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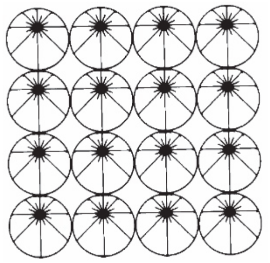

Beyond 5G/6G mmWave and Terahertz Communications Technologies

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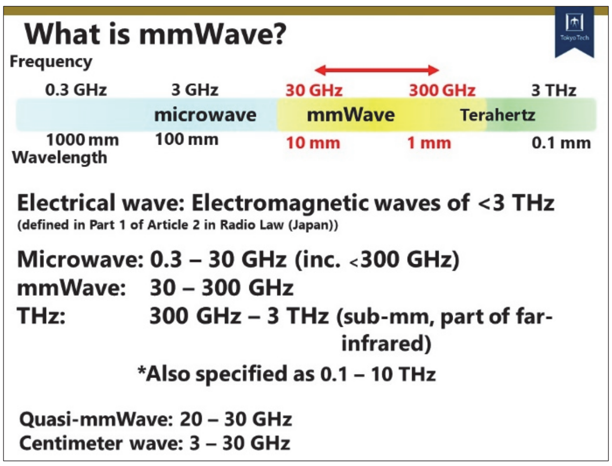
1 mmWave Features and Applications

This article introduces the millimeter waveband (mmWave) and terahertz (THz) communications technologies–especially phased-array antennas–we are researching at Tokyo Institute of Technology to support the Beyond 5G/6G era. Since many readers come from a variety of backgrounds, I will start by explaining the basic differences between conventional microwave and mmWave technologies followed by a description of radio communications using the mmWave and THz bands.

1.1 What is mmWave?



Slide 1

I am sure most of you know the mmWave band is part of the electromagnetic spectrum where alternating electrical and magnetic fields transmit energy, and waves at less than 3 THz, are described as electrical.

Higher frequencies than this are called optical which are one form of electric wave and include infrared, ultraviolet, and visible light. At even higher frequencies, X-rays and gamma rays are also part of the electromagnetic spectrum, excluding alpha and beta waves to fly as particles.

At higher optical frequencies, we use the term "wavelength" rather than frequency. Conversely, the term "frequency" is used for radio waves. And sometimes "wavelength" and "frequency" are used interchangeably! For example, frequencies from 0.3 to 30 GHz, and from 30 to 300 GHz are called the microwave and the mmWave bands, respectively, because the wavelengths are about 1 to 10 mm. Additionally, frequencies from 300 GHz to 3 THz are generally defined internationally as the THz band. The "mmWave" name derives from the wavelength, while the THz band is also called the "sub-mmWave" band following the same logic. "Sub-mm" means wavelengths below 1 mm and is applied to the wavelength domain from 0.1 to 1 mm.

As mentioned above, although 3 THz marks the boundary between electrical and optical waves, there is no sudden transition to optical signals at the boundary and the properties transition gradually from electrical to optical. There is no clear division where one ends and the other starts.

There are various recent definitions about the THz band that loosely cover all THz frequencies from 0.1 to 10 THz. Since the mmWave band covers wavelengths from 1 to 10 mm, there is a relatively clear distinction, but there is the 28 GHz frequency used for "5G". Since 28 GHz is just a little below 30 GHz, it is not strictly mmWave although some people call it "quasi-mmWave" while a few others use the term "centimeter wave". Since 28 GHz is very close to mmWave, it is sometimes described unthinkingly as mmWave.

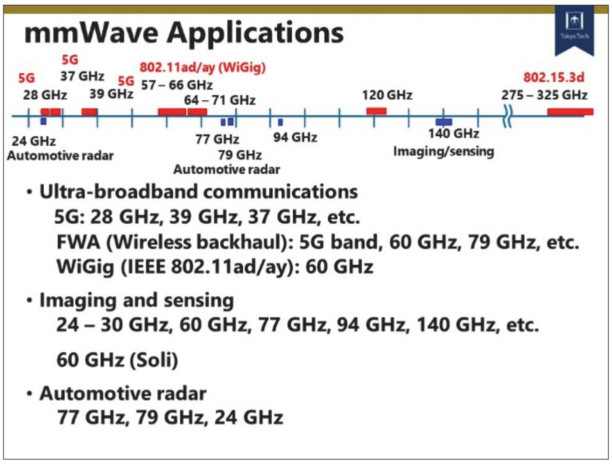
Terahertz suffers from the same ambiguity. Traditionally, THz means the frequency band from 300 GHz to 3 THz but it is defined increasingly as being from 0.1 to 10 THz. When I'm asked about this, I think it may be necessary to comment, "It's called THz but how many frequencies are there?" I'm going to talk about this later, but there are special cases where the frequency around 300 GHz used by next-generation 6G communications is described as THz along with frequencies around 100 GHz. When hearing the term THz, I think it is better to note what GHz value is being referenced.

As you know, 5G uses both frequencies below 6 GHz as well as the mmWave frequencies of 28 and 39 GHz. Originally, there was a misunderstanding that 5G would be entirely mmWave at 28 GHz. This misunderstanding has disappeared with better recent clarity, but I think "THz" is recently in the same situation.

Just for extra clarity, "mmWave" derives from wavelength, while "THz" derives from frequency, and the wavelength of the "microwave" band is not on the order of microns (μm) but is closer to 1 mm. However, there was a trend at the time to think that "micro" might have a better 'feeling'.

The key point is that there really is no exact definition of what constitutes the microwave, mmWave, and THz bands, which requires care about unexpected uses of these terms.

1.2 mmWave Applications



Slide 2

Since THz applications are just starting to take-off, mmWave frequencies are still in general use, so slide 2 shows communications applications in red and sensing applications in blue. Currently, two bands are used: the 60-GHz band used by 5G and WiGig (IEEE 802.11ad/ay), and the 28, 39, and 37-GHz bands used by 5G.

Fixed Wireless Access (FWA) is a form of fixed 5G communications. It is used mostly as wireless backhaul between fixed cellular base stations. There are additional use cases where optical fiber cannot be used, such as between buildings and offices on different building floors.

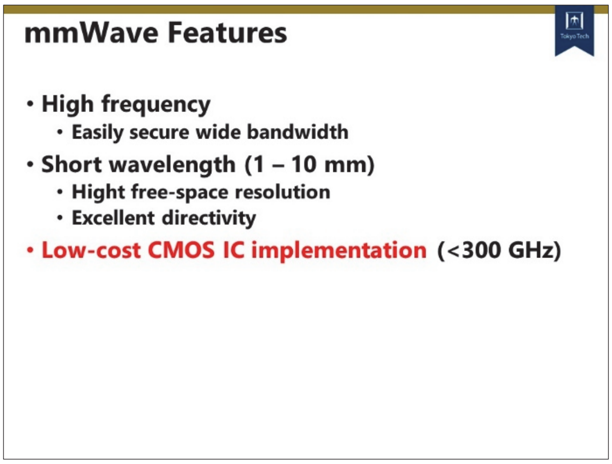
However, there are also expectations for backhaul applications between "small-cell" base stations for short-range wireless communications between base stations where optical-fiber links are unnecessary. Verizon in the US is using 5G FWA technology for "last mile" connections between subscriber premises and the nearest steel base-station tower. mmWave technology is used by these applications as well as by FWA WiGig using the non-5G 60-GHz band or E-band.

Although mmWave applications are consumer-focused, future applications include uses as repeaters for satellite and long-range TV communications.

On the other hand, non-communications applications include use of various other frequencies for imaging, airport security scanners, etc. There are also applications in factory non-destructive testing and package contaminant detection using radio waves to measure and detect items that cannot be seen using visible light. Other application fields include sensing for the presence of foreign materials inside opaque products, such as black automotive tires. Google Soli is another future application using a smartphone with built-in Infineon device to sense hand gestures. And as many of you know, self-driving vehicles use frequencies around 77, 79, and 24 GHz for sensing applications.

Even higher frequencies in the 100 and 300-GHz bands have been standardized by IEEE802.15.3d and progress is being made with the relatively short-range Wireless Personal Area Network (WPAN) technology reaching speeds of more than 100 Gbps.

1.3 mmWave Features



Slide 3

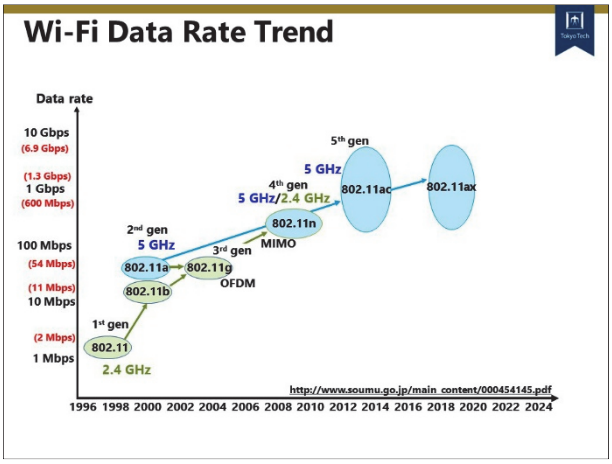
The first mmWave feature is high frequency with easily secured wide bandwidth for fast communication speeds. Since the free space resolution is high due to the short wavelength, mmWave is ideal for sensing applications. Moreover, the directivity is excellent because the frequency is higher and the wavelength is shorter than the microwave band. However, it does not bend around buildings due to diffraction resistance, making it hard for the radio waves to penetrate buildings and it cannot be described as ideal for communications.

At higher THz-band near-optical frequencies, it has properties closer to light with tight radio beams rather like a laser pointer.

A key feature is low-cost implementation using a CMOS IC. In Japan, people talk about the third mmWave boom. Rather than being a simple boom, this time it feels like mmWave is finally “colonizing” the social infrastructure in comparison to when I worked at the NTT Research Institute and one transistor cost ¥800,000; we handled them with great care due to anxieties about damage by electrostatic discharge. The mmWave era using devices with this feature seemed quite long!

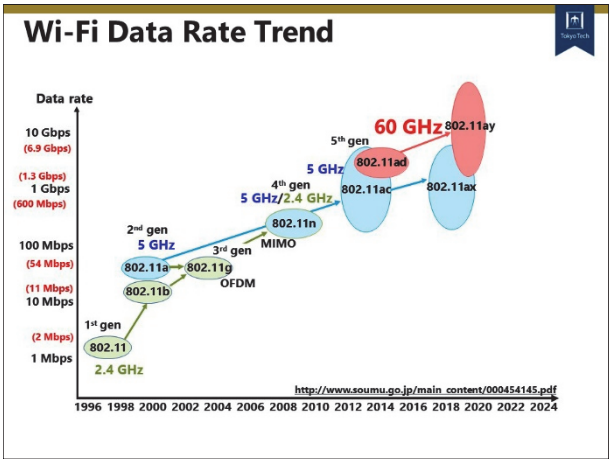
I'm sure many of you know that CMOS is one type of transistor. Although there are bipolar and FET types as well as MOSFETs, CMOS is still used most widely. Smart phone digital circuits, CPUs, etc., all still use CMOS transistors. I am sure all Anritsu engineers know that 99.9% of circuits by number use CMOS transistors, and these low-cost CMOS transistors have played a major role in implementing mmWave wireless devices and CMOS is a basic part of the WiGig implementation too. There has been active research into using CMOS for mmWave communications since about 2000.

1.4 Wi-Fi Data Rate Trend



Slide 4

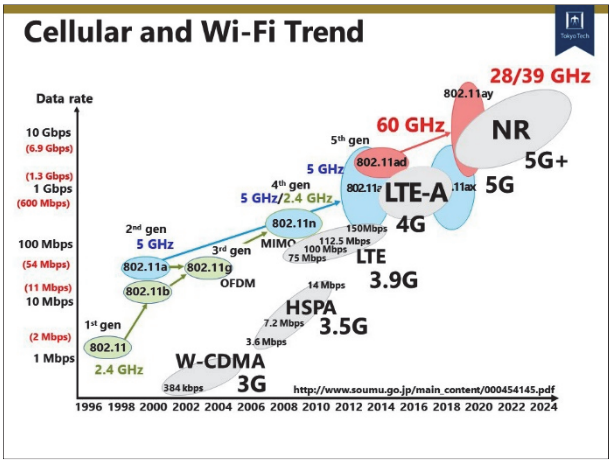
Slide 4 shows a graph of Wi-Fi data rates. The rate was about 2 Mbps at the historic release of the first 802.11 standard and showed a steady increasing trend up to 802.11b when speeds of 54 Mbps were achieved. It was much faster than cellular and, in those days, communications seemed to be fast enough if 54 Mbps. Speed requirements continued increasing to meet video-streaming demand and the newest smartphones supporting 802.11ac, ax have finally reached effective data rates of 1.3 to 1.7 Gbps.



Slide 5

Looking towards the future, research is now targeting data rates of more than 100 Gbps using the 60-GHz band. Unfortunately, this may be a failure in business terms since current speeds of 1 Gbps may well be quite sufficient for most needs and are approaching a huge differential of 100 or 1000 times the first data rates after just 20 years.

1.5 Cellular & Wi-Fi Trend



Slide 6

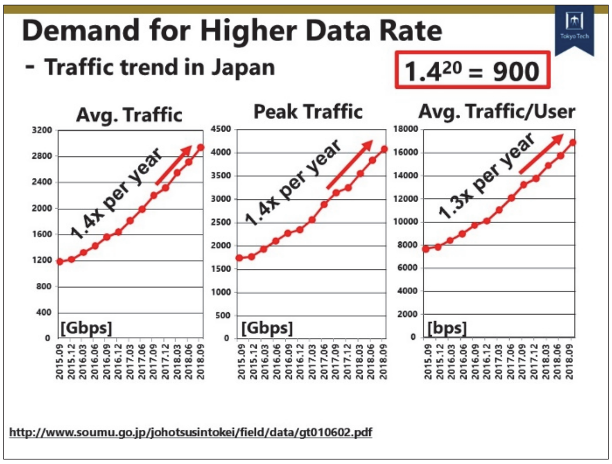
Slide 6 compares the cellular and Wi-Fi trends. With the progress from 3G to 4G and even with the higher i-mode data rates the 384-kbps cellular data rate is still far slower than Wi-Fi.

Development of CDMA, OFDM and MIMO technologies is closing the gap and the recent mmWave implementation now means there is now almost no difference between the data rates. While non-specialist users may feel no difference, the Wi-Fi Alliance Wi-Fi standard and the 3GPP cellular standard are completely different things. However, the historic technology trends are similar.

The data rates are trending in the same direction as the technologies get closer and mmWave is deployed.

This figure in slide 6 shows another trend but what does it mean? As the difference in data rates is closing the target communication ranges are closing too. The Wi-Fi range is about 20 m, which is not much different than the previous 50-m range. On the other hand, while cellular radio waves propagate up to about 1 km from base stations, 5G using small-cell technology is targeting a 400-m range. In other words, there is a common trend towards smaller coverage by one cell and shorter communications ranges. I'll talk more on this a little later, but this is a key point in considering communications speeds.

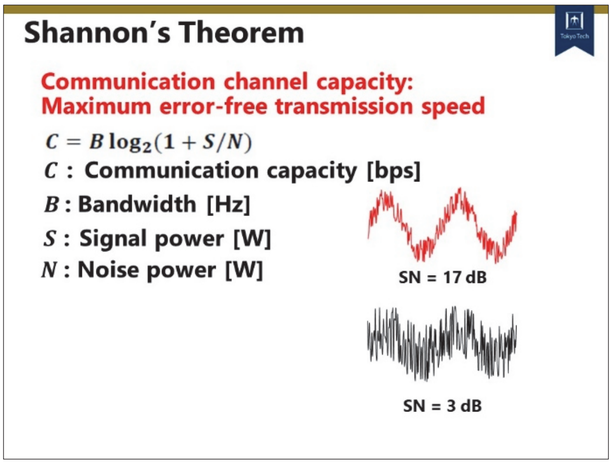
1.6 Demand for Higher Data Rate



Slide 7

I'll provide some more explanation about mmWave because this is an important area. In Japan, both mobile-data average peak traffic and traffic per user are increasing 1.4 times annually, which compounds to 900 times over 20 years. Future advances will require Tbps-class transmission speeds, so what shall we do now to cover this using wireless?

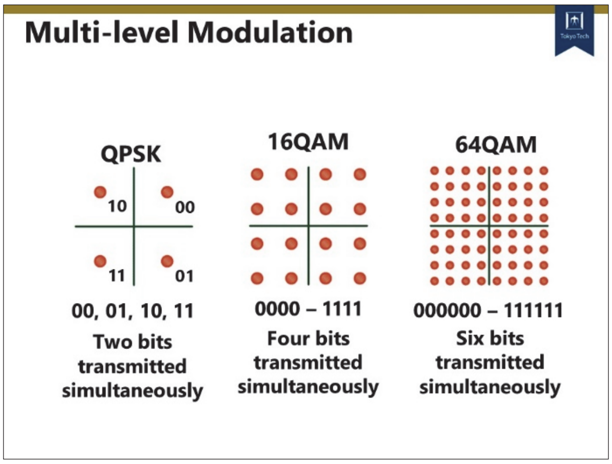
1.7 Shannon's Theorem



Slide 8

Shannon's Theorem is based on understanding this slide 8. Possibly some readers may not be so good at understanding numerical formulae but Shannon's Theorem is taught to second and third-year students of electrical and electronics engineering. Basically, it states that the theoretical upper limit for transmission speed is determined by the bandwidth and signal to noise ratio (SN). If the SN is low, the waveform looks like a sine wave and can be assigned 1, 0, and 1 values. If the SN is high, the waveform can be assigned values of 0, 1, 2, and 3. In other words, more data can be transmitted simultaneously at a high SN. So, what about bandwidth frequency? The transmission speed increases at a wide bandwidth because the 0101… string can be sent quickly.

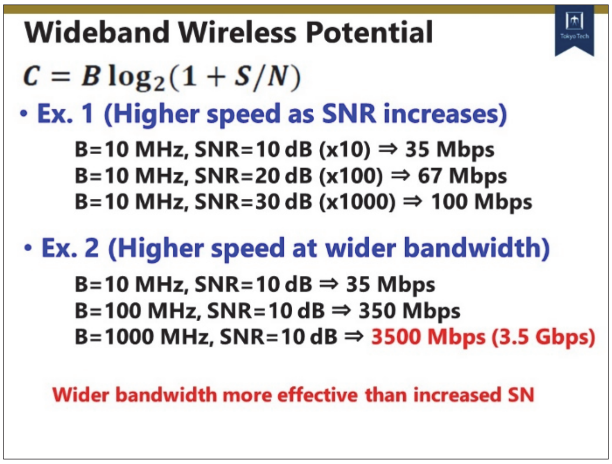
1.8 Multi-Level Modulation



Slide 9

Simultaneous transmission is possible because the sine and cosine components are orthogonal and QPSK is transmitted in this way. Although 16QAM has four times more points than QPSK, the data rate is double. Even though 64QAM has 64 points, the actual data rate is only three times that of QPSK because both need an SN of +6 dB.

1.9 Wideband Wireless Potential

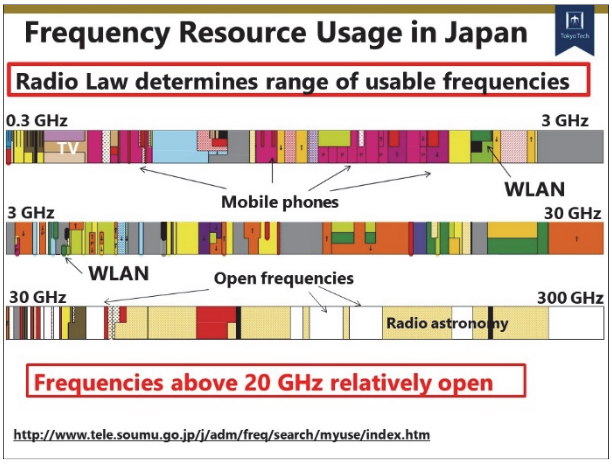


Slide 10

Since this is important, let's look at the figures a little more and think about how the data rate is increased from Shannon's Theorem. When the bandwidth is held at 10 MHz, the cellular transfer rate is about 20 Mbps. If the SN is fixed at 10 dB, the cell data rate is about 35 Mbps. Moreover, if the power is increased by 10 or 100 times, the cell data rate is about 100 Mbps, but the increase is only tripled when using 100 times.

On the other hand, increasing the bandwidth has proportionally less impact on the data-rate increase. Widening the bandwidth is more effective than increasing the SN since a data rate of 3.5 Gbps is achieved at a bandwidth of 1 GHz, but this is not so easy to implement.

1.10 Japan Radio-Wave Usage

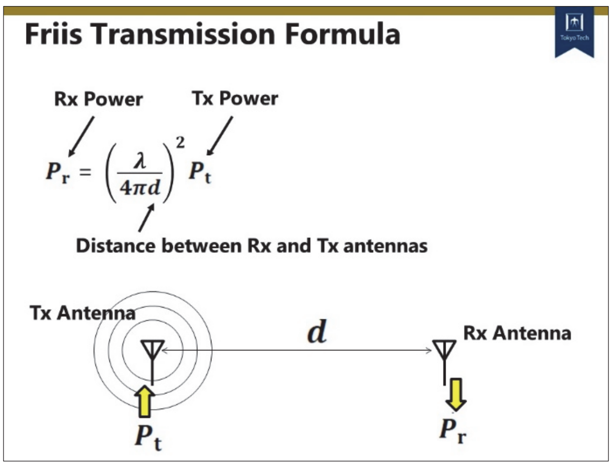


Slide 11

Slide 11 summarizes the allocation of radio frequency resources in Japan. Although these frequency resources are well known, many people are completely unaware that there are no frequencies in use above 20 GHz with bandwidths of ≤1 GHz. Although the lower frequencies are being reorganized with forced spectrum sharing, annual traffic is increasing by 1.4 times and data rates have increased 1000-fold, so there is no way to catch up even if we make the shift now. There is no doubt in my mind that we shall need the mmWave and THz bands in the future.

There are many aspects to consider, such as cost and technical hurdles, ease-of-use, and the match between frequencies and services, but since there are no open spaces in the lower frequency bands, the mmWave band is certainly necessary.

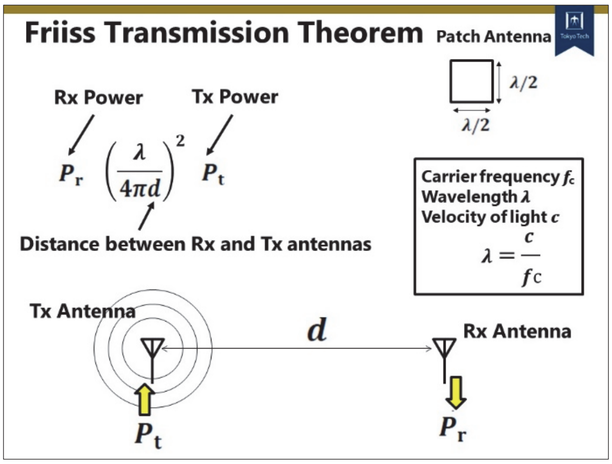
2 Weakness of mmWave



Slide 12

One weakness of mmWave is the signal propagation distance. Although you are probably aware of this shortcoming, I would like to discuss it a little due to its importance.

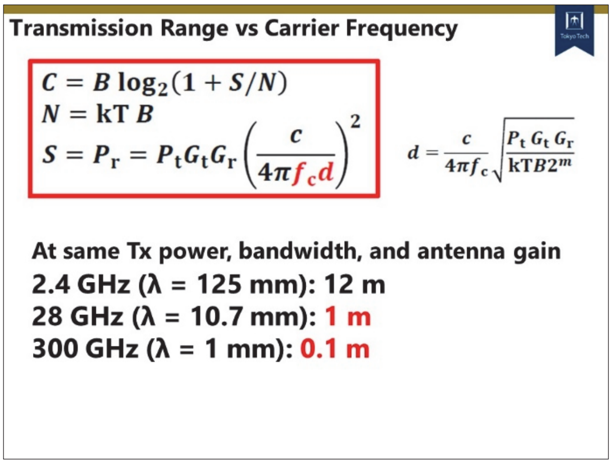
Slide 12 shows the Friis Transmission Formula, where P_t and P_r represent the transmitted and receive powers at the Tx (P_t) and Rx (P_r) antennas, respectively. Since the transmitted signals spread like a concentric sphere from the Tx antenna and range is expressed as d, the power per unit area at the spherical surface is $1/4\pi d^2$ where this is the squared part.



Slide 13

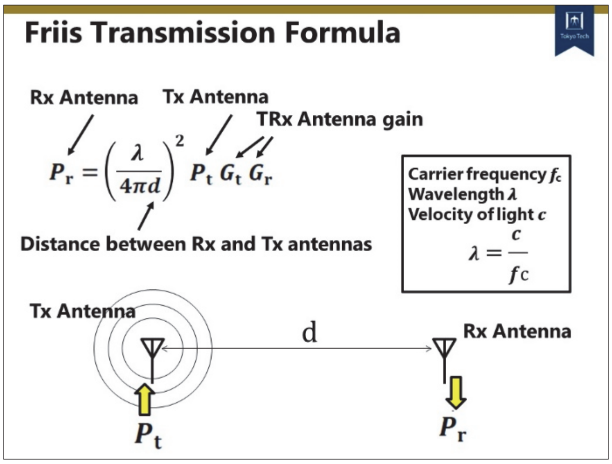
On the other hand, since the size of the antenna, such as a patch antenna, is determined by the wavelength, the wavelength becomes shorter as the frequency becomes higher and the patch antenna becomes smaller. Even though the power per unit area decreases, the Rx power decreases even more as the antenna area decreases. Both the receiving area and the receivable power decrease in proportion to the square of the frequency or the square of the wavelength.

But what about antenna gain?



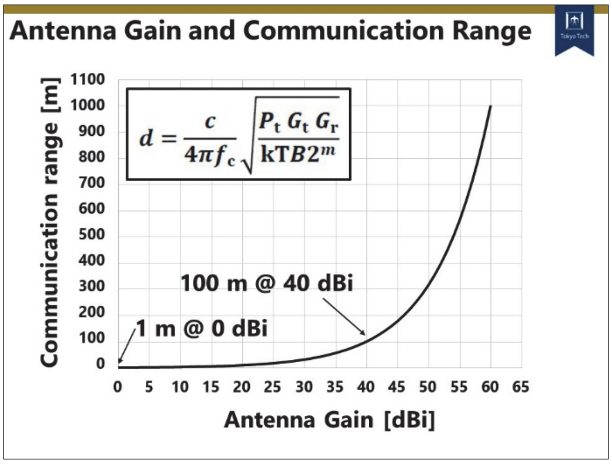
Slide 14

When considering the previously-mentioned Shannon's Theorem, the increase in the power of noise as the bandwidth becomes wider is expressed by the equation for thermal noise ($N = \mathrm{k}TB$), and since the Rx power is the signal power according to the Friis Transmission Formula, this equation in slide 14 can be derived by substitution. At the same signal power, bandwidth, and antenna gain, a 2.4-GHz signal propagates about 12 m at 10 dBm in comparison to just 1 m for a 28-GHz signal. The propagation distance is inversely proportional to frequency. For example, at 300 GHz, the range is just 0.1 m. In other words, range drops as frequency increases. This is a key weakness when using the mmWave and THz bands.



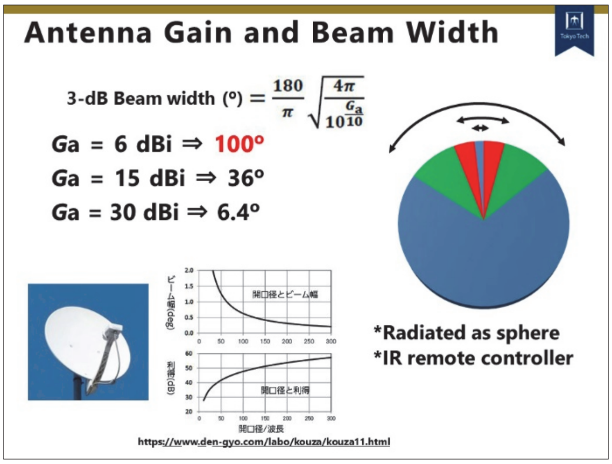
Slide 15

But what exactly is antenna gain? While a radio wave propagates as a concentric sphere from a non-directional antenna, with a parabolic antenna for example, it can be focused in one direction. Doing so increased the antenna gains because there is no unwanted wasted outward signal spreading. Both the Tx and RX gain can be increased by using parabolic TRx antennas, which is why they are used for satellite broadcasts. An extremely high-gain parabolic antenna can reach a value of 50 dBi and 40-dBi parabolic antenna can extend the propagation range to 100 m.



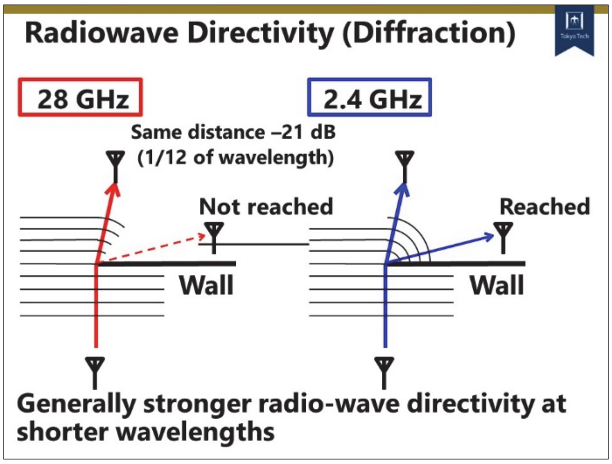
Slide 16

The 1-m range of the previously mentioned 28-GHz signal can be extended to about 300 m using a 52-dBi antenna.



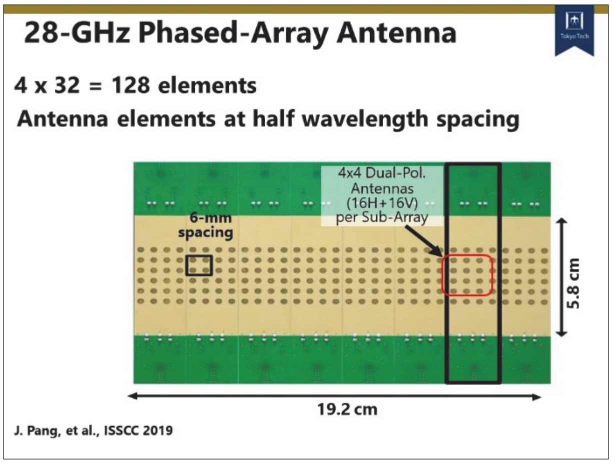
Slide 17

However, beam width becomes very focused when using a parabolic antenna. Mobile phones establish connections easily without worrying about direction while the radio beam using a parabolic antenna propagates in only straight line by focusing the beam. But there is a tradeoff between transmitting a tightly focused beam over a long distance so high-gain parabolic and horn antennas are not used for mobile communications because directional antennas cannot be used.



Slide 18

This 28-GHz signal does not diffract than the 2.4-GHz signal, so it does not reach behind the wall, but the 2.4-GHz signal reaches behind the wall using a diffracted wave. In this case, the 28-GHz signal is received by reflected wave. Since the arrival direction of the reflected wave is unknown, receiving requires some degree of flexibility in terms of directivity.



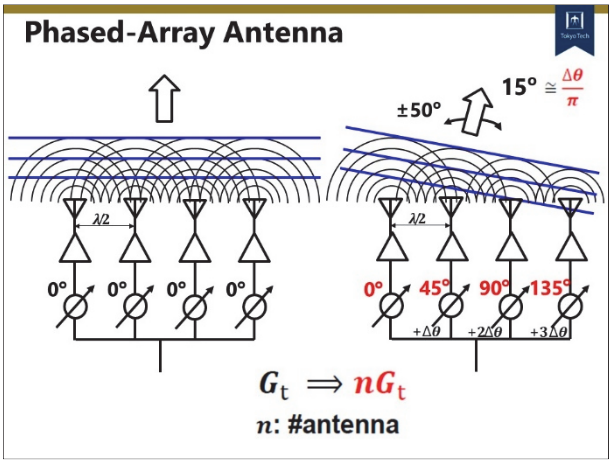
Slide 19

The phased-array antenna solves this problem. When using a mobile in a room for example, since the signal still propagates only in a specific direction when using a high-gain antenna, any obstacle can block communications. If there is an obstruction, the only way to transmit an electrical signal is to transmit the beam in another direction and the phased-array antenna is used to implement this "beam forming".

This (Slide 19) is an example of a 28-GHz phase-array antenna developed by Tokyo Institute of Technology. It is a 4 (vertical) × 32 (horizontal) array. Row 1 (top) and Row 6 (bottom) are dummy antennas with no power supply, so in fact there are 128 elements (4 × 32) in the functioning array.

Each dot in the array is an antenna operating at high frequency, supporting the small antenna design but since this design results in an unwanted smaller Rx surface area, the effective surface area must be widened.

This can be calculated but if the surface area is the same, the propagation range can be extended using either a shorter wavelength or a higher frequency, which is why phased-array antennas are used for satellite communications, etc. I have omitted the equation, but long-range communications are easier for the same surface area.

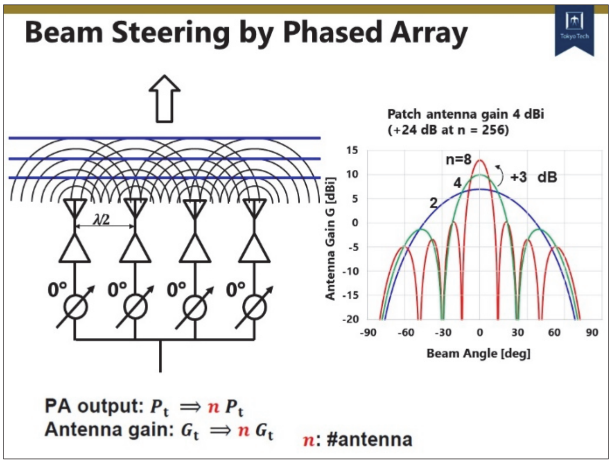


Slide 20

Slide 20 shows the basic principle of the phased array. In this example, four antennas are aligned in one row. Each antenna has an amplifier and a phase shifter to change the phase. The modulation wave is input from the bottom side. Since the electric waveform has peaks and dips, the signal has corresponding strong and weak parts, and transmission of a phase angle of 0º, 0º, 0º, and 0º from each antenna produces a strong signal right in front of the four-antenna array. These peaks and dips are cancelled out in this direction by slightly changing the phase angle.

When phase angles of 0º, 45º, 90º, and 135º (see right side of slide 20) are applied to the row of four antennas (#1 to #4 from left to right), the radio beam propagates from antenna #1 at an angle of 0º, and from antenna #2 with a slight delay at 45º, then from antenna #3 with slightly more delay at 90º, and finally from antenna #4 with more delay at 135º. By doing so, most of the beam power is directed at an angle of +15º. As a result, the maximum beam power covers a range of ±60º (slide 22) even if the phased array shifts the angle from 0º to 180º.

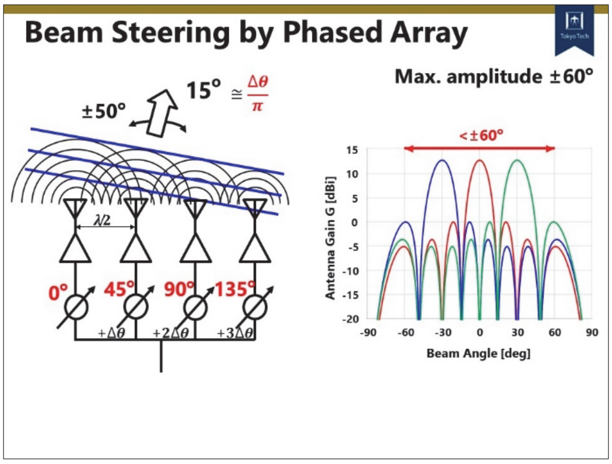
In summary, using such an antenna (Slide 19), viewed from directly in front, the beam does not propagate behind the array or just beside the plane. Despite the beam moving about ±60º up/down and left/right, it never steers to the side or behind.



Slide 21

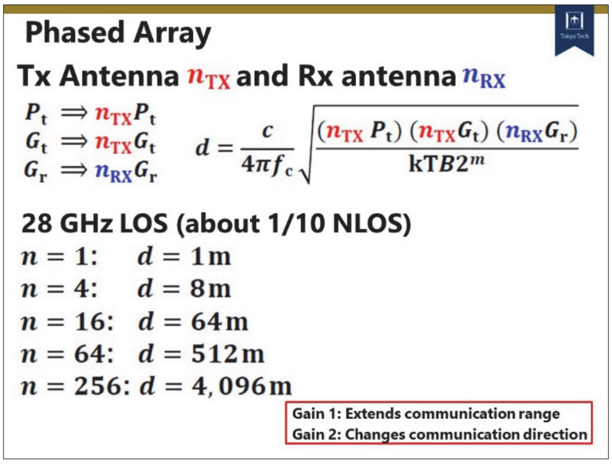
The number of antennas is another key point because the gain can be increased by increasing the number. The blue, green, and red lines in the graph on the right side of slide 21 shows the gain when using two, four, and six antennas, respectively. The power is stronger immediately in front of the array as the number of antennas increases because the beam widths become narrower.

The gain increases to 24 dB as the number of antennas is increased from 32 thru 64 and 128 to reach 256 and the beam becomes sharp with a narrow width. Antenna gain is expressed as n times in the graph on the right of slide 21. This example shows the Tx power for four antennas but the Tx power is 256 times greater for 256 antennas.



Slide 22

Since the beam steers in this manner by applying a phase difference to the antennas and becomes narrower with more antennas, it may be difficult to aim the beam exactly at the receiver side. And if the moving beam is not received exactly by the Rx antennas, the full transmitted power will not be received. Consequently, precise steering control is required.



Slide 23

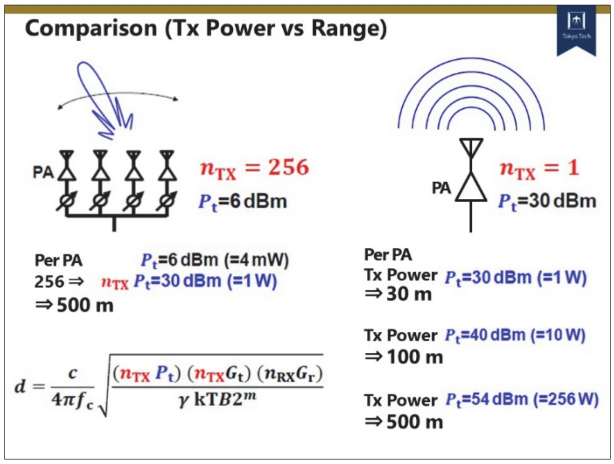
I have already introduced the derivation from Shannon's Theorem and the Friis Transmission Formula, but when using a phased array with 256 antennas, the Tx power (P_t) is 256 times larger. The antenna gain and Rx antenna gain are also 256 times larger. Assuming transmission and reception are both n times here, the distance d is $n^{3/2}$ times.

For example, as previously described, although the communication range at 28 GHz is 1 m, it increases to 8 m with four antennas, 64 m with 16 antennas and 4000 m with 256 antennas.

I have already explained that each antenna becomes smaller as frequency increases, and the range gets shorter, but increasing the number of antennas in an array extends the propagation range to longer distances. Additionally, the communications direction can be changed freely by beamforming.

With microwaves using a non-directional antenna, the beams propagate in different directions to reach devices that are not communicating. By contrast, with mmWave, the beam-forming function steers the radio beam in a specific direction. As a method for sharing a base station between large numbers of mobile subscribers, the available frequency band is shared in a time slot between persons A, B, and C using either the TDMA or FDMA technologies; although there are methods like CDMA, another advantage of using mmWave is the tight beam with free-space multiplexing.

Incidentally, Line of Sight (LOS) and Non-Line of Sight (NLOS) communications means the ability to communicate either when the beam path is unobstructed or obstructed, respectively. Depending on the condition of the reflecting surface, the beam distance in NLOS can be from 1/3rd to 1/10th than in LOS.



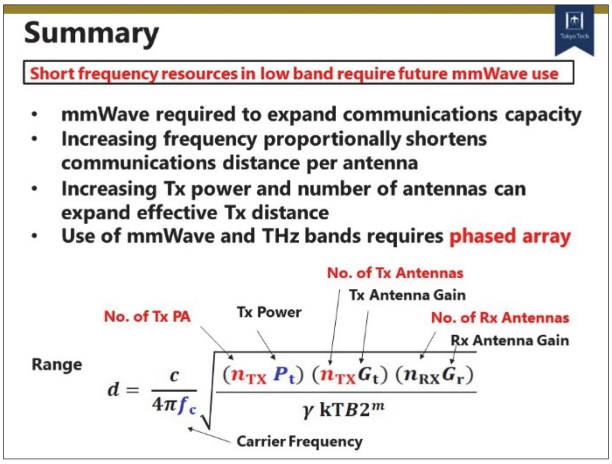
Slide 24

This is a comparison between using a phased array with many antennas and one antenna. It shows a simple method to determine how much power is required by each antenna configuration to transmit a beam for 500 m. For example, achieving a Tx power per antenna of 6 dBm requires about 4 mW per PA. The slide shows a four-antenna array but we can calculate that a total power of about 1 W is required to transmit a beam for 500 m from 256 antennas.

On the other hand, the figure on the right of slide 21 shows that much more power (256 W) is required by a single non-directional antenna to reach the same 500-m distance. While a Tx power of 1 W reaches 30 m, 256 times more power is needed to reach 500 m. These required powers are completely different order of magnitude at 1 W to reach 500 m with a 256 phased-array antenna compared to 256 W using a single unidirectional antenna.

In other words, both can be increased by increasing the number of amplifiers to increase the gain and by increasing the number of antennas (n). The most effective way to transmit a beam over a long distance, d, is by increasing the amplifier power and increasing the number of antennas. Getting the best operation from this large number of antennas requires tight and high-accuracy beam forming and phased-array technology.

Current 5G technology is mostly not using these technologies, especially at the mobile-phone side. The beam forming and beam tracking technology for tracking a moving mobile subscriber have yet to be widely implemented. There have been technology demonstrations of automobile tracking across a wide area but in locations with many reflections, such as Tokyo Central Station where many people carrying mobile phones are on the move, it is difficult to track phones using a 28-GHz beam. Consequently, more research into phased-array control technology is necessary. Although there it not much discussion about this, it is the key point for “Beyond 5G” development.

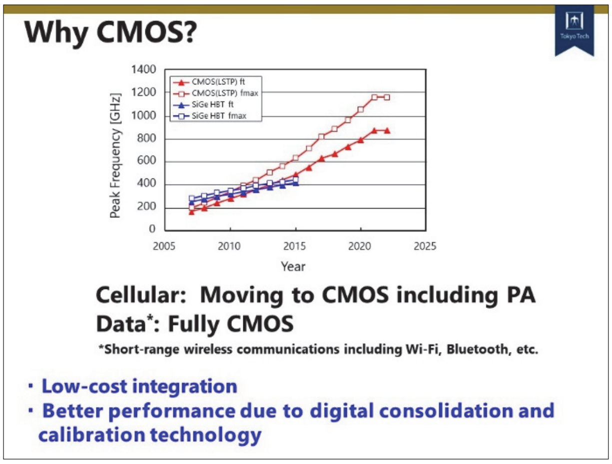


Slide 25

Slide 25 summarizes where we have reached so far. Since there is a shortage of resources in the lower frequency bands, implementing mmWave is essential to assuring sufficient future capacity. This is a certainty.

So, how do we approach the problem? It won’t work if the applications and technologies are mismatched, but this is quite a difficult thing and even the current mmWave mobile environment is not very convenient. To progress from 5G to Beyond 5G, we must solve various problems such as targeting how to reduce power requirements in the current mmWave mobile environment. First, I explained need for phased-array technology to solve the issue of shorter radio beam distances.

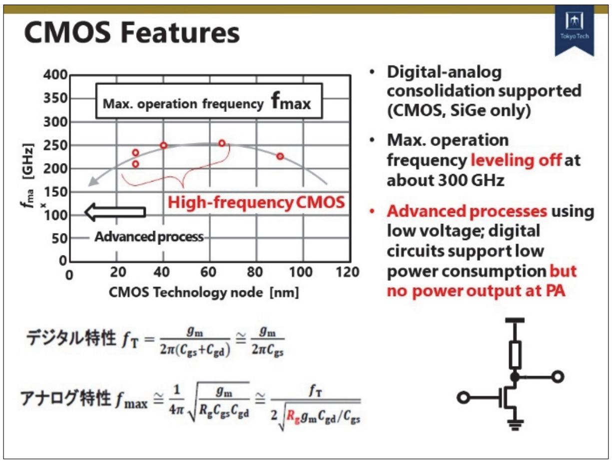
3 CMOS mmWave Wireless Designs



Slide 26

Using CMOS technology is commonly discussed in this field and I am sure everyone here knows how smartphones depend on CMOS technology. Both the Wi-Fi and Bluetooth communications standards were determined on the basis of implementation in CMOS. Both Apple and Qualcomm are replacing PA and LDMOS with CMOS. Although there are still some remaining performance issues, CMOS is undoubtedly the wave of the future based on cost and mass-production aspects.

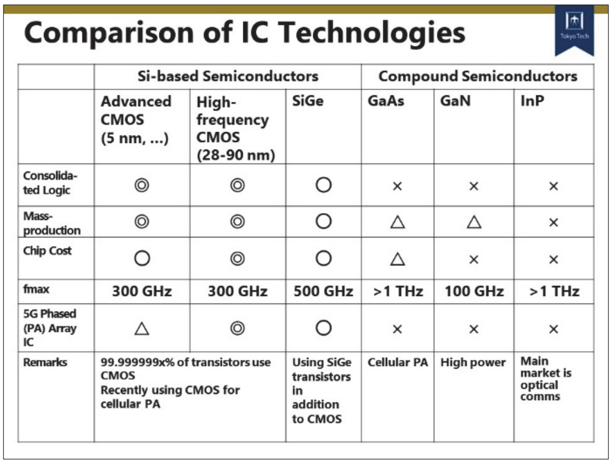
Lower cost is the main reason for implementing in CMOS. In addition, digital mixed mounting of the transceiver also becomes possible. Phased arrays in particular require tuning of the antenna variable-gain amplifiers and adjacent phase shifters, requiring inclusion of control circuits. Therefore, even these radio transceivers require quite large-scale digital circuits including control parts like those in the following photographs.



Slide 27

The graph in slide 27 shows the future increases in CMOS ft and fmax. However, although frequency (ft) is a good way to increase digital-circuit performance, this is not an easy route to follow. In the case of analog circuits, gain is determined by fmax, which is a different characteristic. If the gate resistance is high, it is hard to increase fmax, and fmax does not increase linearly with the latest FinFET technology as the digital ft increases (slide 26). As shown in this graph, the limit is reached between 65 and 28 nm where fmax does not increase.

Here, the maximum value of fmax is 250 GHz. There may be misunderstandings but this value changes according to the layout, transistor size, maker, and fab. In general, at 65 nm, fmax increases up to about 320 GHz. Although there is a slight increase to 350 GHz around 28 and 22 nm, it still does not reach 500 GHz or 1 THz. Since current CMOS technology is limited to the region between 250 and 300 GHz, CMOS implementation for mmWave transceivers faces some hurdles. The last part of this presentation introduces research in this field.



Comparison of IC Technologies

	Si-based Semiconductors			Compound Semiconductors		
	Advanced CMOS (5 nm, ...)	High-frequency CMOS (28-90 nm)	SiGe	GaAs	GaN	InP
Consolida-ted Logic	◎	◎	○	×	×	×
Mass-production	◎	◎	○	△	△	×
Chip Cost	○	◎	○	△	×	×
fmax	300 GHz	300 GHz	500 GHz	>1 THz	100 GHz	>1 THz
5G Phased (PA) Array IC	△	◎	○	×	×	×
Remarks	99.999999x% of transistors use CMOS Recently using CMOS for cellular PA		Using SiGe transistors in addition to CMOS	Cellular PA	High power	Main market is optical comms

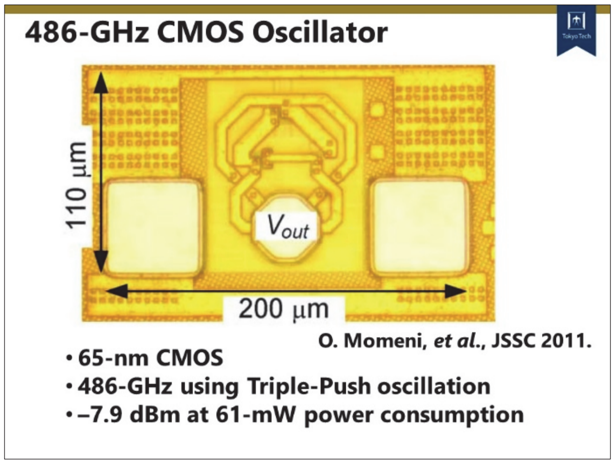
Slide 28

This is a little detailed but there are various Si-based and compound-semiconductor technologies using CMOS, silicon and germanium (SiGe), gallium arsenide (GaAS), etc., but since phased arrays require mixed mounting logic, the only choice has been either CMOS or SiGe, which most current chips and products are using.

This decision was driven mostly by mass-production and digital mixed mounting logic considerations. Some parts are using GaAs and gallium nitride (GaN) but there are very few reports on the results of adopting these compounds semiconductors and all phased-array ICs are implemented in CMOS.

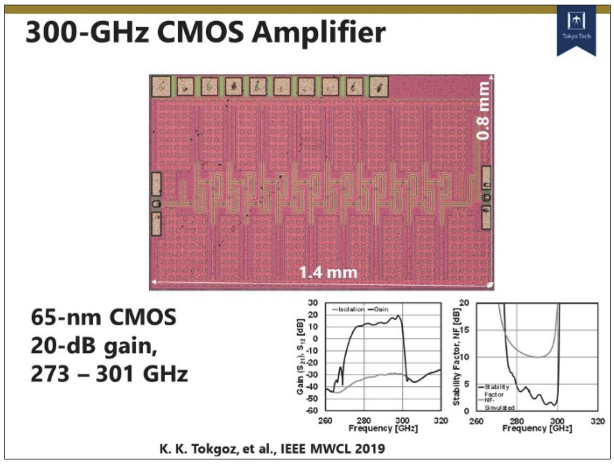
Advanced SiGe and high-frequency CMOS semiconductors use either a 5 or 3-nm process, which has poor withstand voltage characteristics, so both use the 28-nm process because 5 and 3-nm processes do not support power to the PA. Qualcomm is using the 28-nm process too, while we used a 65-nm process with SiGe. Base stations have started using SiGe while mobile terminals are still using CMOS.

While both CMOS and SiGe are considered convenient for these phased arrays, use of compound semiconductors requires a hybrid structure with CMOS.



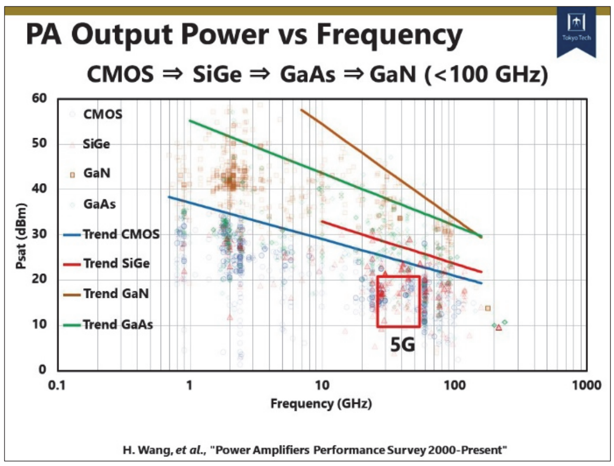
Slide 29

Although CMOS does not handle fmax well, UC Davis has reported fabrication of a 486-GHz CMOS oscillator (slide 29).



Slide 30

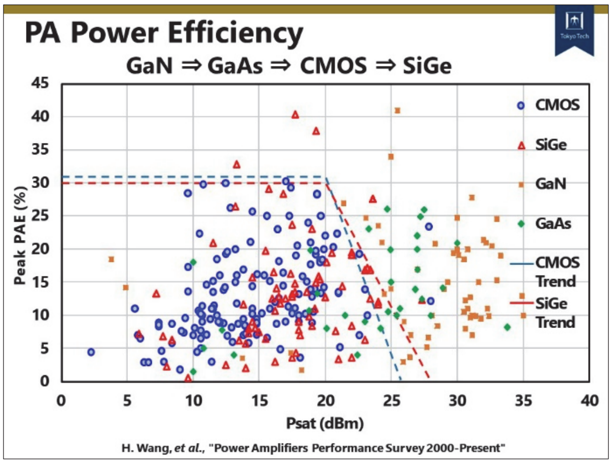
Slide 30 shows a fabricated 300-GHz CMOS amplifier developed by our second-year Tokyo Tech students; it produces gain at around 300 GHz. Despite using CMOS, it cannot be used as it is in a transceiver because the power output is poor.



Slide 31

Slide 31 is a comparison of CMOS, SiGe, GaN and gallium arsenide (GaAs) transistors with frequency on the x-axis and Psat (saturated maximum power) on the y-axis.

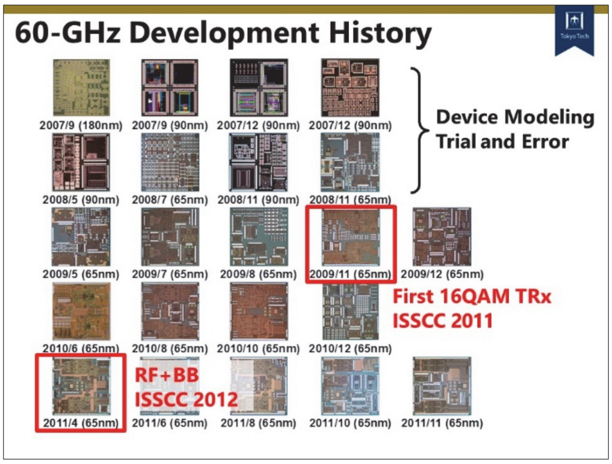
Although it is CMOS, it still outputs nearly 20 dBm at 5G frequencies. Although difficult to exceed 100 GHz, it is possible to implement in CMOS fabrications up to 300 GHz. The GaN fmax value has not increased but values for GaAs and indium phosphide (InP) have exceeded 1 THz.



Slide 32

Power efficiency is determined by fmax and low-gain semiconductors are inefficient. Consequently, the efficiency target is at least 30%, which requires using devices such as SiGe and CMOS with relatively high fmax. Since GaN and GaAs do not have Peak PAE efficiencies of at least 30%, it is thought that CMOS and SiGe are easier development targets for 5G and 6G.

4 Tokyo Institute of Technology CMOS mmWave Designs



Slide 33

This last section introduces our research at Tokyo Institute of Technology.

We started working on high-frequency circuits in summer 2003 followed by research into mmWave as a project for the Ministry of Posts and Telecommunications from 2007. We had many failures at the start, and when we fabricated a 20-dB amp for 60 GHz, it functioned as an attenuator with a gain of –10 dB and even output a signal when there was no input! In other words, it was a terrible oscillator. We had still not made an amplifier 3 years into the 5-year project despite plans to fabricate a prototype, and I was tearing my hair out over the daily nightmare.

As a result, we took a different approach by designing something like a transceiver for around 5 GHz and then extended the design by carefully measuring the parasitic capacity and inductance. However, this failed too and we switched again to a millimeter design flow. We explored how to overcome the problems in various ways, and the step to reaching a transceiver amplifier seemed relatively simple, since we just needed to increase the degree of mmWave integration after simulating the design operation.

We reported development of the amplifier at this time although the success rate was only one-in-three. However, fabricating a transceiver requires an amplifier, a Tx amp, an Rx amp, VGA, mixer, baseband amp, local oscillator and more, and an operating transceiver is impossible without a 95% success rate in fabricating each block.

The difficulty in dealing with mmWave has been in improving the step-by-step design precision and the simulation accuracy. Finally, the transceiver has begun working with gradually improving performance as we moved through these stages.

Lecturer Biography

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Apr 2003	Assistant Professor, Precision and Intelligence Laboratory, Tokyo Institute of Technology
Oct 2005	Assistant Professor, Integrated Research Institute, Tokyo Institute of Technology
Apr 2007	Associate Professor, Department of Physical Electronics, Graduate School of Science and Engineering, Tokyo Institute of Technology
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