first modulated on an optical wavelength λ_2 (1553.75nm) through a direct modulated laser (DML). Then conventional WiFi/WiMAX RoF services are combined with the mm-wave service and delivered to a RAU through 30-km standard single mode fiber (SSMF) transmission.

At the RAU, an optical local oscillator (LO) at wavelength of 1554.23nm is coupled with the downlink signals to generate optical mm-wave signal. It is possible to shift the LO functions at the BBU pool, however since an optical LO source is always needed at the RAU for uplink optical transmission, therefore in this experiment, we reuse the LO source for both downlink optical mm-wave generation and uplink optical transmission. The illustration of the wavelength assignment of the RoF transmission is shown in the inset of Fig. 5. After the RoF signals being detected by a single high-speed PD, both WiFi/WiMAX RF signals and the mm-wave RF signals are recovered and transmitted to corresponding mobile users through separate antennas. At the mobile user side, the received RF signals are downconverted to baseband for bit-error rate (BER) calculation and error vector magnitude (EVM) measurement.

The measured results of WiFi/WiMAX and mm-wave services are shown in Fig. 6. The EVM vs. received optical power curves for 16QAM-OFDM data on 2.4GHz and 5.8GHz are shown in Fig. 6 (a) and (b), respectively. Figure 6 (c) shows the measured BER vs. received optical power of OOK data carried on 60GHz mm-wave, and the performance over different wireless transmission distance for both back-to-back (BTB) and after 30-km fiber transmission case is shown in Fig. 6(d). The penalties induced by 30-km fiber transmission is mainly resulting from the decreased optical signal-to-noise ratio (OSNR) at the photodetection. The penalties related to wireless transmsision distance is due to the high propagation loss at mm-wave band, which is consistent with the Friis transmission equation at short transmission distance [11]. Notice that both conventional WiFi/WiMAX services and the mm-wave services can achieve good performance after optical fiber and wireless transmission, and there is minimal interference observed among different services during the RoF transmission. These results demonstrated the feasibility of delivering both conventional wireless services and future-proof mm-wave services in the shared cloud-RoF access systems without interference.

V. Conclusions

In this work, we have introduced a novel small-cell cloud-radio-over-fiber (cloud-RoF) access network architecture. The system architecture is compared with existing macrocell systems and conventional cloud-RAN systems, and the benefits of proposed cloud-RoF system are further simplified remote antenna unit (RAU) design and the feasibility of infrastructure sharing among multiple services and multiple operators. By combining with WDM techniques, we demonstrated an in-building small-cell cloud-RoF testbed with two-operator coexistence while maintaining independent backhaul configurability. In addition, a proof-of-concept experiment was conducted to demonstrate the feasibility of delivering high-speed mm-wave services with conventional wireless services in a shared cloud-RoF system. We believe the proposed cloud-RoF architecture provides a cost-effective and power-efficient solution for future-proof small-cell wireless access systems.

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