Radio-Over-Fiber Access Architecture for Integrated Broadband Wireless Services

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***Abstract*—This paper introduces two radio-over-fiber (RoF) architectures for the future broadband optical-wireless access network—all-band RoF and band-mapped 60-GHz RoF that can be integrated in ultra-dense wavelength division multiplexing passive optical network (UDWDM-PON). Legacy wireless services and multi-gigabit millimeter-wave (mm-wave) applications are integrated and delivered simultaneously under one shared infrastructure. With centralized system control and signal processing, the proposed systems provide cost-effective and protocol-transparent solutions for the next-generation multi-service bundle in heterogeneous networks (HetNets). In the all-band RoF network where wireless services are kept at their original carrier frequencies, Wi-Fi, WiMAX, and 60-GHz high-speed mm-wave services are transmitted based on subcarrier multiplexing (SCM) and dual-wavelength heterodyne beating techniques in avoidance of optical filters and large-bandwidth optoelectronic components. In the indoor environment, the band-mapped mm-wave RoF design is illustrated with real-time analog television signal, Wi-Fi, and high-speed digital baseband data—all of which are transmitted over unified optical and air links. By mapping various wireless signals into 60-GHz sub-bands, the novel architecture achieves higher spectral efficiency and lower power consumption.**

***Index Terms*—All-band, band mapping, broadband wireless access, radio-over-fiber (RoF), WDM-PON.**

I. Introduction

The proliferation of smart mobile devices is essentially changing the Internet traffic patterns and both wireless and wired network infrastructure [1], [2]. Propelled by emerging applications such as interactive video service, the mobile data traffic is projected to increase 13-fold between 2012 and 2017 [3]. Simultaneously, link speed is expected to grow towards multi-gigabits/second, especially for high-definition television (HDTV) and online gaming. Currently, broadband wireless access (BWA) standards aiming at lower radio frequencies (RFs), such as Wi-Fi (IEEE 802.11), Long Term Evolution (LTE) and WiMAX (IEEE 802.16), are the dominant technologies for wireless communications because of their universal presence and mobility [4]. However, the lower RF bands are becoming over-congested, advanced modulation formats and multiplexing methods have been investigated extensively. For example, the targeted downlink (DL) peak data rate in the LTE-advanced exceeds 1 Gb/s through several techniques, including 64-quadrature amplitude modulation (QAM) and eight-layer multiple-input multiple-output (MIMO) [5]. Meanwhile, it is anticipated that a large number of small cells will be needed in the future, providing economical and practical wireless broadband channels [6]. In addition to the aforementioned techniques to accommodate sharp data rate increase, deployment of the millimeter-wave (millimeter-wave) spectrum range (30–300 GHz), especially the huge 7-GHz license-free spectrum located in 60 GHz has been explored. It is also suitable for small cells due to the high attenuation from free-space path loss (88 dB for 10 m) and atmospheric absorption (about 15 dB/km), and this minimizes co-channel interference in small cell systems [7]. Several emerging 60-GHz standards, including Wireless HD [8], IEEE 802.15.3 c [9], and ECMA 387 [10], are primarily targeting very high data rates over 2 Gb/s for applications such as video streamers and HDTV. IEEE 802.11 as "WiGig" is also a published standard to achieve a theoretical maximum throughput of up to 7 Gb/s as a new tri-band Wi-Fi solution [11].

It is essential that the access network should support a wide range of data rates, formats, protocols, and requirements. The consumers will benefit from a universal user interface that provides wireless access anywhere at anytime with minimal delay and data processing. Radio-over-fiber (RoF) is an attractive technology for such multi-service broadband access networks [12]–[21]. By allocating and controlling multiple wireless services in the central office (CO), RoF systems deliver ready-to-use analog signals to remote access units (RAUs) or base stations (BSs) with no differentiation in protocols or interfaces, and thus greatly reduce the cell site complexity and cost. In particular, the millimeter-wave small cell system can benefit the most from RoF architecture due to its features in low attenuation and cost. Besides analog RoF systems, digitized RoF systems, in the light of recent open BS specifications such as the Common Public Radio Interface (CPRI) [23] and the Open Base Station Architecture Initiative (OBSAI) [24], also attract research interests for their interoperability among different vendors and flexible product differentiation. However, the digital RoF links are at least an order of magnitude more expensive than analog RoF links, as a result of the high line rates required for wideband radio channels [25]. Moreover, the digitization of millimeter-wave signals is impractical. In this paper, we emphasize on the uniformity of the RoF platform that accommodates both legacy wireless services

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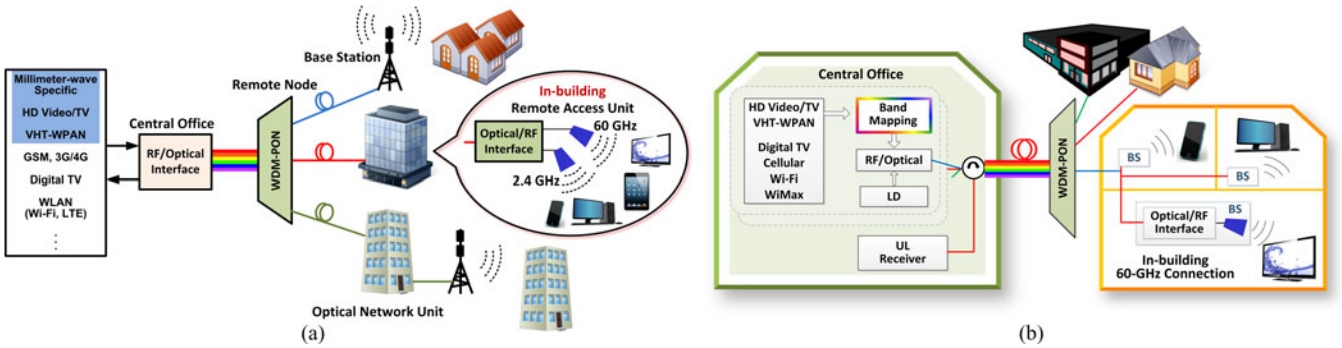


Fig. 1. System architectures of (a) all-band RoF and (b) band-mapped 60-GHz RoF for the unified multi-service optical-wireless access networks.

and advanced millimeter-wave services, and propose two practical and efficient schemes, analog all-band RoF and band-mapped 60-GHz RoF, to cover distinct application scenarios. In the all-band RoF access architecture, lower RF signals and 60-GHz signal are transmitted at their original carrier frequencies, guaranteeing backward compatibility and wide coverage. On the other hand, the band-mapped millimeter-wave RoF scheme, fully utilizing the wide 7-GHz bandwidth at 60 GHz, delivers multiple converged high-speed services only through 60-GHz wireless link, which is especially suited to in-building broadband wireless access.

The remainder of the paper is organized as follows. In Section II, detailed system architectures for the all-band and band-mapped RoF access networks are discussed from the topological to the component level perspective, with a focus on the technical challenges. The novel all-band RoF system featuring relaxed component requirement is introduced in Section III, while a real-time multi-service demonstration in the proposed band-mapped 60-GHz RoF system is presented in Section IV. Finally, Section V concludes the paper.

II. ALL-BAND AND BAND-MAPPED MILLIMETER-WAVE RoF SYSTEM OVERVIEW

Fig. 1 illustrates the two RoF architectures for the next-generation multi-service broadband wireless access networks. These two schemes deliver both multi-gigabit millimeter-wave wireless services and legacy BWA services in their own strength and applicable region, yet conform to one key design rule—unified optical-wireless interface is shared.

All-band RoF refers to a system that maintains each service (except for millimeter-wave services) at its original carrier frequency before electrical-to-optical (E/O) conversion in CO and after optical-to-electrical (O/E) conversion in RAUs or BSs. It is a promising architecture for fiber-connected massively distributed antennas in heterogeneous networks (HetNets) [14]. However, limited by the modulation bandwidth of the laser and modulator (40 GHz commercially available), millimeter-wave signals like 60 GHz and beyond requires special optical millimeter-wave upconversion techniques for downstream, including nonlinear effects, external modulation, and remote heterodyning [15]–[21]. As a result, the key technical innovation of the proposed converged RoF system lies in the design of simple and efficient CO and RAU to simultaneously integrate lower RF wireless services and millimeter-wave channels. Wavelength reuse methods have been proposed for the cost-effective millimeter-wave RoF upstream transmission [17]–[20]. However, in most cases, they require complicated optical filtering, large spectrum occupation, and fixed data formats. Laser source in RAU is preferred in some situations for better flexibility and integration [21]. The all-band RoF access network architecture is shown in Fig. 1(a). As a straightforward way to carry multiple wireless services simultaneously, the all-band RoF system directly adds electrical signals together (millimeter-wave signals may differ) and modulates them onto the lightwave through the RF-to-optical interface in the CO. Different services, naturally separated by frequencies as shown in Fig. 2(a), are grouped and multiplexed in the wavelength division multiplexing passive optical network (WDM-PON). Signals at a single wavelength are demultiplexed and retrieved by a simple optical-to-RF interface at their own carrier frequencies, and finally transmitted by designated antennas to targeted mobile devices. The same infrastructure is also shared by mobile backhaul with a much simplified base station design. Meanwhile, W-band (75–110 GHz) and beyond high-speed wireless communications that replace fiber-optic links in difficult-to-reach terrains or fiber cut can greatly benefit from the RoF architecture as well.

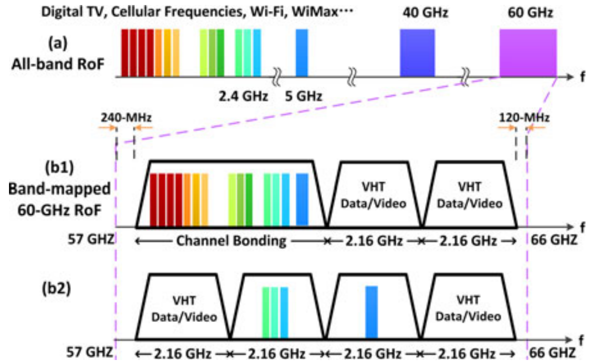


Fig. 2. Spectrum allocations in (a) all-band RoF and (b) band-mapped 60-GHz RoF.

All-band RoF is able to cover wireless services from few GHz to more than 100 GHz, and transmission coverage from few meters to kilometers. However, in most cases, wireless access is done in indoor environment, such as in the office, home, convention center, and stadium. To further exploit this application

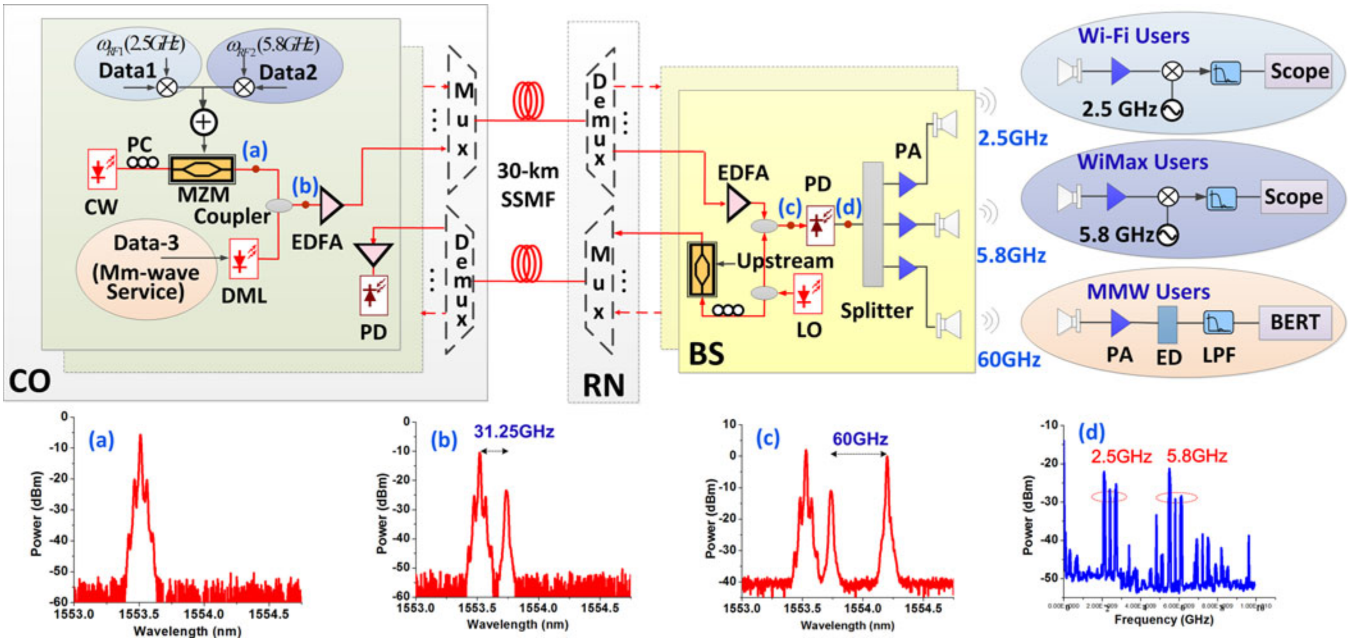


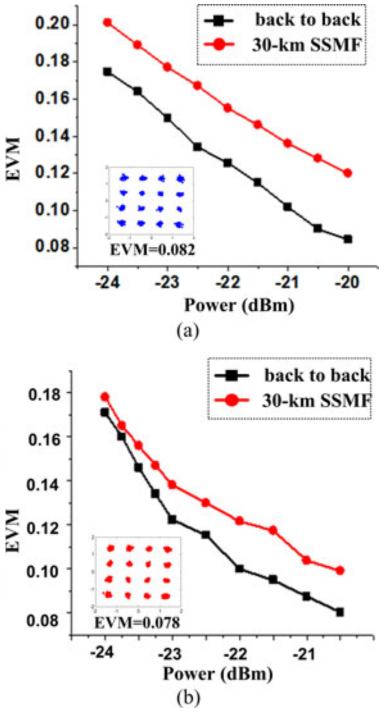
Fig. 3. Experimental setup of the all-band DWDM-RoF-PON system delivering legacy Wi-Fi, WiMAX, and advanced 60-GHz services. (a)–(c) Optical spectra measured at locations from a to c. (d) Electrical spectrum for the Wi-Fi and WiMax signals after PD.

scenario, Fig. 1(b) illustrates a fully-converged 60-GHz RoF network based on the band-mapping concept. Existing wireless services and multi-gigabit millimeter-wave services can be first mapped compactly to four sub-bands (e.g., from 0.24 GHz to 8.88 GHz), and optically upconverted to 60-GHz sub-bands (e.g., from 57.24 to 65.88 GHz) according to ECMA 387 [26], as shown in Fig. 2(b). Therefore, various services are delivered with the same 60-GHz RoF components, introducing little or no system-level complexity. Distinct from all-band RoF system, only one pair of electrical amplifiers and antennas at the 60-GHz band are needed, which greatly reduces the power consumption and component complexity, yet keeps the backward compatibility. By integrating wireless services from different frequency bands into the wide unlicensed 60-GHz band, better usage of available spectrum is thus achieved. Furthermore, the spectrum allocation can be flexible upon request from mobile users and adjustment from CO as shown in Fig. 2(b1) and (b2). For example, the 5.8-GHz WiMAX signal can be mapped to the first two sub-bands (see Fig. 2(b1)) in a highly integrated allocation, or directly fit in the third sub-band without further adjustment (see Fig. 2(b2)). In addition to frequency distribution, power allocation among the signals also requires careful investigation. For example, an orthogonal frequency division multiplexing (OFDM) signal has smaller dynamic range due to high peak-to-average power ratio (PAPR) and subcarrier intermodulation, so does analog signal which is sensitive to nonlinearities and noise. Therefore, an optimal electrical power distribution [22] can be found in both all-band and band-mapped RoF system by setting desired performance for each service. Homodyne downconversion is realized in most off-the-shelf wireless receivers, with a tunable electrical local oscillator for different services in our case. For certain mapping schemes (e.g., the case shown in Fig. 2(b2)), it is preferable to firstly downconvert the millimeter-wave signal to the original four sub-bands in the heterodyne downconversion. Envelope detector (ED) and self-homodyne receiver are also alternatives for amplitude modulated millimeter-wave signals [21].

In summary, while the all-band RoF access network supports services from BWA to W-band signals for both indoor and large-area links through one shared infrastructure, the band-mapped RoF serves as a highly practical and efficient future in-building optical-wireless access architecture, with multiple services simultaneously delivered under a unified optical and wireless 60-GHz interface.

III. WI-FI, WIMAX, AND 60-GHZ MMW IN A SIMPLE FULL-DUPLEX ALL-BAND DWDM-ROF-PON

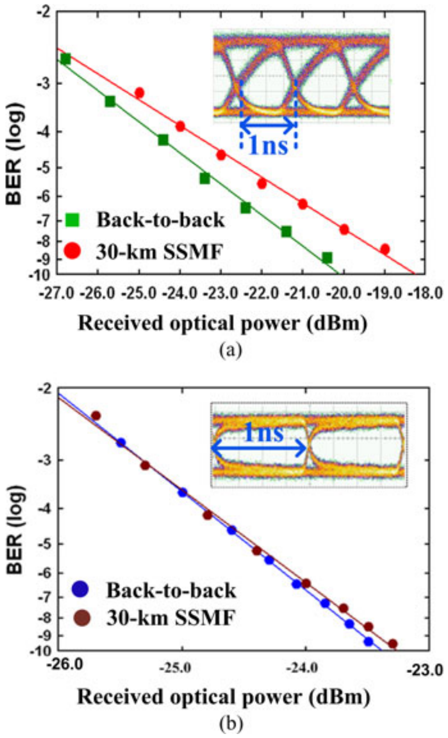
As described in the previous section, the main challenge of the all-band RoF architecture design is the integration of lower RF signals and 60-GHz signal. In our previous work of generating and transmitting 2.4-GHz (Wi-Fi), 5.8-GHz (WiMAX), and 60-GHz optical millimeter-wave signals [27], sophisticated combination of interleavers are used in both intelligent gateway router and BS, which are not favorable for industrial deployment. Furthermore, this setup occupies huge spectrum (120-GHz wide) only for the signals up to 60-GHz, and thus cannot be integrated in the spectral-efficient dense WDM-PON (DWDM-PON). In order to eliminate the complicated filtering components and high-bandwidth modulators, and greatly increase the optical spectral efficiency (SE), we propose the novel all-band DWDM-RoF-PON system, where the Wi-Fi and WiMAX services are realized using subcarrier modulation (SCM) technology and the 60-GHz MMW signal is achieved by dual-wavelength heterodyne beating method. Fig. 3 illustrates the experimental setup of the proposed architecture. In the CO, a continual wave (CW) light (10-MHz linewidth) at 1553.50 nm is fed into a Mach-Zehnder modulator (MZM). Data1 and Data2, generated by an arbitrary waveform generator (AWG) at 2.5-GSa/s sampling rate, are 16-QAM-OFDM data with a central frequency at 0.3 GHz and a bit rate of 400 Mb/s. Data1 and Data2 are mixed with 2.5-GHz and 5.8-GHz intermediate frequency (IF) clocks, respectively, and combined to drive the MZM with a modulation index of 0.15. An optical multiband SCM signal is obtained at the output of the MZM, whose optical spectrum is shown as inset (a) in Fig. 3. A direct modulation laser (DML) (10-MHz linewidth) at 1553.75 nm is driven by Data-3 with an optical modulation index ∼1, the 1-Gb/s pseudo random binary sequence (PRBS) signal, for the millimeter-wave service. The generated SCM and OOK signals are coupled (see Fig. 3(b)) and amplified by an erbium-doped fiber amplifier (EDFA). The two wavelengths with 31.25-GHz spacing can be multiplexed with other groups of wavelengths through an arrayed waveguide grating (AWG) with 50-GHz channel spacing. After the 30-km standard single mode fiber (SSMF) transmission, another AWG in the remote node (RN) demultiplexes each channel to the designated BS. In the experiment, Mux and Demux are not implemented due to device limitation. At the BS, the downstream signal is coupled with an optical local oscillator (LO) (20-MHz linewidth, 3-dBm optical power) at 1554.23 nm (see Fig. 3(c)) to the photodiode (PD), where self-beating and heterodyne mixing are realized. Specifically, the 2.5-GHz Wi-Fi and 5.8-GHz WiMAX data can be generated after self-beating of the multi-band SCM signal, while the 60-GHz signal can be achieved by heterodyne mixing of the optical OOK signal and LO light. The beating between the first wavelength and LO will exceed the bandwidth of the PD, and thus introduce no interference to the millimeter-wave signal. Note that the spacing between the two lasers in the CO can be further reduced in a 25-GHz spaced DWDM system, or even 12.5-GHz ultra-dense WDM-PON (UDWDM-PON). The only concern is to choose proper PD and 60-GHz amplifier and antenna that can filter out the unwanted beating terms from the first wavelength and the LO. The electrical spectrum after the PD is shown in Fig. 3(d), consisting of 2.5-GHz and 5.8-GHz components. Due to bandwidth limitation of the electrical spectrum analyzer (ESA), the spectrum at 60 GHz is not provided. Each of the three services is amplified and transmitted over 3-ft wireless link at its own band. The received Wi-Fi and WiMAX signals are downconverted and sampled by a real-time oscilloscope at 25 GSa/s. The 60-GHz signal is downconverted by an ED and sent to a bit error rate tester (BERT). For the upstream, same LO light is split as the upstream optical carrier and modulated by a 1-Gb/s PRBS data. Upstream channels can be transmitted with another Mux and Demux, with the same channel spacing but shifted passbands compared to the pair for downstream.



(a)

(b)

Fig. 4. EVM Performances of the (a) 2.5-GHz Wi-Fi signal with a constellation at EVM = 0.082, and (b) 5.8-GHz WiMAX signal with a constellation at EVM = 0.078.



(a)

(b)

Fig. 5. BER performances and eye diagrams for the (a) downconverted mm-wave signal and (b) the upstream signal.

The EVM performances of the 2.5-GHz Wi-Fi signal is shown in Fig. 4(a), and 1.8-dB power penalty is observed after 30-km SSMF transmission (received optical power measured before the EDFA at the BS). The EVM of the 5.8-GHz WiMAX signal is shown in Fig. 4(b). The performance of the 2.5-GHz signal is worse than that of the 5.8-GHz signal due to the interference from other commercial 2.4-GHz Wi-Fi services and different antenna responds. The BER performance and eye diagram of the downconverted 60-GHz signal for 5-ft wireless transmission case are illustrated in Fig. 5(a). Power penalty of 1.5 dB is observed after 30-km SSMF transmission compared with back-to-back (BTB) case at BER = 10^{-9}. The BER performance and

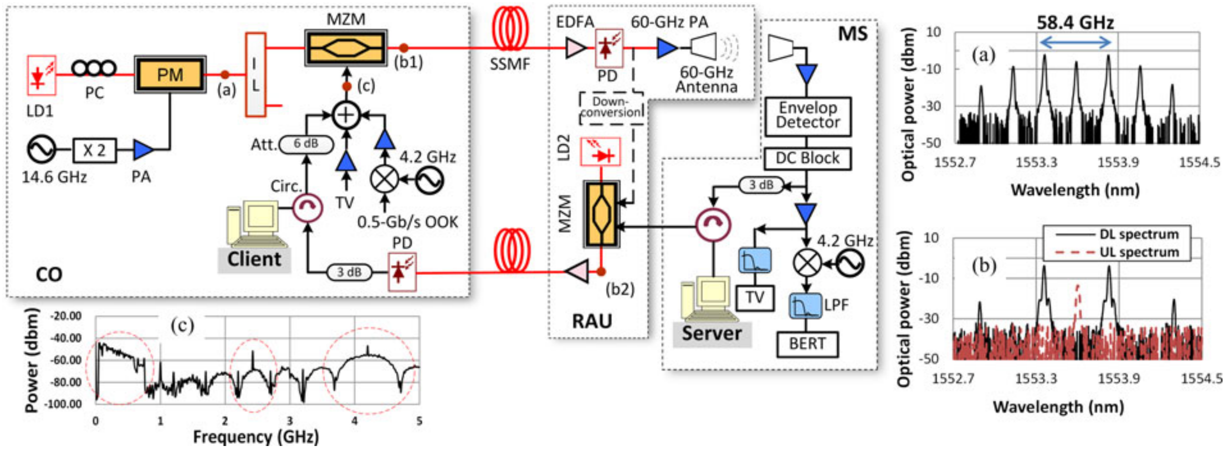


Fig. 6. Experimental setup of the band-mapped 60-GHz RoF system for TV, Wi-Fi, and VHT data. (a) and (b) Optical spectra measured at locations a, b1, and b2. (c) Electrical spectrum measured at location c.

clear electrical eye diagram of the upstream signal are shown in Fig. 5(b) with negligible power penalty after the 30-km SSMF transmission.

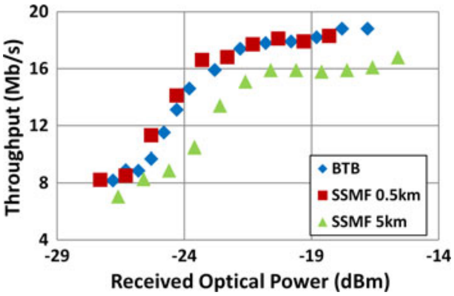


Fig. 7. Wi-Fi throughput versus received optical power for different fiber reach.

IV. REAL-TIME TV, WI-FI, AND VHT DATA DEMONSTRATION IN BAND-MAPPED 60-GHZ ROF SYSTEM

Fig. 6 shows the experimental setup of the real-time band-mapped 60-GHz RoF demonstration with fully converged services inside 60-GHz sub-bands (within the 57–64 GHz license-free spectrum in North America). Three services representing distinct signal types are included, i.e., broadcast television (TV) signal in analog form, Wi-Fi as highly modulated vector signal and digital baseband data for 60-GHz very high throughput (VHT) application. At the CO, a phase modulator (PM) is driven by a 29.2-GHz sinusoidal wave to generate multiple optical subcarriers, shown as inset (a) in Fig. 6. A 33/66 GHz interleaver (IL) is used to separate the 1st-order sidebands from other subcarriers. A HWVG1 Wireless-G Adapter in the client computer is used to transmit and receive 802.11 g Wi-Fi signal of 22-MHz channel width at 2.4 GHz. The transmit power is 17 dBm ± 2 dB, which requires attenuators before driving the MZM. The 0.5-GHz OOK is firstly upconverted to an IF at 4.2 GHz, and combined with the Wi-Fi and TV signals (see Fig. 6(c), Vpp = 0.8, 0.8, and 1.2 V, respectively) to drive the intensity modulator biased at the quadrature point. The downstream spectrum is shown as the solid black line in Fig. 6(b). After fiber propagation, the lightwave is pre-amplified by an EDFA in the RAU and detected by a 60-GHz bandwidth PD to optically upconvert the three services to 60-GHz sub-bands. A pair of 60-GHz horn antenna (15 dBi gain) with 3-ft separation is used for wireless propagation. At the mobile station (MS), an ED downconverts the received 60-GHz band-mapped signal to their original carrier frequencies. The DL Wi-Fi signal is received by an EZ Connect G Wireless PCI Adapter (SMCWPCI-G2) in the server computer. A circulator and 3-dB attenuator are used to isolate the uplink (UL) and DL signals since the generated UL Wi-Fi has much larger power (18 dBm max.) than the DL Wi-Fi signal. The 60-GHz UL, indicated by the dashed flow, is not implemented here on account of insufficient 60-GHz power amplifiers (PA) and mixers. Instead, the 2.4-GHz Wi-Fi UL is directly modulated without millimeter-wave conversion and propagation. Note that the central wavelength of the DL can be reused for upstream transmission in avoidance of any laser source for a simpler RAU. Another laser diode (LD) is deployed for Wi-Fi UL, limited by the available devices, as illustrated in the red dotted line in Fig. 6(b). The DL 0.5-Gb/s OOK signal is downconverted and filtered by a 1-GHz low-pass filter (LPF) before sent to a BERT. Meanwhile, after a 1-GHz LPF, the TV signal is displayed by a HDTV.

Wi-Fi signal throughput is tested by Iperf [28] in three cases: BTB, DL and UL 0.5-km SSMF, and DL 5-km SSMF, UL BTB (see Fig. 7). Reductions of throughput occur around −21 dBm. About 1-dB power penalty after 5-km fiber transmission is observed. The fiber length is limited by the $\mathrm{ACK}_{\mathrm{timeout}}$ defined in Wi-Fi media access control (MAC) layer [29]. It is possible to adjust the $\mathrm{ACK}_{\mathrm{timeout}}$ value to allow longer waiting time, but the throughput will drop as the idle period increases. The throughput versus time is also measured as shown in Fig. 8, with and without RoF system. The received optical power is kept at −14 dBm for the RoF system. The average Wi-Fi throughput in the three-band 60-GHz RoF system without fiber transmission is 19.3 Mb/s, higher than 19.1 Mb/s in the conventional pure Wi-Fi wireless transmission, for the reason that multipath fading

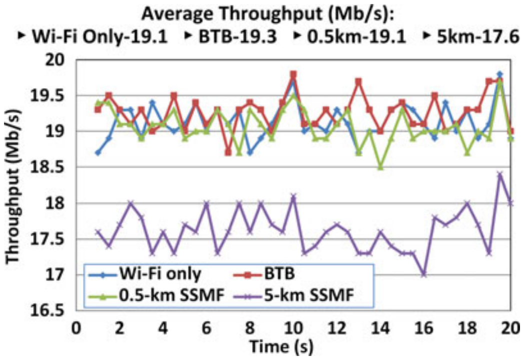


Fig. 8. Wi-Fi throughput in a 20-s interval for conventional Wi-Fi wireless link and multi-service 60-GHz RoF system.

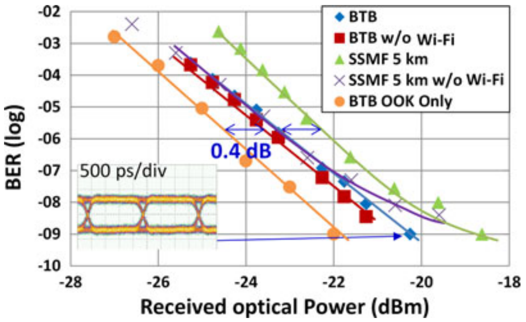
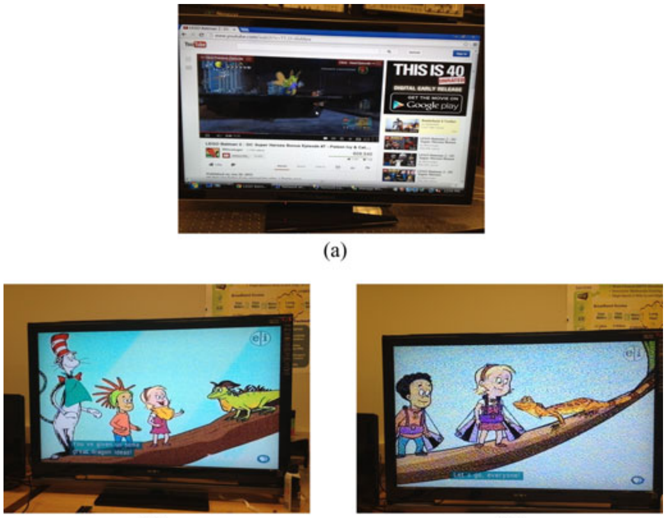


Fig. 9. BER versus received optical power of the OOK data, w/ or w/o Wi-Fi.



(a)

(b)

(c)

Fig. 10. (a) Internet access via band-mapped Wi-Fi in 60-GHz RoF. (b) TV signal alone in 60-GHz RoF. (c) TV signal in the multi-service 60-GHz RoF.

effect is not suffered in the RoF system. Moreover, in the real-time Internet access demonstration, the client computer is set as a hotpot and the server computer is thus connected to the Internet as shown in Fig. 10(a). Fig. 9 illustrates the bit error rate (BER) performance of the 0.5-Gb/s OOK data. The power penalty induced from Wi-Fi to OOK signal is about 0.4 dB in the 5-km fiber transmission case, and negligible in the BTB case. As the fiber length increase, Wi-Fi performance drops (see Fig. 7) due to longer waiting time as well as fiber chromatic dispersion. As a result, Wi-Fi adapters will automatically increase the output power, which will introduce more cross-modulation to other channels [30]. A power penalty due to TV signal is about 0.4 dB, observed between the orange-dot line and the red-square line. Fig. 10(b) shows a clear screenshot of the TV signal received from the 60-GHz RoF system, without Wi-Fi and OOK channels, while Fig. 10(c) shows the TV signal from the 60-GHz RoF system with other channels that is noisier. Since TV signal is analog, any interference or distortion imposed on it will be observable. In order to avoid the intrinsic cross-modulation from the nonlinear transfer function of the optical modulator in the multi-band 60-GHz RoF system, additional modulators can be used for services, such as analog TV signal, that are highly susceptible to distortion.

V. CONCLUSION

We have presented novel optical-wireless access architectures based on RoF technology that provide both legacy wireless services and high-speed millimeter-wave services. With shared optical infrastructure and centralized management, all-band RoF system is capable of covering a wide range of wireless services carried by from few GHz to more than 100 GHz, at various transmission distances, and in both indoor and outdoor environments. Band-mapped RoF system, on the other hand, delivers multiple services at 60-GHz band with one unified optical and wireless interface and features less power consumption and very high spectral efficiency. Both of them are favorable for high-density small cell systems due to the newly proposed BSs with greatly reduced complexity. With remote heterodyning technique, it is possible to integrate both RoF systems into DWDM-PON, or even UDWDM-PON to reach massive amount of users. We have demonstrated simultaneous delivery of independent Wi-Fi, WiMAX and 60-GHz millimeter-wave signals in the all-band RoF system and experimentally evaluated transmission performances over 30-km SSMF. Finally, for the first time, a real-time demonstration of converged TV, Wi-Fi and OOK data in the band-mapped 60-GHz RoF system has been reported. Fiber length limitation, comparison with conventional Wi-Fi link, and cross-modulation among channels have been investigated. By combining low cost, high speed, and high flexibility, the novel RoF access architectures are promising for future broadband wireless heterogeneous networks.

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