Terahertz and photonics seamless networks

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***Abstract*— Radio links using terahertz (THz) waves can provide high-speed wireless transmission whose bitrate is higher than 100Gb/s. Congestion of radio spectrum in THz bands (0.1-10 THz) is not so significant for the time being. However, multi-level modulation formats would be required in in THz bands as well as in conventional millimeter-wave or microwave bands, to increase spectral efficiency. We provide overviews on spectral efficiency and transmission capacity of high-speed radio links using THz bands. Reduction power consumption in radio equipment is also very important to reduce operation cost of networks. We describe a survey result on power consumption of short-distance wireless systems. The result implies that THz high-speed radio links would be useful to reduce power consumption per bit in transmission. However, transmission distances in THz systems would be shorter than a few kilometers due to attenuation in the air. Thus, we should rely on seamless networks consisting of THz radio-links and optical fibers, where devices developed for optical fiber transmission can be used to THz wave generation and detection.**

***Keywords*— THz, millimeter-wave, optical fiber, modulation, transmission**

I. Introduction

5G realized over 10Gb/s high-speed wireless data services, by using the "high-band," whose frequency is above 6 GHz, while the "low-band" is for macro or small cells on coexisting with conventional mobile networks [1]. Congestion of spectrum is significant at frequency bands lower than 100 GHz where it would be rather difficult to increase transmission capacity. In THz bands (0.1-10 THz), wide range of spectrum is available for high-speed wireless transmission whose bitrate is over 100 Gb/s [2, 3]. Due to large THz wave propagation loss, transmission distance would be shorter than a few hundred meters, so that a number of base stations (BSs) and remote antenna units (RAUs) are required to provide wide coverage [3].

Optical fiber transmission is commonly used to connect the BSs and RAUs. Hybrid networks consisting of optical fiber and radio-wave links would play important roles in future mobile networks where a number of BSs and RAUs should be connected. The radio-wave links use THz waves, to reduce the bitrate difference between optical fiber links and radio-wave links. Thus, the hybrid networks would have many interfaces between photonic and THz links. Reduction of the cost and power consumption of the interfaces would be very important issue to realize the future mobile networks with low deployment and operation cost. In addition, latency reduction in the interference is also indispensable for low-latency transmission which is required in mission-critical applications.

To reduce the latency and power consumption, the configuration of the interfaces should be as simple as possible [3,4]. Radio-over-fiber (RoF) which transfers waveforms for radio services over fibers can offer bridge between THz-waves in the air and optical signals in the fibers.

This paper provides overviews on spectral efficiency and transmission capacity of state-of-art THz systems. We define an index to measure impact on congestion mitigation, by a product of carrier frequency and spectral efficiency. The index shows that 300GHz radio links can provide over 100Gb/s high-speed transmission without losing spectral efficiency. This paper also describes a survey result on power consumption of short-distance wireless systems, to discuss that of THz transmission systems. Configurations of seamless networks are provided to discuss solutions for high-speed THz communications.

II. Carrier frequency and spectral efficiency

The use of THz carrier reduces spectral congestion in the frequency lower than 100 GHz. Enhancement of spectral efficiency relaxes the congestion as well. Occupancy of the THz region is so high as of now. However, the congestion in THz will be severe when the THz region is commonly used for various applications. We define a figure of merit by a product of carrier frequency and spectral efficiency, (CFSE: carrier frequency spectral efficiency product), to measure contribution to the congestion mitigation [3].

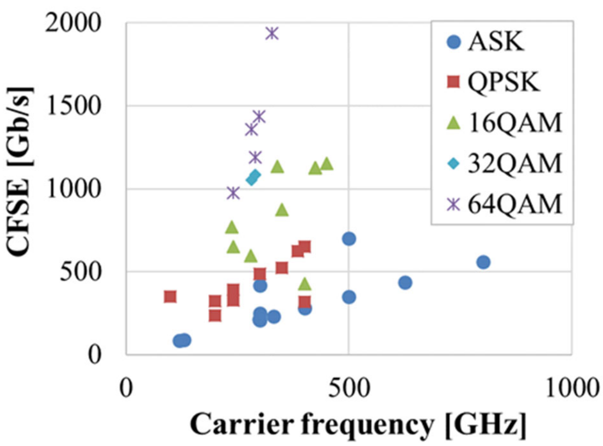

Figure 1 Carrier frequency spectral efficiency product (CFSE) as a function of carrier frequency [3].

Figs. 1 and 2 show the CFSE of the state-of-the-art THz transmission systems, where multi-level modulation formats such as quadrature phase shift keying (QPSK), 16 and 64 quadrature amplitude modulation (QAM) realize large CSFE [5-33]. The CFSE is proportional to the carrier frequency, when the spectral efficiency is constant. However, there is a peak at 300 GHz, as shown in Fig. 1. It shows that multi-level modulation technologies are not matured enough in frequency range over 300 GHz, where precise control of the THz waves is rather difficult as for now. The CFSE is useful to describe the status and trends of the high-speed transmission technologies. Fig. 2 shows the CFSE as a function of the data rate of the THz transmission systems. QPSK provides the largest data rate, while QAM realize large CFSE. High baud-rate QAM would be rather difficult in THz region.

From Figs. 1 and 2, we can conclude that the state-of-the-art THz radio links can provide 100 Gb/s high-speed transmission by the use of 300 GHz frequency region, without losing the spectral efficiency.

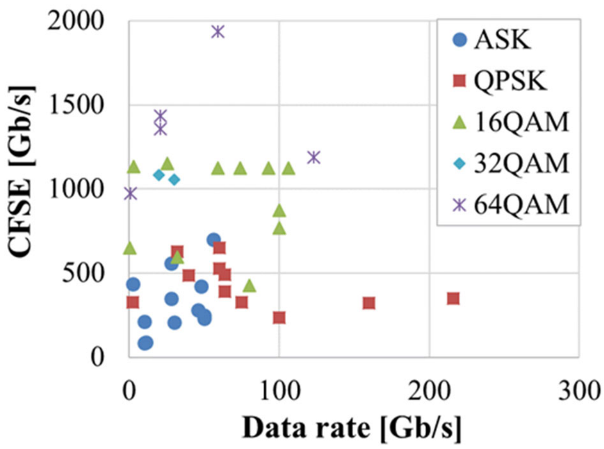

Figure 2 Carrier frequency spectral efficiency product (CFSE) as a function of data rate [3].

III. POWER CONSUMPTION OF RADIO TRANSMITTERS

Future mobile systems would require a number of BSs and RAUs, so that the power consumption reduction of the radio transmitters is very important to reduce the operation cost. Fig. 3 shows the power consumption per bit in various short distance radio transmission systems [3]. The power consumption is described as a function of the bitrate, where the horizontal axis is bitrate of a radio systems.

This plot is based on the specifications of the following wireless modules: Zigbee (NEC ZB24TM-Z2701), Bluetooth (Mitsumi WML-C75), IEEE 802.11n (Silex Technology SX-SDMGN), IEEE 802.11ac (Silex Technology SX-SDMAC-2832S+). For IEEE 802.11ad and WirelessHD, we used specifications in Refs. [34, 35]. The power consumption of an optical transmitter (Finisar FTLC9152RGPL 100G 100m QSFP28 SWDM4 optical transceiver) is also plotted as a reference.

The total radio transmitter power consumption includes the power consumption at the power source, baseband unit for signal processing, radio front-end unit for radio-wave generation and detection, etc. That of particular functions, such as power supply, system management, packet buffering, should be proportional to time duration for transmission. The power consumption per bit would be inversely proportional to the bitrate, if such functions are dominant in the power consumption. Fig. 3 provides a curve fitting result given by

$$y = 1.3 \times 10^2 \times x^{-0.7} \quad , \qquad (1)$$

where the units of x and y axes are nJ and Mb/s, respectively. The curve fitting result has a difference from inverse proportion in the power index of $x^{0.3}$. The difference would be due to large power consumption in the rf front-end units in the transceiver modules.

Although the power consumption of electric circuits would be large in high-frequency operation, high-speed millimeter-wave transmission systems such as 802.11ad and WirelessHD can provide low power consumption and high-speed wireless data links. As for now, data of the power consumption of high-speed radio transmission systems using THz are not available, but we may expect low-power consumption with high-bitrate transmission. Assuming that the power consumption of the THz system whose bitrate is 100 Gb/s would follow the curve fitting result, the power consumption would be lower than conventional radio links and could be close to that of optical transmission.

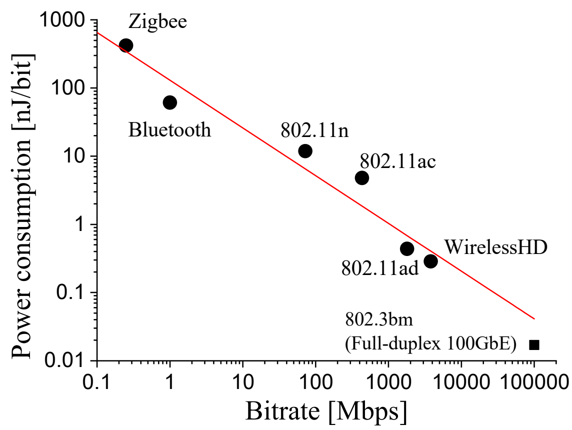

Figure 3 Radio transmitter power consumption [3].

IV. SEAMLESS NETWORKS

Interfaces between photonic and THz links bridge high-speed optical and electric signals, by the use of optical-to-electric (O/E) and electric-to-optical (E/O) conversion. Fig. 4 shows a configuration of THz and photonics interfaces, where multi-level modulation formats such as QAM are utilized both in the optical fiber and radio links. Digital coherent technique is commonly used for multi-level signal detection, where the phase of the detected signal is estimated by using digital signal processing (DSP) units. As shown in Fig. 4, we need many DSP units both in the photonics and THz parts. Latency and power consumption in the DSP units would be an issue for mission-critical applications, while latency in O/E and E/O conversion is only from signal propagation delay in the conversion devices, so that it would be negligible smaller than that in DSP. On the other hand, RoF provides low-latency conversion between radio-wave and optical signals, where waveforms for radio services transferred over fibers. In analog RoF, optical signals modulated by the waveforms are directly converted into radio-waves by using photodetectors. Thus, the total latency of optical and radio links including media conversion would be much smaller than in conventional systems with many DSP units. Even in RoF-based systems, DSP would be required for detection of multi-level signals or compensation of signal deformation [36]. However, the number of required DSP units would be minimized as shown in Fig. 5. Waveforms pass through the interfaces directly, while the DSP unit at the receiver provides comprehensive waveform compensation. At the RoF transmitter, a photonic local oscillator generates optical spectral component whose frequency separation equals the THz carrier frequency.

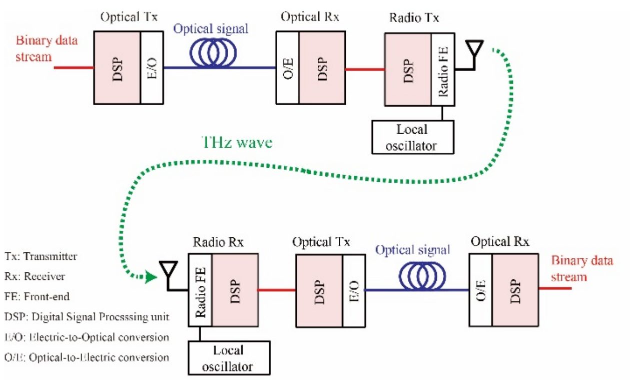

Figure 4 Configuration of THz and photonics interfaces, where coherent transmission is used both in radio and optical links.

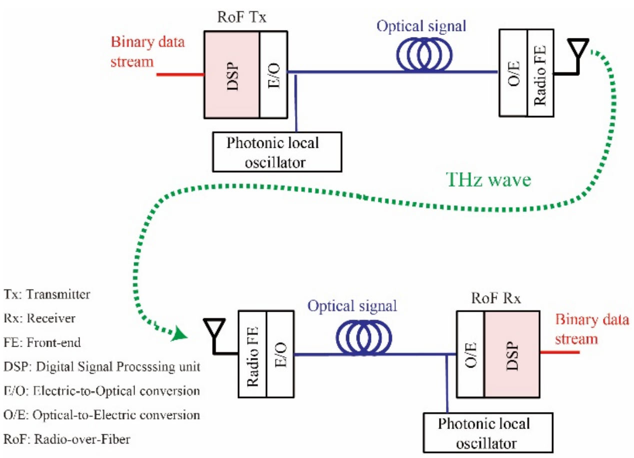

Figure 5 Configuration of THz and photonics interfaces, with RoF.

In RoF based systems as shown in Fig. 5, E/O and O/E conversion devices should respond to the carrier frequency. However, it would be rather difficult to have direct E/O or O/E conversion in THz region. Fig. 6 shows a configuration of IF-over-fiber (IFoF) where the THz carrier is generated in the radio front-end unit by using a frequency multiplier [36]. The IFoF receiver generates local oscillator signals.

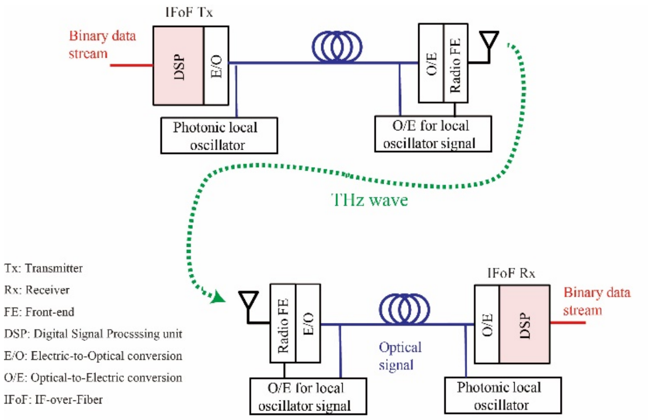

Figure 6 Configuration of THz and photonics interfaces, with IFoF.

Stability of the carrier frequency has a significant impact on radio transmission performance. A THz carrier can be generated by two laser sources whose frequency separation is in THz region, however, the stability depends on that of the two lasers. The linewidth of the THz signal depends on that of the lasers. For stable operation, we need precise temperature and current control for lasers. If we use standard laser diodes designed for optical fiber communications, the linewidth would be a few MHz. The frequency excursion would be much larger than in typical electronic oscillators.

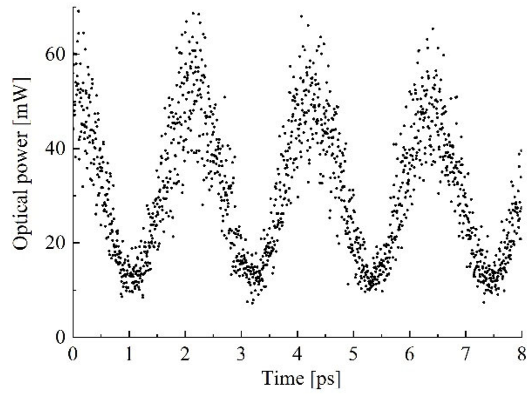

Figure 6 470GHz signal generated by external modulation.

Stable Phase-locked optical spectral components can be generated by using optical external modulators, where the stability is almost same as the electric signal source. Although the frequency response of the modulator is limited up to 100GHz, high-frequency signal generation whose frequency is up to a few hundred GHz can be generated by using high order sidebands in optical phase modulated signals [37, 38]. The THz signal generated from the optical sidebands is very stable in frequency domain as well as in time domain. A reciprocating optical modulator (ROM), consisting of a pair of optical filters (input and output filters) and an optical phase modulator, can generate THz carrier components [37]. Desired optical sideband components would be enhanced by the reciprocating modulation process where intermediate sideband components are confined between the filters. Fig. 7 shows a time domain profile of a 470 GHz signal generated by the ROM [39].

V. Advanced electronics for THz communications

The state-of-the-art THz technologies at 300 GHz can provide 100 Gb/s high-speed transmission, without losing the spectral efficiency, as discussed in Section II. However, most of the results reported recently based on off-line signal processing to show feasibility of such THz links, where a real-time transmission should be realized for actual applications.

To offer a real-time THz transmission, the Horizon 2020 EU-Japan project ThoR ("TeraHertz end-to-end wireless systems supporting ultra high data Rate applications") will develop an over 100 Gb/s radio transmission system using frequency band beyond 275 GHz [40].

The ThoR aims to realize high-speed wireless transmission using key enabling THz technologies. An ultra-broadband, high linearity THz transmitter at 300 GHz will be demonstrated by using photonic local oscillator and multi-functional THz integrated semiconductor circuits for up-conversion and medium power amplification. 300 GHz radio signals will be generated from V- or E-band IF signals, where V- or E-band modems will be used for IF-signal generation from real-time baseband data streams. A Traveling-Wave Tube Amplifier (TWTA) will be required for km-range transmission [41]. A 300 GHz receiver will be developed by using multi-functional THz integrated circuits with high dynamic range, low noise figure and high spectral purity photonic local oscillator generation. The expected output power of the TWTA is 1W at 300GHz, where the integrated semiconductor circuit would generate over 10mW signals to drive the TWTA. The photonic LO signal can be easily distributed over fibers without losing purity of the signal.

Photonics would be useful for generation and distribution of THz signals over optical fibers. High-speed semiconductor integrated circuits are required for THz generation and detection at RF-frontends. TWTAs can amplify the THz signals up to 1W. Combination of such various types of components including photonic devices, compound semiconductors and vacuum tubes, are required for demonstration of over 100Gb/s THz links.

VI. Conclusion

This paper provides research trends on THz and photonic seamless networks which would be useful for future mobile systems, where a number of BSs and RAUs should be effectively connected. CFSE, an index for contribution to mitigation of spectrum congestion, implies that the state-of-the-art THz radio links would provide 100 Gb/s high-speed transmission by the use of 300 GHz frequency region, without losing the spectral efficiency.

The Horizon 2020 EU-Japan project ThoR will demonstrate real-time THz transmission by using high-speed electronics and photonics. The peak in of the CFSE shows the status of the state-of-the art THz technology and the frontline of the THz research. The peak frequency can be increased by developing high-power and pure THz signal generation, with various types of electric and photonic devices.

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