A Novel Multi-Service Small-Cell Cloud Radio Access Network for Mobile Backhaul and Computing Based on 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 capacity demand of the future wireless access networks in a cost-effective and power-efficient way. High-speed and scalable backhaul links between the centralized baseband processing units (BBUs) and the remote antenna units (RAUs) are very important to support the small-cell cloud-RAN. Conventionally, digital baseband I/Q samples are transmitted in the cloud-RAN backhaul, which puts stringent requirements on backhaul bandwidth, latency, and jitter. In this paper, we propose a novel multi-service small-cell wireless access architecture based on radio-over-fiber technologies (cloud-RoF access network). By utilizing analog radio frequency (RF) signal transmission in the optical backhaul links, high-speed data transmission can be achieved with highly simplified RAU design. 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. Two-operator coexistence in a shared small-cell cloud-RoF access network is demonstrated 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 millimeter-wave services is also demonstrated in the proposed multi-service small-cell cloud-RoF access system.**

***Index Terms*—Fiber-optic backhaul, millimeter-wave, radio-over-fiber, small cell, wireless access networks.**

I. Introduction

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 higher-RF-band exploration are the two main directions for the next-generation wireless access networks. By reducing the cell size, limited spectral resources can be reused among small cells more frequently, thus enhancing the total system capacity. On the other hand, by exploiting higher radio frequencies, e.g., millimeter-wave bands, much more spectra are available that can easily support multi-gigabit wireless transmission without requiring time-consuming and complicated modulation and coding schemes. Due to the limited transmission range at higher RF bands, the combination of small-cell architecture and higher RF provides a promising solution to drastically increase the system capacity through frequency exploitation and reuse. Small-cell systems 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 small cells, 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 an important topic and require strong interdisciplinary research efforts.

Recently, cloud-based radio access network (cloud-RAN) of small cells has been proposed in this direction and advocated by both operators (e.g., NTT, KT, France Telecom/Orange, Telefonica, SoftBank/Sprint, and China Mobile [2]) as well as equipment vendors (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 or BBU hotelling) 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 a large-scale small-cell system to be deployed. 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 in the concept of coordinated multi-point transmission (CoMP) and network multiple-input and multiple-output (network-MIMO) [5]. Therefore, cloud-RAN provides a flexible, powerful, and centralized network architecture for future small-cell wireless access systems in a cost-effective and power-efficient way.

However, the design of optical backhaul networks (or commonly referred as fronthaul network for cloud-RAN) to connect BBU pool with many small-cell RAUs and to support high-speed backhaul data transmission is very critical. Currently, 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

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oversampled I/Q streams in the backhaul based on Common Public Radio Interface (CPRI) [6] or Open Base Station Architecture Initiative (OBSAI) [7]. However, due to I/Q streams are oversampled and multiple streams are required to support multiple sectors and multiple antennas for both intra- and inter-cell MIMO applications, this approach requires very high link throughput (~10 Gb/s) and capacity of backhaul networks [6], [8]. In addition, since MAC and PHY layer functions are separated at BBU and RAU respectively, latency and jitter must be carefully controlled in the conventional cloud-RAN backhaul networks.

Therefore, in this paper, evolving from the concept of centralized small-cell cloud-RAN, we propose a novel multi-service small-cell wireless access architecture by using radio-over-fiber (RoF) technologies (cloud-RoF access network). By transmitting analog RF signals over fiber-optic backhaul, the functions of RAUs can be further simplified. More importantly, unlike the conventional digital-baseband-transmission approach that typically supports only one service at a time, the analog-RF-over-fiber method enables multi-service multi-operator coexistence in a shared infrastructure without extra interference. In addition, it is beneficial to integrate with optical wavelength division multiplexing (WDM) techniques to provide more versatility and flexibility to the backhaul networks. Therefore, the proposed system provides multiple system operational advantages: Firstly, multiple operators can co-exist in a shared small-cell infrastructure by using different WDM wavelengths; Secondly, within each operator, different wireless services (including legacy wireless services 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, for each wireless service, multiple MIMO data 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; Finally, multiple operators, multiple services, and multiple wireless techniques can share the same small-cell infrastructure while maintaining independent configurability through the centralized management.

To demonstrate the proposed multi-service small-cell cloud-RoF access system, an experimental 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 higher-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: in Section II, architecture of the proposed small-cell cloud-RoF access system is illustrated and compared with the conventional macrocell systems and the emerging cloud-RAN systems. In Section III, an in-building small-cell testbed of two-operator coexistence with independent configurability is demonstrated. Section IV shows the experimental setup and results for WiFi/WiMAX and future-proof 60 GHz mm-wave services coexistence in a shared cloud-RoF access system. The conclusions are given in Section V.

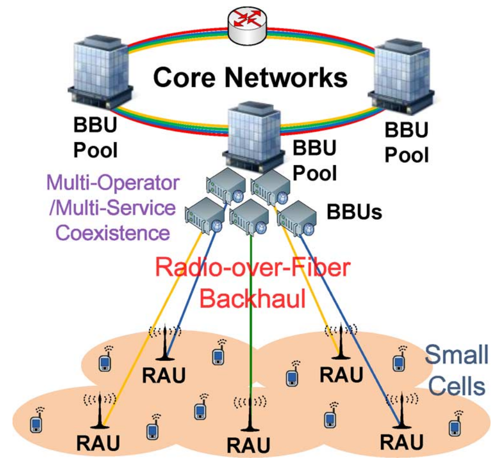

Fig. 1. Architecture of the proposed small-cell cloud-RoF access systems.

TABLE I
COMPARISON OF MACROCELL AND SMALL-CELL CLOUD-ROF SYSTEMS

	Macrocell	**Small-Cell Cloud-RoF**
Cell Size (radius)	1km~10km	10m~100m
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
Backhaul Signal Format	Digital Baseband	Analog RF

II. Cloud Radio-Over-Fiber Access System

The overall architecture of proposed small-cell cloud-RoF access systems is illustrated in Fig. 1, and the comparisons with conventional macrocell systems are summarized in Table I.

First of all, the radius of small cells is reduced from 1 km–10 km of conventional macrocells to less than 100 m. The radio frequency of the small cells can be conventional low-RF microwave (700 MHz–5 GHz) as well as future-proof mm-wave. Notice that for mm-wave small cells, the cell radius is typically limited to ~20 meters due to the high propagation loss, which makes them more likely to be deployed in in-building hot-spot environments. Optical fibers are exclusively used as the backhaul media for the multi-band small-cell cloud-RoF access system.

More importantly, the functions of central office and cell sites (or BBU and RAUs in cloud-RAN systems) as well as the associated signal transmission formats in backhaul links are very different for the cloud-RoF systems. The comparisons are illustrated in Fig. 2. Comparing the emerging cloud-RAN with the conventional macrocell, cell sites are simplified to RAUs by shifting MAC layer functions and baseband signal processing to the central office or BBU, and digital I/Q samples are transmitted in the backhaul. However, for the proposed cloud-RoF system, the function of RAU is further simplified by shifting DAC/ADC and RF frontend functions to the BBU. Therefore, only O/E and E/O conversion, and RF antennas are needed in

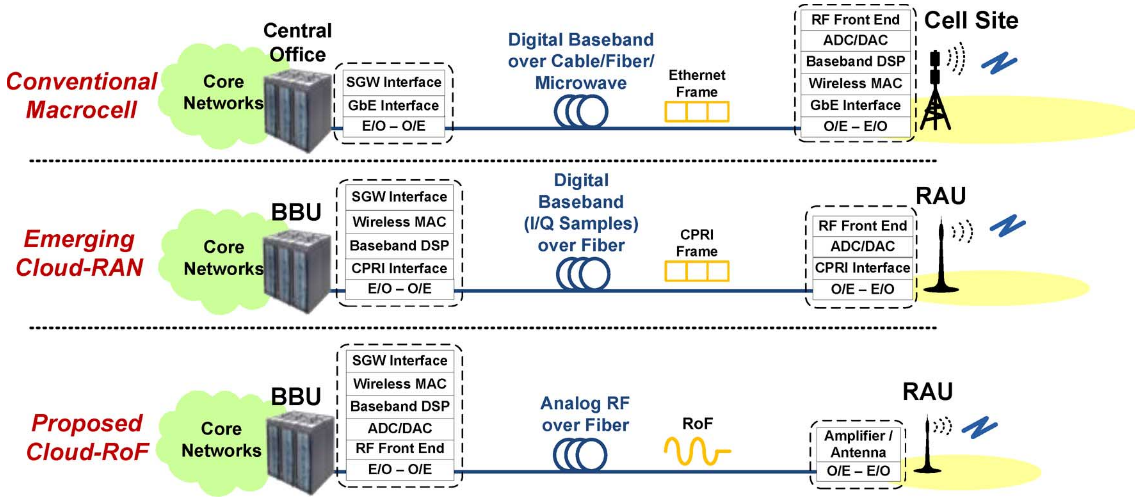

Fig. 2. Functions of central-office and cell-sites (or BBU and RAUs) for macrocell, conventional cloud-RAN, and the proposed cloud-RoF systems.

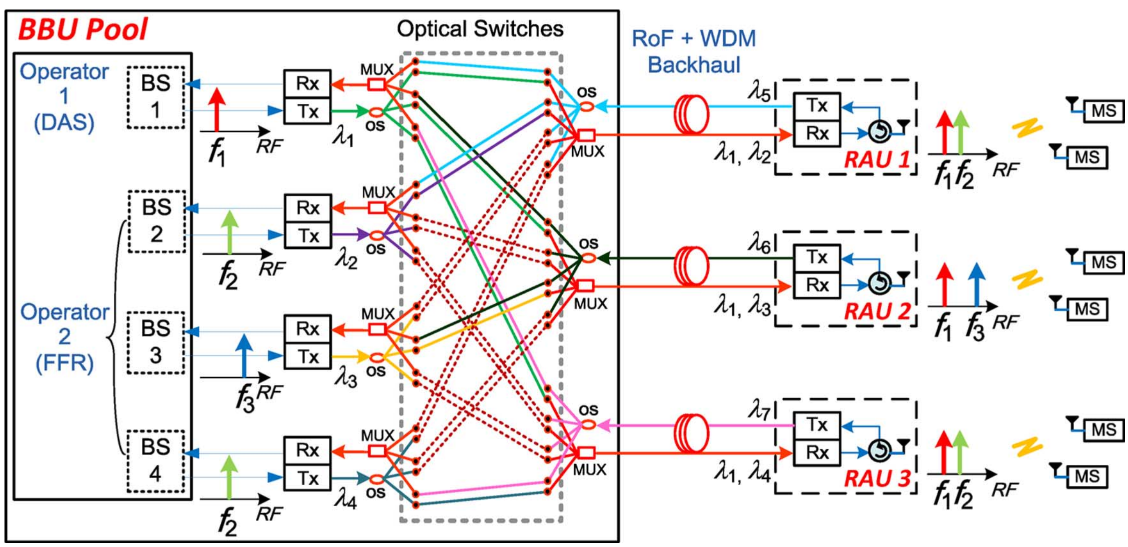

Fig. 3. Reconfigurable small-cell cloud-RoF access architecture for multi-service, multi-operator coexistence.

the modified RAUs. Since RF front-end is shifted to BBU, RF signals are generated at BBU and transmitted to RAUs through RoF backhaul. Therefore, multi-band/-service/-operator radios can coexist in the fiber-optic backhaul just like they coexist in the air. This infrastructure-sharing feature can help to further reduce the cost related to small-cell deployment, and also provide versatility to the proposed cloud-RoF system.

Notice that there are also some challenges of the cloud-RoF backhaul. First of all, the design of O/E and E/O interfaces at both BBU side and RAU side is different from the conventional digital-over-fiber system. High linearity is required for optical signal generation, detection, and fiber transmission. The nonlinearity-induced intra-/inter-band crosstalk in radio-over-fiber system is an important issue, which has been investigated in some recent work [9]–[12]. In addition, to support both legacy wireless services as well as future-proof mm-wave services, the bandwidth requirement of analog RoF interface becomes higher. In Section IV, we propose an interface design that can support microwave and mm-wave services simultaneously based on mm-wave-/microwave-photonics techniques.

III. Two-Operator Coexistence Test

To demonstrate multi-operator coexistence in the proposed cloud-RoF access system and to show the feasibility of incorporating WDM techniques providing flexible configurability for each service and operator independently, an in-building two-operator testbed is implemented [13]. An example of two-operator two-service coexistence is shown in Fig. 3.

At the BBU pool, where the centralized digital processing power is located, baseband data traffic from core networks is processed and up-converted to RF via BBUs. 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 BBUs. Each downstream RF signal is then intensity modulated onto a different CWDM optical wavelength, $\lambda_1, \lambda_2, \lambda_3$, respectively, using integrated off-the-shelf transceivers (Tx/Rx in Fig. 3) for bi-directional intensity modulation and direct detection (IM-DD). 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

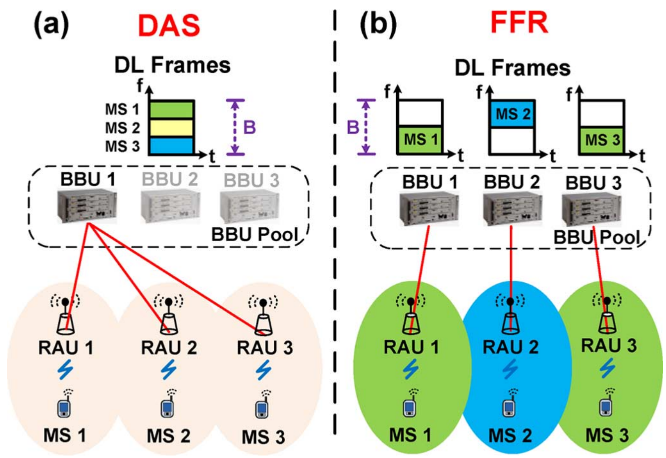

Fig. 4. Illustration of (a) distributed antenna system (DAS) and (b) fractional frequency reuse (FFR) scheme for 3-RAU configuration.

used to establish reconfigurable fiber-optic connections between the centralized BBUs and distributed RAUs.

Two system configurations are considered for two operators independently: distributed antenna system (DAS) and fractional frequency reuse (FFR). An example of 3-RAU configuration is illustrated in Fig. 4. In the DAS scenario, the same signal from a single BBU is distributed to all RAUs to extend coverage, especially for mobile users. However, all three mobile subscribers (MS) share the total bandwidth B, and each one occupies bandwidth of B/3. On the other hand, in the FFR scenario, different signals from 3 BBUs are transmitted to different RAUs to exploit frequency reuse. In this particular example (frequency reuse factor of 2), RAU1 and RAU3 will reuse the same spectrum in non-overlapping geographic regions without interference. Therefore, each MS occupies bandwidth of B/2. While DAS provides less hand-off complexity and better power efficiency to mobile users, FFR increases total system capacity especially for static users.

By properly configuring the optical on-off switches in Fig. 3, the signal from BBU1 on f_1 and λ_1 (from Operator 1) can be distributed to all three RAUs, as in a DAS scenario. To simultaneously emulate the FFR scheme with a spectral re-use factor of 2 for Operator 2, the optical switches can be configured to distribute the signal from BBU2 on f_2 and λ_2 to RAU1, while the signal from BBU3 on f_3 and λ_3 is distributed to RAU2. Notice that the signal from BBU4 reuses f_2, and is modulated on λ_4 and distributed to RAU3. After the optical switch, downstream signals are CWDM-multiplexed and delivered to several in-building RAUs via radio-over-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. This key receiver-side feature of the novel architecture can be analyzed by a dual-wavelength, dual-service example, as follows: the electrical field of the optical multiplexed signals can be represented as:

$$E(t) = [D + \gamma S_1(t)]\cos(\omega_{opt1}t) + [D + \gamma S_2(t)]\cos(\omega_{opt2}t) \quad (1)$$

where $S_1(t)$ and $S_2(t)$ denote the RF signals carried on wavelength λ_1 and λ_2 (angular frequencies ω_{opt1} and ω_{opt2}, respectively), D is the DC bias needed for intensity modulation, and γ represents the optical modulation index. After fiber transmission to the RAU, the signals are directly detected by a single PD. The generated electrical current is then given by:

$$\begin{aligned} I(t) &= |E(t)|^2 \\ &= ([D + \gamma S_1(t)]^2 + [D + \gamma S_2(t)]^2) \\ &\quad + (2[D + \gamma S_1(t)][D + \gamma S_2(t)]cos(\omega_{opt1} - \omega_{opt2})t) \end{aligned} \quad (2)$$

From (2), we observe that the transmitted RF signals can be recovered from the expansion of the first two terms, while the third term represents the crosstalk between the two RF signals, carried on a radio frequency that is determined by the CWDM channel spacing. By proper selection of CWDM wavelengths, this crosstalk term will fall beyond the electrical bandwidth of the receiver-side PD and can thus be ignored. Consequently, the proposed architecture can enable infrastructure sharing among multiple operators without interference. Notice that a single PD has a power constraint of detecting multiple wavelengths, thus the number of operators to share a single RAU is limited. However, for typical applications, the proposed scheme is capable of supporting 3–4 operators simultaneously without power saturation. After photodetection, the multiple RF signals on different carrier frequencies are transmitted wirelessly to MSs, where RF carrier frequency selection is executed, enabling multi-service support. Finally, as shown in Fig. 3, upstream transmission on the same RF spectral bands is enabled by CWDM wavelengths λ_5 to λ_7 using the switching mechanism mentioned above.

Based on this architecture, an in-building small-cell cloud-RoF testbed was set up as shown in Fig. 5(a). In this case, four WiMAX BBUs were centralized at the BBU pool, while three RAUs were distributed in the building as shown on the floor plan of Fig. 5(a). As shown in Fig. 5(b), one WiMAX BBU ($f_1 = 2.57$ GHz) is used in the DAS configuration to serve two mobile users MS1 and MS2 along a moving path denoted by checkpoints L1–L7. The remaining WiMAX BBUs are used in the FFR configuration ($f_2 = 2.61$ GHz, $f_3 = 2.59$ GHz; reuse f_2 for BBU2 and BBU4), serving two static users (SS1 and SS2). Both DAS and FFR configurations were running simultaneously. The output RF signals of four BSs are carried on four CWDM wavelengths ($\lambda_1, \lambda_2, \lambda_3, \lambda_4 = 1490$ nm, 1510 nm, 1530 nm, 1550 nm), respectively, with 4 dBm per-λ optical launch power. The measured downlink throughputs for the DAS and FFR scenarios are shown in Fig. 5(c) and (d), respectively. For Operator 1, since the DAS configuration is used, the mobile users experience no degradation in the steady 6 Mb/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 factor of 2 was exploited for static users, the system throughput is doubled to 12 Mb/s for each user, which demonstrates the capacity benefits of the FFR scheme. Consequently, the new architecture enables both operators to simultaneously run different small-cell backhaul scenarios by sharing the in-building optical infrastructure, without interference.

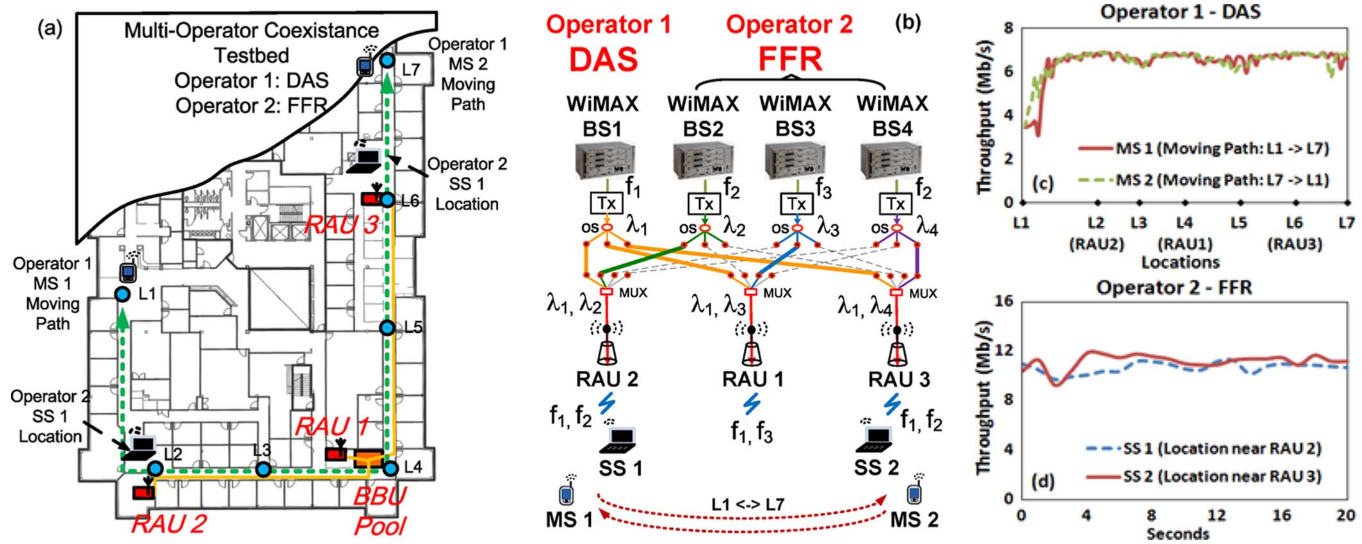

Fig. 5. (a) In-building multi-operator co-existence testbed and (b) detailed network configuration (with only downlink shown here); (c) measured downlink throughput of mobile users of Operator 1 at different locations and (d) measured downlink throughput over time for static users of Operator 2.

IV. Microwave/MM-Wave Coexistence Test

In addition to the coexistence of multiple operators, the proposed cloud-RoF system is capable of supporting different generations of wireless services carried on different radio frequencies in a shared infrastructure.

Recently, the exploration of higher RF bands, especially at the millimeter-wave (mm-wave) band (30 GHz–300 GHz), has attracted huge attention from both industries and academia. Within the mm-wave band, 60-GHz band with 7-GHz license-free bandwidth is a hot topic. Many organizations are working on the standardization of 60-GHz band for high-speed communication applications, including wireless local area network (WLAN) [14], [15], and wireless personal area networks (WPAN) [16]. However, the study of utilizing mm-wave band for mobile access network is still at preliminary stage. As mentioned, the combination of mm-wave radio and small-cell cloud-RoF architecture provides a promising solution for next-generation in-door very-high-speed wireless access networks [17]–[19]. The main challenge is the RoF interface design to support mm-wave services as well as backward compatibility to legacy wireless services. Therefore, in the following work, we propose an RoF interface design and demonstrate the coexistence of legacy wireless services (WiFi/WiMAX) with the future-proof mm-wave services in the proposed multi-service cloud-RoF access system.

A proof-of-concept experiment was conducted as shown in Fig. 6. At the BBU pool, a continuous-wave (CW) tunable DFB laser at wavelength $\lambda_1$of 1553.50 nm is fed into a single-drive Mach-Zenhder modulator (MZM) for data modulation. Data 1 and Data 2 are 400 Mb/s 16 QAM-OFDM signals generated by an arbitrary waveform generator (AWG), and they are mixed with 2.5-GHz and 5.6-GHz sinusoidal RF clocks to emulate the WiFi and WiMAX services, respectively. The output of the mixers are combined and amplified to drive the MZM directly to generate RoF signals. For the mm-wave service, mm-wave generation through the optical heterodyne approach is adopted to avoid the requirement of high-speed optical modulator for direct mm-wave modulation. Data 3 of 1-Gb/s on-off keying (OOK) signal is used to emulate the high-speed data service carried on mm-wave radio. The OOK data is first modulated on an optical wavelength λ_2 (1553.75 nm) through a direct modulated laser (DML), and the mm-wave RF carrier is generated by optical beating at a photodetector at RAU. The conventional WiFi/WiMAX RoF services are combined with the mm-wave data 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 1554.23 nm is coupled with the downlink carriers to generate optical mm-wave signals. The optical spectra of microwave services, mm-wave service, and optical LO are shown in the inset of Fig. 6. Notice that it is possible to shift the optical LO to the BBU pool. However, since a lightwave source is always needed at RAU for uplink optical transmission, we reuse the optical LO source for both downlink optical mm-wave generation and uplink optical transmission in the proposed system setup. The uplink transmission is not demonstrated in this experiment, but through downcoversion of received uplink RF signal to baseband or an intermediate frequency, the uplink data can be modulated on the reused optical LO through an Mach-Zehnder modulator, as illustrated in the RAU of Fig. 6. For downlink transmission, after the RoF signals being detected by a single high-speed PD, both WiFi and WiMAX RF signals, as well as the mm-wave RF signal are simultaneously recovered and transmitted to corresponding mobile users through separate antennas. For the WiFi signal, one pair of WiFi rubber ducky antennas was used for wireless transmission, and the transmission distance is limited to 10 feet due to the dimension of our experimental testbed. Due to the lack of 5.8-GHz antenna, the wireless transmission of the 5.8-GHz signals was not demonstrated, and the WiMAX RF signal is directly connected to the mobile user through an electrical cable. For the 60-GHz mm-wave signal, a pair of rectangular horn antennas was used with antenna gain of 15 dBi. Up to 10-ft wireless transmission was also demonstrated for the mm-wave service. At the mobile user

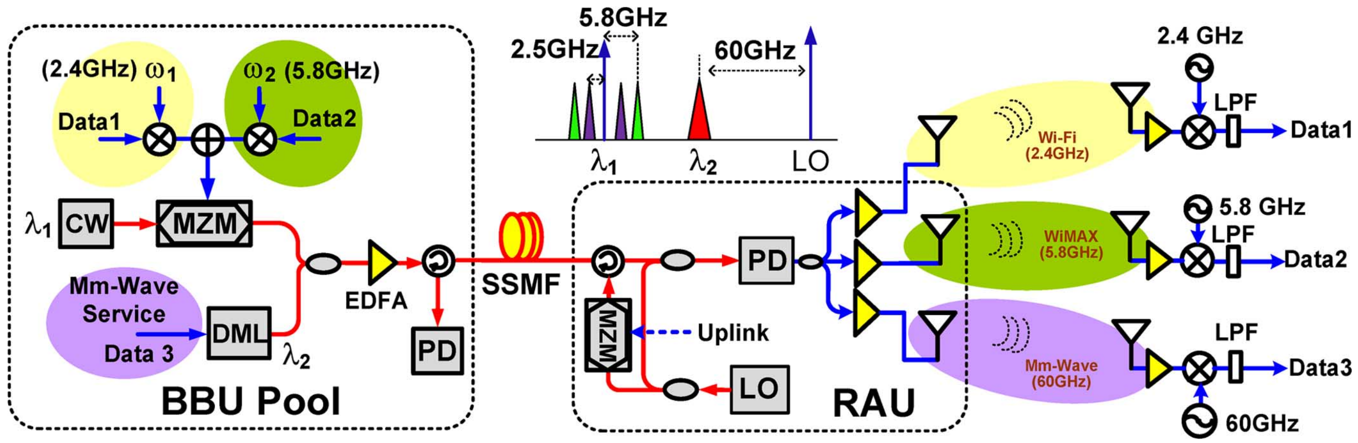

Fig. 6. Experimental setup of conventional wireless services (WiFi/WiMAX) and mm-wave service coexistence in the cloud-RoF system.

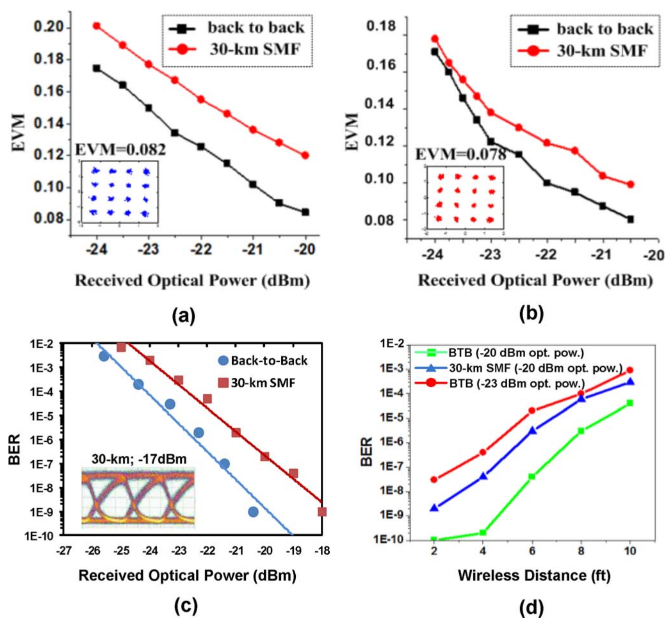

Fig. 7. Measured EVM value vs. received optical power for 16 QAM-OFDM WiFi signals carried on 2.4 GHz (a) and 16 QAM-OFDM WiMAX signals carried on 5.8 GHz (b). Measured BER vs. received optical power (c) and vs. wireless transmission distance (d) for OOK data carried on 60 GHz mm-wave.

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 signals are shown in Fig. 7. The EVM vs. received optical power curves of 16QAM-OFDM data carried on 2.4 GHz and 5.8 GHz are shown in Fig. 7(a) and (b), respectively. After 30-km SSMF transmission, 1.5-dB power penalty was observed compared to the back-to-back fiber transmission case for both WiFi and WiMAX signals. Fig. 7(c) shows the measured BER vs. received optical power of OOK data carried on 60 GHz mm-wave, and the performance over different wireless transmission distances for both BTB and after 30-km fiber transmission cases are shown in Fig. 7(d). Similar power penalties induced by 30-km fiber transmission was observed, which is mainly because the chromatic dispersion and the decreased optical signal-to-noise ratio (OSNR) at the photodetection. The strong penalties related to mm-wave wireless transmsision is due to the high propagation loss at 60 GHz band, which is consistent with the Friis transmission equation at short transmission distance [13]. Notice that both conventional WiFi/WiMAX services and the mm-wave services can achieve good performance after optical fiber and wireless transmission once the received optical power is increased. In addition, negligible interference was observed among different services during the RoF transmission and photodetection. These results demonstrated the feasibility of delivering both conventional wireless services and future-proof mm-wave signals in a shared cloud-RoF access systems without interference.

V. Conclusion

In this work, we have proposed a novel multi-service small-cell cloud-radio-over-fiber (cloud-RoF) access network architecture. Compared with the existing macrocell system and emerging cloud-RAN system, the proposed cloud-RoF scheme further simplifies the design of RAU and enables infrastructure sharing among multiple services and multiple operators. By combining with WDM techniques, we demonstrated an in-building small-cell cloud-RoF testbed with flexible and independent backhaul configurability for two-operator coexistence. In addition, a proof-of-concept experiment was conducted to demonstrate the feasibility of delivering high-speed mm-wave services together with legacy wireless services in a shared cloud-RoF backhaul. We believe the proposed cloud-RoF architecture provides a versatile, cost-effective, and power-efficient solution for the future-proof small-cell wireless access systems.

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