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DRAFT REVISION OF APT REPORT ON "SHORT RANGE RADIOCOMMUNICATION SYSTEMS AND APPLICATION SCENARIOS OPERATING IN THE FREQUENCY RANGE 275 - 1000 GHZ"

At the AWG-23 meeting, APT Report on short range radiocommunication systems and application scenarios operating in the frequency range 275-1000 GHz (APT/AWG/REP-66) was updated in accordance with the input contribution and the working document towards a draft revision to APT Report was developed and carried forward to the next meeting (AWG-23/TMP-52).

Japan supports the upgrade of the text attached to this document to a draft revision of APT Report and submission to AWG plenary.

Attachment: 1

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ATTACHMENT

APT REPORT ON

SHORT RANGE RADIOCOMMUNICATION SYSTEMS AND APPLICATION SCENARIOS OPERATING IN THE FREQUENCY RANGE 275 - 1000 GHZ

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APT REPORT ON

"SHORT RANGE RADIOCOMMUNICATION SYSTEMS AND APPLICATION SCENARIOS OPERATING IN THE FREQUENCY RANGE 275 - 1000 GHZ"

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1. Introduction

Due to remarkable progress in the recent technologies above 275 GHz, the integrated devices and circuits operating above 275 GHz enable us to achieve the sophisticated applications, such as spectroscopy, imaging, non-destructive testing and THz camera. Although the advantages of such high frequencies are to use ultra-broad bandwidth which cannot be allotted in the microwave and millimetre-wave frequency bands, those advantages are not yet utilized to develop the short range radiocommunication systems.

In addition to remarkable progress of RF technologies operating in the band above 275 GHz, IEEE802 currently published IEEE Std. 802.15.3d^{TM}-2017 which provides 100 Gbit/s wireless switched point-to-point physical layer operating at the frequency ranges 252-325 GHz [1]. However, the frequency ranges above 275 GHz for active services are not yet identified, nor have allocations made to any services in this range in the Radio Regulation. It is also important from the regulatory point-of-view to understand the potential applications and the corresponding benefits for wireless communities in the future. ITU-R has published the technical and operational characteristics and spectrum needs of land-mobile and fixed services planned to operate in the frequency range 275-450 GHz [2]-[3] and technology trends of active services in the frequency range 275-1 000 GHz [4].

This Report overviews the short range radiocommunication systems, application scenario and typical use cases operating in the frequency range 275 - 1000 GHz and intends to provide technical information for future relevant study in this band.

2. Overview of frequency range 275 - 1000 GHz

2.1. Definition of Terahertz waves

Terahertz wave in this report refers to the frequency range 0.1 - 10THz, the corresponding wavelength from 0.03 - 3 mm. The frequency range between 275 - 1000 GHz is the main part of Terahertz band. Terahertz waves are also known as submillimeter radiation. The position of Terahertz band in the electromagnetic spectrum is shown in Figure 1.

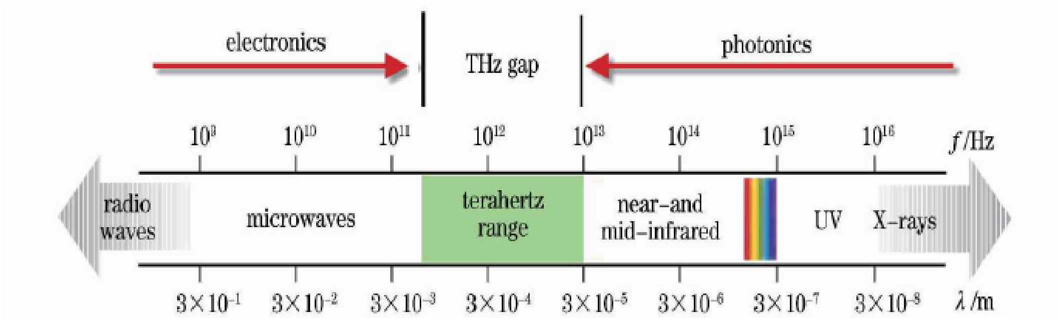


Figure 1

Position of Terahertz band in the radio spectrum

2.2. Footnote No. 5.565 in Radio Regulation

No. 5.565 of the Radio Regulation was amended to identify for use by administrations for passive service applications, such as radio astronomy service, earth exploration-satellite service (passive) and space research service (passive) at WRC-12. RR (Edition of 2012). **No. 5.565** is shown below:

5.565 The following frequency bands in the range 275-1 000 GHz are identified for use by administrations for passive service applications:

- radio astronomy service: 275-323 GHz, 327-371 GHz, 388-424 GHz, 426-442 GHz, 453-510 GHz, 623-711 GHz, 795-909 GHz and 926-945 GHz;
- Earth exploration-satellite service (passive) and space research service (passive): 275-286 GHz, 296-306 GHz, 313-356 GHz, 361-365 GHz, 369-392 GHz, 397 399 GHz, 409-411 GHz, 416-434 GHz, 439-467 GHz, 477-502 GHz, 523 527 GHz, 538 581 GHz, 611-630 GHz, 634-654 GHz, 657-692 GHz, 713 718 GHz, 729 733 GHz, 750-754 GHz, 771-776 GHz, 823-846 GHz, 850 854 GHz, 857-862 GHz, 866-882 GHz, 905-928 GHz, 951-956 GHz, 968-973 GHz and 985-990 GHz.

The use of the range 275-1 000 GHz by the passive services does not preclude use of this range by active services. Administrations wishing to make frequencies in the 275-1 000 GHz range available for active service applications are urged to take all practicable steps to protect these passive services from harmful interference until the date when the Table of Frequency Allocations is established in the above-mentioned 275-1 000 GHz frequency range.

All frequencies in the range 1 000-3 000 GHz may be used by both active and passive services. (WRC-12)

2.3. Estimation of available contiguous bands

Figure 2 shows gaseous attenuation characteristics in the frequency range from 100 GHz to 1000 GHz [5]. There are the specific resonant attenuation by oxygen and water vapour. The contiguous band is simply estimated by avoiding the resonance attenuation lines. Table 1 summarizes the estimation of frequency range and the contiguous bandwidth. Although the contiguous bandwidth of 120 GHz is achievable in the frequency band in the range 200-320 GHz, the frequency bands such as 200-209 GHz, 226-231.5 GHz, 235-238 GHz and 241-252 GHz are not allocated for mobile services. To comply with the current provision of RR, the frequency band (1) in Table 1 should be modified in the range 252-320 GHz and its contiguous bandwidth becomes 68 GHz which may be a sufficient bandwidth to transmit a high data rate 50-100 Gbps. The other bands which can provide the contiguous bandwidth in the frequency range above 200 GHz are summarized in Table 1.

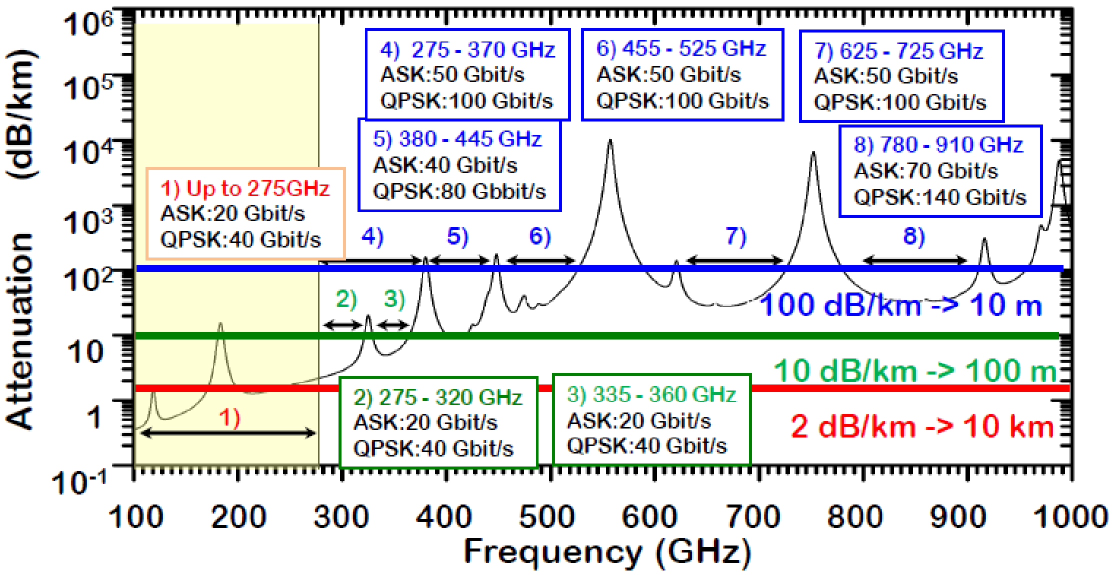


Figure 2

Attenuation characteristics and available contiguous bands in the frequency range from 100 GHz to 1000 GHz.

Table 1

Estimation of frequency ranges and contiguous bandwidth

	Frequency range (GHz)	Contiguous bandwidth (GHz)	Loss (dB/km)
(1)	200-320	120	< 10
(2)	275-320	45	< 10
(3)	335-360	25	< 10
(4)	275-370	95	< 100
(5)	380-445	65	< 100
(6)	455-525	70	< 100
(7)	625-725	100	< 100
(8)	780-910	130	< 100

3. Characteristics of the frequency range 275 - 1000 GHz

Because of its unique properties, the band between 275 and 1000 GHz has many special characteristics comparing with other radio frequency band. The main unique characteristics are as followed:

(1) High permeability

Radio signal between 275 and 1000 GHz has good penetration of many dielectric materials and non - polar liquid, it can be used for the prospective imaging of opaque materials or objects, also could be used for non-destructive testing in safety inspection or quality control. Besides, its wavelengths is greater than the size of suspended dust or dirt particles in the air, this band has a very small transmission loss in the dust or smoke and could be used for imaging in the smoke environment like fire rescue field and wind dust environment such as desert.

(2) Rapid attenuation in the water

Radio signal between 275 and 1000 GHz has a severe attenuation in water. This property can be used in medical field, as measuring the water content in tumor tissues which is significantly different from the normal tissue cells, so the cancer tissues can be located by analysing the tissue water content.

(3) Safety

The photon energy of the terahertz is particularly low, which is in the order of only milli-electron volt. This is below the energy of the most chemical bonds and is not causing ionization reaction. This feature is very important for the detection of biological samples and the human body check. In addition, water has a strong absorption effect in this band. Radio signal in this frequency range can’t get through human skin. Therefore, it is safe for people, so it could be used for medical detection such as skin diseases detection.

(4) Spectral resolution

Terahertz band contains abundant spectral information including physical and chemical information. Many molecules, especially organic molecules have relatively strong dispersion and absorption properties in this band. Through the study on spectral properties of material in this band, we could understand the structure characteristics of material, identify their composition, and analyse its physical and chemical properties.

(5) High spatial resolution

The frequency range between 275 and 1000 GHz has relatively better spatial resolution than microwave band. Theoretically speaking, because of its shorter wavelength, imaging using this band should have higher imaging resolution than microwave.

(6) Short wavelength and good directivity

Compared with the microwave, the frequency of terahertz is higher. Therefore, it could be used as the communication carrier to carry more information in a unit of time. Also since its wavelength is shorter and it has with good directivity, it is very promising to be used in certain wireless communication application scenarios.

4. Application scenarios in the frequency range 275 - 1000 GHz

With more research on the terahertz wave, its outstanding characteristics are more and more developed. Currently the frequency range between 275-1 000 GHz is still mainly used for astronomical observation. Recently, with the advent of high power terahertz radiation sources, the frequency range between 275 and 1000 GHz shows the potential broad prospects to be used in more applications. There are following several potential typical application scenarios:

(1) Application in astronomy

Celestial and interstellar radiation contains abundant spectral information, many of them are in the frequency range between 275 and 1000 GHz, and the background noise of terahertz spectrum is lower than spectral noise of other frequency ranges, so the research and development of the frequency range between 275 and 1000 GHz are from astronomy at the earliest stage. Except the infrared telescope and the Hubble space telescope, people have invented terahertz radio telescope to research the complex physical state of interstellar cloud in the galaxy, including the largest far infrared telescope in the world.

(2) Application in molecular detection

All matters have movement, even though the object looks stationary, its internal molecular has a fast motion. While there is motion there is radiation, electromagnetic radiation has its own vibrating frequency or wavelength, this wavelength is the so-called "fingerprint spectrum". Since the most of the molecular "fingerprints" are in the infrared range and the frequency range between 275 and 1000 GHz, the terahertz solid-state laser can be used to detect the radiation caused by small molecular vibrational which can’t be detected by infrared ray.

(3) Application in the security inspection

Since the majority of molecular rotational levels of explosives and drugs are in the terahertz region, the spectroscopy of the terahertz range could be usable to conduct safety inspections of the human body for the detection of explosives, drugs, biological macromolecules, weapons and other contraband. Different from the existing X ray and ultrasonic imaging technology, spectroscopy and imaging can provide not only the shape of the object but also comparison of the measured spectral information with existing hazard terahertz spectrum library to identify the material properties. Because, the terahertz wave has very low energy, it will not produce harmful ionization to biological tissues. Therefore, compared to the shortcomings of X rays which cause potential harm to human body and which metal detectors cannot detect non-metallic material, terahertz technology has a good application prospect in the security inspection.

(4) Application in biomedicine

Radio signal between 275 and 1000 GHz is easily absorbed by polar molecules like water or oxygen, and different molecules have different absorption spectrum. Through the use of these spectral lines and the imaging technology, the diagnosis of early lesions caused by skin cancer and other surface tissue damage can be done. In the surgical operation, the terahertz imaging system is often used to check cancer excision in real-time. This method can produce more clear soft tissue imaging than ultrasonic. In addition, we can also use the terahertz time-domain spectroscopy system (THz-TDS) to study organic macromolecules which those biological molecular vibration energy levels or rotational levels are in the terahertz region, then the result can be used as a guide to the drug production and medical research.

(5) Application in the wireless communication

The frequency range between 275 and 1000 GHz is in the transition position from optical to electronics, it has both characteristics of microwave & lightwave communications, also has many of its own nature. First of all, with the rapid development in communication field, the traditional microwave communication has been difficult to meet the requirements of high-speed broadband wireless communications. while the terahertz range could be used for future wireless communications due to its high data transmission rate and wide spectrum bandwidth. On the other hand, the lightwave has large transmission attenuation in the dust, walls, plastic, cloth and other non-metallic or nonpolar substances. The band frequency range 275 and 1000 GHz can penetrate these substances with a low attenuation, and this makes it has very good penetration in harsh environment. However, this band also has its own shortcomings, the most fatal one is that it can be easily absorbed by polar molecules in the atmosphere. Therefore, its atmospheric attenuation is relatively strong especially in rainy days. Because of these characteristics, the terahertz waves can mainly be used for future interplanetary communications, ground short range wideband mobile communication in the harsh environment such as the dry and smoky climate or the battlefield.

5. Typical use cases of short range radiocommunication systems operating in the frequency range 275 - 1000 GHz

5.1. Use cases of close proximity communications

5.1.1. KIOSK downloading

Use of smart phones and tablet terminals have been tremendously spread across the world and the penetration rate of smart phones exceeds over 60% of mobile phones in Japan. Since we can enjoy movies, news, magazines and music by the smart phones and tablet terminals, the terminals should be wirelessly connected to the network to download various contents from the providers. WLAN devices provide wireless broadband connections, but the maximum speed of these devices specified in IEEE802.11 standard is limited by operational and environmental conditions of WLAN systems and the actual observed transmission rate sometimes far from the standard specifications.

Kiosk systems, as shown in Figure 3, are introduced to download the heavy contents to the user terminals wirelessly. Kiosk terminals are connected to the network through wired systems and located in public areas such as train stations, airports, shopping malls and etc. The distance between user and Kiosk terminals is typically less than 10 cm and contents are downloaded and/or uploaded to/from user terminals. The user terminals are connected to the network through Kiosk terminal, and the data files are uploaded to the network and/or downloaded to the user terminal.

In order to download two hours movie whose size is about 900 MB to the user terminal, the download time of 1.6 sec, 1.1 sec and 0.11 sec is required if effective throughput of 4.6 Gbps, 6.9 Gbps and 66 Gbps between two devices is used, respectively [1]. The data transfer speed in the rage 10-100 Gbps is achieved applying multi-modulation method and carrier frequencies above millimetre waves. The large contiguous bandwidth is feasible in the frequency band above 252 GHz as discussed in section 2.3, In a case of utilizing a large contiguous bandwidth, a simple modulation scheme such as ASK, PSAK, QPSK can be applied to transmit heavy contents in a short time period.

Figure 3

KIOSK downloading.

5.1.2. Toll gate downloading

The toll gate downloading devices have two functions of IC-card type ticket and close proximity point-to-point communication. Figure 4 illustrates the user terminal pays fare as well as downloads video contents such as news, movies, etc. instantaneously. In order to download the contents at the toll gate, high-speed data transmission functions are also required for both user terminal and toll gate. The transmission range covered by these devices is limited to 5 cm or less to avoid frequency interferences between devices [1]. To meet these requirements, the frequency band above 252 GHz which provides a broadband bandwidth and short transmission capability should be utilized to this type of application. The link set up time between devices is now being discussed within IEEE 802.15 group.

Figure 4

Toll gate downloading [1].

5.1.3. Chip-to-chip communication for data center

There has been increasing interest in applying wireless links for data centers to replace wired connections. Since wireless links can provide beam steering functions to data centers, it has been recognized that wireless steered-beam links can introduce efficient reconfigurable links with low latency which dynamically reduce the workload of data center networks and cabling complexity. Since the significant volume of space is occupied by complex wiring for inter- and intra-rack communications, the wireless connections also reduce the cabling cost and improve the overall cooling efficiency. The current device technologies can make it possible to integrate one of rack functions in data centers into one chip. Wireless inter- and intra-chip communications become important elements to overcome wiring problems of data centers, as shown in Figure 5. The frequency band between 275 and 1000 GHz is suitable for chip-to-chip communication because the aperture diameter is proportional to the operational frequency

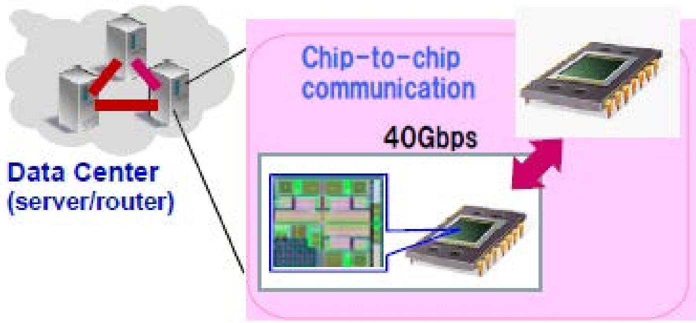


Figure 5

Concept of chip-to-chip communication

5.2. Use cases of indoor communications

5.2.1. Super high vision (4K/8K) video transmission

Although IEEE 802.15.3c, IEEE802.11ad and WiGig standard can transmit the maximum data rate of 7 Gbps, the next generation wireless HD standard extends the transmission data rate up to 10-28 Gbps [6] to transmit 3D and 4K videos using 60-GHz unlicensed bands. One organization demonstrated 28 Gbps data transmission using 16QAM/channel and 4-channel bonding, and 10.5 Gbps using 64QAM and one channel [7]. However, the current frequency allocation at 60-GHz band is not sufficient to transmit a data rate over 40 Gbps, as shown in Figure 6, in terms of a channel bandwidth and a number of channels. The new frequency bands which have broader bandwidth than 60-GHz band are expected to use to transmit much higher data rate than 10-28 Gbps. The frequency band above 252 GHz is also suitable for video transmission due to availability of broader bandwidth.

Figure 6

Super high vision video transmission.

5.2.2. 0.34-THz WLAN based on IEEE802.11

Figure 7 shows the schematic of 0.34-THz WLAN, which is realized by a 0.34-THz wireless communication transceiver end based on solid state semiconductor electronics technology and a WLAN device based on IEEE802.11. the speed data of 0.34-THz WLAN can be 6.536 Mbit/s over 50 m and its BER is lower than 10^{-6}. The MAC layer and partial physical layer are established through a commercial IEEE802.11 wireless module, which operates at 2.4 GHz and its speed data is 150 Mbit/s. the 2.4 GHz carrier based on IEEE802.11 can by moved to 16.8 GHz by using mixer. The 16.8 GHz carrier signal is received by the transceiver end of 0.34-THz WLAN and moved to 0.34 THz, and then the 0.34 THz signal is launched by antenna. If the transceiver end of 0.34-THz receives signal, which down converts the signal to 2.4 GHz and sends it to wireless device based on IEEE802.11.

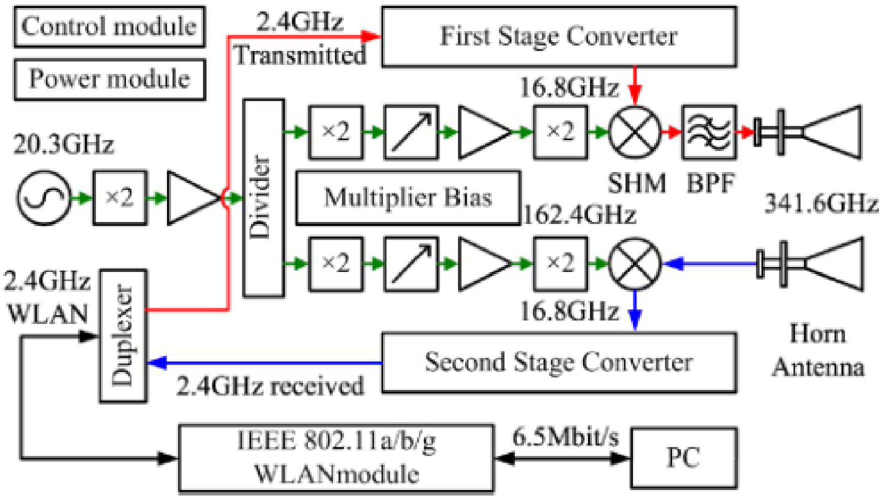


FIGURE 7

Schematic of 0.34-THz WLAN node

Figure 8 shows the constructure of transceiver front end of 0.34-THz, which is composed of 0.34-THz cavity filter, 0.34-THz harmonic mixer, 0.17-THz double frequency chain and feed bias circuit. 0.34-THz harmonic mixer is the most important module of transceiver front end; its working principle is based on anti-parallel schottky diode nonlinear current-voltage (I-V) effect. 0.17 THz double frequency chain with 8 harmonic structure provides vibration signal to 0.34-THz harmonic mixer, which is composed of Q band two frequency multiplier, Q band amplifier, Q band power divider, W band two frequency multiplier, W band adjustable attenuator, W band amplifier, G band two frequency multiplier etc. It also includes three two time and two driving amplifier.

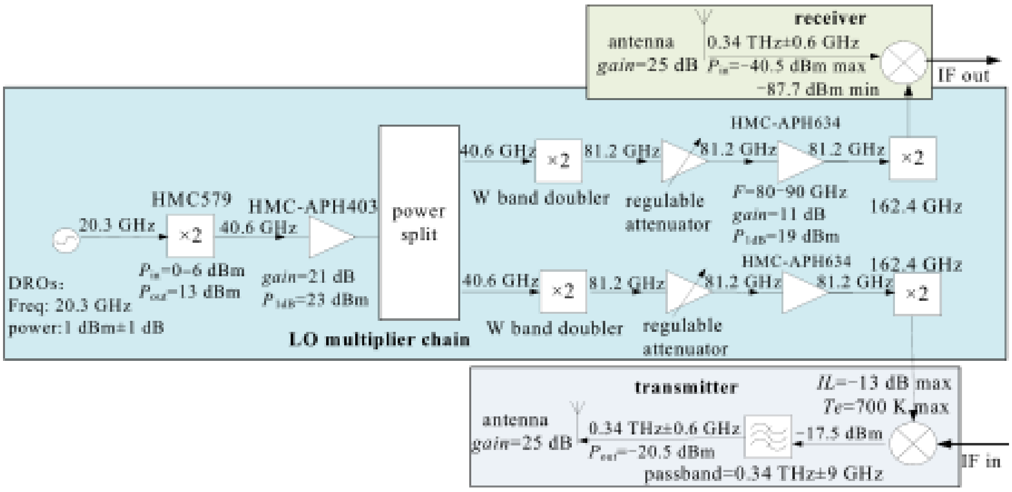


FIGURE 8

Transceiver end of 0.34-THz WLAN

5.2.3 Wireless data center

Data centers interconnect tens of servers, switches and routers which require reliable and high-speed connectivity. Cabling complexity brings inefficient data center cooling and increases energy consumption. One possibility to reduce cabling complexity in data centers is to replace cabling networks with wireless interconnection which may remarkably reduce the number of cables and switches as well as the equipment, installation and reconfiguration costs. Table 2 shows an example of an industry-standard specification that defines an input/output architecture used to interconnect servers, communications infrastructure equipment, storage, etc. The aggregate capacity of this specification exceeds a bit rate of 100 Gbit/s which requires contiguous broad bandwidth or multi-level modulation method.

Table 2

Example of industry specified link data rates [16]

InfiniBand rate designator	Per-lane signaling rate, GBd	Unit Interval (UI) or bit period, ps	Codec	Aggregate full duplex throughput, GB/s (GBytes/sec) Link Designator			
				4X interface		12X interface	
SDR	2.5	400	8b/10b	(1+1) GB/s	10G-IB-SDR	(3+3) GB/s	30G-IB-SDR
DDR	5.0	200	8b/10b	(2+2) GB/s	20G-IB-DDR	(6+6) GB/s	60G-IB-DDR
QDR	10.0	100	8b/10b	(4+4) GB/s	40G-IB-QDR	(12+12) GB/s	120G-IB-QDR
FDR	14.0625	71.1111	64b/66b	(6.8+6.8) GB/s	56G-IB-FDR	(20.4+20.4) GB/s	168G-IB-FDR
EDR	25.78125	38.7878	64b/66b	(10+10) GB/s	104G-IB-EDR	(30+30) GB/s	312G-IB-EDR

5.3. Link analysis

The link budget is calculated using technical parameters, as shown in Figure 9. The transmitting power, carrier frequency and transmission distance are assumed to be 10 dBm, 300 GHz and 1 m, respectively. The total antenna gain of transmitter and receiver over 47 dBi is required to attain a data rate of 100 Gbps by ASK with FEC if BER is less 10^{-9}. Since the spectrum efficiency is 1 bps/Hz in this case, a bandwidth of 100 GHz is needed to attain 100 Gbps. Noting that a bandwidth of 68 GHz in the frequency band 252-320 GHz may be realizable in the current regulation, the modulation scheme such as QPSK whose spectrum efficiency over 2 bps/Hz is preferable for short-range high-speed radiocommunication systems.

Quantity	Symbol	Value
Transmitting power	P_t	**10 dBm**
Carrier frequency	f_c	300 GHz
Wavelength	λ_c	1 mm
Distance	d	**1 meter**
Atmospheric attenuation	α_a	0.1 dB/m @ f_c
Noise spectral density	N_0	-178 dBm/Hz
Spectral efficiency		1 bps/Hz
Noise bandwidth	B	Data rate × spectral efficiency
Total noise figure	**NF**	**15 dB**
System margin	M	10 dB

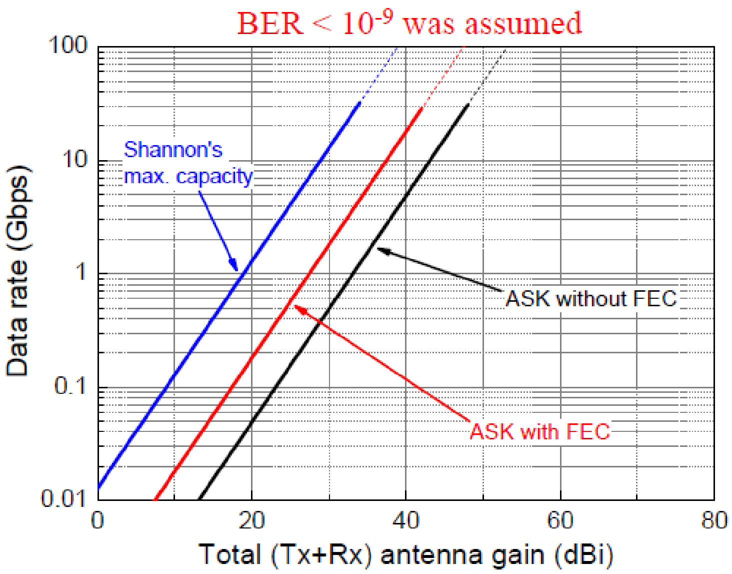


Figure 9

Link budget for KIOSK downloading [8]

5.4. Transceiver technologies

5.4.1. RF integrated devices

The blockdiagram of Tx module and Rx module is shown in Figure 10. The Tx module consists of ASK modulator module and power amplifier module. The ASK modulator module has functions of multiplication, ASK modulation and medium power amplification. The output power of the power amplifier module is 8.3 dBm at a frequency of 300 GHz, and high-density via holes to the ground plane are fabricated within a thin substrate whose thickness is 50μm. A horn antenna with 32 dBi gain is used for evaluation of Tx module. ASK modulator consists of the distributed SPDT (single-pole double throw) switches using shunt circuits of transistors [10]. The ON/OFF ratio larger than 15 dB is achieved in the frequency range of 252-325 GHz, as shown in Figure 11. The insertion gain is about 10 dB, when the ASK modulator is ON-state where the supply voltage and current are 1.0 V and 33 mA, respectively.

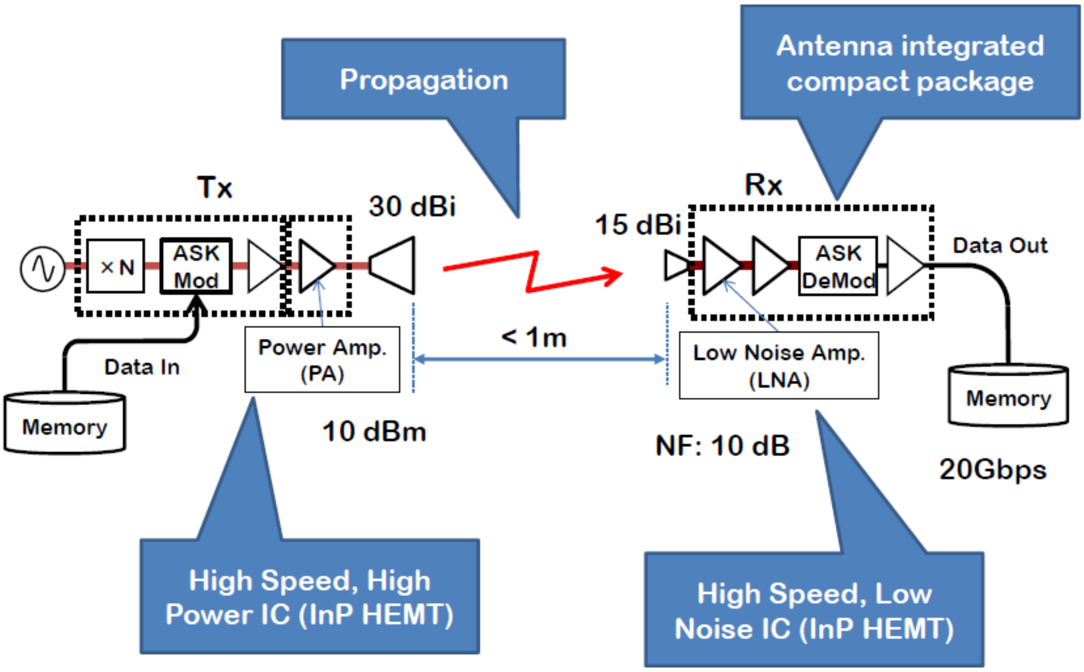


Figure 10

Block diagram of 300 GHz transmitter and receiver [9].

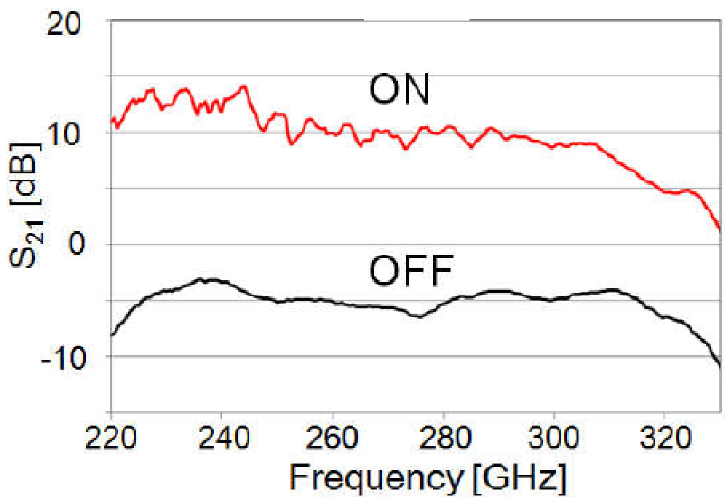


Figure 11

Frequency response of On- and Off- state ASK modulator [10].

The Rx module consists of low nose amplifiers with a small signal gain of 30 dB and a noise figure of 9.8 dB at 300 GHz, an envelope detector with a sensitivity of 250 mV/mW and a baseband amplifier with a small signal gain of 20 dB. The output DC voltage of the Rx module as a function of the carrier frequency is shown in Figure 12, when the input power of Tx antenna is chosen to be -30 dBm. Although the output voltage larger than 300 mV is achieved in the frequency range of 270-300 GHz, the broader frequency response is required to meet the spectrum demand for 100Gbps data transmission.

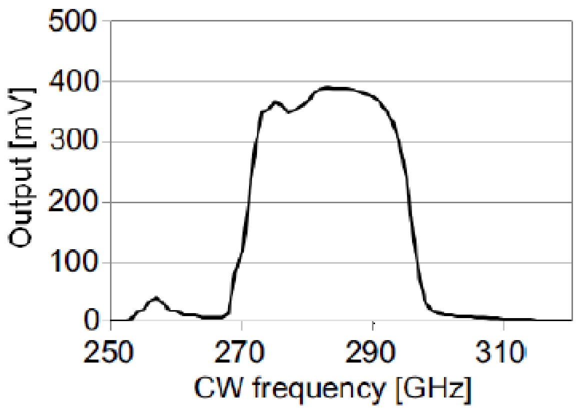


Figure 12

Frequency response of output voltage of detector with baseband amplifier [10].

The Rx module consists of integrated antenna, low noise amplifier and ASK demodulator. LTCC (Low-Temperature Co-fired Ceramic) multi-layer package techniques are applied to integrate antenna function with other RF MMICs (Monolithic Microwave Integrated Circuits), as shown in Figure 13 [11][12]. The stepped horn antenna with a gain of 18 dBi is successfully integrated with MMIC low noise amplifier whose gain is 22 dB at 300 GHz. Figure 14 shows the frequency characteristics of antenna gain, and a gain larger 15 dBi is achieved in the frequency range from 252-325 GHz. The LTTC integration techniques have advantages of not only high efficiency and compactness of antennas whose size is about 2.8 mm x 5.0 mm x 5.0 mm but also high-integration capability and low cost for high-volume production at the frequency band above 252 GHz. Figure 15 shows the measured beam pattern and a beam width whose antenna gain is larger than 15 dBi is about 20 degrees.

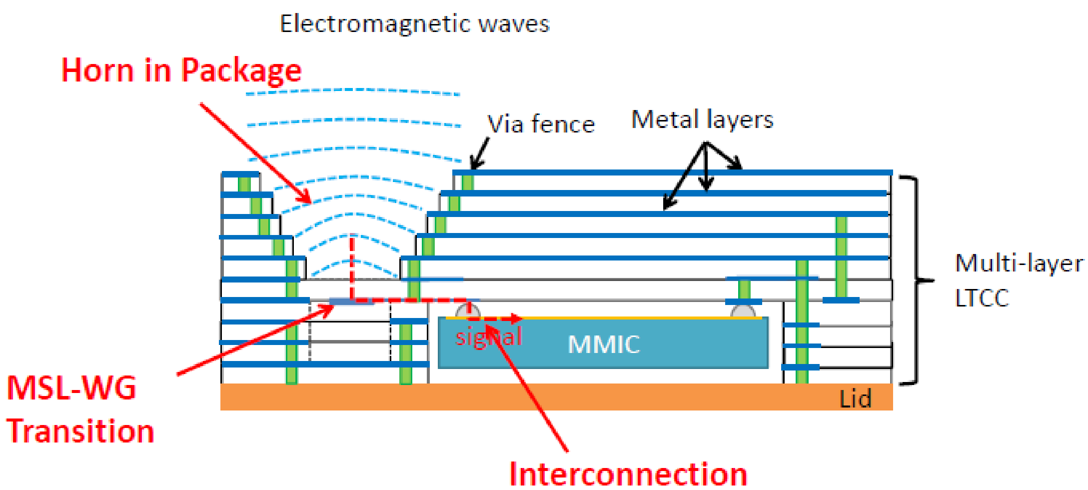


Figure 13

Cross sectional view of LTCC package [9].

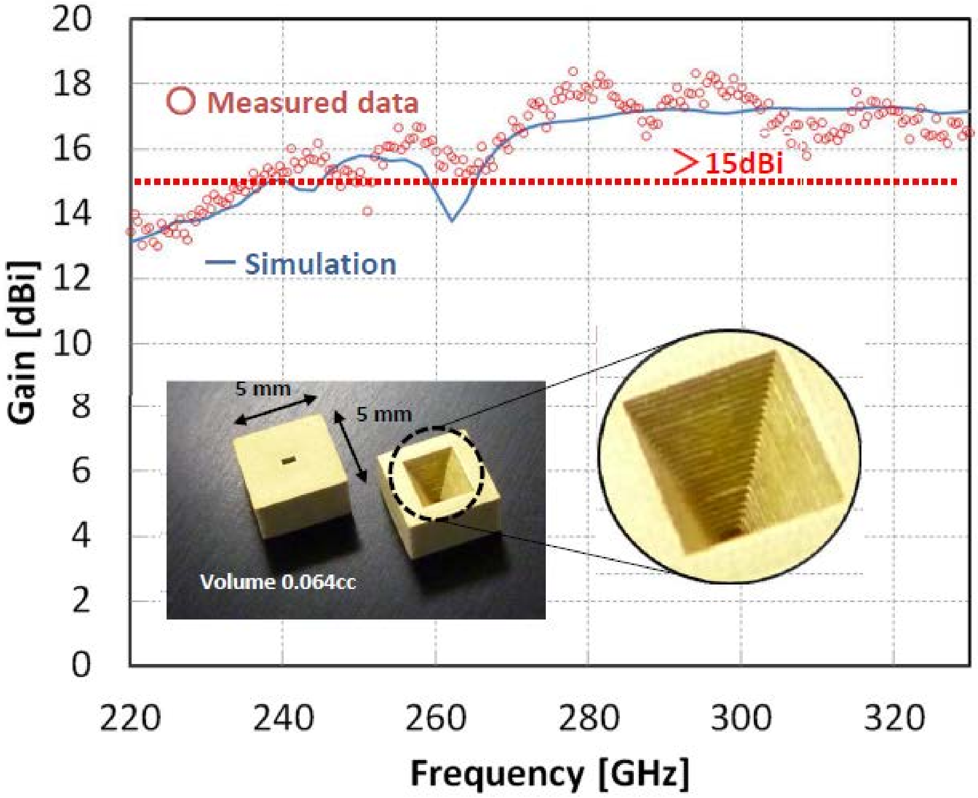


Figure 14

Characteristics of horn antenna integrated on LTCC package [12].

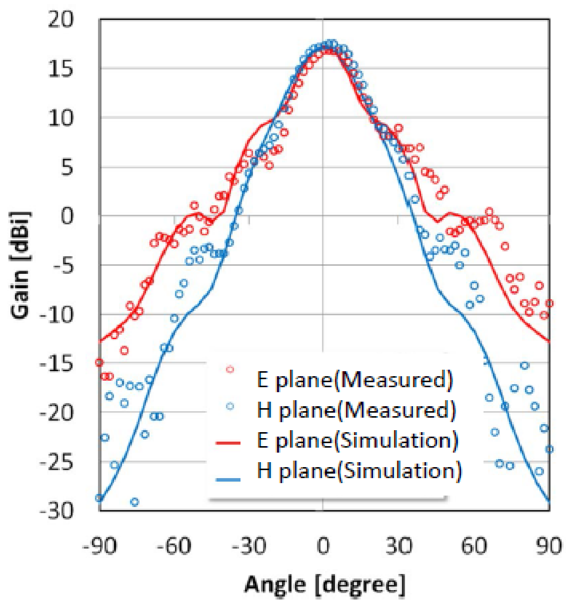


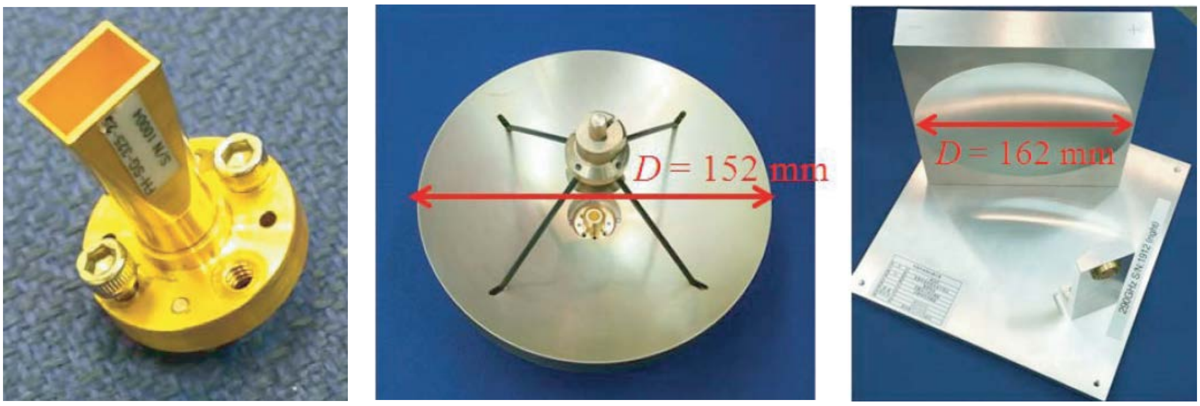
Figure 15

Antenna beam pattern of LTCC horn antenna [12].

5.4.2. High-gain antennas

In outdoor applications such as fronthaul and backhaul applications, high-gain antennas with low side-lobe level are desirable to extend communication distances and avoid frequency interferences to other radiocommunication systems. Two high-gain antennas (cassegrain and off-set parabola) are introduced, and the measured radiation patterns are evaluated with the mathematical models [13] [14] [15].

The rectangular horn antenna, as shown in Figure 16 (a) is used as reference antenna to measure radiation patterns of high-gain antennas. The gain and directivity of horn antenna are measured by using two-antenna method with 3m antenna separation in an anechoic chamber. The maximum gain of 25 dBi is estimated by calculation using Friis' transmission equation.

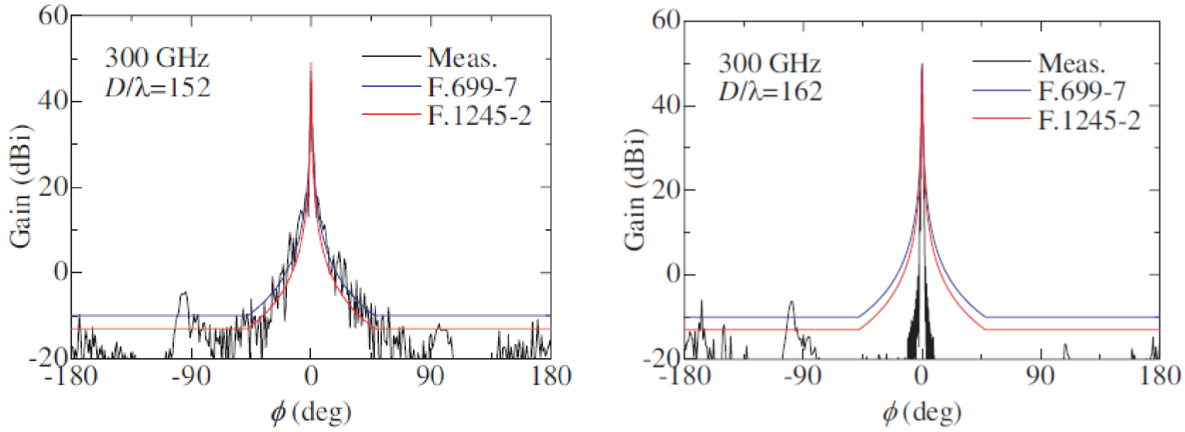


(a) Rectangular horn (b) Cassegrain (c) Off-set parabola

Figure 16

External view of 300-GHz band reference antenna and high-gain antennas.

The measured radiation patterns of cassegrain and off-set parabola antennas are shown in Figure 17. The antenna patterns calculated from antenna models defined by Recommendation ITU-R F.699-7 [13] and F.1245-2 [14] are also included in Figure 17 for reference, because these models are used for line-of-sight point-to-point fixed service application antennas in the frequency range 1-70 GHz. The difference between two models are that Recommendation ITU-R F.699-7 provides the peak envelope of side-lobe patterns and Recommendation ITU-R F.1245-2 the average of side-lobe patterns. The measured maximum gain of cassegrain antenna is 6-dBi lower than the calculated one because of blockage by the refection submirror. The beam width of the measured radiation pattern of the off-set parabolic antenna is narrower than that of the cassegrain antenna. Due to the narrow beam width, the off-set parabola antenna has better performance to avoid interference to other radiocommunication services. The measured maximum gain of 49 dBi is agreed with the designed value.



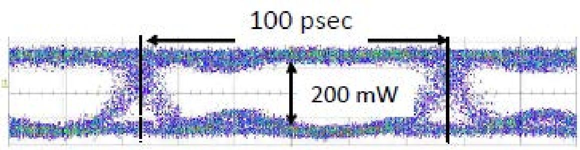
(a) Cassegrain antenna (b) Off-set antenna

Figure 17

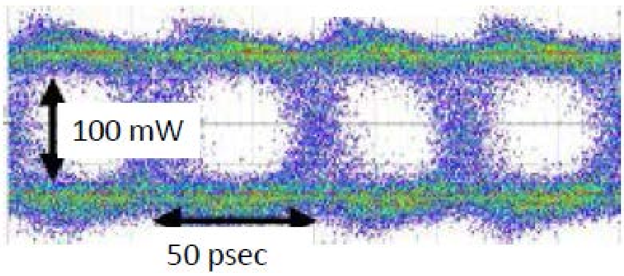
Radiation pattern of cassegrain and off-set antennas at 300-GHz band.

5.5. System demonstration

10 Gbps and 20 Gbps data transmission characteristics are demonstrated using Tx and Rx modules described in Figure 10. Figure 16 (a) and (b) show the output waveforms when the pseudo random bit sequence of 2^{31}-1 with 10 and 20 Gbps is transmitted, respectively. Although this is the first demonstration of 20 Gbps data transmission using 300-GHz carrier frequency and ASK modulation method, it can be noted that the terahertz device technologies can have potentiality to transmit 100 Gbps data transmission for close proximity and short range radiocommunication applications.



(a) 10 Gbps data transmission demonstration



(b) 20 Gbps data transmission demonstration

Figure 16

Measured output waveform of ASK modulated signals at a carrier frequency of 300 GHz [10].

5.6. Indoor propagation characteristics

Recommendation ITU-R P.1238 provides guidance on indoor propagation over the frequency range from 300 MHz to 100 GHz. However, path loss models at 300-GHz band in the office, corridor and data center environment were recently developed and those path loss coefficients were included in the revision of Recommendation ITU-R P.1238-8. The following table is extracted from Table 2 of Annex 1 to Recommendation ITU-R P.1238-9.

Table 3

Power loss coefficients for indoor transmission loss calculation [17]

Frequency	Residential	Office	Commercial	Factory	Corridor	Data centre
300 GHz(1)		20			19.5	20.2

(1) Transmit and received antennas have 10 ° beam width.

6. Conclusion

The systems operating in the frequency band between 275 and 1000 GHz have such features as large contiguous bandwidth, high attenuation loss, high effective isotropic radiated power (EIRP) and extremely small dimensions of components. The large contiguous bandwidth can be utilized to transmit high speed data rate such as 50-100 Gbps by binary or quadrature modulation schemes which make transceiver simple. These features are able to accelerate the terahertz devices to the markets in the near future.

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[16] InfiniBand™ Architecture Specification Volume 2, Release 1.3.

[17] Recommendation ITU-R P.1238-9, Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz (Question ITU-R 211/3).

Annex 1

Article 5 to Chapter II to Radio Regulations

248-3 000 GHz

Allocation to services		
Region 1	Region 2	Region 3
248-250	AMATEUR AMATEUR-SATELLITE Radio astronomy 5.149	
250-252	EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) 5.340 5.563A	
252-265	FIXED MOBILE MOBILE-SATELLITE (Earth-to-space) RADIO ASTRONOMY RADIONAVIGATION RADIONAVIGATION-SATELLITE 5.149 5.554	
265-275	FIXED FIXED-SATELLITE (Earth-to-space) MOBILE RADIO ASTRONOMY 5.149 5.563A	
275-3 000	(Not allocated) 5.565	