*International Journal of Engineering Research and Applications (IJERA) ISSN: 2248-9622*
*Recent Trends in Mobile & Cloud Computing*
*(NCRMC- 08th & 09th October 2015)*

RESEARCH ARTICLE OPEN ACCESS

# Radio-Over-Fiber Access Architecture

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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 pas-sive optical network (UDWDM-PON). Legacy wireless services and multi-gigabit millimeter-wave (mm-wave) applications are inte-grated and delivered simultaneously under one shared infrastruc-ture. 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 heteroge-neous 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 opti-cal 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 uni-fied 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 ac-cess, radio-over-fiber (RoF), WDM-PON.

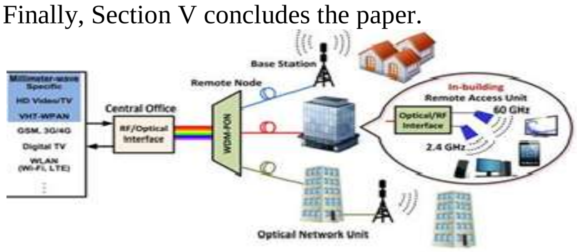
## I. INTRODUCTION

HE proliferation of smart mobile devices is essentially changing the Internet traffic patterns and both wirelessand wired network infrastructure [1], [2]. Propelled by emerg-ing applications such as interactive video service, the mo-bile 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 frequen-cies (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 broad-band channels [6]. In addition to the aforementioned tech-niques 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 lo-cated 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 target-ing 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 through-put of up to 7 GB/s as a new tri-band Wi-Fi solution [11].

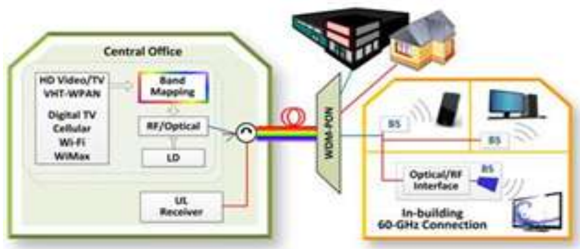
It is essential that the access network should support a wide range of data rates, formats, protocols, and requirements. The consumers will benefit from a universal user interface that pro-vides wireless access anywhere at anytime with minimal delay and data processing. Radio-over-fiber (RoF) is an attractive technology for such multi-service broadband access networks [12]–[21]. By allocating and controlling multiple wireless ser-vices 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 Archi-tecture 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 and advanced millimeter-wave services, and propose two prac-tical 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 frequen-cies, 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 topo-logical 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.




**(a)**




**(b)**

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.

## II. ALL-BAND AND BAND-MAPPEDMILLIMETER-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 fre-quency 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 dis-tributed 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, in-cluding nonlinear effects, external modulation, and remote het-erodyning [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. Wave-length reuse methods have been proposed for the cost-effective millimeter-wave RoF upstream transmission [17]–[20]. How-ever, 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 di-rectly adds electrical signals together (millimeter-wave signals may differ) and modulates them onto the lightwave through the RF-to-optical interface in the CO.

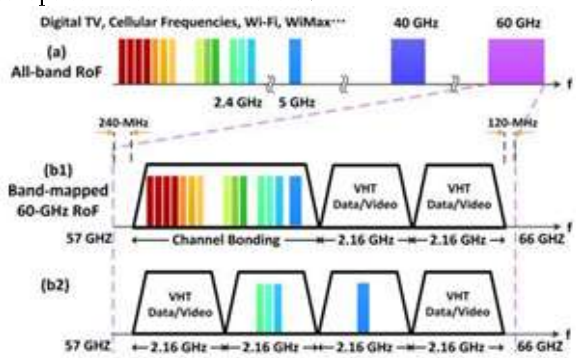



**Fig. 2. Spectrum allocations in (a) all-band RoF and (b) band-mapped 60-GHz RoF**

Different services, naturally separated by frequencies as shown in Fig. 2(a), are grouped and multiplexed in the wavelength division multiplexing passive op-tical network (WDM-PON). Signals at a single wavelength are demultiplexed and retrieved by a simple optical-to-RF inter-face at their own carrier frequencies, and finally transmitted by designated antennas to targeted mobile devices. The same in-frastructure is also shared by mobile backhaul with a much sim-plified 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.

All-band RoF is able to cover wireless services from few GHz to more than 100 GHz, and transmission coverage from few me-ters to kilometers. However, in most cases, wireless access is done in indoor environment, such as in the office, home, con-vention center, and stadium. To further exploit this application scenario, Fig. 1(b) illustrates a fully-converged 60-GHz RoF network based on the band-mapping concept. Existing wire-less 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 sys-tem, only one pair of electrical amplifiers and antennas at the 60-GHz band are needed, which greatly reduces the power con-sumption and component complexity, yet keeps the backward compatibility. By integrating wireless services from different frequency bands into the wide unlicensed 60-GHz band, bet-ter usage of available spectrum is thus achieved. Furthermore, the spectrum allocation can be flexible upon request from mo-bile 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 inte-grated 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 di-vision 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 non-linearities and noise. Therefore, an optimal electrical power dis-tribution [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 down convert 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 mod-ulated millimeter-wave signals [21].

In summary, while the all-band RoF access network sup-ports 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

The EVM performances of the 2.5-GHz Wi-Fi signal is shown in Fig. 3(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. 3(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 downconverted60-GHz signal for 5-ft wireless transmission case are illustrated in Fig. 4(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 clear electrical eye diagram of the upstream signal are shown in Fig. 4(b) with negligible power penalty after the 30-km SSMF transmission.

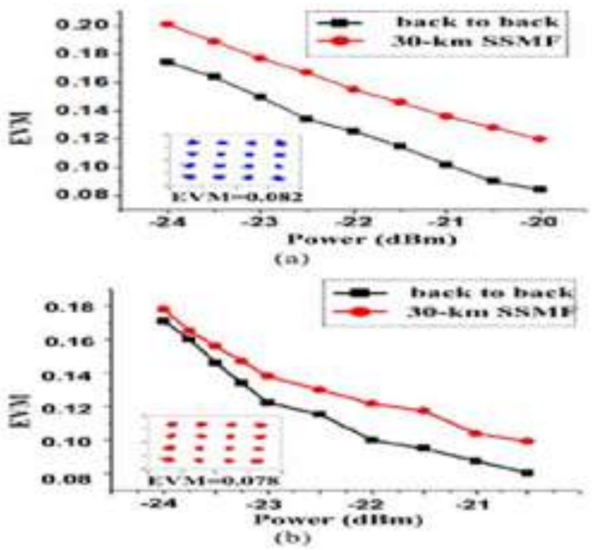



**Fig. 3. EVM Performances of the (a) 2.5-GHz Wi-Fi signal with a constella-tion at EVM = 0.082, and (b) 5.8-GHz WiMAX signal with a constellation at EVM = 0.078.**

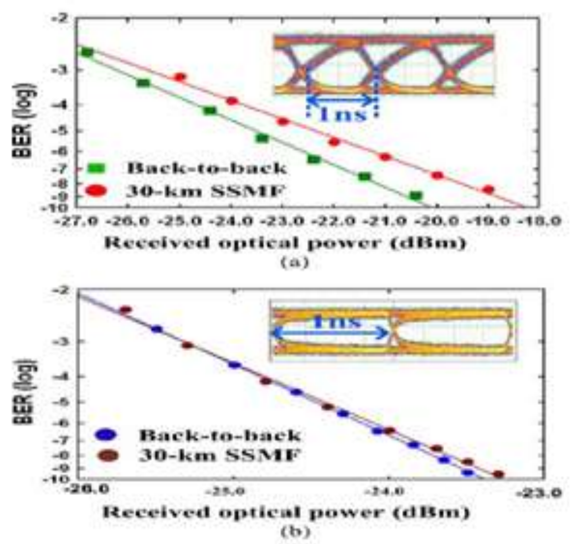



**Fig. 4. BER performances and eye diagrams for the (a) downconverted mm-wave signal and (b) the upstream signal**

## IV. CONCLUSION

We have presented novel optical-wireless access architectures based on RoF technology that provide both legacy wireless ser-vices and high-speed millimeter-wave services. With shared op-tical 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 trans-mission distances, and in both indoor and outdoor environments. Band-mapped RoF system, on the other hand, delivers multiple 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 perfor-mances 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 has 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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