Present and Future of Terahertz Communications

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(Invited Paper)

***Abstract*—Recent changes in how people consume multimedia services are causing an explosive increase in mobile traffic. With more and more people using wireless networks, the demand for the ultra-fast wireless communications systems is increasing. To date, this demand has been accommodated with advanced modulation schemes and signal-processing technologies at microwave frequencies. However, without increasing the carrier frequencies for more spectral resources, it may be quite difficult to keep up with the needs of users. Although there are several alternative bands, recent advances in terahertz-wave (THz-wave) technologies have attracted attention due to the huge bandwidth of THz waves and its potential for use in wireless communications. The frequency band of 275 $\sim$ 3000 GHz, which has not been allocated for specific uses yet, is especially of interest for future wireless systems with data rates of 10 Gb/s or higher. Although THz communications is still in a very early stage of development, there have been lots of reports that show its potential. In this review, we will examine the current progress of THz-wave technologies related to communications applications and discuss some issues that need to be considered for the future of THz communications.**

***Index Terms*—Future wireless communications, terahertz communications, THz-waves.**

I. Introduction

IN 1901, Marconi and his colleagues demonstrated the first transatlantic wireless communications [1], and since then, electromagnetic waves have been used for communications over long distances. However, only quite recently have radio systems been used to deliver information or data other than voice or simple text messages. Various multimedia services based on the Internet were introduced during the 1990s and traffic related to such services has been steadily increasing worldwide, until recently, but this traffic has normally been consumed via wired networks. However, with the introduction of new mobile devices and new multimedia services working in wireless environments over the last few years, we are seeing changes in how people consume multimedia services. The number of users of wireless networks is dramatically increasing. Moreover, users are consuming many more packets and much more digital information with mobile devices than they did with stationary personal computers connected to the wired network. The Japanese government estimated a compound annual growth rate of mobile traffic in Japan of around 71% from 2007 to 2017, with mobile traffic in 2017 becoming 220 times more than that in 2007 [2]. One market research firm has also forecasted a similar trend for the U.S. market: Rising by a rate of 117%, mobile traffic will reach 327 PB (PB $= 10^{15}$ Byte) per month in 2015, which will be 40 times more than that in 2010 [3]. To satisfy the needs of users, the data capacity of wireless communications has been improved over the last a couple of decades, with progress in speed that has been much faster than for wired ones, and this trend will continue for a while [4]. Eventually, we will be able to enjoy the full speed of future wired networks in a wireless environment, which will be around 10 Gb/s or even faster.

In many current wireless communications systems operating at microwave frequencies, data capacity has been improved by increasing the spectral efficiency by means of advanced modulation schemes and signal processing technologies [5], [6]. However, achieving rates of 10 Gb/s or faster looks quite challenging because of a fundamental limitation of current technologies—narrow bandwidth. For future wireless communications systems, it is obvious that more spectral resources are necessary. In the race toward ultra-fast future wireless communications systems [7], several candidates, including ultra wideband (UWB) [8], 60-GHz radio [9]–[12], free-space optical communications (FSO) [13], [14], and IrDA [15], have been being investigated, and terahertz (THz) waves have recently joined in the race [16]–[20].

THz waves, which are located between millimeter waves and infrared lightwaves in the electromagnetic spectrum, had rarely been utilized, except in astronomy and other related fields [21], because of the lack of devices for generating and detecting them. The emergence of femtosecond lasers and photoconductive antennas during the 1980s made it possible to use THz waves for various applications [22], [23], such as bio- and medical science, pharmacology, and security [24], [25]. Recently, compound semiconductor devices operating at up to 1 THz have been reported [26], [27], and even Si-CMOS technologies, which had been assumed not to be suitable for THz-wave applications because of the lossy substrate, exhibit a reasonable power gain at frequencies of over 100 GHz [28], [29]. These recent advances have attracted attention toward the huge bandwidth of THz waves and its potential for use in wireless communications. For future wireless systems with data rates of more than 10 Gb/s, especially of interest is the frequency band of 275 $\sim$ 3000 GHz, which has not been allocated for specific uses yet.

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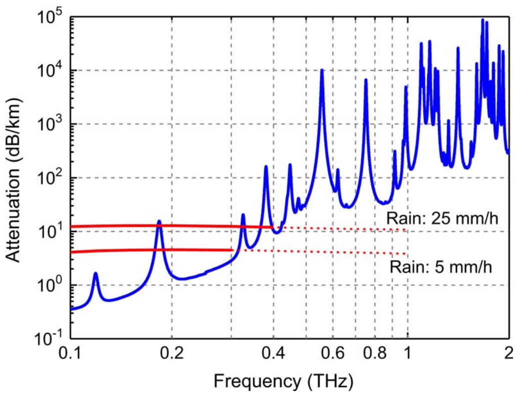

Fig. 1. Atmospheric attenuation computed with ITU-R and *am* models and attenuations due to rain rates of 25 and 5 mm/h. The atmospheric conditions for the calculation are sea-level altitude, water content of 7.5 g/m^3, and atmospheric temperature of 20 °C.

TABLE I
PARAMETERS FOR LINK BUDGET CALCULATION

Quantity	Symbol	Value
Transmitting power	P_t	0 dBm
Carrier frequency	f_c	300 GHz
Wavelength	λ_c	1 mm
Distance	d	5 meter
Atmospheric attenuation	α_a	0.01 dB/m @ f_c
Excess loss	L_{ex}	0 dB
Noise spectral density	N_0	-178 dBm/Hz
Spectral efficiency		1 bit/s/Hz
Noise bandwidth	B	Data rate × spectral efficiency
Total noise figure	NF	15 dB
System margin	M	10 dB

Recently, Federici and Moeller [18] and Kleine–Ostmann and Nagatsuma [20] have discussed the potential and feasibility of using THz waves in the range of 100 GHz $\sim$ 10 THz for future wireless communications and broadly investigated enabling technologies and ongoing research. In this review, while avoiding duplication with these two articles, we overview the most recent progress in fundamental technologies for THz communications and discuss several issues and technical barriers that need to be taken into consideration for the deployment of practical systems in the future. In Section II, we will discuss whether THz-waves are feasible for wireless communications on the basis of a simple link budge calculation and explain what can be done with THz communications in the future. In Section III, present technologies for THz communications will be overviewed with respect to channel modeling, device technologies for the front end, and experimental demonstrations of data transmission at THz frequencies. In Section IV, we cover several issues that need to be addressed for the future of the THz communications systems.

II. Terahertz Waves for Wireless Communications

A. Atmospheric Attenuation

THz waves are attractive for wireless communications because they can offer huge bandwidth, which is essential for increasing data capacity. However, there is an obvious disadvantage: large signal loss. The attenuation in the atmosphere at frequencies above 100 GHz is much larger than that in the microwave frequency band [31], and the large attenuation not only limits service converge but also degrades the signal-to-noise ratio (SNR) of the system, which influences data capacity as well. Fig. 1 shows the atmospheric attenuation and the attenuations due to rain rates of 25 and 5 mm/h [30], computed at frequencies up to 2 THz with the ITU-R [31] and the *am* [32] models. As can be seen in Fig. 1, the frequency region above 1 THz seems to be unsuitable for wireless communications because of the many absorption lines of H_2O and other atmospheric gases. Although there are several frequency windows between water absorption lines below 1 THz, it would be difficult to use the THz waves as a data carrier outdoors considering the additional inevitable losses due to weather conditions, such as rain. However, the attenuation level in the frequency windows may not be a big problem for indoor applications, where the range is likely to be a few ten meters or less. For example, 300-GHz signal will be attenuated by around 0.1 dB or less for a 10-m-long indoor link, which is negligible.

B. Link Budget for Short Range Applications

To get an idea of how much data capacity is available with THz waves, a simple link budget analysis has been conducted using the Friis formula. Received power P_r and $\mathrm{SNR_{dB}}$ at the receiver are given as

$$P_r = P_t + G_t + G_r + 20\log\left(\frac{\lambda_c}{4\pi d}\right) - \{\alpha_a(f_c)\cdot d\} - L_{\mathrm{ex}} \qquad (1)$$

$$\mathrm{SNR_{dB}} = P_r - (N_0 + 10\log(B) + \mathrm{NF} + M) \qquad (2)$$

where P_t is the power input to the transmitting antenna. G_t and G_r are antenna gains of the transmitting and receiving antennas, respectively. D and λ are the distance and wavelength. $\alpha_a(f)$ is the atmospheric attenuation at frequency f. L_{ex} is an excess loss not included in free-space loss. NF and M are the total noise figure of the receiver and system margin in decibels. N_0 is the noise power spectral density. B is the system noise bandwidth.

In this analysis, ASK with incoherent detection and BPSK with coherent detection are assumed with additive white Gaussian noise. Spectral efficiency was fixed to 1 bit/s/Hz and, though unrealistic, it was assumed that the system uses sufficient bandwidth for a specific data rate. To simplify the discussion, G_t and G_r are assumed to be equal. The parameters used in the calculation are summarized in Table I. In Fig. 2, Shannon's maximum data capacity and available data rates with ASK and BPSK modulations for BER of 10^{-6} are plotted as a function of antenna gain in the transmitter and receiver. As can be seen, for 10 Gb/s, antenna gain of 28 $\sim$ 31 dBi is necessary, depending on the modulation format, and these results show good agreement with those in [17]. Since the antenna gain is linked to the SNR of the system, traces in Fig. 2 will move horizontally if some parameters affecting the SNR or the modulation format change. An antenna with the gain of 30-dBi

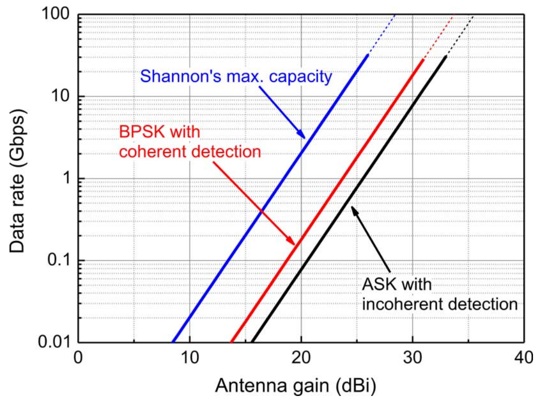

Fig. 2. Calculated Shannon's maximum data capacity for spectral efficiency of 1 bit/s/Hz, and available data rates at BER of 10^{-6} for ASK with incoherent detection and BPSK with coherent detection.

would be impractical for indoor applications at microwave frequencies because of its huge size. However, at THz frequencies, size won't be a problem at all. For 30-dBi antenna gain at 300 GHz, effective antenna aperture $A_e = g_r \cdot \lambda^2/4\pi_e$ would be around 80 mm^2, which is comparable to the cross-sectional area of a pencil.

However, since the half-power beam width for 30-dBi antenna gain is quite narrow, around $6^\circ \sim 7^\circ$, the transmitter and receiver should be on line-of-sight (LOS) for proper operation. To avoid a link failure due to an obstacle in the LOS path, walls, ceilings, or floors can be used as reflectors so that the link can be kept alive. For such a non-LOS operation, the additional loss due to the reflection should be considered in the link budget calculation as well.

Note that the values of the parameters used in this link budget calculation are not beyond those achievable with current device technologies. Advanced devices and a more sophisticated modulation scheme with a better understanding of THz channels would enable us to achieve extremely high throughput even up to 100 Gb/s.

C. *Application Scene of THz Communications*

WLAN and WPAN systems are the most common indoor communications systems these days and we can conceive that THz communications will be used in a similar way at first. The Wi-Fi Alliance, an organization promoting WLAN technologies worldwide, has categorized the usage models of future WLAN into 1) wireless displays, 2) in-home distribution of HDTV and other content, 3) rapid uploading and downloading of large files to and from a server, 4) backhaul traffic in a mesh or point-to-point configuration, 5) campus/auditorium deployments, and 6) manufacturing-floor automation [33]. As can be seen in the list above, home wireless networks for digital video would be one of the most common applications. Although the current HDTV (1080p60) video format requires "just" around a 3-Gb/s data rate, the required data rate for future video format will dramatically increase with increasing resolution. For example, one future video format called Super Hi-Vision, which has a resolution of 7680 × 4320, 16 times larger than the current 1080p format, requires more than a 24-Gb/s data rate, depending on the frame rate and color depth. Therefore, future WLAN and WPAN systems will have to provide at least a couple of ten Gb/s, and, for this purpose, THz wave communications will play an important role, though beam-forming techniques for avoiding obstacles, such as persons moving around, will be an issue

Britz has proposed a little more advanced concept—the so-called "triple-stack nanocellular architecture" [34]. In this concept, three different radios for cellular, Wi-Fi, and THz communications are installed in a mobile handset in parallel. The cellular and Wi-Fi radios provide wide coverage with a slower rate, while the THz communications link offers extremely high throughputs where THz communications services are available.

In addition, Koch [16] and Federici *et al.* [18] have shown another possible use of the THz communications: a secure wireless system, which is likely to be used on the battle field. Since the THz beams are highly directional and atmospheric attenuation is very high, unauthorized persons would have to be on the same narrow beam path to intercept messages. Another approach is to spread the data signal over a wide spectral span in THz bands using a long code sequence, for example, at a chip rate of 100 Gb/s. The high-order encryption with the long code would make the system strong against a jamming attack.

III. Present Terahertz Communications

In this section, we review present technologies for THz communications, with the focus on channel modeling, device technologies for the front-end, and demonstrations for testing the feasibility of THz communications.

A. *Channel Modeling*

In order to design or analyze a wireless communications system before practical development, some model of the channel that adequately describes the environment must be developed. However, there have been few reports on channel measurement or characterization at THz frequencies. In part, the reason would be that the sensitivity of present measurement systems is not high enough in this high frequency region.

A German group involved in the Terahertz Communications Laboratory has conducted some analyses of reflection and scattering on building materials, which may have rough or multilayered surfaces [35]–[39]. To deal with the rough surfaces, they used Kirchoff's scattering theory and Fresnel equations [37]. The specular reflection from a rough surface is given by multiplying Fresnel's equations with a Rayleigh roughness factor, which can be calculated from the measured surface roughness. Recently, Priebe *et al.* measured channel properties and compared the results with simulations based on ray-tracing techniques at 300 GHz [39]. The simulation also considered the effect from the building materials with the approach mentioned above. Measured and simulated channel impulse responses showed very good agreement.

B. *Device Technologies for Front End*

Unlike channel modeling, various kinds of device technologies that can be implemented at the front end of THz communications have been extensively reported and demonstrated. To avoid overlap with other related review papers [40], [41] in this field, we will briefly cover only a few selected results here.

Compound semiconductor transistors have always been considered to be the strongest candidates for high-frequency applications, especially for millimeter-wave and THz-wave bands. Recently, InP HEMT devices with a cutoff frequency of over 1 THz have been reported [26], [27] and demonstrated for amplifiers and other elementary components at up to around 500 GHz [42]–[44], and 10-Gb/s QPSK modulator and demodulator chip sets for a 120-GHz band have recently been demonstrated [45]. In addition, though not for communications applications, a single-chip receiver integrated with a mixer, amplifier, and frequency multiplier operating at around 220-GHz band has already been demonstrated [46], [47]. State-of-the-art solid-state power amplifiers can provide more than 50 and 10 mW at 220 [48] and 338 GHz [49], respectively. Note that, even with the current technologies, 10 mW at 300 GHz looks feasible, which is ten times higher than the power assumed in the link budget calculation in the previous section.

It has been assumed that Si-based technologies such as CMOS and SiGe would not be suitable for THz-wave applications because of the relatively high loss of the base material. However, recently, several components operating at over 100 GHz have been reported, and the results show a great potential for the development of cost-effective THz communications systems [50]. Although the output is still too low for practical applications, oscillators producing THz waves at 324 [51] and 410 GHz [52] have been developed with standard Si-CMOS technologies. Fully integrated transmitter and receiver chip sets with a state-of-the-art SiGe BiCMOS technology have also been presented for 160-GHz-band application [53]. The transmitter and receiver provide output power of more than 3-mW and a noise figure of less than 14-dB, respectively.

Asada's group at the Tokyo Institute of Technology has reported simple THz-wave generators with resonant tunneling diodes (RTDs) [54], [55]. They obtained fundamental oscillation up to 1.04 THz at room temperature [55]. The RTD oscillators have a very simple structure, consisting of a single RTD and a planar antenna for radiating THz waves. The oscillation frequency is determined by the LC resonance, where the inductance L is from the antenna and the capacitance C is from both the RTD and the antenna. An output power of 7 μW has been demonstrated at 1.04 THz.

Schottky barrier diodes (SBDs) have been used for detecting or mixing THz waves for a long time. The cutoff frequency of state-of-the-art SBDs on GaAs substrate is expected to be beyond the resonance frequency of material [56], [57], and SBD detectors and mixers operating at over 1 THz are already available on the commercial market. SBDs made with a standard Si-CMOS process can also operate at over 1 THz [58], and frequency multipliers and mixers using the Si-SBDs have been successfully demonstrated at over 100 GHz [59]–[61].

In addition to the electronic devices, photodiodes and other photonic devices originally developed for fiber-optic communications have been used for generating millimeter and THz waves. Especially for THz-wave applications, uni-traveling carrier photodiodes (UTC-PDs) have shown promising performance in output power and operation frequency compared with conventional p-i-n type PDs [62]. Nippon Telegraph and Telephone Corporation (NTT) has demonstrated various types of UTC-PDs for different applications. For a J-band UTC-PD module packaged in a WR-3 waveguide, the maximum output power is around 0.5 mW at 350 GHz, and the 3-dB bandwidth is around 140 GHz in the range of 270 $\sim$ 410 GHz [63].

C. Demonstrations at Over 100 GHz

To date, a few experiments for demonstrating the feasibility of THz communications have been conducted. They have normally been done in the frequency band below 350 GHz, because of limited output power and sensitivities of transmitters and receivers at higher frequencies, respectively.

One of the most successful demonstrations is a wireless data transmission system using the 120-GHz band developed by NTT. The aim of this system is to relay a large volume of digital data, where a high-data-rate link over a few kilometers is temporarily necessary. In the early version of the system, photonic technologies were used for generating and modulating a carrier signal [64]. Later, an InP HEMT power amplifier was added to compensate for the limited output power from the UTC-PD [65], which extended the link distance to a few hundred meters. In order to improve mobility outdoors, all the photonic components were replaced with InP HEMT MMICs [66], [67]. During the Beijing Olympic Games in 2008, this system was utilized by Fuji Television Network, Inc., one of the Japanese broadcasting networks, to relay HD video signals of live TV shows from a studio to the International Broadcast Center over approximately a 1-km distance [68]. Recently, the data rate has been increased to 20 Gb/s by using polarization multiplexing techniques [69].

NTT and Osaka University have demonstrated a THz communications link in the 250- and 300-GHz bands as well [70], [71]. The experiment setup is shown in Fig. 3(a). Like in the initial version of the 120-GHz wireless system, photonic technologies were used for the transmitter. Since no amplifier was available, two dielectric lenses offering around 15-dB link gain per lens were used. The total gains of the transmitter and receiver antennas are expected to be around 40 and 35 dBi, respectively. In the first preliminary experiment, 8- and 2-Gb/s error-free transmission was achieved at 250 and 300 GHz, respectively, over a 0.5-m distance with ASK modulation. Taking the carrier frequency into consideration, the link should provide higher data capacity, and it was found that the maximum data rates of 8 and 2 Gb/s were limited by the bandwidth of the SBD detectors used as the receiver, not by the limited power and sensitivity of the transmitter and receiver. Using the improved version of the detector with a wider bandwidth characteristic, error-free transmission at over 10-Gb/s was demonstrated in the 300-GHz band [72]. The highest bit rate confirmed with error-free performance is 16 Gb/s, as shown in Fig. 3(b) and (c). Note that 6-mA photocurrent corresponds to the output power from the UTC-PD of about 20 μA. According to the bandwidth performance of the new receiver and available output power from the UTC-PD, error-free transmission at over 20 Gb/s is anticipated.

Using harmonic mixers, Jastrow *et al.* have demonstrated the transmission of analog and digital video signals in the 300-GHz band [73], [74]. For digital video transmission, they used two different modulation formats: DVB-S2 with a

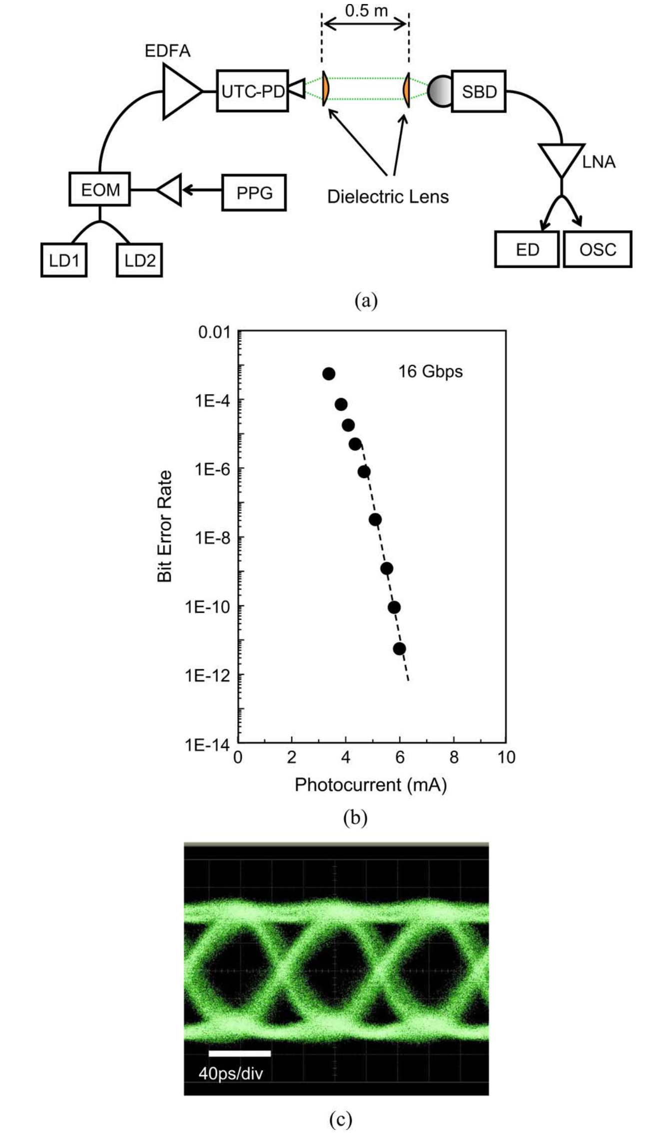

Fig. 3. (a) Experimental setup for data transmission link at 300 GHz (LD: laser diode; EOM: electrooptic modulator; PPG: pulse pattern generator; EDFA: erbium doped fiber amplifier; UTC-PD: uni-traveling photodiode; SBD: Schottky barrier diode; LNA: low noise amplifier; ED: error detector; OSC: oscilloscope). (b) Measured BERs. (c) Eye diagram at 16-Gb/s data rate.

single carrier 8 PSK (96 Mb/s) and DVB-T with multi-carrier 64 QAM (31.668 Mb/s). Quasi-error-free transmission ($\mathrm{BER} < 2 \times 10^{-4}$) over 52-m-long distance was achieved for DVB-S2 signal with two dielectric lenses for the transmitter and receiver. For the multicarrier modulation, link failure was observed when the number of the OFDM carriers was increased. The authors assumed that this was due to intercarrier interference caused by phase noise of the 300-GHz carrier signal.

IV. Future of Terahertz Communications

Though achieved under well-controlled conditions, including dielectric lenses, fine beam alignment, and a stationary transmitter and receiver, error-free transmission at over 10 Gb/s has already been demonstrated at 300 GHz. Probably, in the near future, the need for such well-controlled conditions can be eliminated by using advanced device technologies and precise THz channel models. Considering that research on the THz waves for communications applications is still in the beginning stage; we expect lots of issues will arise along with various technical barriers. In this section, we address some of the issues that we can predict at this time for the future of THz communications.

TABLE II
Minimum Distance not Causing Interference

Frequency bands	Minimum distance (km)
275 ~ 320 GHz	55
335 ~ 360 GHz	26
380 ~ 445 GHz	14
Above 450 GHz	6

A. Frequency Conflict With Astronomy Applications

In the introduction section, it was mentioned that the frequency band above 275 GHz is not allocated for specific uses yet and that no one uses the band. However, practically speaking, this is not true: Specific frequency bands corresponding to natural resonances of molecules have been used in radio astronomy applications for a long time, and many of them are located in the range of 100 $\sim$ 3000 GHz. Even though the atmospheric attenuation at THz frequencies is very high as shown in Section II, the sensitivity of radio telescopes is so extremely high that very-low-level signals from several thousand light years away are detectable. Therefore, any possible conflict or interference from the THz communications systems with radio astronomy systems should be carefully considered. Recently, this issue has been investigated by ITU-R Study Group 7 under the near-worst-case assumptions listed as follows [75]:

- high output power from interfering transmitter based on the empirical equation given by (3);
- interfering transmitter directed toward radio telescope;
- 30-cm diameter antenna in interfering transmitter (corresponding to 58 dBi at 275 GHz);
- radio telescope looking at the sky;
- 0-dBi antenna gain of telescope in the direction of interfering transmitter;
- radio telescope and interfering transmitter at same altitude of 3000 m;
- radio astronomy protection criteria defined in ITU-R Recommendation RA.769;

and

$$P_T = 0.01 \times (1000 - f_{\mathrm{GHz}}) \text{ in dBm.} \quad (3)$$

Under these extreme conditions, the minimum distance at which the interfering signal would not be detected by a radio telescope was calculated for frequencies between 275 $\sim$ 3000 GHz. The results are summarized for several frequency bands of interest in Table II.

As can be seen in Table II, the minimum distance at which there is no interference decreases with increasing frequency because of the larger atmospheric attenuation at higher frequencies. For example, if a THz communications system operates

at 300 GHz with a transmitting power of 7 dBm, the transmitter should be kept outside of 55-km radius from radio telescopes. Radio telescopes are normally located at isolated sites far from the cities or towns in which THz communications systems would likely be used. Taking this into account along with the fact that the study is based on the near-worst-case scenarios, the optimistic view is that radio astronomy and active THz services for communications in practical scenes should be able to share the THz-wave band.

B. Technical Barriers

Probably, many readers have already noticed that beam-steering techniques will be absolutely necessary to establish and track a successive THz radio link because of the high diffraction loss of THz waves. In general, a phased-array antenna and optics components such as lenses or mirrors are used in the microwave band and infrared region, respectively, for steering the beam direction. For THz waves located between the two bands in the electromagnetic spectrum, both approaches would be available. Taking into account the complexity and loss of signal distribution networks for phased-array antennas, approaches with lenses or mirrors possibly made by MEMS or meta-material technology look more promising.

Packaging would be another challenging issue. To date, metal packaging with coaxial or waveguide ports is commonly used for high-frequency components. Although metal housings provide reasonable loss even at THz frequencies, they are obviously too big and too heavy to use in THz mobile handsets for future WLAN and WPAN systems. Although the possibility of using current packaging techniques in the frequency band above 100 GHz has not been thoroughly studied, it can be simply predicted that unavoidable dielectric loss and insufficient patterning accuracy may limit the use of current techniques for THz-wave applications and that some breakthrough for THz integrated circuits is required.

V. Summary

In this review, we saw that THz communications offers an alternative for future wireless communications systems, especially for indoor applications such as WLANs and WPANs. Although high-gain antennas should probably be employed because of the large free-space loss at THz frequencies, the huge bandwidth of THz waves will enable us to achieve data rates of 10 Gb/s or higher easily even with simple data modulation.

The potential of the huge bandwidth has been verified by several feasibility tests as well as by theoretical calculations. Several kinds of devices have been demonstrated for various MMICs operating at over 100 GHz with remarkable performances. Although the progress in speed has been quite slow because of the lack of proper instruments at THz frequencies, studies of THz channel characteristics are being steadily conducted. Looking at the results to date, with current state-of-the-art device technologies and a better understanding of THz channel characteristics, a 100-Gb/s data rate will not remain unreachable, as shown in the technology road map of THz communications towards 100 Gb/s [Fig. 4] made by the study group

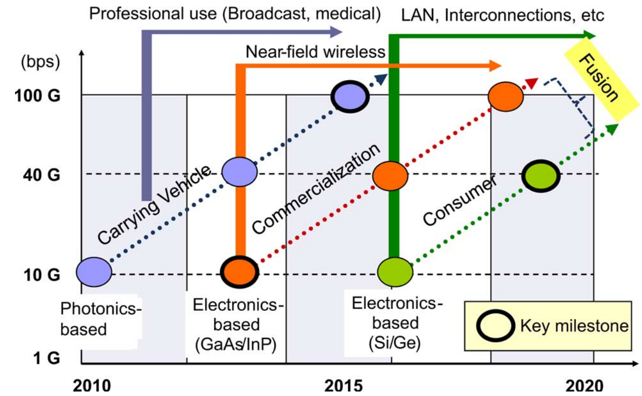

Fig. 4. Technology road map of THz communications.

on THz ICT at Kinki Bureau of Telecommunications, Ministry of Internal Affairs and Communications, Japan [76].

Because THz-frequency bands have been used in radio astronomy science for a long time, any possible interference from THz communications services should be carefully predicted and investigated. In addition, we also have to overcome some other technical barriers, such as beam steering and packaging, in order to make THz communications a reality.

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