Evolution of Millimeter-Wave Multi-Antenna Systems in the IoT Era

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SUMMARY   In this paper, we present the roles played by millimeter-waves in the realization of an Internet of Things (IoT) society. Millimeter-waves are becoming essential frequency resources, enabling ultra-high-speed wireless networks supporting massive data traffic and high-resolution sensor devices. Multiple antenna technologies such as phased arrays, sector antennas, and MIMO signal processing are key technologies for putting these into practical use. In this paper, various examples of integration of multi-antenna systems are shown, as well as demonstration on 60 GHz-band millimeter-wave wireless access and 79 GHz-band high-resolution radar. We also propose applications to ITS for an IoT society, combining millimeter-wave wireless access and radar sensors, and discuss technical issues to be solved in the future.

key words: *IoT, millimeter-wave, 5G, radar, phased array, MIMO*

1. Introduction

With the spread of mobile devices such as smartphones, mobile data traffic has been increasing exponentially from year to year. Furthermore, with the progress towards an IoT society where everything communicates with each other, the amount of data traffic will increase even further. In view of this, the realization of 5th generation (5G) mobile networks [1], [2], which will be a key communication network environment supporting the needs of an IoT society, is eagerly anticipated. In order to accommodate huge amount of data traffic, there have been increasing expectations for the effective utilization of the millimeter-wave bands [3].

Millimeter-waves are expected to be used for high-speed wireless communication, and in the beginning of the year 2000, a small prototype device [4] was actively developed for that purpose. Ever since, standards for communication in millimeter-wave bands have been developed and the momentum for practical use has been picking up. With the emergence of OFDM and MIMO technologies, which are technologies for improving frequency utilization efficiency, yet further potentials are made possible for speeding up data communication in order to fully maximize utilization of millimeter-waves. For 5G, the scarcity of the frequency resources is obvious. Therefore, in order to fulfil the system requirements, utilization of the millimeter-wave and terahertz is indispensable. Several frequency bands have been studied in the millimeter-wave band, between 24.5 and 86 GHz. Among them, 7 to 9 GHz of bandwidth has been allocated as unlicensed band at frequencies around 60 GHz, thereby providing an excellent mean to achieve very high data rate above multi-gigabits. In addition, international standards targeting indoor short-range communication, such as IEEE 802.11ad/WiGig, having been developed [5] and put into practical use, are expected to be an important element of 5G [6].

On the other hand, research and development of sensor applications utilizing millimeter-waves has also been proceeding. A typical example application is a collision avoidance radar for automotive purposes, where a 76 GHz-band in-vehicle radar is put into practical use for collision avoidance or automatic cruise control (ACC) [7]. In order to further improve the sensor resolution, use of the 79 GHz band was also considered, with frequency allocation for the band of 77 GHz to 81 GHz subsequently completed in the World Radio Conference in 2015 (WRC-15) [8]. It is expected that the 79 GHz-band radar will be popular in the future. Research and development on the use of millimeter-wave exceeding 100 GHz has also been made to further improve the sensor resolution [9]. One of the reasons for the active utilization of these millimeter-wave bands is that CMOS technology capable of large-scale integration has been realized [10].

In this paper, in Sect. 2, we first show the roles that frequency bands of millimeter-waves play in the future IoT era. Section 3 shows the feasibility of millimeter-wave CMOS, demonstrating that it can be used to enable wireless access by introducing beamforming and sector antenna technologies. In Sect. 4, we introduce an example of the realization of a high-resolution, three-dimensional scanning radar using MIMO technology. In Sect. 5, we propose vehicle-to-everything (V2X) applications for IoT combining millimeter-wave radio access technology and sensor technology.

2. Evolution of IoT

Here we consider the role of millimeter-wave in IoT. Figure 1 shows a conceptual diagram of IoT. In Fig. 1 (a), the data output from the sensor device is gathered in the cloud through the access network, gateway, and core network. The cloud analyzes data and gains an insight by artificial intelligence (AI) technology. Subsequently, it returns a control signal to the node terminal. The principle of IoT is to gener-
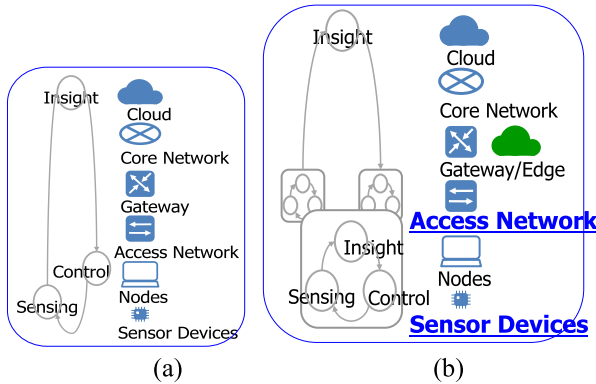
Fig. 1 Internet of Things (IoT) architectures (a) conventional IoT structure and (b) evolved IoT structure with edge computing

Fig. 2 Analog beamforming architecture

ate added value in the flow of these data. As IoT evolves, the number of sensor devices increases tremendously, resulting in vast explosion of data traffic that the existing networks can no longer accommodate. For applications that analyze and collect data gathered from sensor devices without latency, such as automatic driving assistance system (ADAS), it is necessary to analyze the data and gain an insight with a processor located physically close to the sensor devices. The area close to the sensor device is commonly called the "edge", giving rise to the term "edge computing" [11] to refer to data processing close to the sensor device, as shown in Fig. 1 (b). Since the "edge" exists in front of the cloud, it is also called "fog computing" [12]. In the evolved IoT, as shown in Fig. 1 (b), multiple local IoTs analyze data and gain insights at the edge close to the sensor devices. In addition, the hierarchical structure connects data from the edge to the cloud through the core network.

By employing millimeter-wave band for the access network, it is possible to aggregate huge amount of sensor data at the edge and realize advanced processing with low latency. Furthermore, since the amount of data flowing in the core network can be filtered at the edge, the load on the core network can also be reduced.

Wireless transmission using millimeter-wave is weak against non-line-of-sight (NLOS). Nevertheless, high-speed transmission is still possible if the line-of-sight (LOS) environment can be secured, allowing it to achieve real-time capability. In the following sections, millimeter-wave wireless local area network (WLAN) as access network, and millimeter-wave radar as sensor devices will be described.

3. 60 GHz-band WLAN for Network Access

In the 60 GHz band, research and development has been actively conducted for short-range wireless access, and the resulting IEEE 802.11ad/WiGig standard holds the status of "de facto". IEEE 802.11ad, also known as WiGig, was published in December 2012, and an interoperability certification program based on the standard was launched by Wi-Fi Alliance in October 2016 [13]. IEEE 802.11ay is currently being developed as the next generation 60 GHz technology
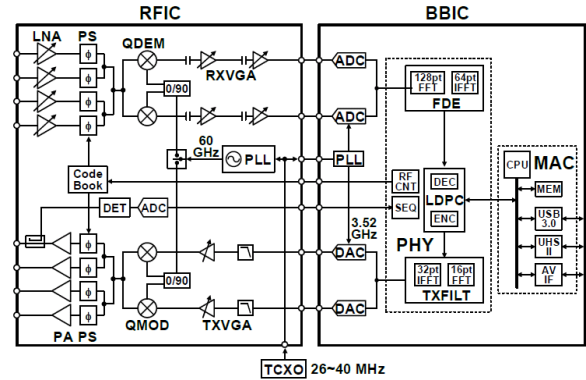
which extends the IEEE 802.11ad standard in order to realize high speed of above 20 Gbps, high density support, and other features which are required in 5G [14].

3.1 Analog Beamforming for Phased Array Antenna

The authors have already developed a compact, low power consumption CMOS chipset targeted at mobile terminals such as smartphones [15]. The fabricated CMOS chipset employed various technologies, such as 1) Direct conversion architecture, 2) Frequency domain equalizer that compensates circuit frequency deviation and multipath fading, 3) Reduction of Fast Fourier Transform (FFT) size. Although it showed excellent performance as a chip set for mobile terminal from the viewpoint of low power consumption, performance as an access point (AP) was insufficient in view of the coverage area. Practical applications of 60 GHz-band millimeter-wave originally focused on point-to-point (P-P) link communication due to the narrow coverage of directional antennas. For IoT applications, in order to communicate with multiple sensors, it is necessary to realize point-to-multi-point (P-MP) connection. Therefore, integration of a beamforming circuit for electronically controlling the directivity of millimeter-waves has been realized. For beamforming, analog beamforming, which essentially uses a phased array antenna approach, was adopted. In addition, as a realization method of the phase shifter in the phased array antenna, a vector synthesis in the RF path [9] was adopted. The reason for selecting the RF path is that the power consumption can be minimized. Figure 2 shows the architecture and Fig. 3 shows the chip micrograph. Figure 4 shows the measured phase shifter characteristics. As shown in Fig. 2, in order to realize beamforming, a phase shifter (PS) is inserted in the receiver after the low nose amplifier (LNA) and in the transmitter before the power amplifier (PA). It adopts a vector phase shift synthesis circuit in the 60 GHz band.

The chip size is 3.2 mm × 5.1 mm and is implemented with 40 nm CMOS. The antenna module size is 11 mm × 12 mm. 4-elements patch antennas in both transmission and reception realize a phased array antenna. Figure 4 shows the results of evaluating the characteristics of the vector phase shifter, which has 6 bits resolution both in I and Q channels.
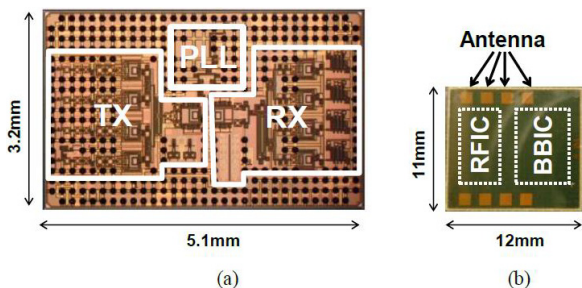
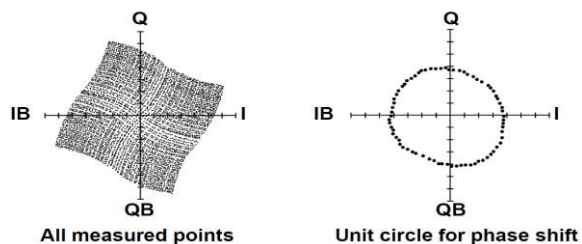**Fig. 3** Fabricated 60 GHz RF chip with analog beamforming in 40 nm CMOS

Fig. 4 Measured phase-shifter characteristics
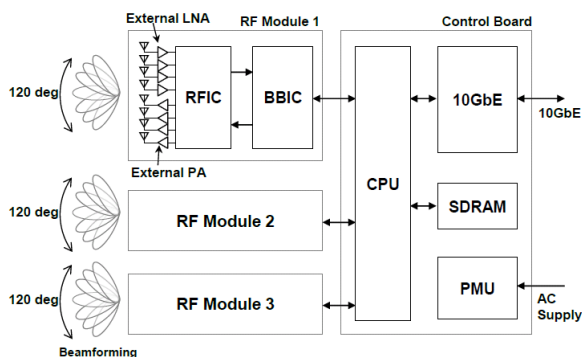

Fig. 5 Fabricated IEEE 802.11ad/WiGig access point (AP) block diagram

64×64 ways of amplitude and phase control were made possible as shown in the left figure of Fig. 4. Result of selecting a point which becomes a unit circle is shown in the right figure of Fig. 4.

PS with an angular resolution of 5° was made possible. Since 360° can be divided into 128 points, ideally a resolution of less than 2.8° can be realized. However, degradation due to circuit imperfection resulted in resolution of about 5°. By designing the 3-dB beamwidth of the patch antenna to 120°, a coverage area of 120° can be realized using a single phased array.

3.2 W-LAN System with 3-Sector Antennas

By having a WiGig module covering 120° and defining that as one sector, a 360° area coverage can be realized using three such sectors. Figure 5 shows a block diagram of a WiGig AP that is based on multiple WiGig modules. A fab-
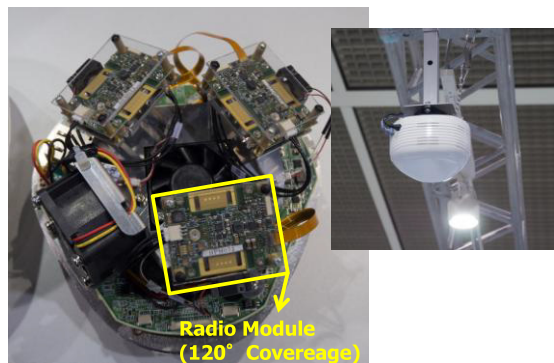

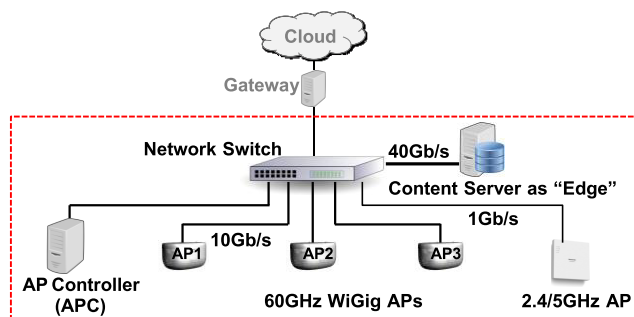**Fig. 6** Fabricated IEEE 802.11ad/WiGig AP

Fig. 7 Contents delivering system by WiGig AP with contents server controlled by 2.4/5 GHz AP

ricated WiGig AP is shown in Fig. 6. A high-speed content delivering system using the WiGig AP has been developed as shown in Fig. 7 [16]. It consists of multiple WiGig APs, an AP controller (APC) and a legacy 2.4 or 5 GHz WLAN AP. All devices are centralized by a network switch and contents server. The APC manages frequency resources of WiGig APs, such as frequency channels and sector ID, to enable seamless handover. The 2.4 or 5 GHz AP can support the WiGig APs' coverage. It enables heterogeneous network (HetNet) to support mobility. In order to enable downloading of large size contents instantly from a cloud, contents server plays a significant role to shorten the system latency. It can be considered as an "edge" cloud. The above-mentioned system showed that the 60 GHz millimeter-wave band is sufficient to provide radio access networks with multi-gigabits capability.

4. 79 GHz Radars for Mobility Sensors

Millimeter-wave can also be applied as high-resolution radars because of their broadband frequency resources. Due to the nature of radio waves, they are excellent for object detection even in environments that are difficult to detect with visible light cameras, such as darkness, fog and dust. IoT applications based on such radars are expected in the mobility field such as for automobiles.
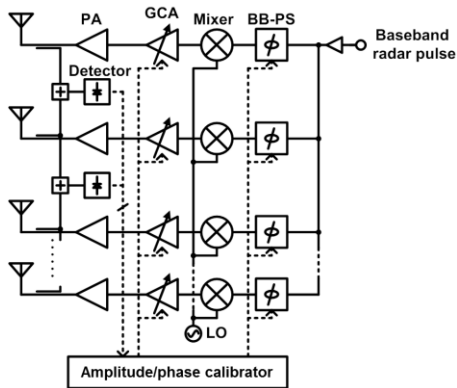
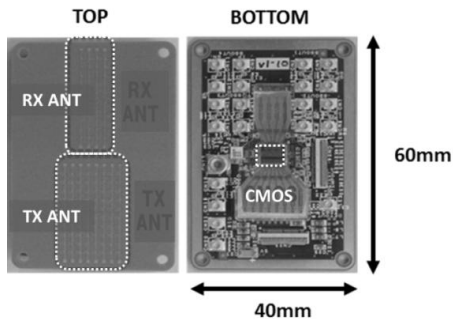**Fig. 8** Block diagram of phased array antenna for 79 GHz Radar Transmitter

Fig. 9 Fabricated 79 GHz Radar front-end module

Fig. 10 Measured baseband phase shifter (BB-PS) characteristics
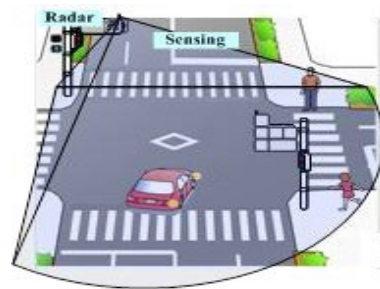
Fig. 11 Usage scenario of 79 GHz-band infrastructure Radar

4.1 79 GHz Radar System Integration in CMOS

Collision avoidance radar in the 76 GHz band has already been put to practical use for automotive applications. Practical applications of the 79 GHz band for a higher-resolution radar capable of utilizing broad frequency band, is under development. In the conventional millimeter-wave radar, the viewing area is narrow due to the narrow range of the directional antenna. To address this, the use of the phased array antenna introduced in Sect. 3 can be applied here as an effective mean to realize a wide viewing angle.

In order to realize a CMOS front-end for 79 GHz-band radar, an optimum phase shift circuit was researched [17]. In Sect. 3, a phase shifter is inserted in the RF path, but for radar, it is necessary to suppress the side lobe of the antenna. This is because unwanted signals from the side lobe direction can cause detection errors. In order to suppress the side lobe, a phase shifter was inserted into the baseband instead of the RF because accuracy in angular resolution is necessary.

Figure 8 shows a block diagram, and Fig. 9 shows a photo of the module with a CMOS chip mounted. The baseband phase shifter (BB-PS) is inserted after dividing the baseband radar pulse signal into 8 branches. Each signal is up-converted to the 79 GHz band by a mixer and then fed to each antenna. A power detector at power amplifier (PA) output 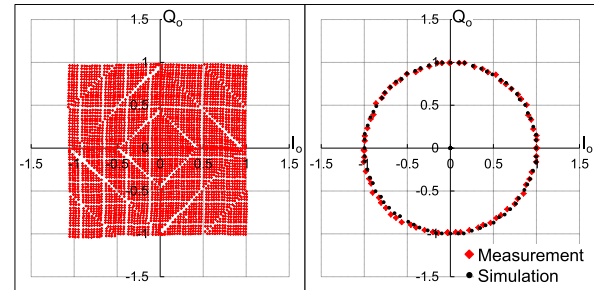for correcting the amplitude error between the 8 branches is inserted in each branch. The fabricated module with 8 branch transmitters (TX) and 4 branch receivers (RX) is 40 mm × 60 mm.

Figure 10 shows the measured BB-PS characteristics. The BB-PS has resolution of 6 bits for each of the I and Q channels. As shown in Fig. 10 (a), it can be set to 64 × 64 points of phase and amplitude. Figure 10 (b) is the result of setting the bit condition to become a circle with amplitude 1.

The BB-PS achieved a performance of less than 2° angle resolution, which is 2.5 times higher than a 60 GHz-band phased array with an RF PS.

4.2 Infrastructure Radar System for Pedestrian Safety

The 79 GHz-band radar with high resolution and wide viewing angle is expected to be utilized as infrastructure radar for preventing pedestrian accidents at intersections with poor visibility [18]. Figure 11 shows the usage scenario at the intersection. There are still many cases where pedestrians are injured in traffic accidents at intersections with poor visibility. Since the developed 79 GHz radar, shown in Sect. 4.1, has a higher angular resolution, it can detect a pedestrian and a vehicle as separate objects even in an environment, such as at an intersection, where they both coexist. As it is possible to separate and detect pedestrians at intersections, the "Infrastructure Radar System" aims to prevent accidents by notifying this data to the driver.

Figure 12 shows a photograph of a radar prototype installed close to the traffic signal. Figure 13 shows a cross section of the installation conditions. It was designed such that the radar device is tilted downward by 8° from the
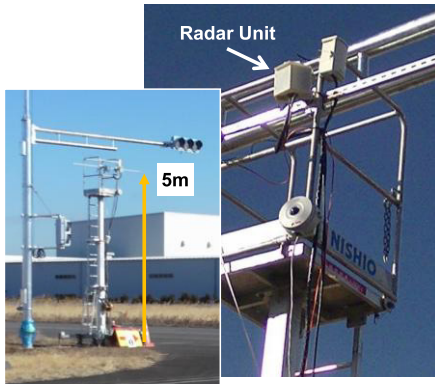
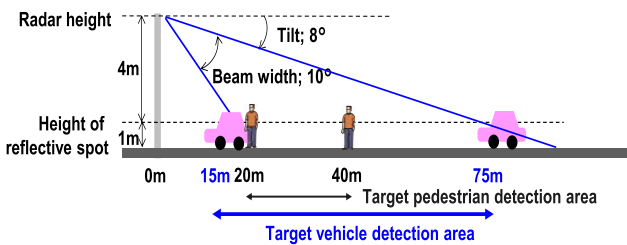**Fig. 12** Experimental Radar setup at a crossing

Fig. 13 Cross-sectional view of infrastructure Radar setup

Table 1 Measured detected range for various types of vehicles

Category	Detected Range [m]	Sample Number
Track	13.7 – 87.1 m	Overall Frames: 1005 (100.5sec) Undetected Frame:1 (0.1sec)
Wagon	12.8– 83.9 m	
Minivan	12.3 – 75.3 m	
Sedan	14.9– 75.4 m	

height of installation at 4 m and to detect vehicles in the range of 15 to 75 m. Pedestrians can be detected in the range of 20 to 40 m.

Table 1 shows the results of evaluation on the test course. Among the four models used in the experiment, since the sedan car has the lowest reflectance, the detectable distance is the narrowest. Nevertheless, the target distance of 15 to 75 m could still be achieved. Next, as shown in Fig. 13, the detection rate of pedestrians on the crosswalk diagonally opposite to the radar was evaluated. For the pedestrian on the pedestrian crossing, the detection rate was high, between 99.8 to 99.9%.

4.3 3D-MIMO Radar System [19]

The infrastructure radar shown in Sect. 4.2 has resolution in the distance direction and angle resolution in the horizontal direction, thus, can be termed as a radar with two dimensional (2D) scanning. If the angle resolution in the vertical direction is added, information on the height of the target can be obtained, thereby enabling more accurate detections. In order to obtain angular resolution in the vertical

Fig. 14 Top view of crossing

Table 2 Measured detect probability of pedestrian

Target Area	Probability	Sample
Crosswalk A	99.8%	N=949
Crosswalk B	99.9%	N=719
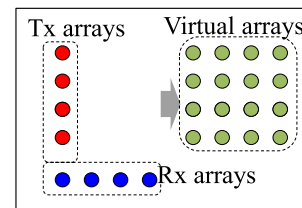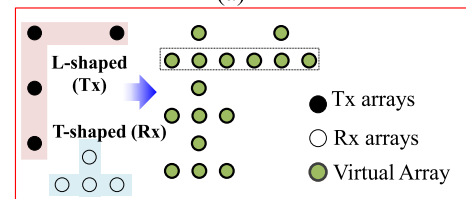
Fig. 15 Virtual antenna array, of (a) conventional and (b) proposed unequal spacing array

direction, it is necessary to arrange a plurality of antennas in the vertical direction in addition to the horizontal direction. This means that a very large antenna array is required. For this reason, techniques for virtually increasing the number of antennas, without increasing the number of physical antennas, by MIMO signal processing have been studied. Figure 15 (a) shows a virtual array antenna using conventional MIMO radar. Virtually 4×4, equal to 16 arrays, can be realized by 4 transmit and 4 receive arrays. As shown in Fig. 15 (b), by allocating antenna elements at unequal intervals, it is possible to enlarge the virtual array by interpolation techniques. Virtually, the realized performance is close to a 36 elements array of 6×6.

Figure 16 shows the block diagram of the MIMO radar, and Fig. 17 shows the fabricated MIMO radar module and prototype. The fabricated MIMO radar consists of the TX 4 branches (Nt = 4) and the RX 4 branches (Nr = 4). In order to perform MIMO processing in time division, switch (SW) is inserted for both TX and RX, and each TX branch and
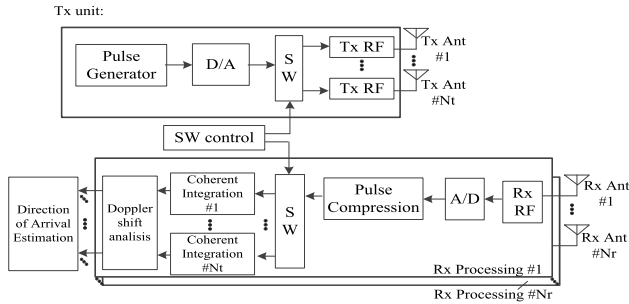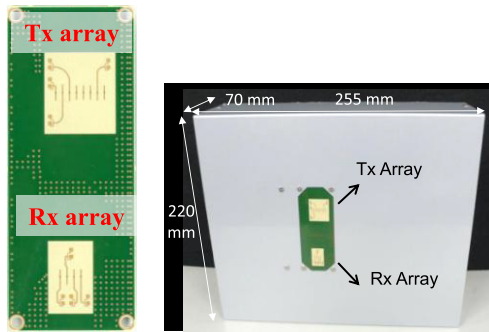
Fig. 16   MIMO Radar block diagram

Fig. 17   Fabricated MIMO Radar module and prototype

each coherent integration in the reception (RX) are selected at each timing.

Using this MIMO radar, separation performance in the horizontal direction and vertical direction was realized. Figure 18 (a) shows the evaluation result for the case that two standard corner reflectors (CRs) are placed in the vertical direction, and Fig. 18 (b) shows a similar case for the horizontal direction. "Setup" shows initial setting. Figure 18 (a) right figure shows measured results at $-10°$ offset in the azimuth, and $+5°$ and $-5°$ offset in the elevation, respectively. Similarly, Fig. 18 (b) shows the measured results at $0°$ offset in the elevation, and $15°$ and $-5°$ offset in the azimuth, respectively.

It was confirmed that each of two objects can be separated and detected. However, an error of 2 to $3°$ occurs in both the azimuth and the elevation direction, which is a future research topic.

5.   V2X Applications Using mmW in Future IoT

In order to realize ADAS and autonomous driving, it is necessary to utilize various data. Moreover, if autonomous driving is realized, the in-vehicle comfort level must be enhanced. In the future, the data collected by in-vehicle devices is expected to become huge. The data collected by a roadside unit (RSU) also becomes more advanced, and so the high speed performance provided by the 60 GHz band, as described in Sect. 3, is very attractive.

In Fig. 19, we propose example applications for 60 GHz-band wireless access in the ITS field. Figure 19 (a) is an example illustrating content download from a RSU.
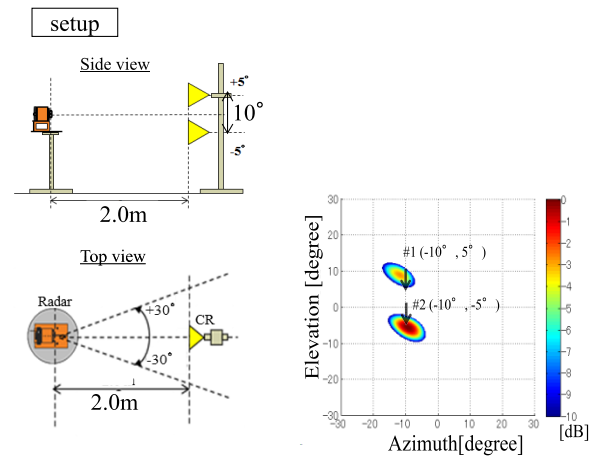
(a)
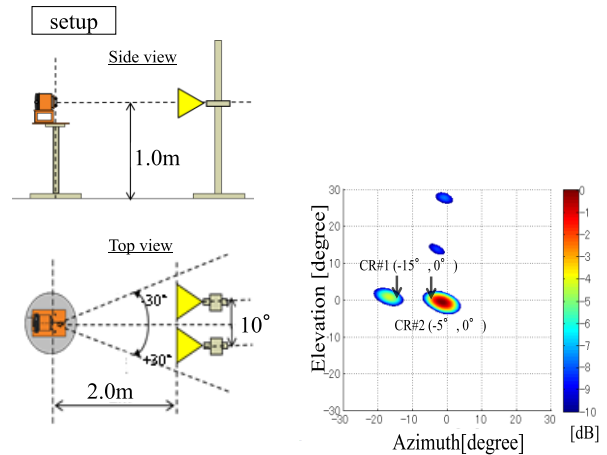
(b)

Fig. 18   Measured MIMO Radar for two obstacles for (a) vertical scan and (b) horizontal scan
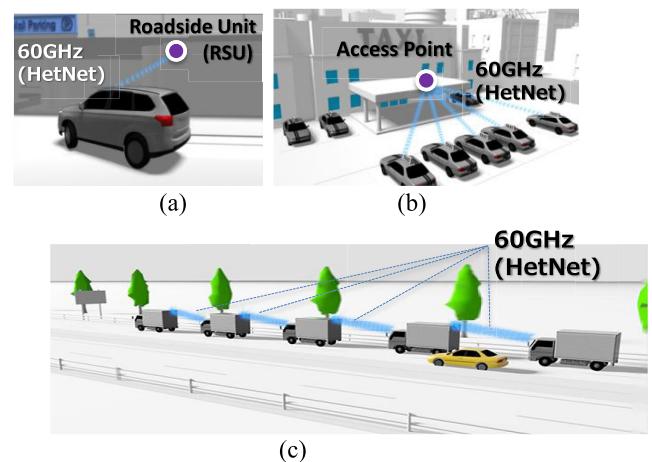
Fig. 19   V2X Applications by mmW as future ITS; (a) instant 3D-map delivery, (b) driving recorder data uploading and (c) multi-hop video data sharing in platooning

It is effective for delivery of 3D-maps necessary for autonomous driving. Figure 19 (b) is an example illustrating contents uploading from an in-vehicle device. It is conceiv-
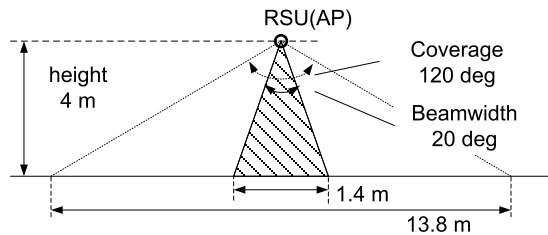
Fig. 20 Basic cell design for RSU based on IEEE 802.11ad/WiGig AP

able to collect accumulated data from driving recorder and use it for operation management. Figure 19 (c) shows an example of sharing data between vehicles during platooning. Because of the narrow beam nature of millimeter-waves, it is possible to communicate while suppressing interference from surroundings.

Figure 20 shows a basic cell design example based on a IEEE 802.11ad/WiGig AP. When the AP with a coverage beam angle of 120 degrees is installed at a height of 4 m, the area diameter becomes 13.8 m. Assuming that the antenna beam angle is 20 degrees, the area diameter covered by one antenna beam is 1.4 m. Assuming a travelling velocity of 100 km/h, it takes 49 ms to move 1.4 m. In other words, by scheduling the beamforming at least once every 49 ms, a vehicle moving at 100 km/h can be tracked continuously.

According to the IEEE 802.11ad/WiGig standard, it is possible to control the beam in every beacon interval. The standard does not define the beacon interval time, although it is typically implemented to about 100 ms. In other words, by designing the implementation of the beacon interval, it can be said that even with the IEEE 802.11ad/WiGig standard, it is possible to upload and download mass data content in the context of high-speed mobility. In order to cope with high-speed mobility exceeding 100 km/h, it may be necessary to consider further design for existing protocol. Furthermore, HetNet, which integrates millimeter-waves and microwaves, can be employed to realize excellent V2X that achieves both high speed and high reliability.

6. Conclusion

We have discussed the role of millimeter-waves in the future evolving IoT society. In IoT, edge processing which performs data processing near the sensor becomes important in applications requiring high speed and low latency such as ITS. Millimeter-waves will play a major role as a transmission path connecting sensors and edge processing. In addition, as the edge processing environment becomes viable, sensors are becoming more sophisticated, and the roles of millimeter-waves as high resolution sensors will also become more prominent. In employing these millimeter-waves, multi-antenna technologies such as phased arrays, utilization of sector antennas, MIMO signal processing and the like are very important. In 5G, it is also important to utilize microwave technology to compensate for the nature of millimeter-waves, such as to enhance the coverage area of WLAN AP, and to support high-speed mobility for V2X

applications. In addition, the technology of HetNet will become increasingly important in the future IoT era.

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