ENABLING FIBER–WIRELESS TECHNOLOGIES FOR RADIO COMMUNICATIONS IN MILLIMETER-WAVE AND TERAHERTZ-WAVE BANDS IN IMT-2030 AND BEYOND

Pham Tien Dat, Yuya Yamaguchi, Kouichi Akahane

National Institute of Information and Communications Technology, Tokyo, Japan

ABSTRACT

Radio communications in high-frequency bands are crucial for providing high-speed and low-latency services. Research efforts are being made worldwide; however, several bottlenecks still exist, such as high free-space loss, weak penetration, and limited coverage, making the deployment of high-frequency radio communications challenging. To attain sustainable development goals, cost-effective, high-speed, and energy-efficient communication infrastructure should be developed. Photonic technology and its convergence with radio counterparts are promising for high-frequency radio communications. In this paper, we present key fiber–wireless technologies, including a high-speed fiber–wireless bridge system for fixed wireless access and emergency communications, transparent relay and routing of radio signals for coverage extension, and simultaneous generation, transmission, and reception of multiple radio signals in different frequency bands, to overcome the bottlenecks. For each technology, we present the system concept and proof-of-concept demonstration. The achieved results reveal the potential of the proposed solutions and can pave the way for the deployment of radio access networks in the millimeter-wave and terahertz-wave bands in IMT-2030 and beyond.

Keywords – 5G-Advance and 6G, convergence of wired and wireless, millimeter-wave, emergency communications

1. INTRODUCTION

Telecommunications plays a vital role in attaining sustainable development goals, and millimeter-wave (mmW) frequency resources are essential for high-speed and low-latency communications, especially for indoor offices, hotspots, and fixed wireless access (FWA). mmW is allocated worldwide; and by 2022, they were available in 31 countries [1]. Currently, research efforts are being made for ultra-high-speed, large-capacity, and ultra-low-latency communications in 6G networks. Radio access networks (RANs) are expected to continue up to 100 GHz and beyond in international mobile telecommunications (IMT) 2030 [2]. However, the use of mmW bands remains limited because of several bottlenecking challenges. The propagation loss increases significantly in the mmW band, making the cell size much smaller than that in the microwave band. In addition, line-of-sight communication is required because of the large shielding loss, which makes antenna installation difficult and expensive. The penetration of mmW signals is also limited, making it challenging to extend the communication coverage to wide areas and indoor environments. The coexistence of multiple RANs in different frequency bands and the use of integrated access and backhaul (IAB) have been proposed to expand coverage and increase the throughput of radio communications in the mmW and terahertz (THz) bands [3]. These methods are promising for improving the network efficiency. However, their implementation remains difficult, particularly for communication with indoor users. Electronics-based solutions, such as reflecting radio signals on reconfigurable intelligent surfaces [4] and using smart repeaters [5], have been recently proposed; however, the system is relatively complicated, and the coverage extension is still limited. New solutions are in high demand to facilitate communications in the mmW and THz bands, which are crucial in 6G networks. Photonic technology is promising for the generation, transmission, and reception of radio signals; thus, it can be used as an efficient solution. A fiber–wireless bridge system can provide a high-speed and easy-to-install solution for fixed access and emergency communication. However, the cost, complexity, and power consumption increase significantly when an electronic method [6] or optical coherent detection [7] is used. The direct detection and downconversion of radio signals using photonic technology is promising for simplifying the systems [8, 9]. However, a system that can provide a transmission capacity of up to 100 Gb/s is yet to be demonstrated. For radio coverage extension application, radio-over-fiber (RoF) systems are useful [10, 11]. Radio signals can be converted into optical signals for transmission and regenerated to communicate with users at the ends of the links. However, a system that can relay signals at a data rate exceeding 40 Gb/s has not yet been reported. Photonic technology is also promising in facilitating multi-RAN and IAB technologies. However, to date, there have been no reports on these applications.

In this paper, we present key fiber–wireless technologies to facilitate radio communications in the mmW and THz bands. First, a high-speed fiber–wireless bridge system was demonstrated using photonic technology for radio signal generation, transmission, reception, and downconversion.

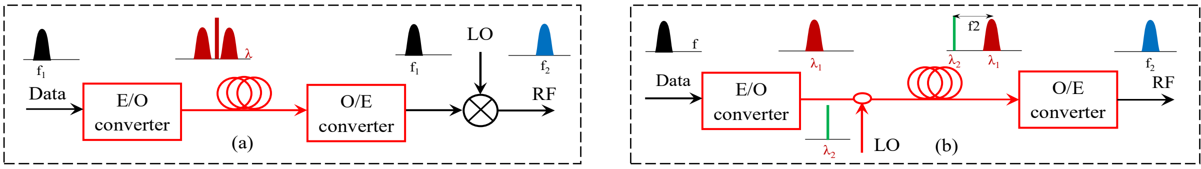

Fig. 1 Radio signal generation and transmission: (a) electrical method; (b) optical method.
E/O: electrical-to-optical; O/E: optical-to-electrical; LO: local oscillator; RF: radio frequency.

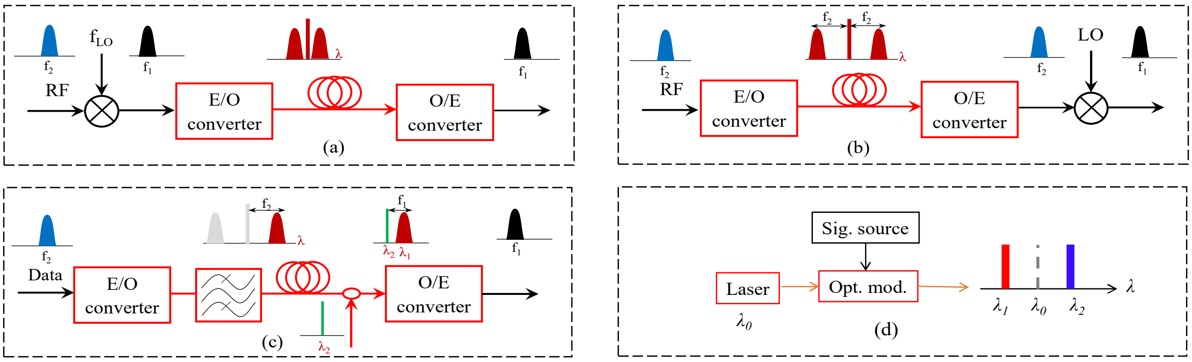

Fig. 2 Radio signal detection and down-conversion: (a) electrical method; (b) direct radio-to-optical conversion; (c) photonic down-conversion; (d) two-tone optical signal generation.

Using the system, the antenna sites and transceivers were significantly simplified, rendering the system a promising solution for high-speed, low-latency, and energy-efficient communications in FWA and emergency events. The possibility of transmitting a line rate of up to 100 Gb/s over the system in the 100-GHz band was confirmed, which is the highest transmission over a direct-detection bridge system to date. Second, a dual-hop access network using a broadband RoF system for transparent radio signal relay and routing is demonstrated for coverage extension. As a proof-of-concept demonstration, we transmitted orthogonal frequency-division multiplexing (OFDM) signals over a cascaded fiber–wireless–fiber–wireless system in the 100-GHz band and achieved a line rate of up to 50 Gb/s, the highest over a relay system reported so far. Finally, we propose and demonstrate a novel system for the simultaneous generation, transmission, and reception of multiple radio signals in different frequency bands. Using this system, radio signals in the 28- and 92-GHz bands can be generated and transmitted simultaneously over a cascaded fiber–wireless–fiber system, and down-converted and transmitted to end users over different radio links. For the proof-of-concept demonstration, 5G New Radio (NR) standard-compliant signals were transmitted over the system in both frequency bands. The system can provide a cost-effective and flexible solution for multi-RAN and IAB applications in 5G-Advanced and 6G networks. The technologies presented in this paper can be important topics for standardization in the ITU, especially for the studies on feasible technical requirements of IMT towards 2030 and beyond in the ITU-R and mobile transport and home access networks in the ITU-T SG-15. The remainder of this paper is organized as follows. Section 2 presents seamless fiber–wireless systems that employ electrical and photonic methods. Section 3 presents a high-speed fiber–wireless bridge system for FWA and emergency communications. This is followed by a transparent relay and routing system for radio signals in section 4. Section 5 presents a novel system for the simultaneous generation, transmission, and reception of radio signals in the 28- and 92-GHz bands. Finally, the conclusions and outlook are presented.

2. SEAMLESS FIBER–WIRELESS SYSTEM

2.1 Radio signal generation and transmission

Radio signals in the mmW and THz bands can be generated using either electrical or photonic methods. In the former, as shown in Fig. 1(a), a signal in a low-frequency band, such as the baseband or intermediate frequency (IF), is generated and transmitted over an optical fiber link. At the end of the link, the original signal is recovered and upconverted to a high-frequency band using an electrical upconverter. Using this method, signal transmission over optical fiber links matures because inexpensive optical devices such as electrical-to-optical (E/O) and optical-to-electrical (O/E) converters in the low-frequency band can be used. However, local oscillator (LO) sources are required for signal upconversion at the antenna site, which significantly increases the complexity, footprint, cost, and power consumption. In the photonic method, shown in Fig. 1(b), a signal in the baseband or IF band is modulated onto an optical carrier signal at wavelength λ_1. The modulated signal is combined with an optical LO signal at wavelength λ_2. The combined signal is transmitted over an optical fiber link and input to a high-speed O/E converter to generate a high-frequency radio signal at the end of the link. The beat note between the two optical signals generates a radio signal with a frequency identical to the frequency difference between the two optical signals, that is, $f = |c/\lambda_1 - c/\lambda_2|$. Radio signals at different frequencies can be generated by changing the wavelength of the optical signal(s). This method provides a simple yet

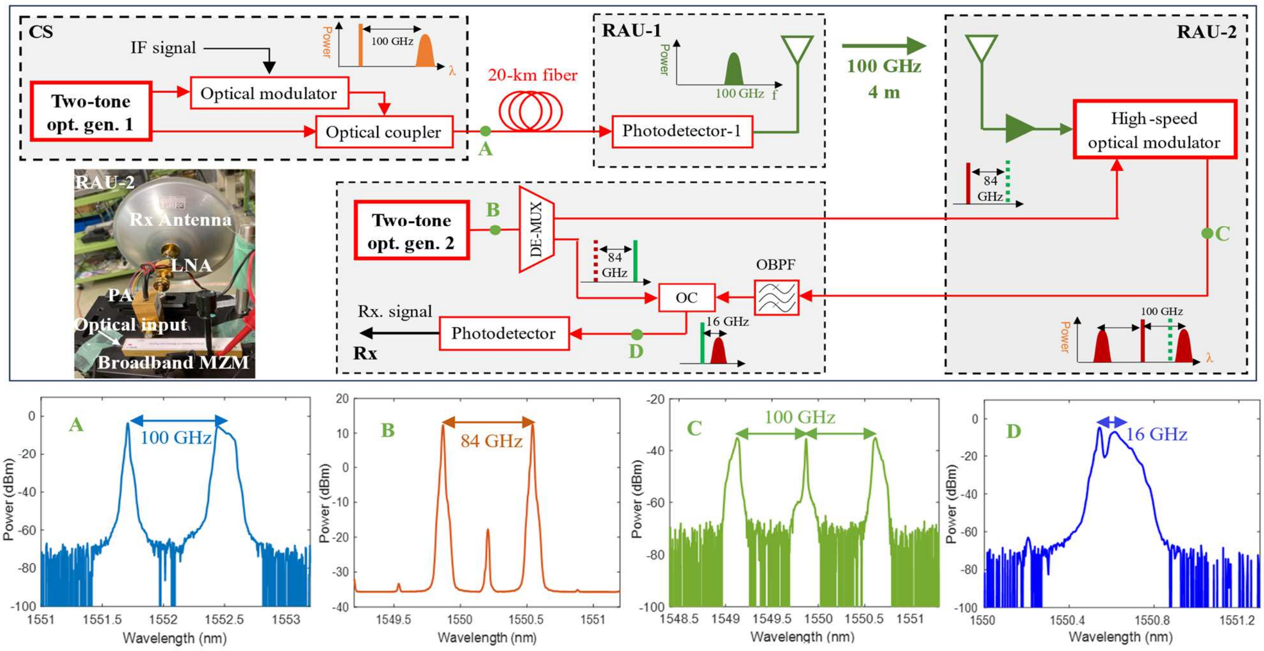

Fig. 3 Schematic of seamless fiber–wireless bridge system. CS: central station; RAU: remote radio head; Rx: receiver.

flexible solution for generating radio signals. The antenna site can be significantly simplified using this method. An optical heterodyne method using free-running lasers can provide ultrawide frequency tunability for radio signal generation. However, frequency instability is significantly high, resulting in large frequency fluctuations and phase noise in the generated radio signals. An optical self-heterodyne method using stabilized optical signals from a single laser source can generate radio signals with high frequency stability and low phase noise.

2.2 Radio signal reception and down-conversion

Radio signals can be received and down-converted to a lower-frequency band using either electrical or photonic methods. Using the electrical method, shown in Fig. 2(a), the signal is input to an electric mixer for downconversion to a lower-frequency band using an LO signal. The down-converted signal can be transmitted over a fiber link to the receiver. However, an LO source is required at the antenna site. Using the photonic method, shown in Fig. 2(b), the incoming radio signal is directly converted into the optical domain using a high-speed E/O converter. This method provides a straightforward approach for simplifying the antenna sites because LO signals are not required. The modulated signal is transmitted to the receiver using a fiber link. A high-speed O/E converter at the end of the link can convert the modulated signal back to a radio signal. The regenerated signal can be transmitted to end users or down-converted to a lower-frequency band using the electrical downconversion method. The signal can also be down-converted to a lower-frequency band using photonic downconversion, as shown in Fig. 2(c). Using this method, an optical LO signal is generated and combined with one of the modulated sidebands. The combined signal comprising unmodulated and modulated sidebands can be input to a low-speed O/E converter for conversion into a radio signal in the low-frequency band. The frequency of the down-converted signal equals the frequency difference between the LO and the modulated sideband. Similar to the signal generation, a free-running laser can be used as an optical LO for signal downconversion. However, random wavelength fluctuations of lasers increase the frequency instability and phase noise of the generated signals. Frequency-stabilized two-tone optical signal generation, shown in Fig. 2(d), using an optical signal from a single light source is appropriate for photonic up- and down-conversion. In the following sections, we present fiber–wireless systems that use photonic up- and down-conversion methods with stabilized two-tone optical signal generation for different application scenarios.

3. FIBER–WIRELESS BRIDGE SYSTEM

A schematic of a fiber–wireless bridge system using all-photonic transceivers is shown in Fig. 3. The central station (CS) generates and modulates the signal, and the receiver (Rx) receives and demodulates it. The optical-to-radio conversion is performed at remote antenna unit 1 (RAU-1), and RAU-2 converts the radio signal back to the optical domain for further transmission. At the CS, a two-tone optical signal with a frequency separation of 84 GHz was generated using a high-extinction-ratio optical modulator. The two sidebands were separated, and the upper sideband was modulated by an IF OFDM signal at 16 GHz using an optical intensity modulator. A double-sideband carrier-suppressed (DSB-SC) signal was generated, and the upper modulation sideband was selected using an optical filter. The signal was combined with the unmodulated sideband from the two-tone optical signal and transmitted to RAU-1 using a 20-km single-mode fiber (SMF). The signal was input to a high-speed photodetector (PD) for conversion to a THz signal at 100 GHz (= 84 + 16 GHz). The signal was

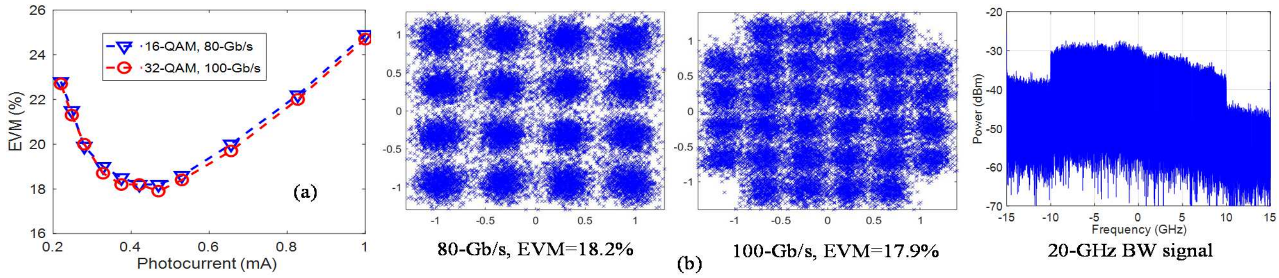

Fig. 4 Performance of fiber–wireless bridge system: (a) EVM vs. photocurrent at RAU-1; (b) constellations and spectrum of 20-GHz bandwidth signal.

transmitted to free space using a 35-dBi antenna. After transmission over approximately 4 m, the signal was received using a 42-dBi antenna at RAU-2. The signal was amplified and converted to the optical domain using a high-speed optical modulator. A photonic downconversion method was employed to simplify the antenna site and receiver. Using this method, another two-tone optical signal with a frequency separation of 84 GHz was generated at the Rx. The two sidebands were separated, and the lower sidebands were transmitted to RAU-2 for signal modulation. The modulated DSB-SC signal was transmitted to the Rx, and the upper modulated sideband was selected and combined with the unmodulated sideband. The combined signal with a frequency separation of 16 GHz (= 100 – 84 GHz) was input to a low-speed PD for conversion to an electrical signal. Finally, the signal was sent to a real-time oscilloscope and demodulated offline. A photograph of the RAU-2 setup and the optical spectra at different points along the system are shown in the figure.

Table 1 – Fiber–wireless bridge system

Parameter	Values	Parameter	Value
Frequency	100 GHz	Distance	4 m
Tx. antenna	35 dBi	Rx antenna	42 dBi
16 QAM signal	80 Gb/s	EVM	18.2%
32 QAM signal	100 Gb/s	EVM	17.9%

The key parameters and performance of the system are listed in Table 1. An OFDM signal with a bandwidth of 25 GHz at 16 GHz consisting of 2,048 subcarriers, of which 20% were inactive at the band edges, was generated and transmitted, and its performance in terms of the error vector magnitude (EVM) was evaluated. The performance of the 16-QAM and 32-QAM signals for different photocurrents of the PD, corresponding to different transmission powers of the THz signal at RAU-1, are shown in Fig. 4 (a). Fig. 4(b) shows examples of the constellations and spectra of the received signals. The EVM values required for the 16-QAM and 32-QAM signals to satisfy a 20% forward error correction (FEC) overhead are 22.09 and 15.96%, respectively [12]. The optimal performance was achieved at a photocurrent of approximately 0.4 mA. Further increasing or decreasing the photocurrent beyond the optimal value degrades the performance because of signal-to-noise ratio (SNR) reduction and nonlinear distortion. For the 16-QAM signal, satisfactory performance was obtained for the photocurrent

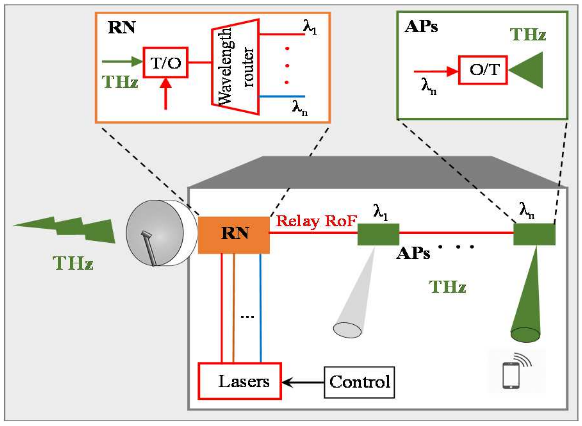

Fig. 5 Schematic of radio signal relay and routing. RN: relay node; T/O: terahertz-to-optical; AP: access point: THz: terahertz.

in the 0.22–0.8 mA range, attaining a line rate of 80 Gb/s. For the 32-QAM signal, EVMs were slightly higher than the requirement. This could be caused by the low SNRs in some subcarriers owing to the non-flat frequency response of the devices, which can be overcome by fully optimizing the system. In addition, basic digital signal processing (DSP) using classical methods was applied for OFDM signal generation and demodulation. Performance and capacity can be improved using a signal calibration algorithm or by applying an adaptive bit and power loading to the signal. By operating the system under optimized conditions and applying a robust DSP at the receiver, a transmission capacity of 100 Gb/s or higher can be expected for FWA and emergency communications.

4. MOBILE COVERAGE EXTENSION SYSTEM

A schematic of the radio signal transparent relay and routing from outdoor to indoor environments is shown in Fig. 5. Radio signals can be received at relay nodes (RNs) and directly converted to the optical domain for transmission to different access points (APs) located indoors to communicate with end users. RNs can be installed on the rooftops or windows of buildings to receive radio signals. RNs comprise a high-speed optical modulator for direct THz-to-optical (T/O) conversion and radio front ends. At the APs, the modulated optical signals are converted back to THz signals using optical-to-THz (O/T) converters. The APs can be flexibly placed at different locations to optimize the communication capacity and coverage. RNs and APs are

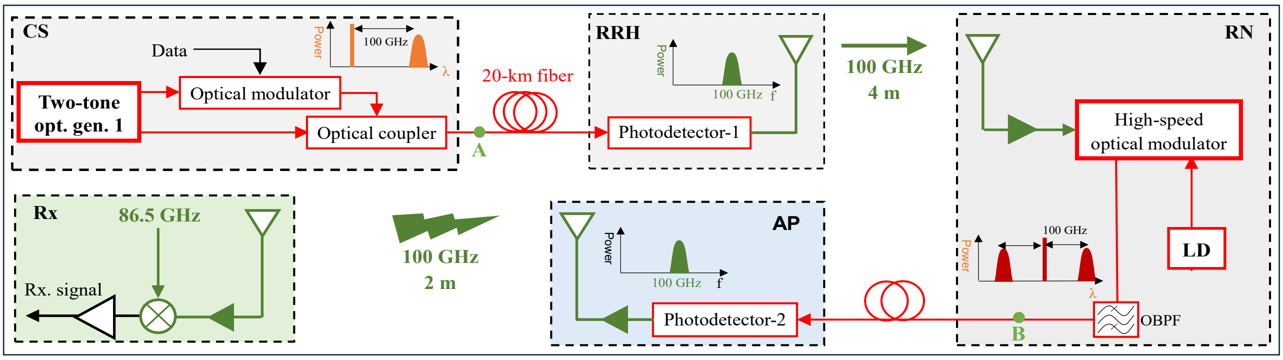

Fig. 6. Experimental setup for radio signal transparent relay and routing.
CS: central station; RRH: remote radio head; RN: relay node; AP: access point; Rx: receiver; LD: laser diode.

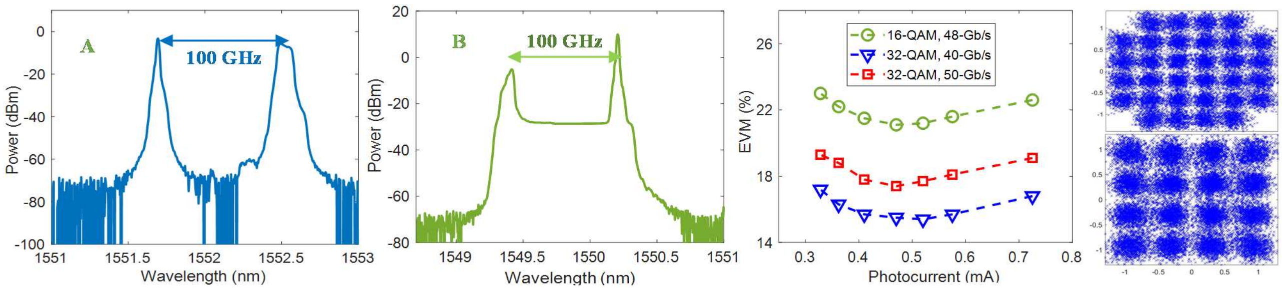

Fig. 7. Performance of transparent relay and routing system.

significantly simplified using photonic transceivers. This system enables the transparent relay and routing of mmW and THz signals to indoor environments. In this system, radio links in both the outdoor and indoor environments are access networks; however, they are separated to construct a dual-hop access network to avoid high penetration losses. In this subsection, we present a proof-of-concept demonstration of the generation, transmission, reception, and relay of radio signals in the 100-GHz band over a dual-hop access system.

Table 2 – Mobile coverage extension system

Parameter	Values	Parameter	Value
Radio link 1 (RRH to RN)			
Frequency	100 GHz	Distance	4 m
Tx. antenna	35 dBi	Rx antenna	42 dBi
Radio link 2 (AP to Rx)			
Frequency	100 GHz	Distance	2
Tx. antenna	23 dBi	Rx antenna	23 dBi
16 QAM (15 GHz)	48 Gb/s	EVM	21.1%
32 QAM (12.5 GHz)	50 Gb/s	EVM	17.4%
32 QAM (10 GHz)	40 Gb/s	EVM	15.4%

Figure 6 presents the setup for the generation, transmission, and relaying of a 100-GHz radio signal from outdoor to indoor environments. A two-tone optical signal with a frequency difference of 84 GHz was generated at the CS. The two sidebands were separated, and the upper side was modulated by an OFDM signal using an intensity optical modulator. The bias voltage applied to the modulator was controlled to generate a DSB-SC signal. The signal was amplified, and the upper modulation sideband was selected and recombined with the unmodulated sideband from the two-tone optical signal. The signal was transmitted to a remote radio head (RRH) using a 20-km SMF and upconverted to a THz signal at 100 GHz using a high-speed PD. The generated signal was emitted into free space using a 35-dBi Cassegrain antenna. The signal was transmitted over approximately 4 m in free space and received using a 42-dBi antenna at the RN. The signal was amplified and converted into an optical signal using a broadband optical modulator. The carrier-to-sideband ratio was optimized by controlling the bias voltage to the modulator. To reduce fiber dispersion effects, one of the modulation sidebands was suppressed using an optical filter. The signal was transmitted to the APs using a fiber link. For simplicity, only one AP was included in the experiment. However, in practical systems, the modulated optical signal can be divided and transmitted to several APs. At the AP, the signal was input to another high-speed PD to convert it back to a 100-GHz radio signal. The power input to the PD was adjusted using an optical attenuator. The generated signal was transmitted to free space using a 23-dBi horn antenna. After transmission over approximately 2 m in space, the signal was received using another horn antenna at the Rx. Finally, the signal was amplified, down-converted to 16 GHz using a subharmonic mixer, and demodulated offline.

Table 2 summarizes the key parameters of the system and the transmitted signals. OFDM signals with a bandwidth of 10, 12.5, and 15 GHz, comprising 2,048 subcarriers, of which 20% at the band edges were inactive, were transmitted over the system. The signal performance is shown in Fig. 7, including the optical spectra of RoF signals at the CS and RN, the signal performance for different photocurrents of the PD at the RRH, and constellations of the received 50- and 48-

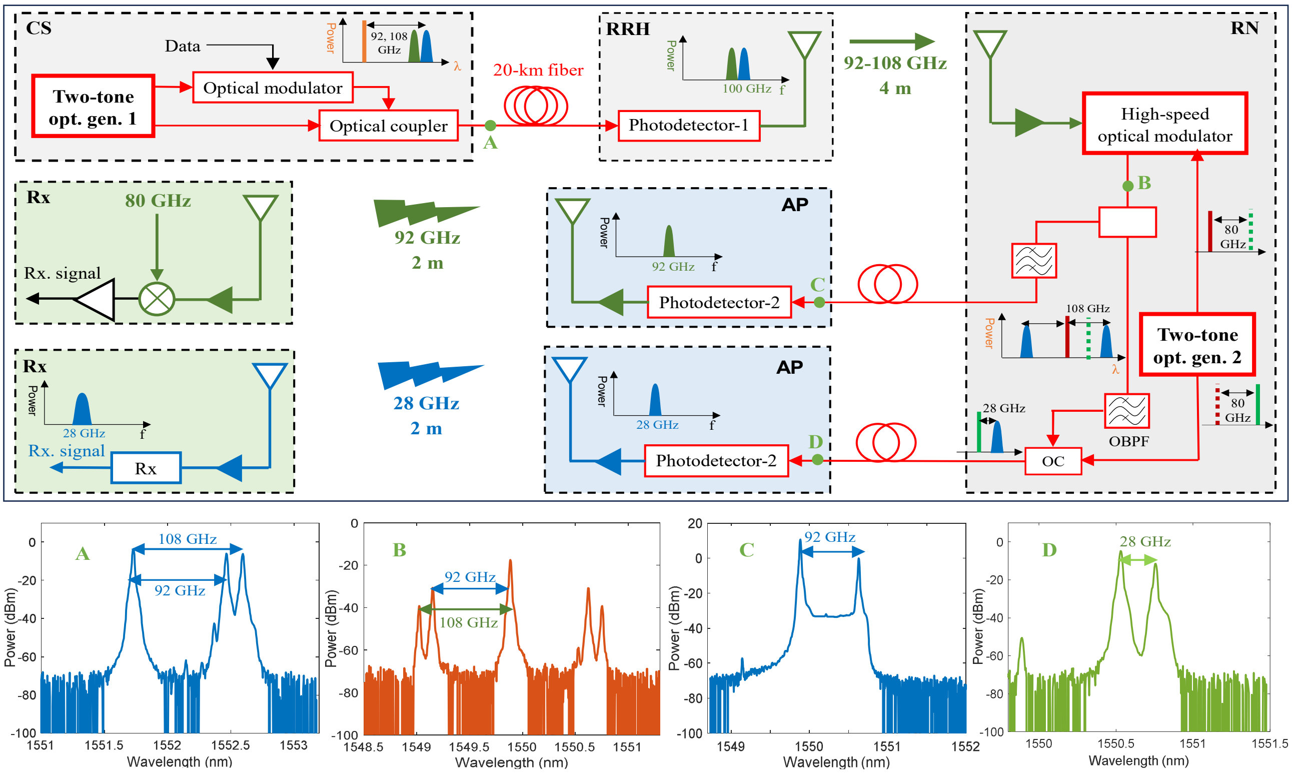

Fig. 8. System diagram for simultaneous generation, transmission, and reception of 28- and 92-GHz signal.
CS: central station; RRH: remote radio head; RN: relay node; AP: access point; Rx: receiver.

Gb/s signals using 32-QAM and 16-QAM modulation. Satisfactory performance was confirmed for the 16-QAM signal, achieving a transmission line rate of 48 Gb/s. For the 32-QAM signal, a 40-Gb/s signal was successfully transmitted with EVMs satisfying the 20% FEC limit. The performance of the 50-Gb/s 32-QAM signal was slightly above the required threshold, which could be attributed to the low SNRs in some subcarriers. Similar to the bridge system, this problem can be solved by optimizing the system and applying a robust DSP. The system is flexible and can be applied to the generation, transmission, and relay of radio signals in higher-frequency bands. To date, the transmitted data rates are the highest over a relay system, confirming the potential of the proposed system for high-speed radio communications in 6G networks.

5. MULTI-RAN AND IAB SYSTEM

In 5G-Advanced and 6G networks, the coexistence of multiple RANs in different frequency bands is important for supporting different use cases. RANs in the low mmWave band can be deployed for wide coverage and popular uses, whereas high-frequency RANs are useful for high-speed and low-latency services. However, the deployment of multi-RANs poses significant challenges to transport networks. The simultaneous generation and transmission of multi-RAN signals over common transport systems is crucial for reducing the cost and complexity. In this case, the signals must be multiplexed and demultiplexed before and after the transmission. These technologies are also important for facilitating IAB technology. In IAB applications, wireless backhauling uses the same wireless spectrum for coverage and backhaul connectivity, which can enhance signal performance and spectrum usage and reduce equipment costs. In both cases, the multiplexing and demultiplexing of radio signals from/to different frequency bands play vital role. Electrical multiplexers and demultiplexers can be developed and employed for signal multiplexing and demultiplexing. However, their efficiency and frequency are limited by the roll-off factor and bandwidth limitations of electrical devices. In this subsection, we propose a novel system using photonic technology for the efficient multiplexing and demultiplexing of radio signals. The proposed system was applied to the simultaneous generation, transmission, reception, and distribution of 28- and 92-GHz radio signals over a single fiber–wireless system in the 100-GHz band.

A diagram of this system is shown in Fig. 8. A two-tone optical signal with a frequency separation of 80 GHz was generated at the CS. The two sidebands were separated, and the upper sideband was used for data modulation. In the experiment, 5G NR signals at 12 GHz and 28 GHz were generated and combined using an electrical combiner. The combined signal was fed to an intensity optical modulator for conversion into an optical signal. The upper sideband of the modulated signal was selected and combined with the lower sideband of the two-tone optical signal. The frequency differences between the unmodulated and modulated sidebands were 92 GHz (= 80 + 12 GHz) and 108 GHz (= 80 + 28 GHz) as shown in inset A of Fig. 8. Notably, 5G NR signals can also be converted into the optical domain using different optical modulators. The combined signal was transmitted to an RRH using a 20-km SMF. At the RRH, the signal was input into a high-speed PD for simultaneous conversion to radio signals at 92 and 108 GHz. The generated signals were fed to a 35-dBi antenna and transmitted into free space using an identical wireless link with those shown in Figs. 3 and 6. Photonic downconversion was employed for signal demultiplexing. Another two-tone optical signal with a frequency separation of 80 GHz was generated. The two sidebands were separated, and the lower sideband was used for signal modulation. At the output of the modulator, the signal, as shown in inset B of Fig. 8, was divided into two parts using an optical coupler. In one part, the signal was input to an optical filter, and the optical carrier and one modulated sideband of the 92-GHz signal were selected. The selected signal, shown in inset C of Fig. 8, was transmitted to an AP and input to another high-speed PD to generate a signal at 92 GHz. The signal was transmitted to an Rx using the same 2-m wireless link as that shown in Fig. 6. Finally, the signal was down-converted to the microwave band and demodulated using 5G NR software. In the other part, photonic downconversion was employed to down-converting the 108-GHz signal to 28 GHz. The upper modulated sideband of the 108 GHz signal was selected and combined with the upper unmodulated sideband of the two-one optical signal. The frequency separation between the two sidebands of the combined signal was 28 GHz (= 108–80 GHz), as shown in the inset D of Fig. 8. The combined signal was transmitted to an AP and input to a low-speed PD for conversion into a radio signal at 28 GHz. The signal was transmitted to free space using a 28-dBi horn antenna. After transmission over approximately 2 m in free space, the signals were received using another antenna and sent to a receiver for demodulation.

Table 3 – Multi-RAN and IAB system

Parameter	Value	Parameter	Value
Radio link 1 (RRH to RN)			
Frequency	92, 108 GHz	Distance	4 m
Tx. antenna	35 dBi	Rx antenna	42 dBi
92-GHz radio link (AP to Rx)			
Frequency	92 GHz	Distance	2
Tx. antenna	25 dBi	Rx antenna	25 dBi
5G NR 64 QAM	200 MHz	EVM	5.3%
28-GHz radio link (AP to Rx)			
Frequency	28 GHz	Distance	2m
Tx. antenna	28 dBi	Rx antenna	28 dBi
5G NR 64-QAM	200 MHz	EVM	4%

Table 3 summarizes the main parameters and performance of the system. We transmitted 5G NR standard-compliant signals over both the 28- and 92-GHz systems. A 200-MHz bandwidth 64-QAM 5G NR signal at 12 and 18 GHz was generated using commercial software and transmitted over the system. Figure 9 shows the performance of the 28- and 92-GHz signals for different photocurrents of the PD at the RRH. The EVM required for a 64-QAM signal is 8% [13]. For comparison, the signal performances with and without the simultaneous transmission with the other signal are also shown in the figure. In the case of a single-signal transmission, the other 5G NR signal was turned off at the CS. Satisfactory performance was achieved for all signal transmissions. For the 28-GHz signal, the performance of the single transmission was better than that of the simultaneous transmission, especially in the high-photocurrent region. However, the performance of the 92-GHz signal for simultaneous transmission was slightly better. This could be due to the optimal ratio of the optical carrier and modulation sidebands in each case. Moreover, the 28-GHz signal performed better than the 92-GHz signal. This is attributed to the superior performance of the devices at 28 GHz. The results confirmed the possibility of simultaneous generation, transmission, reception, and distribution of multiple radio signals in different frequency bands. The system is flexible and can be used in different applications, including multiple-RAN coexistence and in-band and out-band IAB.

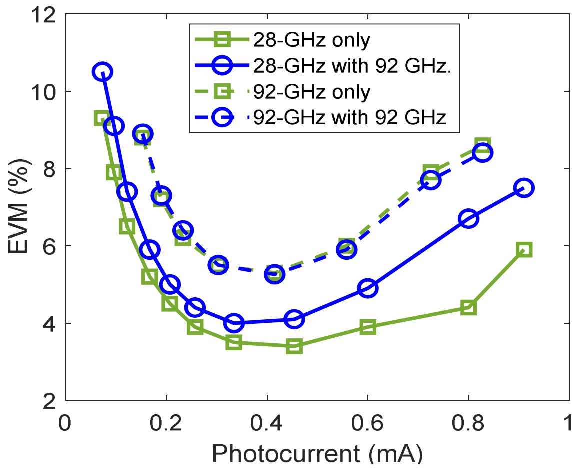

Fig. 9. Performance of 28- and 92-GHz signals.

6. CONCLUSIONS AND OUTLOOK

Radio communications in the mmW and THz bands play a vital role in providing high-speed and low-latency services. However, current bottlenecks must be overcome to construct a high-speed, cost-effective, and energy-efficient network for achieving sustainable development goals. Photonic technology is promising not only for generation and transmission, but also for the reception and downconversion of radio signals to reduce the cost, complexity, power consumption, and footprint of antenna sites and transceivers. In this paper, we present key fiber–wireless technologies that can enable the deployment of radio communications in the mmW and THz bands. A seamless fiber–wireless bridge system using all-photonic transceivers is useful for high-speed, low-latency, and energy-efficient communications in FWA and emergency events. A radio signal transparent relay and routing system is promising for extending the coverage to indoor environments and dead-zone areas. Additionally, the simultaneous generation, transmission, and reception of multiple radio signals in different frequency bands can facilitate the deployment of multiple RAN and IAB technologies in 6G and beyond networks. The obtained results confirm the potential of the proposed systems and can pave the way for the deployment of radio communication in high-frequency bands in IMT-2030 and beyond.

The proposed systems were demonstrated under specific conditions as the examples to prove the proposed concepts. However, they are flexible and can be applied to different use cases. Photonic technology has been used for radio signal generation and transmission. However, the use of photonic technology for radio signal reception and downconversion has not been widely considered. The simplicity of signal generation, transmission, and reception using photonic technology can enable high-speed, cost-effective, and energy-efficient radio communications in the mmW and THz bands. High-speed optical modulators are key components to facilitate the direct conversion of radio signals to optical signals. The conversion gain is an important parameter; thus, designing a high-conversion-efficiency modulator is crucial for achieving high performance. These features can be realized using thin-layer structure modulators [14]. Furthermore, high-speed optical modulators with operating frequencies of up to 500 GHz have been demonstrated using an electro-optic-polymer-based plasmonic modulator [15] and a thin-film LN modulator [16]. These developments reveal the possibility of converting high-frequency THz signals to optical signals. Consequently, the proposed systems are rendered feasible even in higher-frequency bands. Regarding the transmission capacity, based on the achieved results, 100- and 50-Gb/s systems can be expected for fixed access and mobile coverage extension applications, respectively. These systems can be further optimized to increase their performance and capacity. Moreover, the distance of the wireless links was limited in the experiments because of space limitations. Due to the short wireless links, the transmission power was limited to less than -25 dBm. By increasing the optical power to the PDs, radio signals with a power of -5 dBm can be generated. The distance of the wireless links can be extended to hundreds of meters using a power amplifier and high-gain antennas.

The technologies presented in this paper can be important topics for standardization in the ITU and other organizations. Currently, ITU-R is developing a framework for IMT towards 2030 and beyond, in which IMT-2030 is expected to support an enriched immersive experience, enhanced ubiquitous coverage, and new usage scenarios. Radio communications in the mmW and THz bands are considered key technologies for attaining the targets of IMT-2030. A report on the technical feasibility of IMT in bands above 100 GHz is being studied by the ITU-R. The presented technologies in this paper can be technical inputs for consideration, and the achieved results can provide valuable evidence for the feasibility study of radio communications above 100 GHz. In addition, Study Group 15 of ITU-T is studying key optical transport systems for home and access networks, including RoF systems. Consequently, the presented technologies can be topics for further study as potential transport solutions and use cases for future fixed and mobile access networks.

ACKNOWLEGEMENT

This work was supported in part by JSPS KAKENHI under Grant 22K04116 and by JST SICORP Grant Number JPMJSC22E1.

REFERENCES

[1] GSMA Vision 2030: mmWave Spectrum Needs, Full Report https://www.gsma.com/spectrum/wp-content/uploads/2022/06/5G-mmWave-Spectrum.pdf

[2] Recommendation ITU-R M.2160-0, "Framework and overall objectives of the future development of IMT for 2030 and beyond," (11/2023).

[3] NTT Docomo white paper, "5G Evolution and 6G," Jan. 2023.

[4] J. Sang et al., "Coverage Enhancement by Deploying RIS in 5G Commercial Mobile Networks: Field Trials," IEEE Wirel. Commun., 31(1), 172 - 180, Feb. 2024.

[5] D. N.P. Thalakotuna et al., "Overcoming 5G Millimeter Wave Black Holes," IEEE Future Networks Tech Focus, Volume 3, Issue 3, Nov. 2019.

[6] S. Koenig et al., "High-Speed Wireless Bridge at 220 GHz Connecting Two Fiber-Optic Links Each Spanning up to 20 km," Proc. OFC 2012, OM2B.1.

[7] Y. Horst et al., "Transparent optical-Thz-optical link transmission over 5/115 m at 240/190 Gbit/s enabled by plasmonics," in Proc. Opt. Fiber Commun. OFC, San Francisco, CA, USA, 2021, pp. 1–3.

[8] T. McKenna et al., "Photonic Downconverting Receiver Using Optical Phase Modulation," Proc. IMS2014.

[9] P. T. Dat et al., "Transparent Fiber-Millimeter-Wave-Fiber System in 100-GHz Band Using Optical Modulator and Photonic Down-Conversion," J. Light. Technol., 40(5), pp. 1483–1493, Mar. 2022.

[10] A. Kanno et al., "Multigigabit Relay Link Using Millimeter-Wave Radio-Over-Fiber Technologies," IEEE Photonics J., 5(6), 7902909, Dec. 2013.

[11] P. T. Dat et al., "Terahertz Signal Transparent Relay and Switching Using Photonic Technology," J. Light. Technol. 42(3), pp. 1173-1182, Feb. 2024.

[12] H. Mahmoud et al., "Error Vector Magnitude to SNR Conversion for Nondata-Aided Receivers," IEEE Trans. Wirel. Commun., 8(5), May 2009.

[13] 3GPP TR 38.834.

[14] Y. Yamaguchi et al., "Advanced Optical Modulators for Sub-THz-to-Optical Signal Conversion," IEEE J. Sel. Top. Quantum Electron., 29(5), Sept.-Oct. 2023.

[15] M. Burla et al., "500 GHz plasmonic Mach-Zehnder modulator enabling sub-THz microwave photonics," APL Photon., vol. 4, no. 5, 056106, May 2019.

[16] A. J. Mercante et al., "Thin film lithium niobate electro-optic modulator with terahertz operating bandwidth," Opt. Express, 26(11), 14819, May 2018.