Terahertz and Photonics Seamless Short-Distance Links for Future Mobile Networks

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Abstract

High-speed data transfer and high-performance imaging can be realized by using radio-waves in high-frequency bands, such as millimeter-waves and THz-waves, where wide frequency bands are available. However, the cell size would be smaller than a few hundred meters, due to large free space propagation loss and large atmospheric attenuation. Thus, many base stations, which are connected by networks, are required to offer nation-wide or global network services by such high-frequency radio-bands. The networks would be constructed by various transmission media including optical fibers and fixed wireless links, where many media converters are required. This paper reviews various technologies for seamless bridges between radio and optical links. For the time being, congestion of radio spectrum in THz bands is not significant. However, if we look at the history of radio-wave technologies, spectral congestion has been high even in newly developed high frequency bands. Even in active radio services in millimeter-wave or THz-wave bands, interference mitigation with passive services such as radio astronomy and Earth observation satellites is an important issue, as of now. This paper describes research trends of THz-wave technologies from the point of view of a figure of merit defined by a product of the carrier frequency and spectral efficiency, to discuss the significance of spectral efficiency enhancement in the high-frequency region. Analysis of power consumption of short distance radio systems is also shown to discuss expected performance of THz-wave links.

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Key Points:

- Seamless networks consisting of high-speed wireless and wired links can offer nationwide or global high-performance radio services.
- Multi-mode radio-over-fiber can be used for short-distance waveform transfer in future mobile networks.
- Interference mitigation is an important issue even in THz bands.
- High-speed wireless links can offer low-power consumption data transfer.

Abstract

High-speed data transfer and high-performance imaging can be realized by using radio-waves in high-frequency bands, such as millimeter-waves and THz-waves, where wide frequency bands are available. However, the cell size would be smaller than a few hundred meters, due to large free space propagation loss and large atmospheric attenuation. Thus, many base stations, which are connected by networks, are required to offer nationwide or global network services by such high-frequency radio-bands. The networks would be constructed by various transmission media including optical fibers and fixed wireless links, where many media converters are required. This paper reviews various technologies for seamless bridges between radio and optical links. For the time being, congestion of radio spectrum in THz bands is not significant. However, if we look at the history of radio-wave technologies, spectral congestion has been high even in newly developed high frequency bands. Even in active radio services in millimeter-wave or THz-wave bands, interference mitigation with passive services such as radio astronomy and Earth observation satellites is an important issue, as of now. This paper describes research trends of THz-wave technologies from the point of view of a figure of merit defined by a product of the carrier frequency and spectral efficiency, to discuss the significance of spectral efficiency enhancement in the high-frequency region. Analysis of power consumption of short-distance radio systems is also shown to discuss expected performance of THz-wave links.

1 Introduction

In 5G mobile system, over 10-Gb/s high-speed radio data transmission is realized by the “high-band”, of which frequency is above 24 GHz, while the “low-band” below 6 GHz is for large cells on coexisting with various conventional radio services [1]. Radio services using high-frequency bands draw a great deal of attention from researchers as transmission media for high-speed data transmission. Congestion of radio spectrum is an issue especially in microwave bands, by which various radio services including wireless local area networks (WLAN) are provided. Recently, interference mitigation becomes important, even in millimeter-wave bands whose frequencies are below 0.1 THz, where broadband wireless links for high-speed rails and high resolution radar imaging for airport runway surveillance have been developed [2,3]. Thus, it would be rather difficult to achieve wireless transmission whose bitrate is over 100 Gb/s by using frequency bands below 0.1 THz. In THz bands (0.1–10 THz), wide range of spectrum is available for mobile services are expected to offer over 100-Gb/s transmission for future mobile services such as beyond 5G [4, 5]. However, the expected transmission distance is shorter than a few kilometers due to large free-space propagation loss and atmospheric absorption in the THz bands, so that a number of base stations (BSs) are required to offer nationwide or global services by the THz bands.

A wide variety of transmission media, including optical fibers, fixed wireless radio links, satellite links, etc., are utilized for mobile backhaul (MBH) networks which connect BSs. Optical fiber transmission offers high-speed transmission, while fixed wireless and satellite links can provide easy-deployable networks for rural areas [6, 7]. More than 60% MBH links are based on optical fiber transmission in North-East Asia and North America. On the other hand, less than 10% links are optical in Sub-Sahara Africa, for example. In developing countries and regions, MBH depends largely on fixed wireless, which are based on microwave long-distance transmission. The transmission capacity of such wireless links is much smaller than in optical fiber links, because of the limit in the available radio bandwidth in microwave. Rapid growth of the share of optical fibers in MBH is expected in the world to mitigate huge data transmission demands in the MBH networks. However, according to the prediction in Ref. [6], the share of optical fibers in MBF for small cells will decrease in North East Asia. The share of fixed wireless by high-frequency bands will increase, while that of fixed wireless whose carrier frequencies are below 40 GHz will also decrease. In 5G with the high-band, many BSs should be connected to core networks through MBH, where it would be rather difficult to connect all the BSs only by optical fiber links. Thus, the share of the fixed wireless by high-frequency is expected to be increased to offer high-speed links with particular conditions where fiber deployment is not easy. In contract to conventional fixed wireless systems using microwave bands, the transmission distance of the wireless links by high-frequency bands is limited. Thus, we should construct hybrid networks consisting of optical fibers and radio-links, where many media converters bridging radio and optical signals. In beyond 5G systems, required transmission capacity for networks connecting BSs would be over 100 Gb/s. This paper focuses on seamless networks consisting of THz and photonic links, which can offer high-speed transmission for many BSs under various conditions. Signal conversion between THz and lightwave plays very important roles in such seamless networks. Radio-over-fiber (RoF) would provide effective and low-latency signal conversion.

Section 2 describes a concept of THz and photonic seamless networks dedicated for mobile services, where many BSs are effectively connected to core networks. Waveform transfer over fiber can be used for seamless media conversion between THz and photonic links. The RoF offers low-latency signal conversion with simple configuration. Section 3 provides THz link design with 0.3 THz and 0.5 THz as examples. Interference mitigation would be an issue even in such high-frequency bands. Fixed service (FS) would induce non-negligible interference to short-distance land mobile service (LMS). Due to propagation loss in the air, the expected transmission distance is shorter than a few kilometers, however, the loss due to absorption by atmospheric gases is not so significant at 0.3 THz. Section 4 reviews power consumption of commercial short-distance wireless transmission systems. Power consumption per bit can be described by a decreasing function of the bitrate. That implies that over 100 Gb/s radio transmission would offer low-power consumption short-distance links. Section 5 reviews recent THz transmission experiments by using a figure of merit defined by a product of the carrier frequency and spectral efficiency.

2 Concept of THz and photonic seamless network

Global mobile services including 5G are provided through many BSs, whose functions can be categorized into the following two parts: 1) baseband units (BBUs) which convert binary data streams into waveforms for radio-services and vice versa, and 2) antenna units which transmit and detect radio-waves. In dense urban areas, remote antenna units (RAUs) are commonly used to construct many small cells. Fig. 1 shows a schematic of networks connecting BBUs and RAUs, where mobile backhaul (MBH) links transfer digital data streams from BBUs to a backbone network, and mobile fronthaul (MFH) links transfer radio waveforms between RAUs and BBUs. While the MBF links can be offered by digital optical transmission as in conventional digital networks, the waveform transfer in the MFH links can be realized by analog or digital RoF. As of now, most of MFH systems are based on digital RoF, because digital data transmission whose bitrate is up to 10 Gb/s can be offered by low-cost optical transponders. The digital RoF interfaces are defined by the Common Public Radio Interface (CPRI), where the required bandwidth for Long-Term Evolution (LTE) based mobile systems is less than 10 Gb/s. However, the 5G NR (New Radio), which provides multi-gigabyte data transfer on demand, massive connections for many sensors, and ultra-reliable low-latency communications requires over 100-Gb/s high-speed digital transmission for CPRI-based MFH links. To reduce the required bandwidth for MFH, a part of signal processing functions in the BBUs are moved to the remote units. The configuration of the remote units would be complicated. In beyond 5G or 6G networks, the number of the remote units would be much larger than that of users, so that the configuration of the remote units should be simplified as much as possible to reduce the total installation cost. One of possible configurations to connect many simple RAUs would be wired and wireless hybrid networks shown in Fig. 1, where high-speed photonic and THz links are seamlessly bridged each other through wired and wireless media converters [4, 8]. Analog RoF can be used to simplify the configuration of the media converters, where the waveforms are converted into optical signals by high-speed optical modulators. At an RAU, the waveform can be derived from the optical signal by using a photodetector. For THz-wave systems, it would be rather difficult to generate radio-waveform directly from optical signals due to limitation of high-speed response of photodetectors. To overcome this difficulty, we can transfer a waveform as an intermediate frequency (IF) signal. The IF signal is converted into a THz signal through frequency conversion at the RAU. This scheme is called IF over fiber (IFoF). Fig. 2 shows configurations of the digital RoF and the analog RoF (IFoF). Analog RoF which can transmit waveforms for radio services with a very simple configuration. However, the waveform would be degraded by nonlinearity, reflection and excess noise in electric and optical components. When large over sampling rate is available, delta-sigma modulation can be used for waveform transfer, where the radio-wave can be derived by a simple RAU consisting of a photodetector, similar to that of analog RoF [9].

Single mode fibers (SMFs) are commonly used for analog RoF systems. However, multi-mode fibers (MMFs) or plastic optical fibers (POFs) can be also used for short-distance RoF transmission [10–13]. Fig. 3 shows a configuration of an in-vehicle RoF system which bridges 5G NR signals in the air and user terminals in a car cabin. A 28-GHz 5G NR signal generated by an arbitrary waveform generator for an IF signal generation and a signal generator used as a local oscillator is emitted through an amplifier and an transmitter (Tx) antenna. The radio-wave detected by a receiver (Rx) antenna on the roof of the car is converted into an optical signal for RoF transmission. A bend-insensitive MMF (BI-MMF) and a BI-graded-index POF (BI-GI-POF) were used for this demonstration. Fig. 4 shows measured error vector magnitudes (EVMs) for RoF transmission over a 20-m BI-MMF and a 5-m BI-GI-POF, where a reference signal was measured with a link over a 1-m coaxial cable. The receiver sensitivity was -60 dBm. The power penalty in the RoF transmission was less than 3 dB for a 64-QAM (quadrature amplitude modulation) OFDM (orthogonal frequency domain multiplexing) 5G NR signal whose bandwidth is 200 MHz. RoF with MMF or POF offers low-cost and light-weight solution which can be used for radio-wave distribution to small cells as well as for in-vehicle wiring applications.

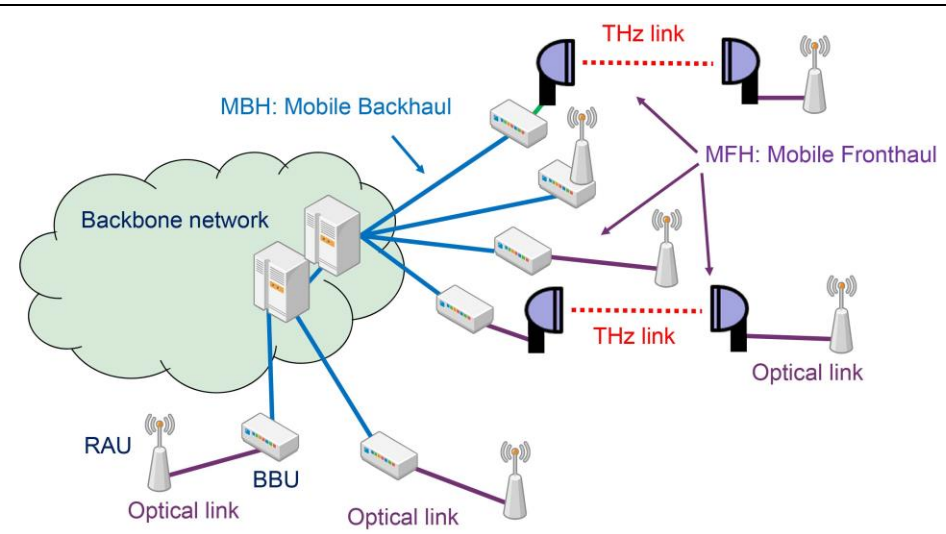

Figure 1. Configuration of MBH and MFH consisting of photonic and THz links.

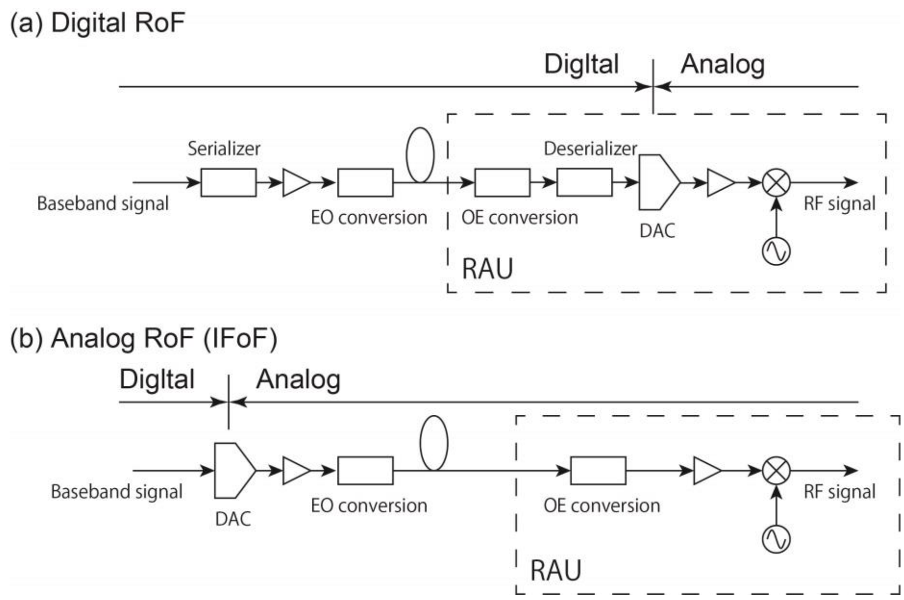

Figure 2. Configurations of RoF transmission. (a) Digital RoF, and (b) Analog RoF.

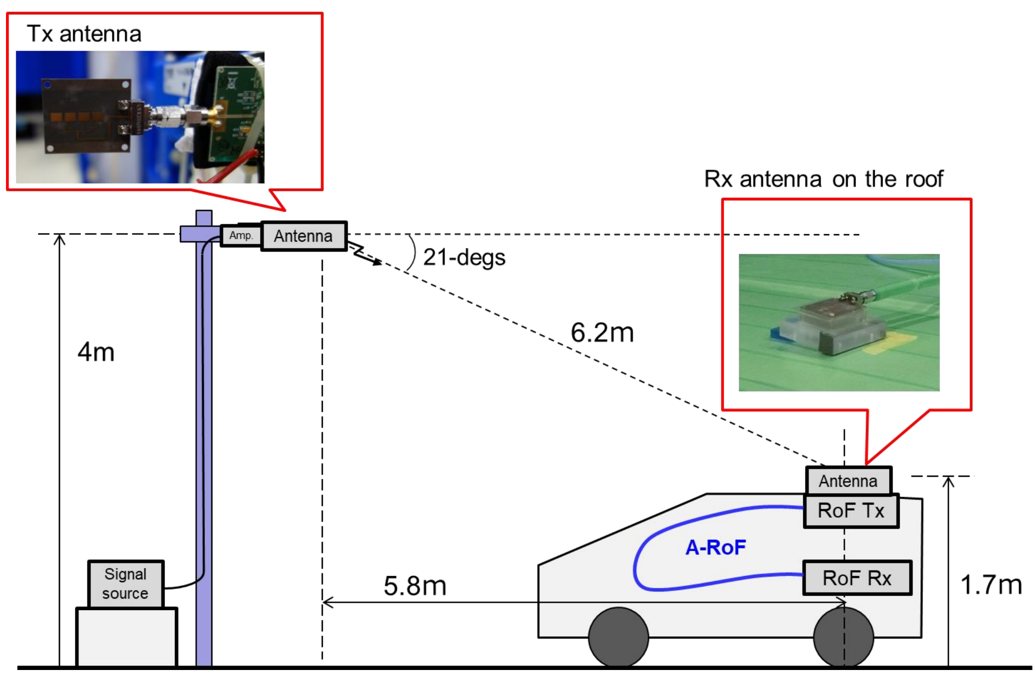

Figure 3. Experimental setup for an in-vehicle RoF system.

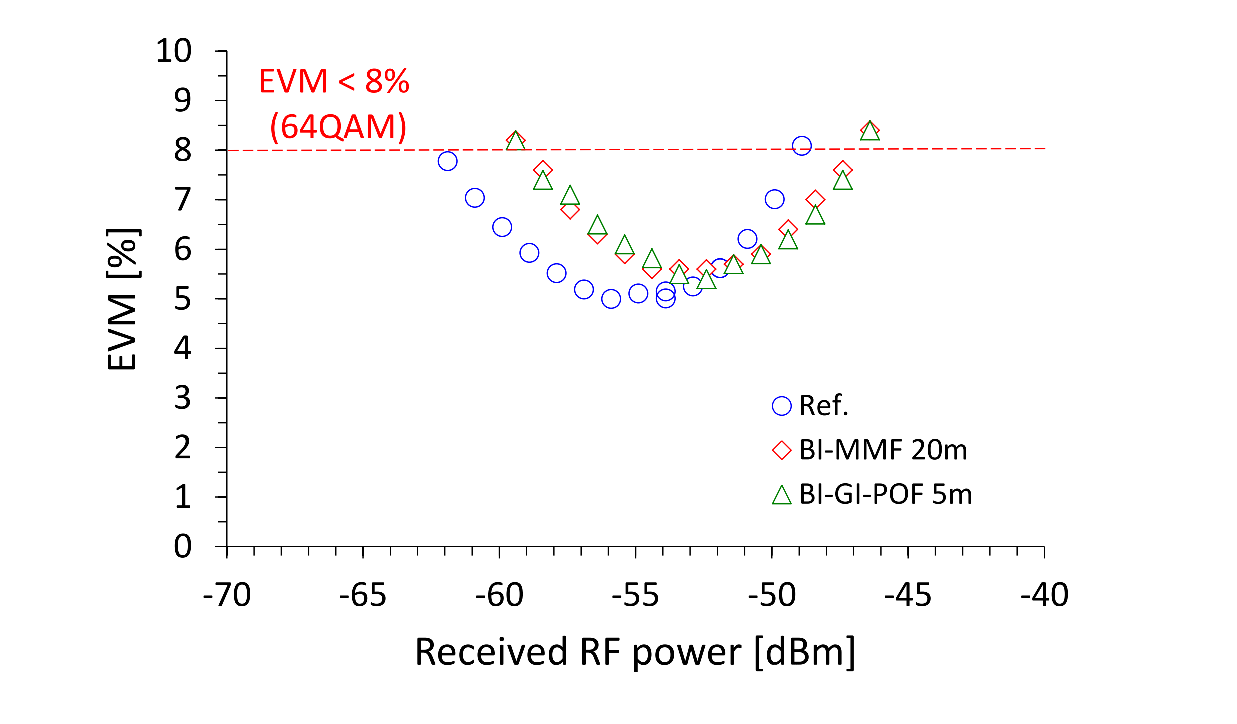

Figure 4. EVM of in-vehicle RoF transmission.

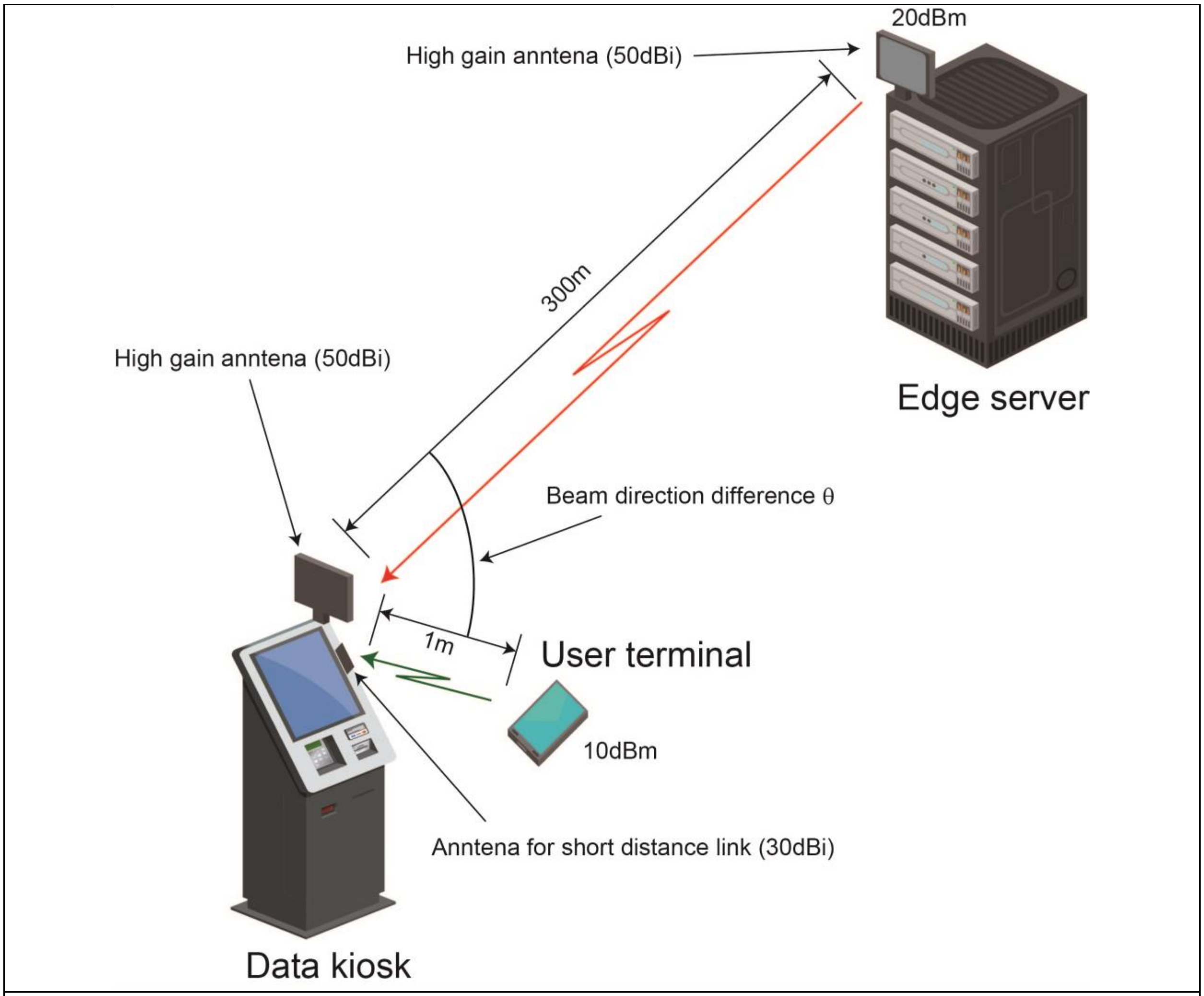

Figure 5. Interference between FS and LMS in 300-GHz band.

3 THz link performance

Transmission distance of THz links is limited by large free-space path loss and atmospheric absorption. As reported in Refs. [14, 15], a wide variety of radio services such as FS and LMS have been developed in a frequency range of 275–450 GHz, so that interference among different radio services would degrade THz-wave transmission performance. Here, as shown in Fig. 5, we consider interference between LMS and FS at 300 GHz, as an example. The LMS for short-distance connection between a data kiosk and user terminals would have interference from the FS for a few hundred meter transmission. The data kiosk has a high-speed FS link to an edge server. The transmission distance of the FS is assumed to be 300 m, while that of the LMS is 1m. The transmission power is 10 dBm for the short-distance LMS, and 20 dBm for the FS. A data kiosk has an antenna of 30-dBi gain for the LMS connecting user terminals and a high-gain antenna whose gain is 50 dBi for the FS. The atmospheric attenuation coefficient, defined by Ref. [16], is 5.24 dB/km for 300 GHz, where atmospheric pressure, water vapor pressure, water vapor density and temperature are assumed to be 1013.25 hPa, 9.9729 hPa, 7.5 g/m^3 and 288.15 K which are referred as a standard atmosphere (at sea level) defined in Ref. [17].

In the interference scenario shown in Fig. 5, the desired-to-undesired ratio (D/U) can be defined by the ratio of the LMS signal power and the FS signal power detected by the 30-dBi antenna at the data kiosk. Fig. 6 shows the D/U as a function of the main beam direction difference between the LMS and FS signals (θ in Fig. 6), where the antenna pattern offered in Ref. [18] was used to estimate the interfering signal (FS) detected by the antenna for the LMS. Here, we assume that the required signal-to-noise-power ratio (SNR) for 32-QAM is approximately 20 dB. When the direction difference angle θ is larger than 10 degrees, the interference signal power would be less than the maximum noise level defined by the required SNR. Thus, the angle θ should be approximately larger than 10 degrees to suppress the interference to the LMS by the FS. However, the short-distance LMS is aimed to connect many small terminals around a data kiosk and to bridge between a server and small displays. Thus, it would be rather difficult to avoid particular beam directions for interference mitigation. This result implies that interference suppression techniques and spectral efficiency enhancement would be important issues even in THz bands. One of possible solutions is to use new frequency resources such as over 400-GHz bands.

To discuss basic characteristics of THz-links, ideal SNR of THz transmission with 300 GHz and 500 GHz is investigated by using the Friis transmission equation, where the noise floor is assumed to be equal to the thermal noise level. Figs. 7 and 8 show SNRs of THz links with 300-GHz and 500-GHz carriers, respectively. The antenna gain is assumed to be 50 dBi (both for the transmitter and receiver). The transmission power is 20 dBm. The thermal noise power at 288.15 K is estimated -64.00 dBm for a 100-GHz bandwidth (BW) system. For 2-GHz BW, the noise power is -80.99 dBm. The atmospheric attenuation coefficients are 5.24 dB/km for 300 GHz and 66.23 dB/km for 500 GHz, with the standard atmosphere. On the other hand, rain attenuation is insensitive to carrier frequency in THz region [19]. The attenuation coefficients under 5mm/h rainfall are 4.47 dB/km and 4.27 dB/km for 300 GHz and 500 GHz, respectively. Those under 50 mm/h are 18.99 dB/km and 17.83 dB/km for 300 GHz and 500 GHz, respectively. The free-space path loss coefficients are 142.0 dB for 300 GHz and 146.4 dB for 500 GHz. Thus, the major part of the difference in the SNR is due to the atmospheric attenuation. For short-distance THz-links, the SNR is not so sensitive to the rainfall especially in the 500 GHz FS link case.

The transmission capacity depends on the modulation format and the noise figure of the THz link. For quadrature phase shift keying (QPSK), the required SNR is approximately 10dB. By assuming that the noise figure is 15 dB as shown in Ref. [15], the required SNR margin is 25 dB approximately. The modulation speed (baud rate) can be assumed to equal to the signal BW when the THz-wave is modulated by an ideal filtered QPSK waveform. Thus, the transmission capacity of the 100-GHz BW link would be 200 Gb/s. Here, we consider expected link distances for 200-Gb/s transmission under light rain (5 mm/h) and heavy rain (50 mm/h) conditions. As shown in Fig. 7, over 1-km transmission can be achieved by the 300-GHz link under light rain condition, while the expected link distance would be 780 m under heavy rain condition. For the 500-GHz link, the expected link distances are 380 m and 310 m for light rain and heavy rain conditions, respectively. When the transmission power is 0 dBm, the expected link distances are for 130 m and 110 m for light rain and heavy rain conditions, respectively. Due to large atmospheric attenuation, the link distance in the 500-GHz band is much less than in the 300-GHz band. However, the expected distance is still larger than 300 m even in heavy rain condition. Thus, we can use the 500-GHz link to bridge many small cells, without any interference to 300-

GHz short-distance links. The antenna size for 500-GHz is much smaller than in conventional bands. For example, the diameter of a 50-dBi parabolic antenna would be 8.5 cm when the aperture efficiency is 50%.

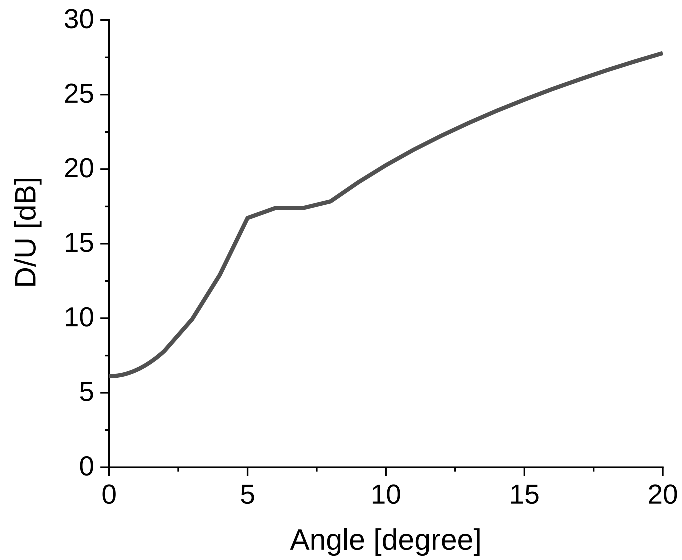

Figure 6. Desired and undesired signal ratio.

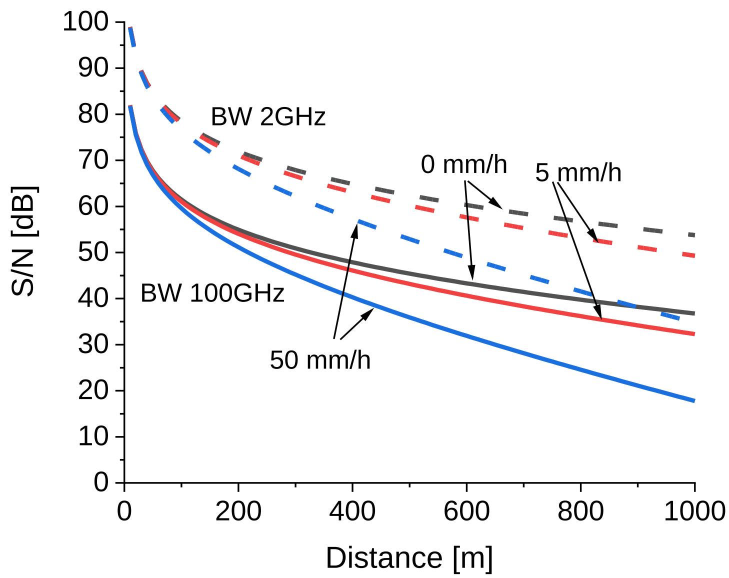

Figure 7. SNR of 300-GHz radio links. Solid lines and dashed lines are for 100-GHz and 2-

GHz bandwidth links, respectively.

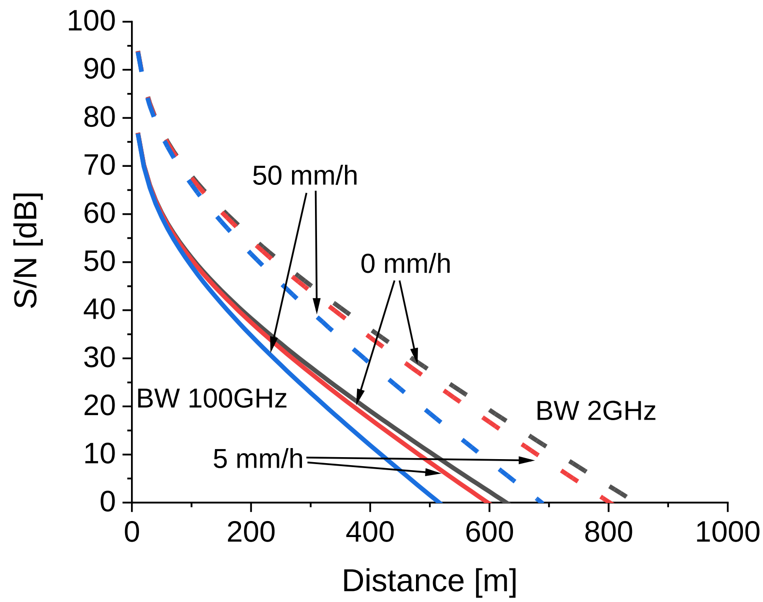

Figure 8. SNR of 500-GHz radio links. Solid lines and dashed lines are for 100-GHz and 2-GHz bandwidth links, respectively.

4 Power consumption of short-distance wireless systems

Many small cells should be connected through THz and photonic seamless networks, where many media converters are required. Thus, the reduction of power consumption in radio transmitters is one of very important technical challenges for wired and wireless seamless networks [4]. Fig. 9 shows the radio transmitter power consumption per bit, which can be defined by the ratio of the total power consumption in Watt (Joule per second) to the bitrate in bit per second, for various short-distance wireless transmission systems [5]. The vertical axis denotes power consumption of radio transmitters per bit. The horizontal axis shows the wireless transmission bitrate. As reported in Refs. [5, 20], high speed wireless links which largely reduce the time duration for data transmission can provide low power consumption transmission. Power consumption for particular functions, such as management of baseband signal processing and power supply would be proportional to the time duration. The power consumption per bit would be inversely proportional to the bitrate, if such functions are dominant in the power consumption.

A curve fitting result for the power consumption per bit for short-distance wireless transmission systems including Zigbee, Bluetooth, WLAN (IEEE802.11n, 802.11ac and 802.11ad), and WirelessHD is given by

$$y = 130 \times x^{-0.7} \quad , \qquad (1)$$

where the units of x and y axes are Mb/s and nJ, respectively. The curve fitting result has a difference of a factor of $x^{0.3}$ from ideal inverse proportion. We deduce that this is due to degradation of power efficiency of electric circuits in high-frequency region. In ideal transmitters and receivers, the power consumption per bit would not depend on the bitrate under the same SNR. However, the power consumption would be large in high-frequency or high-bitrate systems, because the circuits should manage electric signals in high-frequency region where ohmic loss is large. Despite such effect, high-speed wireless transmission systems can provide low power consumption data transfer. For example, millimeter-wave systems, such as 802.11ad and WirelessHD can offer low power consumption and high-speed wireless data links. For reference, the power consumption per bit of a 100GbE system (IEEE802.3bm) is plotted in Fig. 9. The curve fitting result in 100 Gb/s and the power consumption of the 100GbE system are in the same order of magnitude. This results implies that power consumption of over 100-Gb/s short-distance wireless links realized by using THz bands would be less than in conventional radio links using low-frequency radio-waves.

Fig. 10 shows power consumption survey results performed in 2012 [20] and in 2018 [5]. The curve fitting result for the result reported in Ref. [20] is

$$y = 260 \times x^{-0.6} \quad . \qquad (2)$$

The dependency on the bitrate x is similar to that of Ref. [5]. However, if we look at the power consumption of the radio equipment for the same bitrate, the power consumption surveyed in 2018 is less than in 2012. The difference in the coefficients in Eqs. (1) and (2) reflects power efficiency improvements in high-speed electric circuits during 2012–2018.

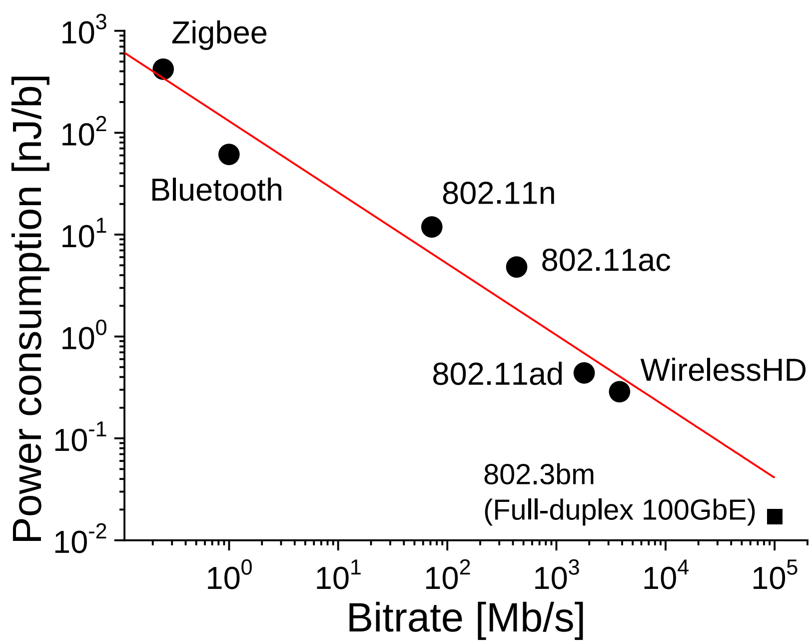

Figure 9. Power consumption per bit in short-distance wireless systems [5].

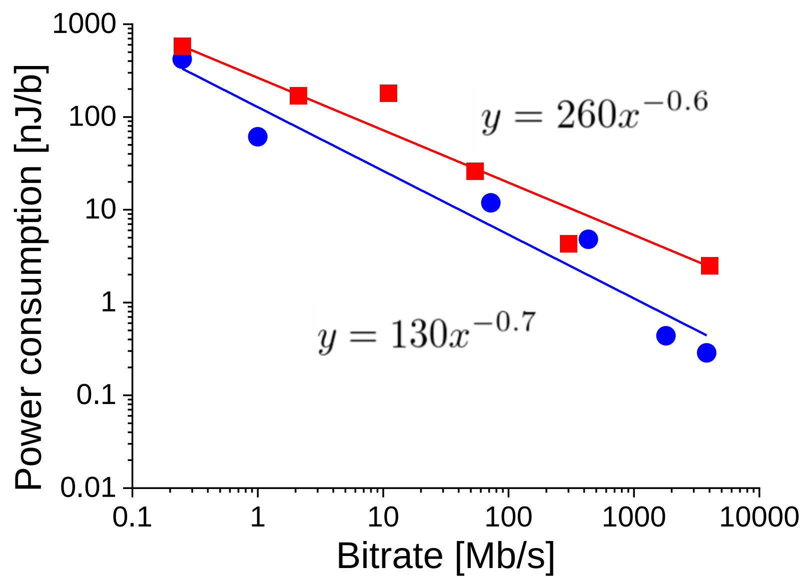

Figure 10. Power consumption per bit surveyed in 2012 (squares) [20] and in 2018 (dots) [5].

5 Spectral efficiency and transmission capacity

A figure of merit has been defined by a product of carrier frequency and spectral efficiency, (CFSE: carrier frequency spectral efficiency product, henceforth), in order to measure impact on congestion mitigation by high spectral efficiency and high carrier frequency [5]. Fig. 11 shows CFSE of THz transmission experiments reported recently is shown in Fig.11, as a function of the data rate. QPSK offers the largest data rate, while 16-QAM and 64-QAM offer large CFSE. Due to limitation of high-speed operation of electric and optical devices, there is a trade-off relation between CFSE and data rate. Complicated modulation formats such as 16-QAM and 64-QAM could not be applied to high baud rate systems. Fig. 12 shows CFSE for various carrier frequency (CF). If the spectral efficiency (SE) does not depend on CF, the CFSE is proportional to CF. However, the CFSE has a peak at 300 GHz. It shows that modulation formats with many symbols are not mature enough in THz bands above 300 GHz. These results indicate that CFSE would be useful to describe contribution to mitigation of spectral congestion. Figs. 11 and 12 implies that the bitrate of THz links can be increased without losing spectral efficiency in frequency range below 300 GHz, where the bit rate would be up to 100 Gbit/s.

The product of the CFSE and data rate of the THz transmission systems is shown in Fig. 15, to investigate the trade-off between the spectral congestion mitigation and transmission capacity, where the transmission performance is described by the data rate. The product has a maximum at 0.3 THz and decreases rapidly for CF larger than 0.5 THz. The use of a CF between 0.3 THz and 0.5 THz provides a well-balanced high-speed radio transmission system.

6 Conclusions

This paper reviewed seamless networks consisting of high-speed wireless and wired links which can offer nationwide or global high-performance radio services with limited radio spectrum. The number of BSs would be much larger than that of users, and the diameters of cells would be less than a few hundred meters. Thus, a number of short-distance high-speed links are required, where various transmission media including optical fibers and THz links would be used to configure the seamless networks. To bridge wired and wireless links, effective waveform transfer is required, where the power consumption and latency should be minimized by simple media converters. One of possible solutions for this issue is to use RoF, where a radio-wave is transmitted over an optical signal. Multi-mode radio-over-fiber would offer a low-cost waveform transfer option for short-distance links. This paper also investigated potential interference in THz bands, where various radio services have been already proposed. In the 300-GHz band, the interference from a FS link signal to a short-distance LMS link would be an issue. By using 500-GHz band, we can construct FS links whose distance is up to a few hundred meters. Although attenuation in the air is very large, over 100-Gb/s transmission can be designed by using a small antenna. If we can use the 500-GHz band for such FS links, we can avoid the interference in 300 GHz. We also discussed the power consumption of short-distance radio transmission systems. Based on survey for commercial radio systems, we can deduce that high-speed wireless links can offer low-power consumption data transfer. That implies that over 100-Gb/s wireless links realized by THz-bands can offer low-power consumption data transmission. Such technologies would be applied to high-speed short-distance transmission for data center or in-car applications. We also investigated the spectral efficiency and carrier frequency of THz transmission systems. In frequency range below 300 GHz, we can increase the bitrate without losing the spectral efficiency. However, in the higher frequency range, the spectral efficiency would be degraded. The peak of the CFSE would describes the frontline of the research on THz hardware.

Acknowledgments

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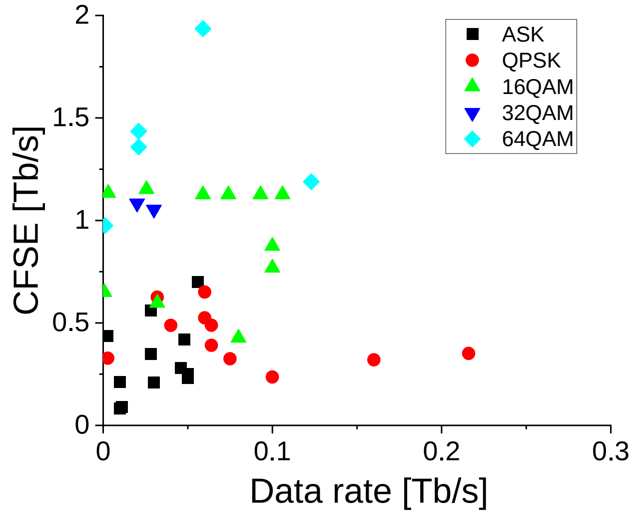

Figure 9. CFSE with respect to data rates [5].

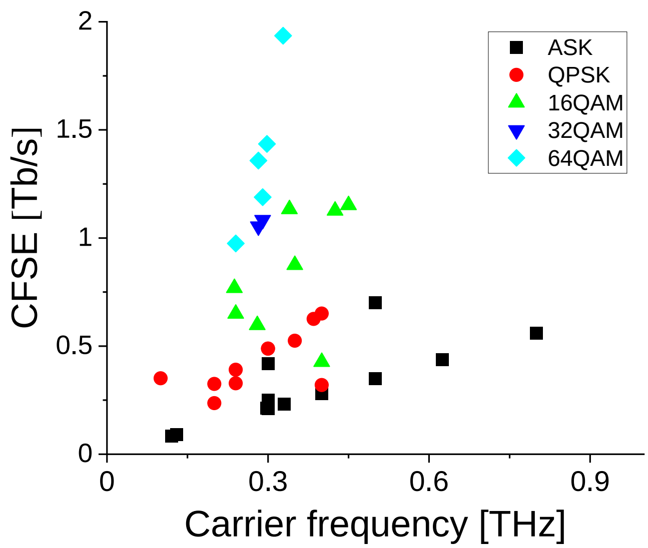

Figure 10. CFSE with respect to carrier frequency [5].

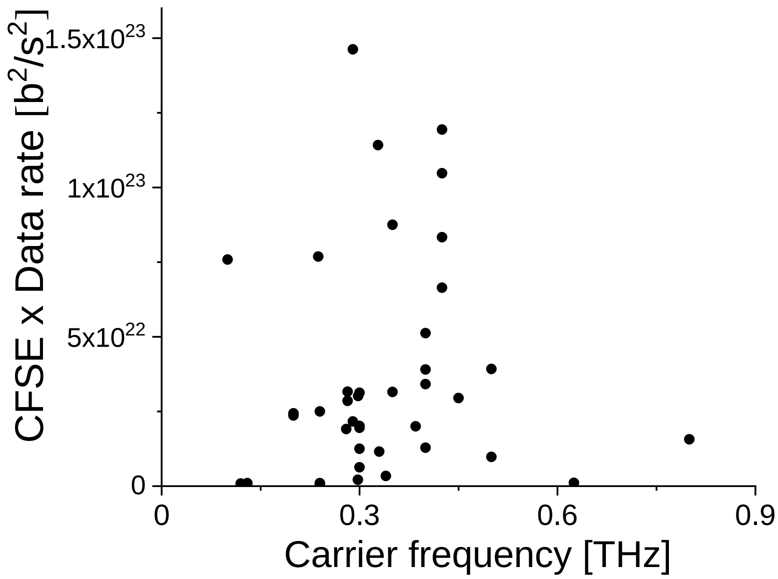

Figure 11. Product of CFSE and data rate.

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