Multi-service small-cell cloud wired/wireless access network based on tunable optical frequency comb*

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(Received 10 October 2015)

In this paper, we demonstrate a novel multi-service wired/wireless integrated access architecture of cloud radio access network (C-RAN) based on radio-over-fiber passive optical network (RoF-PON) system, which utilizes scalable multiple-frequency millimeter-wave (MF-MMW) generation based on tunable optical frequency comb (TOFC). In the baseband unit (BBU) pool, the generated optical comb lines are modulated into wired, RoF and WiFi/WiMAX signals, respectively. The multi-frequency RoF signals are generated by beating the optical comb line pairs in the small cell. The WiFi/WiMAX signals are demodulated after passing through the band pass filter (BPF) and band stop filter (BSF), respectively, whereas the wired signal can be received directly. The feasibility and scalability of the proposed multi-service wired/wireless integrated C-RAN are confirmed by the simulations.

Document code: A **Article ID:** 1673-1905(2015)06-0444-5

DOI 10.1007/s11801-015-5194-8

Operators[1] and equipment vendors[2,3] have proposed and advocated a cloud radio access network (C-RAN) of small cells to meet the network demand. Recently, lots of researchers focus on this field[4,5]. C-RAN architecture is composed of the baseband unit (BBU) and the remote radio heads (RRHs). Gee-Kung Chang team[6,7] proposed a C-RAN structure based on RoF technology. This structure utilized analog radio frequency (RF) signal transmission in the optical backhaul links, so that the design of RRHs can be further simplified. In addition, by combining RoF with optical wavelength division multiplexing (WDM) techniques, multiple bands, multiple services and multiple operators can coexist in a shared optical infrastructure without interference. Ismael Gomez- Miguelez[8] demonstrated a cloud-based massive distributed multiple-input multiple-output radio access network (MD-MIMO RAN) for the exploitation of licensed shared access (LSA) spectrum sharing concept. Based on the different functionalities of BBU and RRHs, C-RAN can be roughly categorized into two different types of full centralization[9,10] and partial centralization. C-RAN has been regarded as a cost-effective and power-efficient candidate for multi-service optical transport networks.

The higher bandwidth requirement for data transmission has made optical orthogonal frequency division multiplexing (OFDM) as the most popular modulation type[11-14]. Many researchers have carried out the optical OFDM enabled passive optical networks (PONs), such as direct-detection optical OFDM-PON[15,16], coherent optical OFDM-PON[17], polarization division multiplexing (PMD) based OFDM-PON[18] and WDM based OFDM-PON[19]. Because of these advantages of OFDM, our proposed C-RAN uses OFDM as the modulation technique.

In this paper, we propose a multi-service small-cell with wireless/wired and WiFi/WiMAX access architecture supported by RoF-PON. In this scheme, the tunable optical frequency comb (TOFC) is used to build the scalable multiple-frequency millimeter-wave (MF-MMW) generator, which is a cost-effective method. For realizing multi-service in small-cell, the generated optical comb lines are modulated into wired, RoF and WiFi/WiMAX signals, respectively. Because of the reduction of the cell size, the limited spectral resources can be reused more frequently, which enhances the total system capacity. On the other hand, different wireless frequency spectra and optical carriers are available, which can easily support the multi-gigabit wireless and wired transmission without time-consuming and complicated modulation and coding schemes.

Fig.1 shows the architecture of C-RAN with multi-service small cells. We can see that the data from core networks enter BBU, and the BBU is composed of the high-performance programmable processors and the real-time virtualization technology, where centralized

* This work has been supported by the National Natural Science Foundation of China (No.61301156).

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data processing and exchange take place. The centralized process has the advantages of easy upgrading, network capacity expansion, supporting multi-standard operation and maximum resource sharing. Moreover, it's more convenient to support the multi-cell collaborative signal processing. Since the powerful centralized data processing and data exchange processes are majorly performed in BBU, the complexity of the RRH is reduced only to photovoltaic conversion.

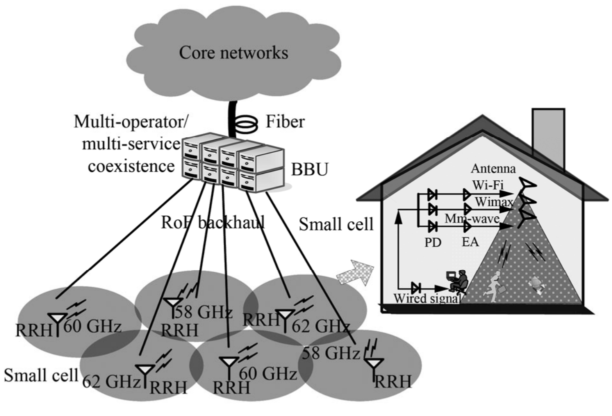


Fig.1 Structure of C-RAN system

The schematic diagram of the multi-service wired/wireless access network is shown in Fig.2. The proposed multi-service small-cell provides RF, Wi-Fi, WiMAX and baseband services, which also has additional service capacity and data rates beyond macro-cellular capability. The performance of system can be easily promoted by installing new RRHs and upgrading the BBU pool's hardware to accommodate the increasing load of the network and obtain the strong processing capacity. Since the radius of small cell is less than 100 m, the small cells are arranged in such a way that the adjacent small cells have MMWs with different frequencies, which reduces the crosstalk between adjacent cells and largely improves the flexibility of spectrum utilization.

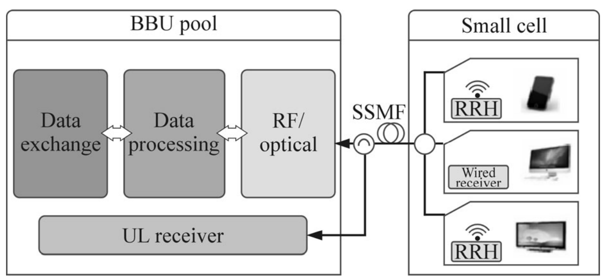


Fig.2 Schematic diagram of multi-service wired/wireless access network

The schematic diagram of multi-service small-cell architecture supported by TOFC is shown as Fig.3. It can simultaneously provide bidirectional OFDM-based wired and wireless services, such as WiMAX and long term evolution (LTE), for both downlink and uplink transmissions. Compared with the on-off keying (OOK) modulation, OFDM has the following advantage: using 16 quadrature amplitude modulation (QAM) for a transmission data rate of 10 Gbit/s cuts down the bandwidth occupation to only 3 GHz, while OOK mode needs 10 GHz bandwidth. One of the main difficulties to achieve high-capacity long-haul optical fiber transmission is the dispersion effect of fiber. As the optical fiber chromatic dispersion tolerance is inversely proportional to the square of the bandwidth, the optical OFDM bandwidth is divided into a plurality of mutually orthogonal sub-bands, so that the chromatic dispersion tolerance increases. It is noteworthy that the coherent optical orthogonal frequency division multiplexing (CO-OFDM) signal processing function is placed on the transmitter, which can help to achieve adaptive advantage of the software-defined optical transmission (SDOT) using the digital signal processing (DSP) technology for a variety of modulation formats. One of the major advantages of CO-OFDM is the ability to manipulate the frequency domain at the transmitter.

In addition to the coexistence of the multiple operators, the proposed cloud-RAN system is capable of supporting different generations of wireless services carried on different radio frequencies in a shared infrastructure. According to ECMA-387, the unlicensed 8 GHz bandwidth is actually divided into 4 sub-bands, which are centered around 58 GHz, 60 GHz, 62 GHz and 64 GHz respectively with frequency separation of about 2 GHz. Lots of schemes have been proposed to generate multiple-frequency MMWs for 60 GHz RoF system for the application of multi-service in multi-occasion. However, the study of utilizing MMW band for mobile access network is still at preliminary stage. As mentioned, the combination of MMW radio and small-cell cloud-RoF architecture provides a promising solution for next-generation in-door very-high-speed wireless access networks[14,15]. The main challenge to implement it is the RoF interface design to support MMW 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 MMW services in the proposed multi-service cloud-RoF access system.

The structure of TOFC generator is shown in Fig.4. The TOFC generator is composed of one laser diode (LD), an RF source, a phase modulator (PM), two intensity modulators (IMs) and two power control modules. Here, the LD is a distributed-feedback (DFB) laser which is used as an optical source. A sinusoidal RF source is applied to drive the cascaded PM and IMs. A tunable electrical amplifier and electric attenuator are employed to control the input RF signal voltage of the PM, so as to dynamically revise the scalability of the advanced TOFC generator. A phase shifter (PS) is adopted to adjust the phase of the electrical signal injected to the two IMs. The optical comb lines with the frequency spacing of 2 GHz generated by the TOFC generator are used as the source for the proposed multi-service C-RAN system as shown in Fig.3. An arrayed waveguide grating (AWG), which is denoted as AWG1, is employed to separate the optical combs. 7 optical comb lines out from the generated comb lines are selected and used as carriers to carry the OFDM signals. Among the 7 optical comb lines, three of them (λ_1, λ_2 and λ_3) are used as the RF carrier, λ_c is used as wired signal carrier, and λ_m is used as WiFi & WiMAX signal carrier. One of the rest optical comb lines λ_{j-1} is used as difference-frequency carrier in small cell, and the other λ_j is used for uplink signal. The 7 selected comb lines are combined by AWG2, and then sent to different small cells through standard single mode fiber (SSMF). In the small cell, an AWG is utilized to filter out the carriers on different comb lines. The basic principle behind this is to select an RF signal carrier, the wired signal carrier, the WiFi & WiMAX signal carrier and the difference-frequency carrier. And then the difference-frequency carriers are combined with RF modulated signal to get RF signal using a linear photodiode (PD) to perform the optical heterodyning. In our proposed architecture, we can get 3 RF signals with different frequencies of 58 GHz, 60 GHz and 62 GHz, which are all near 60 GHz band with 7 GHz license-free bandwidth, through the RF signal carrier beating with the difference-frequency carrier. The RF signals are distributed across the small cell according to the principle of reducing the crosstalk between border small cells. The wired signal is directly obtained from the optical signal.

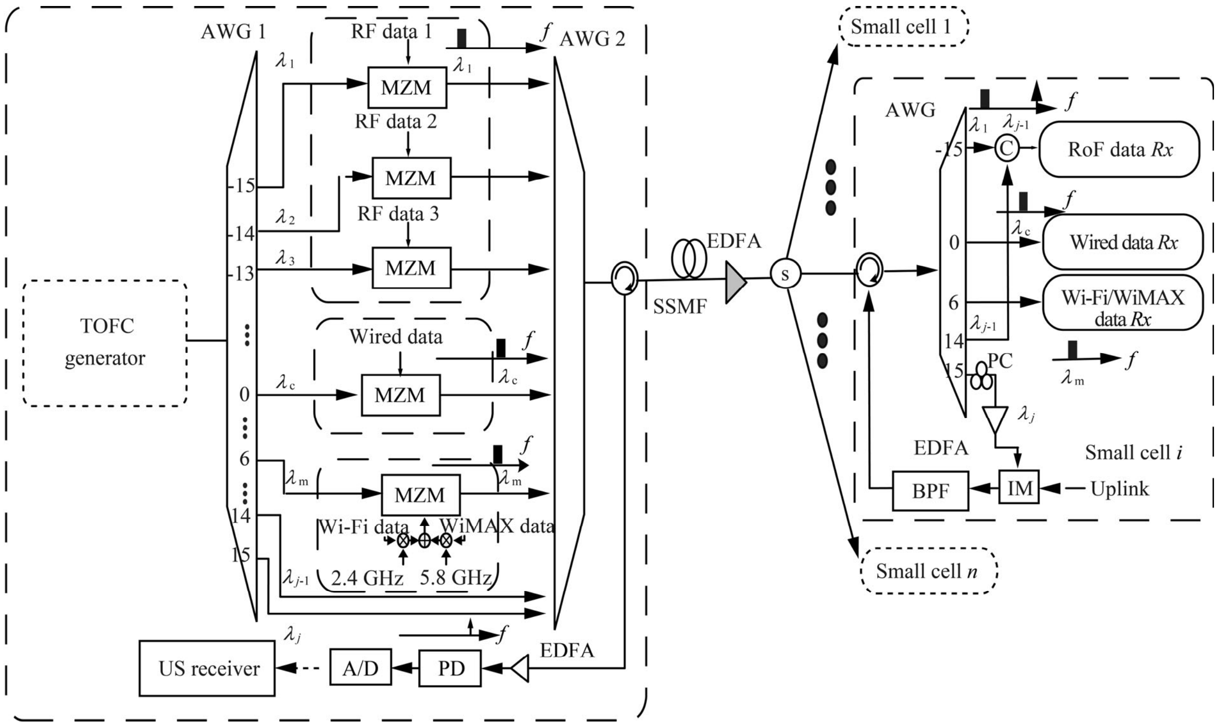


Fig.3 Schematic diagram of multi-service C-RAN system based on TOFC

Corresponding simulations are conducted. The continuous-wave (CW) tunable DFB laser at 193.1 THz in TOFC generator at the BBU pool is used to generate the optical comb signal. Through the AWG, the generated optical comb lines are separated and then fed into a single-drive Mach-Zehnder modulator (MZM) for data modulation. In simulations, the OFDM modulation technology based on Hermite transform is used for generating RF baseband signal at 3.3 Gbit/s, WiFi and WiMAX baseband signals. There are 32 subcarriers in each OFDM signal, but only 15 subcarriers are modulated 16-QAM data. The cyclic prefix of OFDM is 1/8 of the adopted length of OFDM. For further optimizing the transmission performance, we load the power to every subcarrier of OFDM signal according to the channel characteristics of subcarrier in 25 km-long SSMF. The clipping level is 13 dB to limit the peak average power ratio (*PAPR*) of OFDM signal. 8 bit digital to analog converter (DAC) and analog to digital converter (ADC) are used for digital/analog (D/A) conversion and analog/digital (A/D) conversion, respectively. Before intensity modulation, OFDM signals of WiFi and WiMAX should be up-converted to 2.4 GHz and 5.8 GHz, respectively. After 25 km-long SSMF transmission, the WiFi/WiMAX and RoF signals are delivered to RRHs.

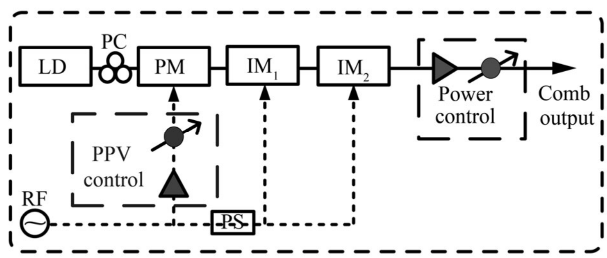


Fig.4 Structure of the TOFC generator

In the small cell, the frequency λ_{j-1} is used as difference-frequency for downlink optical MMW generation through PD. λ_j is also used for optical uplink transmission at RRH. The uplink transmission is not demonstrated in this simulation, but through (or after) down conversion of received uplink RF signal to baseband or an intermediate frequency, the uplink data can be modulated on λ_j through a Mach-Zehnder modulator (MZM) and a band pass filter (BPF), as illustrated in Fig.3. For downlink transmission, λ_1 is selected with λ_{j-1}, then those two optical signals are sent to PD, and RF signal is generated as shown in Fig.5. WiFi and WiMAX optical signals are separated to two branches, one is sent to BPF and PIN to get WiFi wireless signal, and the other is sent to band stop filter (BSF) and PIN to get WiMAX wireless signal. The spectra of WiFi and WiMAX signals are shown in Fig.6. After photoelectric conversion, the wired signal is directly demodulated by OFDM receiver.

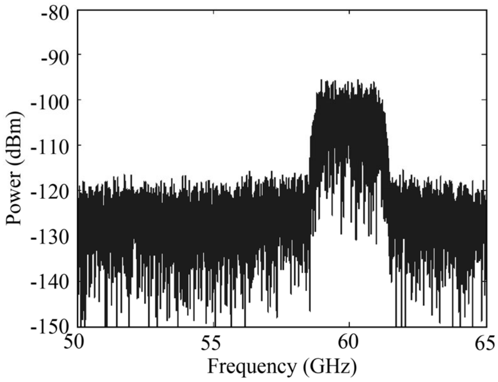
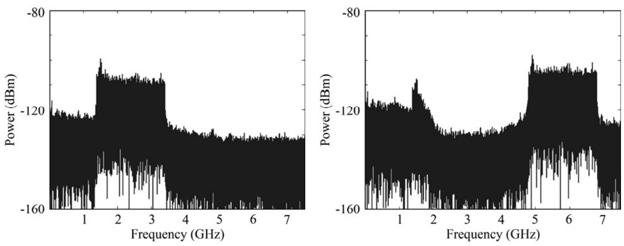


Fig.5 Frequency spectrum of the 60 GHz RF signal



(a) (b)

Fig.6 Frequency spectra of the 2.4 GHz (a) WiFi and (b) WiMAX signals

Fig.7 shows the bit error rate (*BER*) performance of a 1.25 Gbit/s OFDM wired access network for both back-to-back (B2B) and 25 km SSMF transmission cases. It is indicated that the sensitivity degradation at *BER* of 10^{-3} is 0.22 dB after transmission over 25 km SSMF. The insets of Fig.7 show the constellation diagrams for B2B and 25 km SSMF transmission cases, which indicate good performance. Fig.8 shows the measured *BER* versus the received optical power of OFDM data carried on 58 GHz MMW for B2B and 25 km SSMF transmission cases, and the sensitivity degradation induced by 25 km fiber transmission is 0.23 dB. The curves of *BER* versus the received optical power of 16QAM-OFDM data carried on 2.4 GHz WiFi signal and 5.8 GHz WiMAX signal are shown in Figs.9 and 10, respectively. When the

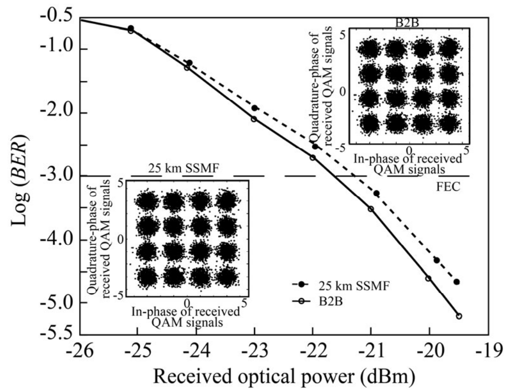


Fig.7 *BER* performance for wired access network after B2B and 25 km SSMF transmissions with corresponding constellation diagrams

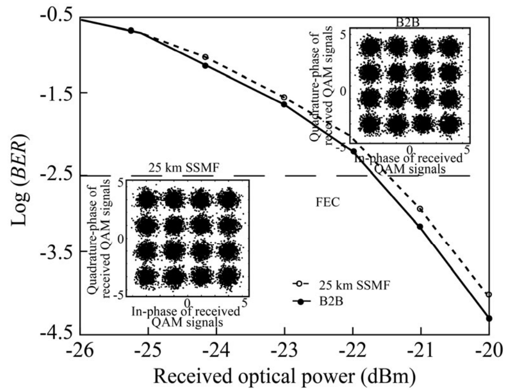


Fig.8 *BER* performance for RF access network after B2B and 25 km SSMF transmissions with corresponding constellation diagrams

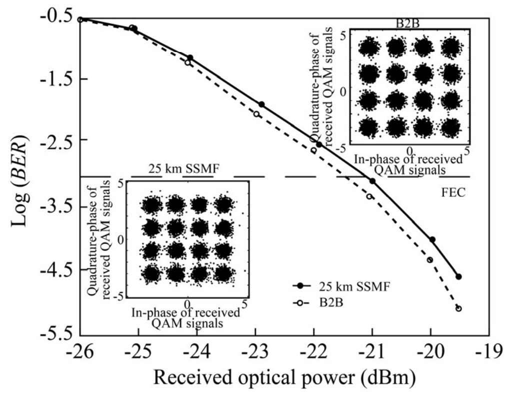


Fig.9 *BER* performance for WiFi access network after B2B and 25 km SSMF transmissions with corresponding constellation diagrams

BER is 10^{-3}, the sensitivity degradations are 0.24 dB and 0.28 dB after transmission over 25 km SSMF for WiFi and WiMAX signals, respectively. Comparing Figs.7−10, we can know that the degradations of system performance are all less than 0.4 dB affected by fiber chromatic dispersion in wired and wireless transmission, and it is caused by the small bit rate of OFDM signal transmission in our simulation. In practical application, we can adopt high speed ADC and DAC to generate high speed OFDM baseband signal to satisfy the requirement of high speed communication.

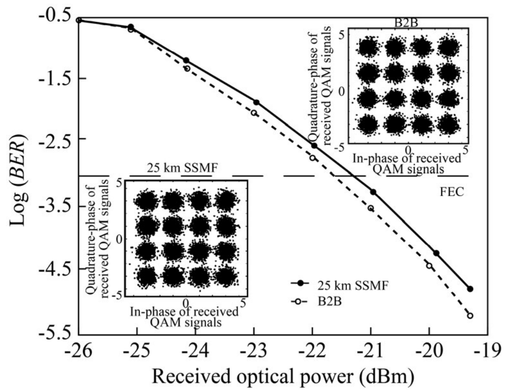


Fig.10 *BER* performance for WiMAX access network after B2B and 25 km SSMF transmissions with corresponding constellation diagrams

In this work, we propose a novel multi-service C-RAN architecture. Compared with the existing macro-cell system and emerging cloud-RAN system, the proposed scheme further simplifies the design of RRH and enables infrastructure sharing among multiple services and multiple operators. Using the TOFC technique, we demonstrate an in-building small-cell C-RAN testbed with flexible and independent backhaul configurability for two-operator coexistence. In addition, simulations are conducted to demonstrate the feasibility of delivering high-speed MMW services together with legacy wireless services in a shared C-RAN backhaul. We believe that the proposed C-RAN architecture provides a versatile, cost-effective and power-efficient solution for the future small-cell wireless access systems.

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