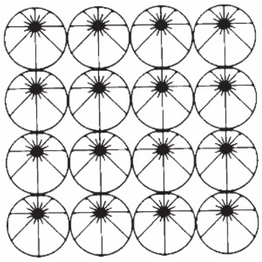
Recorded Lecture



Beyond 5G
Network Technology for 5G/6G

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1 Introduction

First, thank you for this valuable opportunity today. I am Tetsuya Kawanishi of Waseda University. As introduced previously, I have specialized in the field of optical physics, spending some time in research. Before my move to Waseda, I was a part of NICT, researching propagation of radio waves via photon optics. Therefore, I have over 20 years of experience in capturing a 60-GHz radio waves as optical signals. After 20 years, contrary to the significant doubts of my fellow peers, I finally feel that my research field has gained some traction in the world.

In contrast to 5G, which has been defined and standardized globally, 6G is still at an experimental stage, where everyone has their own opinions about it. Consequently, I would also like to share my own opinions today. Hence, I hope you all will give me some leeway about it.

I would like to start this lecture with the increasing demand for wireless technology and its integration with wired technology. As you all may know, wireless demand is high, and end users tend to prefer wireless over optics. However, as I state in my university lectures, "if radio waves are a necessity, wired/fiber optic cables are also a necessity."

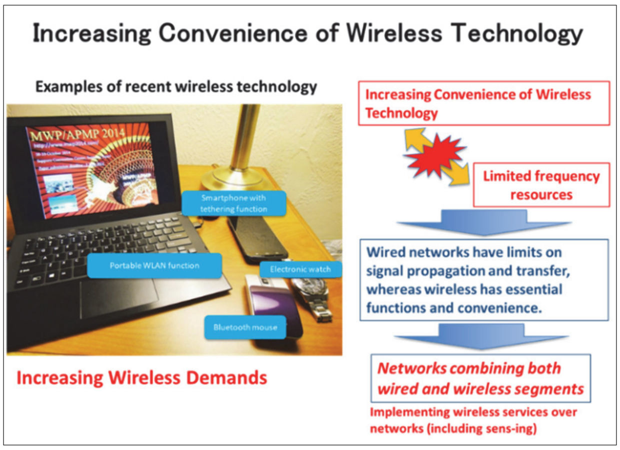
Next, I would like to explain about fiber wireless technology (Radio over fiber, RoF). This is the foundational technology for sending radio waves via optical fiber and I would like to compare the digital and analog format of this technology. Personally, I think this is the most important point within this topic.

I would also like to share how wireless signaling created by optical technology might also be a key factor in this field, although this section is heavily influenced by my personal research. In addition, I plan to share my ideas one R&D of the prototype foundational system leading to 6G.

Regarding the term, 'terahertz,' I would also like to introduce the Japanese–European co-funded projected on terahertz (THz) waves and debates about future applications of THz system integration; I will also give an example of a basic study on performance of THz wave links.

2 Increasing Wireless Demands and Need for Wired Integration

As an introduction, I'll give a simple explanation how, as the market adoption of wireless technology increases, it will also become necessary for the corresponding radio technology to develop too.



Slide 1

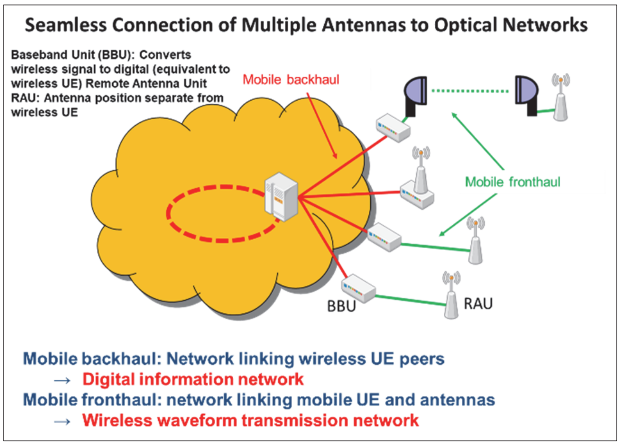
Slide 1, shows an image I made for the 2014 OFC (The Optical Networking and Communication Conference & Exhibition)*1 to introduce the MWP2014 (International Topical

Meeting on Microwave Photonics) international conference where I served as chairperson. I took an image of a wireless connected device placed above my desk. To this day, I still use the mouse and watch in the image. However, if you look carefully, the smartphone is not wireless but wired!

I remember that the phone series I was using back then had problems with high power consumption, low battery, and constant need for restarting. Subsequently, I was forced to use it constantly on wired charge. Thinking about this, this image perhaps implies that mobile and wireless systems had to lower the power consumption (increase its efficiency) for practical use. As shown, since the phone is wired for charge, the wireless functions, such as tethering via Bluetooth and Wi-Fi, seems redundant because it is not serving its full capability. Basically, it's not being used properly. This passage may be slightly off topic but since energy consumption is covered later, I've touch lightly on the subject here.

Full wireless implementation is the ideal, but since we don't have limitless frequency resources, this won't be happening for a while. Perhaps we were even lucky about this. Distributing HD (High Definition) digital images to the whole of Tokyo is possible using just one Tokyo Skytree. However, when individual performance and applications are added, this model fails and, just like with electricity, we have to implement wires in the wall.

Next, I would like to talk a little about something foundational. Slide 2 show a network-connected base station.



Slide 2

As you see, the network connecting the base station has a mobile backhaul and fronthaul. The backhaul is a regular digital network connecting signals between a network of wireless devices.

On the other hand, the mobile fronthaul connects devices with an antenna, enabling it to send radio waveforms. As such, I believe the key characteristics in Slide 2, are the parts with green arrows. I plan mainly to cover this aspect today. As some of you have realized, the above diagram representing the mobile fronthaul is also partly connected by radio frequency. In Japan, fibers are usually used for this connection.

The shares of the transmission media used in this base-station network is projected in a report[1)] published by the GSMA (GSM Association).[*2]

It compares 2017 results with the projections for 2025. In Japan, optical fibers have dominated more than half the market share, but on a global scale, fixed wireless still has a strong presence. As a matter of fact, about 75% are fixed wireless. In 2025, it is projected that this will be replaced by fiber optics.

Looking at the 2017 results, although already redundant in Japan, globally, the 2G GSM (global system for mobile communications) still exists. As high-performance mobile networks evolved from 2G to 3G and then to 4G, the necessity for transmitting large amounts of data has also made it necessary for increased use of fiber optics. The 2025 projections again show an increase in fiber optics, but at the same time notes an interesting point that when comparing 5G and 4G, implementation of the former will cause fiber optics to decrease. The reason is as follows.

First, let's look at the projected shares by region.

Although Japanese people may find this unfamiliar, ITU (International Telecommunication Union) divides regions in the following order: Europe, Northeast Asia, North America, Latin America, Central South America, Near and Middle East, North Africa, Sub-Saharan Africa, South Africa, South Asia, and Southeast Asia.

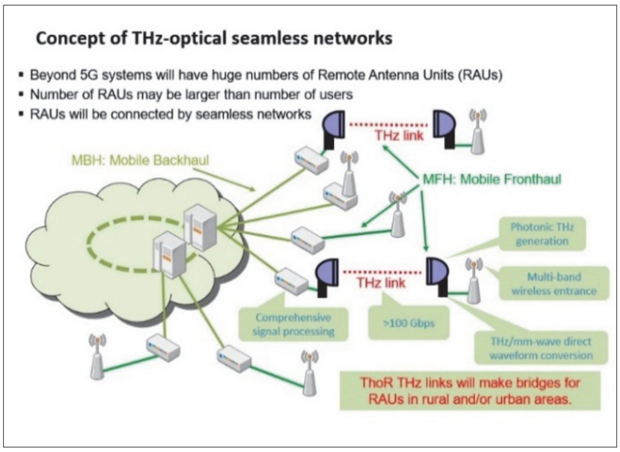
Europe is the easiest example to understand. Since fiber optics are still rare in Europe, it is projected that implementation is on the rise. This is the same for less industrialized countries and for North America. However, it is projected that Northeast Asian countries such as Japan, China, and South Korea will in turn see a decrease in this share. This does not mean old-fashioned fixed wireless will be increasing but the GSMA projections show that because 5G and 6G requires a large number of extremely small femtocells, parts must rely on short-range millimeter-wave fixed wireless. This is quite obvious when looking at the details.

It is projected that when analyzing microwaves under 40 GHz and high-frequency millimeter waves individually, fixed wireless using high-frequency waves will be on the rise by 2025.

There are other interesting points for each country, so if you would like to know more, I recommend reading the details in this document. As an example, Europe is seeing a dramatic rise with the implementation of millimeter-wave fixed wireless. This reliance on millimeter waves is due to unfortunate geography making it hard to use fiber optics.

As with Northeast Asia, which includes Japan, the low implementation of fixed wireless is expected to reverse with this millimeter-wave fixed wireless. However, this does not mean fiber will be eradicated. Specifically, short-range millimeter-wave communications will serve a partial role in the backhaul, while the fiber implementation will also increase.

Although the GSMA only made projections up to 100 GHz, if we extrapolate those projections, fixed wireless could perhaps reach higher frequencies. We could even apply it partially in the mobile backhaul and fronthaul. In summary, although connection via fiber optics is ideal, due to limitations in implementation costs, parts of the infrastructure should be wireless based. We expect this is where THz links will play a major role. To implement something on a par with fiber optics, the necessary bandwidth must be about 100 Gbps, although some conditions may vary.

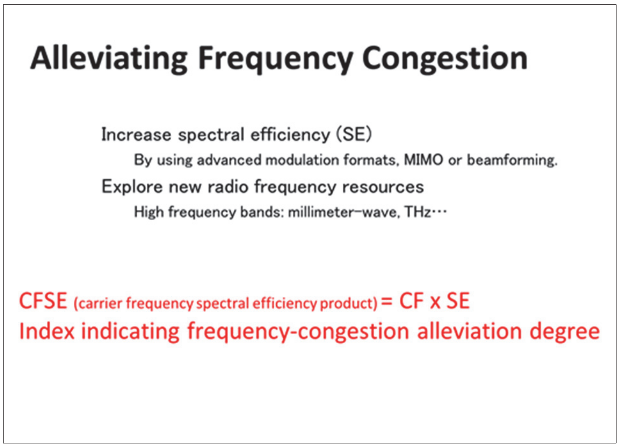


Slide 3

Previously, I mentioned the good luck to be able to broad cast terrestrial digital with just one base station (Skytree). Similarly, I believe we had some luck about the following. Currently, because we lack radio-frequency resources, we are forced to implement a large number of cells. Consequently, the distance between base stations varies from 100 to 200 m. Subsequently, this enabled application of the once-obsolete THz band. This may be in reverse, but it seems that new demand caused potential release for wireless links with different specs compared to predecessors.

The key is where a 'network cannot be built solely on wireless links' and therefore, the projected network would simultaneously go back and forth from optical fiber to wireless. I believe this will make it necessary for direct signal conversion between the two.

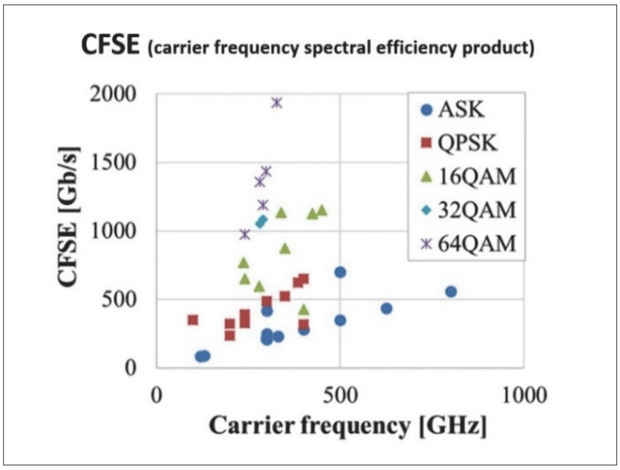
The THz bandwidth is said to be wide enough for extensive usage. However, I would like to explain how even the THz band could be strained potentially.



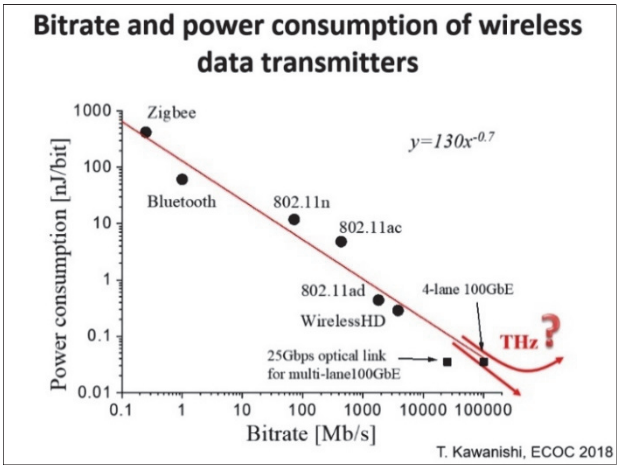
Slide 4

To increase radio-frequency usage, the Ministry of Internal Affairs and Communications is working on various R&D projects. One objective behind this is to optimize frequency use to relieve the strain on frequency bands as stated above. Another objective is to develop new frequency bands. The ideal is to accomplish both objectives simultaneously. However, due to the high estimated costs for supporting such new bandwidth, it is projected that this optimization will be difficult to accomplish. However, if we give up balancing and accomplishing both goals, potentially, reimplementation of new frequencies could become a huge burden in the future.

Consequently, by using the CFSE (Carrier Frequency Spectral efficiency Product) graph, cross-referencing the relationship between frequency and its efficiency/optimization, I would like to show an example analysis for recent research trends.



Slide 5



Slide 6

The x-axis in Slide 5 shows the change in carrier frequency to demonstrate a THz transmission experiment for radio frequencies over 100 GHz.

The CSFE on the y-axis increases up to 300 GHz. When the spectral efficiency is kept constant, the CFSE and carrier frequency show a positive correlation until passing 300 GHz when the CFSE drops dramatically. I believe this means that the frontline for cutting edge research on THz is 300 GHz.

Although I'm no professional in scientific history, I expect this frontline shifts constantly when studying previous articles on radio frequencies. It may be interesting to plot a graph recording the highest frequency each measurement instrument manufacturer, including Anritsu, was able to record with their instruments when this shift occurs.

The ITU wireless communications department, also known as ITU-R (ITU Radiocommunication Sector), is right in the middle of this standardization between 300 GHz. I include this simple graph because it may be a useful method in clarifying the progress of new research projects, which are common in this area.

As the bitrate drops dramatically when passing 100 Gbps, when demonstrating high-speed transmission experiments using the latest equipment, one optimum will be 300 GHz at 100 Gbps. At device research, aiming for 400 to 500 GHz might be the recommendation.

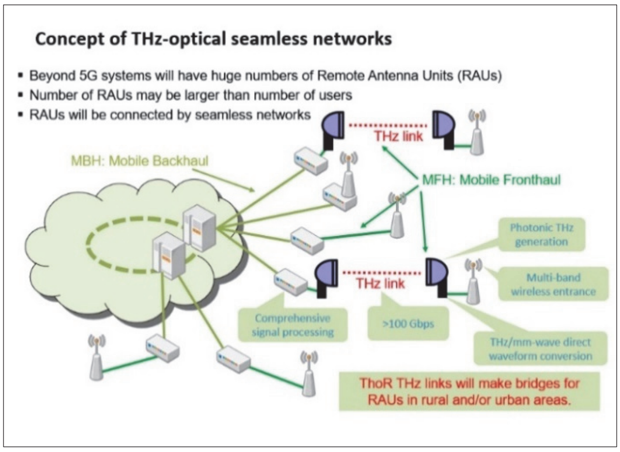
Next, I would like to give a simple explanation about power consumption.

Currently, we don't have an actual power consumption measurement for devices using THz bands. Based on research into measuring equipment, the added power consumption is expected to be quite high.

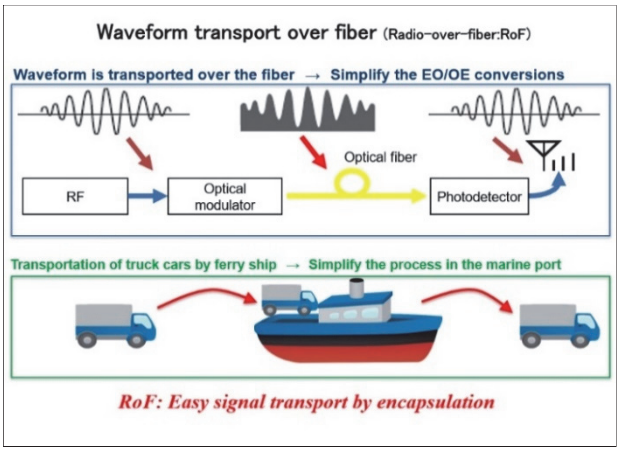
Slide 6 plots the power consumption for modular short-range transmission devices. For wireless devices, it shows that the power consumption per bit drops as the bitrate increases. When looking in bits, Bluetooth actually has quite high-power consumption compared to its trademark low power consumption. Although extrapolation may be an inadequate index, when plotting the 100-GHz wireless above the red line in Slide 6, its power consumption is expected to be similar to the recent 100-Gbps optical units.

However, this comparison with optical units at 100G Ethernet may be an unfair comparison. Instead of the latest equipment, perhaps a fairer comparison with a device that is high functioning and low-energy consumption would lower power consumption by one order. Despite this, the difference is minimal when placing it above the red line. As an example, when using THz-technology in data centers, power consumption is not expected to increase by 3 or 4 digits.

To apply THz in mobile fronthaul, R&D is necessary for viable application. I would like to talk about some specifics today.



Slide 7



Slide 8

ThoR (TeraHertz end-to-end wireless systems supporting ultra-high data Rate applications)*3 at the bottom right of slide 7 is a European project targeted at fixed wireless. For technology and budgetary reasons, we should work first on fixed wireless and try to work up to mobile in the final stages. As I said before, since fixed wireless can potentially support mobile fronthaul, cultivating it through investment in development environments and device price optimization could be feasible.

*1: OFC (The Optical Networking and Communication Conference & Exhibition): Largest exhibition on optical communications technology in North America.

*2: GSMA (Global System for Mobile Communications Association): Business group composed of telecommunication carriers supporting GSM mobile communication system, and related companies.

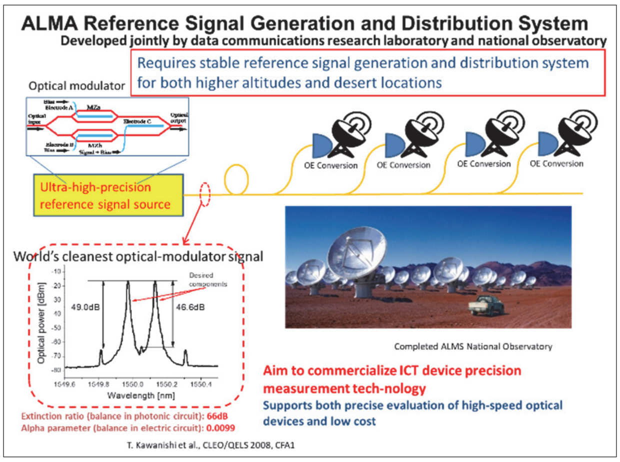
*3: ThoR (Terahertz end-to-end wireless systems supporting ultra-high data Rate applications): Development of THz end-to-end wireless connection system for large-capacity applications: Industry–academic joint Japanese–European research project aiming to build 300-GHz band high-speed wireless transmission system supporting network connection.

3 Radio over Fiber Technology

From here on, I would like to talk about radio over fiber (RoF).

RoF is the technology to send radio waveforms via fiber optics. It sends waveforms modulated by an optical modulator then to detect by a photodetector. The diagram in slide 8 shows an explanation. Although explanation is unnecessary for everyone, as shown, what we want to transport is the cargo of the truck and not the truck itself, so it's important to design the technology carefully, or else everything may come to waste.

I think RoF has the same effect as virtualization/digitization. The segment controlling signal processing can be moved freely. In comparison with maritime transport, the main point is that it enables cargo transfer not only just in ports. Because fiber optics are based on analog technology, some people may think virtualization/digitization is contradictory, but since the processing unit can be moved freely, perhaps its purpose is identical. I would like to explain parts of the RoF technology below.



Slide 9

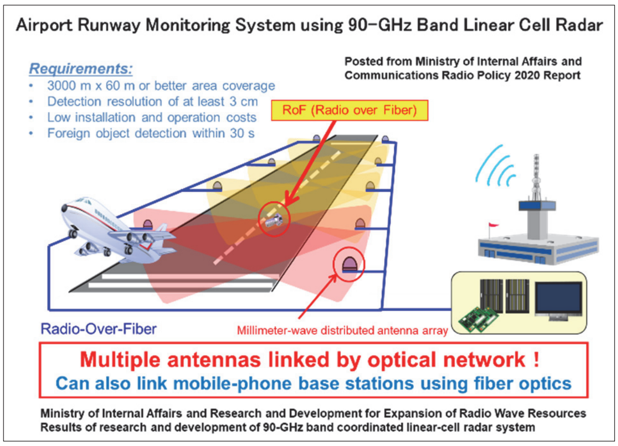
As pre-existing technology, there is the radio-astronomy reference signal source. These reference signals are used to synchronize all radio-astronomy antenna by applying the stabilized frequency difference of the two signals created by the modulator. This technology has been around for more than 10 years since 2008; when I worked with the national observatory, we increased its provision by applying a special device on the modulator.

There are examples of RoF technology already being used in government R&D projects and I would like to give an introduction to some of them. First, is the system implemented for high-speed trains.

Currently, although 4G can be used in trains, there's still a problem with handover overload due to the moving train carriages and subsequent movement of people causing constant signal transitions. To resolve this, it's necessary to establish millimeter-wave communication to the train while locating small base stations in carriages, so customers can connect via the base stations.

RoF signals will actively utilize location information as the train moves. In doing so, the wireless devices have no involvement in the system. If we can create and control a one-to-one relation between the train location and fiber network, it is possible to maintain constant connections without handover.

This mechanism can also be applied to radar or to research on systems for finding foreign objects on airport runways.



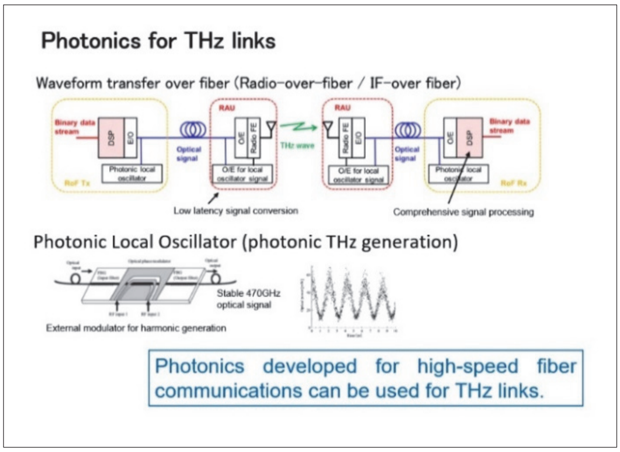
Slide 10

Some people may remember the danger of foreign objects on runways after the Concorde disaster. This system developed by the Ministry of Internal Affairs and Communications is designed to quickly find (in seconds) cm-size foreign objects on 3000-m long runways using radar detection and camera verification. Not just one, but multiple radars are implemented for this procedure, which RoFs are used to manage.

Interestingly, implementation of THz technology in optics is something that has already been done in the past. We used to call them as terabits. Although mostly now out of production, prior to the golden age of WDM (Wavelength Division Multiplexing), there were measuring instruments designed to detect 160-Gbps light, as well as optical sampling oscilloscopes, created as an outcome of market competition and debate between the superiority of either WDM or TDM (Time Division Multiplexing). As a result, researchers interested in the property of high-speed optics conducted many research projects.

As an example, there was research on how many hundreds of GHz an optical mode-locked laser pulse would create. Digging into this old research might discover something useful.

Slide 11 shows a typical RoF system configuration.



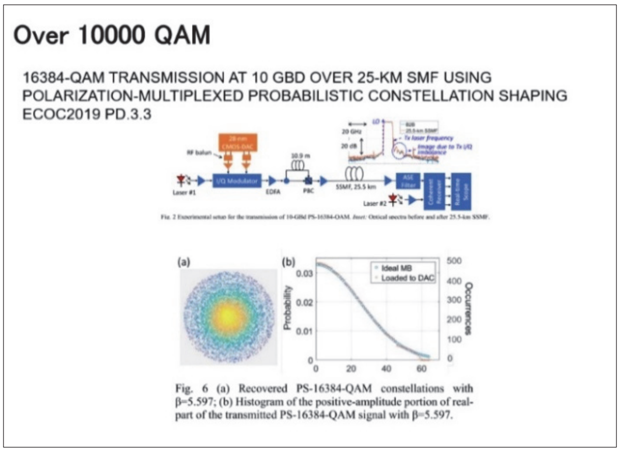
Slide 11

As data are sent via THz waveforms, the sending configuration is expected to be a mixed of IF, due to the inefficiency of sending THz waveforms as optical signals, and local signals sent separately via optics. Basically, we want to create local signals using optics.

This is shown in the lower diagram in slide 11. Although this is from my work conducted over 10 years ago, I succeeded in creating a 470-GHz clock signal using filters so the light would make many round trips within the optical modulator.

Back then, it was quite common to see devices using beat signals to observe the time axis. Measurements by a high-speed optical sampling oscilloscope are an example. In this respect, this is a retro-technology that may still be useful.

From here on, I would like to talk about carrying the data being.

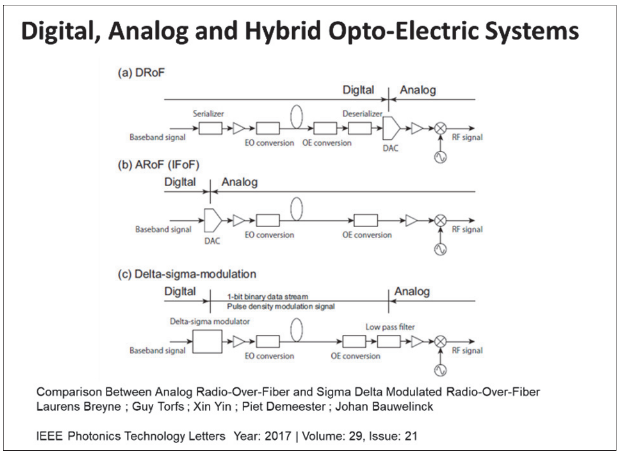


Slide 12

Previously, I explained about either using digital or analog. Although I demonstrated examples using analog technology in the prior section, the continuous growth of digital technology has supported implementation of 16384 QAM. I think this is the equivalent of performing 7-bits I&Q. At this point, distinguishing between analog and digital seems to be a matter of semantics.

Even a Constellation diagram looks like this cloud. Currently, it is rare to see a purely analog oscilloscope or signal generator. Like the difference in viewing as a waveform or as a dot, perhaps the strict separation of digital and analog may be out of date.

As an example, I would like to show a comparison between RoF systems.



Slide 13

The DRoF (Digital Radio over Fiber) system in slide 13 (a), sends waveform data, created using baseband signals, via digital similar to a CD or mp3. This information is then captured at the antenna, before conversion by the DAC (Digital to Analog Converter). Therefore, it is necessary to have DACs at each locale.

The analog RoF (ARoF: Analog Radio over Fiber) system in (b), is configured for conversion to analog waveforms at the main base station.

Diagram (c) shows a middle ground between the previous two. It is called delta-sigma modulation, where the signal waveform is generated by binary on/off (0 or 1). This is easy due to the nature of binary, but oversampling is required in return. The receiver simply receives as analog and the DAC has no role here. In fact, the DAC acts like the whole transmission route. There are movements favoring use of this technology for mobile-phone networks. Now, although some of you may already know, slide 14 shows the capacity required for DRoF, which is already used by 3G and 4G.

DRoF: CPRI data rate options (for LTE 20MHz CC)

Option	No. of CCs	Line coding	Bit rate (Mb/s)	Examples
1	0.5	8B/10B	614.4	Only I or Q component
2	1	8B/10B	1228.8	One CC with I and Q components
3	2	8B/10B	2457.6	2 × 2 MIMO or 2 CA
4	2.5	8B/10B	3072	
5	4	8B/10B	4915.2	4 × 4 MIMO or 4 CA
6	5	8B/10B	6144	5 CA
7	8	8B/10B	9830.4	8 × 8 MIMO or 8 CA
7A	8	64B/66B	8110.08	8 × 8 MIMO or 8 CA
8	10	64B/66B	10137.6	5 CA + 2 × 2 MIMO
9	12	64B/66B	12165.12	3 CA + 4 × 4 MIMO

For 400-MHz 5G NR, 20.274 Gb/s for a CC, and 324.384 Gb/s for 16 CA.

More than 1 Tb/s is required for RAUs with massive MIMO and beamforming.

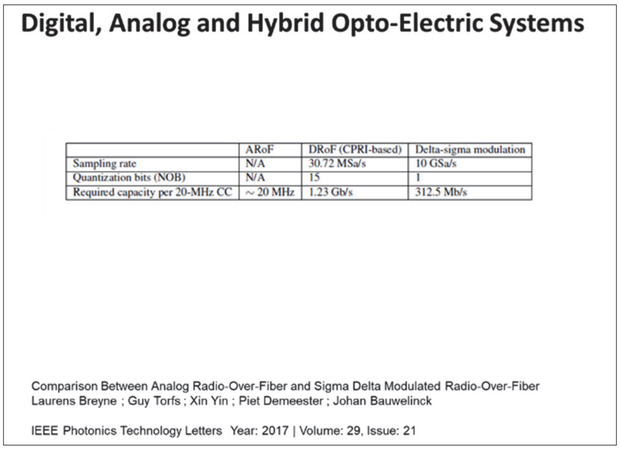
→ Function split or ARoF?

Slide 14

It takes 1.2 Gbps to send data through one LTE channel. Even using carrier aggregation (CA), transmission usually occupies about 10 Gbps. Because optics are currently quite cheap even at 10 Gbps, DRoF will only be supported up to 4G.

5G requires 20 Gbps for 400-GHz 5G NR (New Radio)*4 signals. This would require multiple antennas and therefore over 1 Tbps of data if done using conventional DRoF. Hence, the concept of 'function split' has been proposed as a solution. Conventionally, virtualizing would allow us to centralize the signal processor and make the antenna lighter. However, in this case, we must unwillingly add extra functions to the antenna section. If we take this path, we will require a decent count of this split function when establishing a vast number of base stations. Currently, 5G tries to avoid this problem of immense transmission capacity caused by function split. The final success and failure, depends on whether the communication or function distribution becomes cheap. Whatever happens, I believe this will become an interesting topic to talk about in the near future. In summary, digital technology cannot stay the same and has to change.

Slide 15 compares the required capacity between digital and analog.



	ARoF	DRoF (CPRI-based)	Delta-sigma modulation
Sampling rate	N/A	30.72 MSa/s	10 GSa/s
Quantization bits (NOB)	N/A	15	1
Required capacity per 20-MHz CC	~ 20 MHz	1.23 Gb/s	312.5 Mb/s

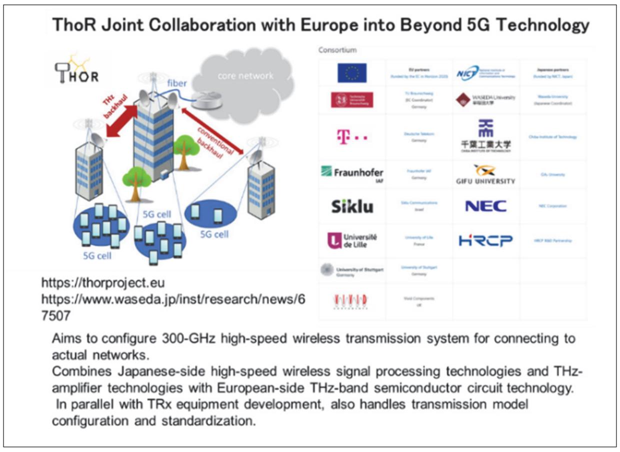
Slide 15

Ideally, ARoF (Analog Radio over Fiber) will support transmission of 20-MHz signals at 20 MHz. Even when taking a greater margin, it should only be several times greater. However, with DRoF, this value jumps to 1 GHz. For delta-sigma, the value lies between digital and analog; an extra digit on top of the ARoF value. Adopting only one format will make system management easy, but may cause complications going beyond 5G/6G, without smart combination of the three formats.

*4: 5G NR (5th generation new radio): New wireless access technology specified and developed by 3GPP for fifth-generation communications systems.

4 Introducing Japanese-European Joint Project (ThoR[4)])

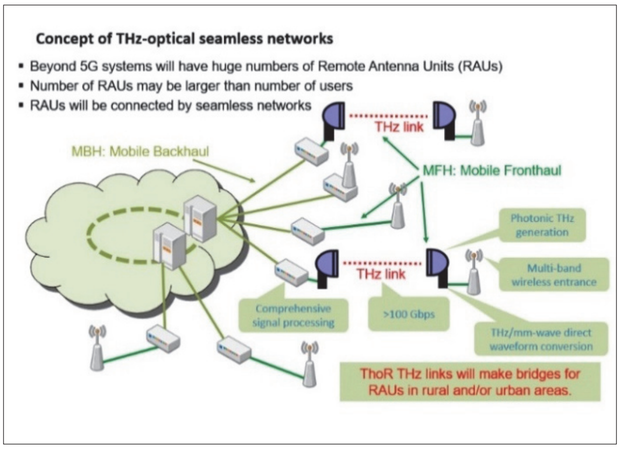
From here on, let's talk about the collaboration between Japan and Europe.



Slide 16

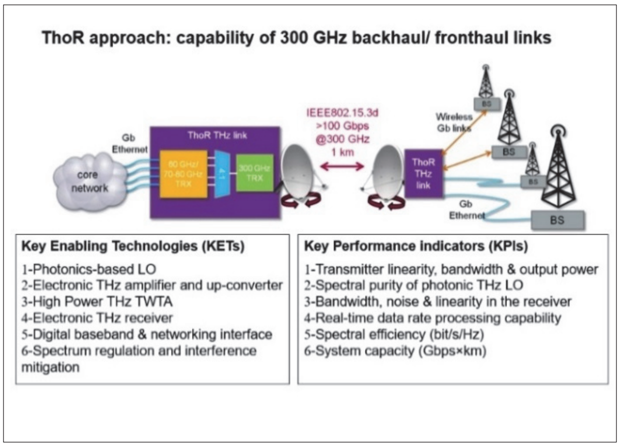
As stated previously, I believe it will become necessary to connect certain bases using THz. On the Japanese side, we have teamed-up a consortium between our research group, makers, and universities. On the European side, the Technical University of Braunschweig, where Carl Friedrich Gauss studied, leads members, such as European operators and research institutes for high-speed electric circuits.

Research on THz has existed prior to the current cycle and I would like to introduce some characteristics. As shown in slide 17, ThoR is a European project designed to implement THz links.



Slide 17

This project has a few points I would like to introduce.

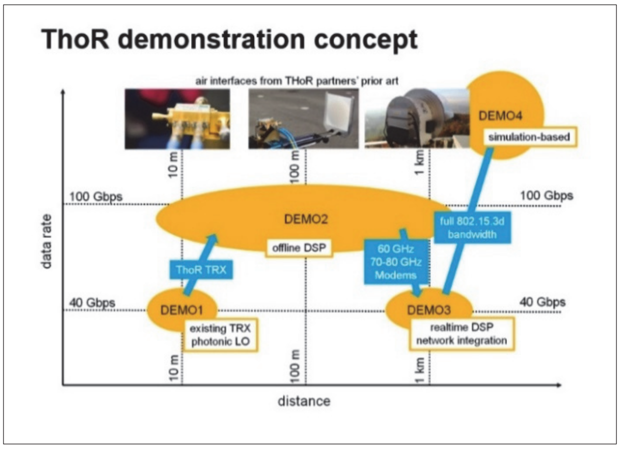


Slide 18

It is designed to accomplish high-power THz by distributing local signals using optics, developing RF frontends to amplify, convert, and receive THz signals, and developing TWT (travelling-wave-tube) amplifiers (although this is the Japanese side's role). In addition, It was common for THz transmission experiments to be offline processed based on measuring instruments, but now we are starting to establish online network connections from basebands for this.

It would also be worthwhile brainstorming how to apply, propagate, and remove interference from frequencies to create viable THz. One objective of this project is to create a signal from basebands that are compatible with the international standard for wireless/radio formats set by the head team of the Europe group.

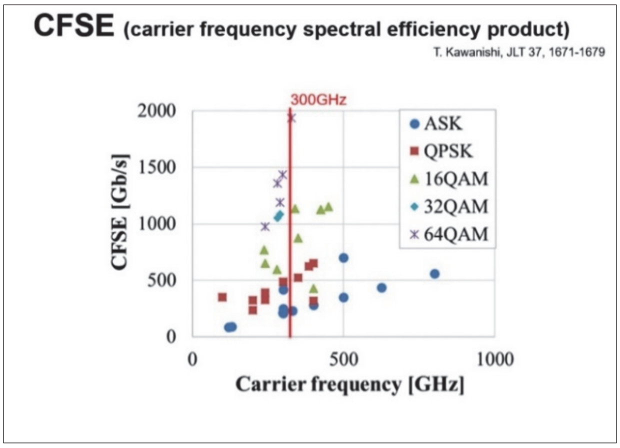
Slide 19, is an experimental demonstration of this.



Slide 19

Due to the limits on budget and real time, and the nature of offline experiments and simulations, this demonstration was conducted by combining what they currently have on hand, while simultaneously adding necessary factors bit by bit. To implement 40 Gbps at the 1-km limit, it is necessary to conduct simulations from real measured data. I expect this is the experiment that stands out most.

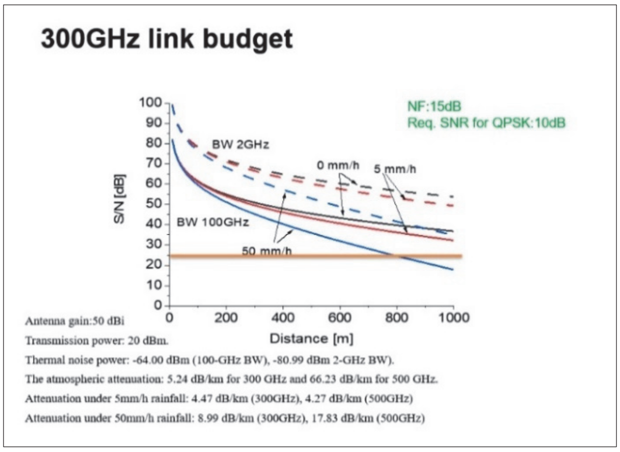
This may be repetitive, but looking the CFSE graph, the peak is at 300 GHz.



Slide 20

This project also aims to work at this ideal value of 300 GHz at 100 Gbps as I explained earlier. Although the graph (slide 20) in my academic paper has no correlation with initiating this project, in retrospect, the highest position of this graph coincidentally became the focal point of this project.

From here on, I would like to show examples of THz link budgets (profit value from communication channels). Although anyone with access to textbook data and various models from international standard websites can calculate this value, there are still areas within it lacking data. I would like to talk about this as well.

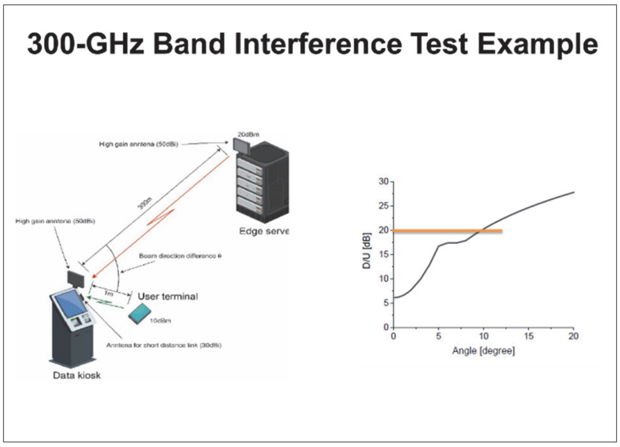


Slide 21

Slide 21 is a graph based on fixed wireless with a very high antenna gain of 50 dbi. The bandwidth maybe abnormally wide, but it compares 100 GHz to 2 GHz at a transmission of

20 dBm. As everyone suspects, the necessary QPSK is 10 dB S/N and as the margin, I projected the NF at 15 dB represented by the orange line. Referring to that line, when raining at 50 mm/h, the 100 GHz bandwidth at 300 GHz will only extend to 800 m. Still, when using indoors, the 100 GHz bandwidth could easily link up a to a few hundred meters.

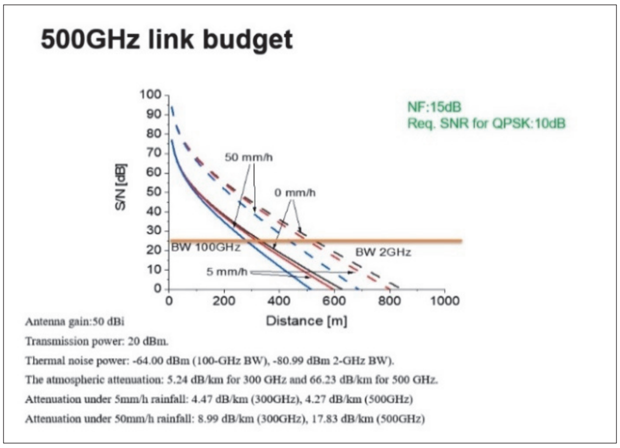
Some may claim that "interference will not occur because no one uses 300 GHz," but interference testing has already been started considering the effects on remote sensing and astronomical radio. Slide 22 shows an example of this examination between radio source interference.



Slide 22

Assume there's an application which connects via fixed wireless the data kiosk and the data core network represented as "edge server" in slide 22. When the surrounding users use the same 300 GHz with an angle difference of less than 10 degrees, the D/U ratio will be less than 20 dB. Assuming the necessary S/N is about 20 dB and the necessary D/N ratio is the same, the required margin has to be about 10 degrees. This can be easily dealt if it is between fixed wirelesses, but since the current experiment deals with both fixed and movable wireless, these interference problems can occur.

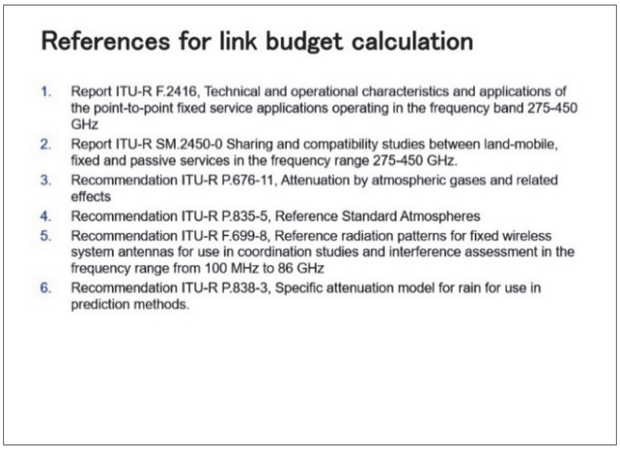
Consequently, I would like to elaborate on the opinion about moving to 500 GHz. 500 GHz creates more loss and therefore will decrease the transmission range. Even using the 100-GHz bandwidth with it will require some elaboration on the arrangement due to the absorption line of 500 GHz. The graph on slide 23 ignores this fact.



Slide 23

If so, it becomes about 200 m. Going beyond 5G, because the picocell radius is within 100 m, 50 mm of rain will not have an effect. In addition, it is obvious that atmospheric attenuation will become prevalent, decreasing the influence of rain at 500 GHz. Rain will not matter if it is absorbed beforehand. Therefore, rain will not have much influence even if the design only anticipates clear weather. However, this does not mean the system has a wide range so the aspect changes slightly.

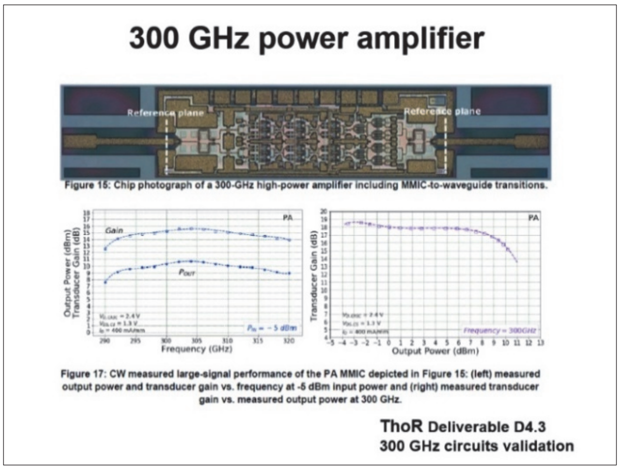
We are also preparing intelligent infrastructure needed to calculate these items.



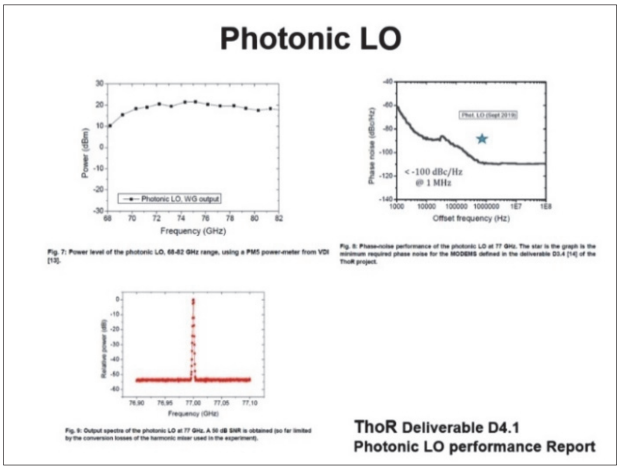
Slide 24

Slide 24 shows a document list from ITU-R, where it states the frequency limit on one of the items is 86 GHz. The calculation becomes difficult if these items lack support for THz bands.

From here on, I would like to introduce the conducted in Europe. Slide 25 shows an example of a 300-GHz power amplifier.



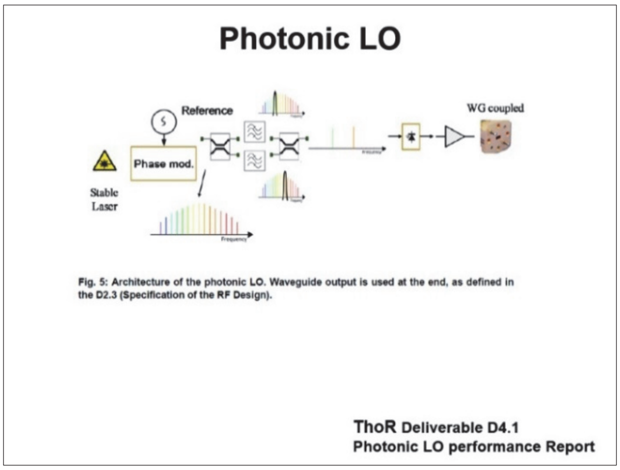
Slide 25



Slide 27

Its output is about 10 dBm with a wide bandwidth of about 20 GHz. The design is a joint effort by the Fraunhofer Society and the University of Stuttgart.

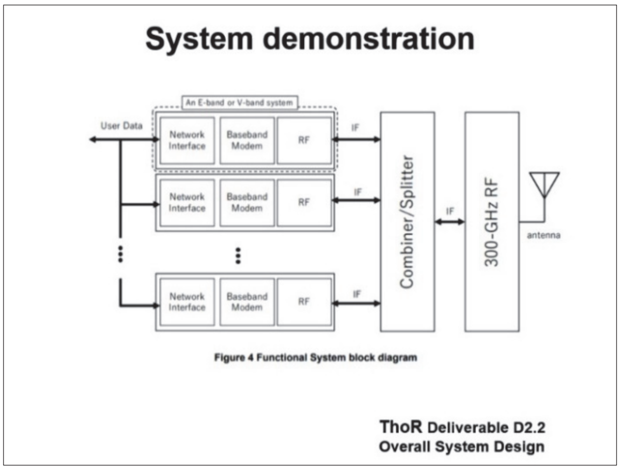
As shown in slide 26, there is a French team working on photonic LO, which I believe Anritsu is also working on.



Slide 26

I expect listeners already know quite a lot about this, but nevertheless, it modulates optics to create a sideband to be added in the waveguide coupling element. Although the mechanism itself is clear, the French team are dedicated to add functions such as lowering phase noise and tunability to their invention.

Slide 28 shows the block diagram of the experimental system.

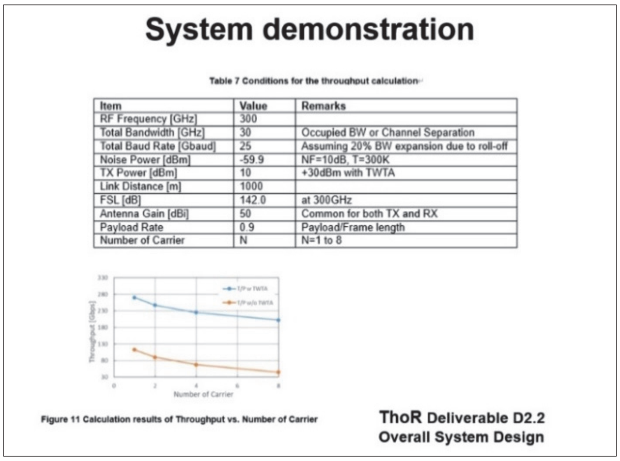


Slide 28

Its characteristic is that it can process real data and has a network interface. The implementation was accomplished by using the system of the developed and 99% complete or already marketed E and V bands as IF signals. The E band system being used here is a commercial product of Siklu from Israel and the V band system is a product of HRCP (High-Rate Close Proximity) from Japan.

These systems are united/coupled as a modem or IF signal. When looking back at past millimeter systems, these types of structures were common at the initial development. In addition, because it's difficult to suddenly prepare basebands for high-frequency devices—for which the market is still small—it is more efficient to utilize and unite pre-existing system devices as IFs for FDM (frequency-division multiplexing).

Slide 29 shows an example of specifications.

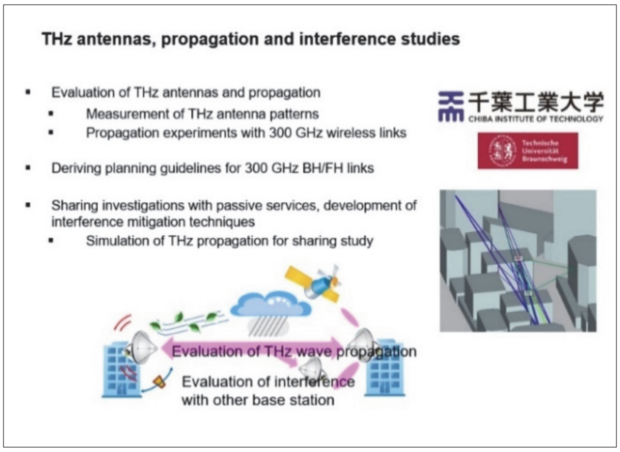


Item	Value	Remarks
RF Frequency [GHz]	300	
Total Bandwidth [GHz]	30	Occupied BW or Channel Separation
Total Baud Rate [Gbaud]	25	Assuming 20% BW expansion due to roll-off
Noise Power [dBm]	-59.9	NF=10dB, T=300K
TX Power [dBm]	10	+30dBm with TWTA
Link Distance [m]	1000	
FSL [dB]	142.0	at 300GHz
Antenna Gain [dBi]	50	Common for both TX and RX
Payload Rate	0.9	Payload/Frame length
Number of Carrier	N	N=1 to 8

Slide 29

I assume we don't have enough time to go through all the slides, so I highly recommend checking deliverable 2.2 of the ThoR project. In simple terms, if the total bandwidth is set at 30 GHz, the link distance becomes 1 km. Also, the antennas used are slightly bulky.

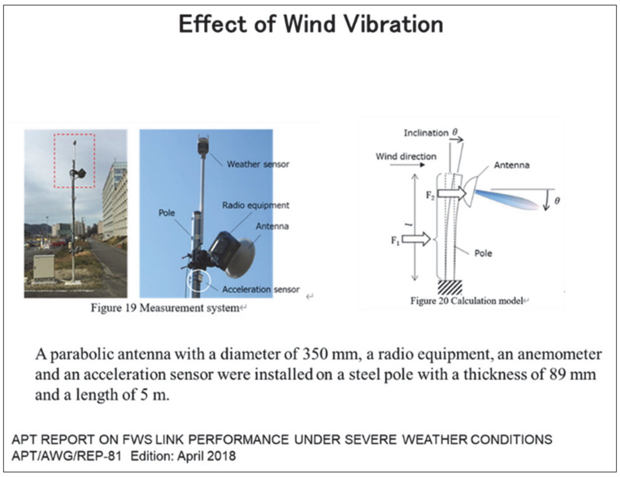
There are also various propagation experiments, such as the research on effect of rain and wind using real-life models of Shinjuku, Berlin, and Hanover to test the optimum arrangement.



Slide 30

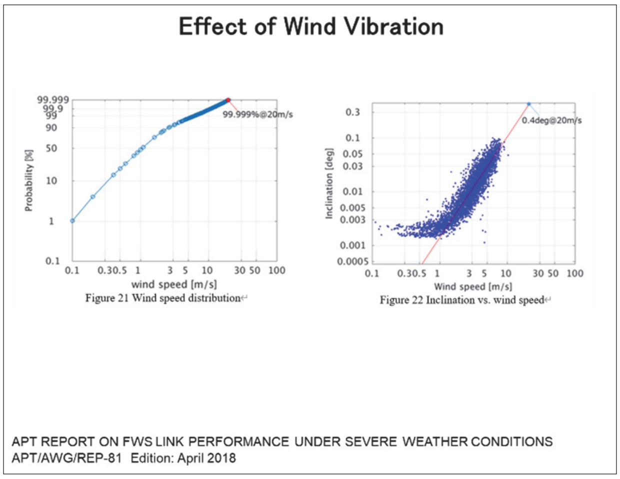
Although I haven't attached it as a source today, the research I did for my degree was on diffusion. Interesting phenomena can be observed when slight roughness is added to a surface with 1° flatness. In the world of radar, it is known as sea (surface) clutter where phenomena similar to reflection or diffusion occur. We performed replication experiments of that phenomena with optics, but unfortunately, this was theory-orientated back in those days and even that theorized phenomena itself was quite rare to find. However, I believe with THz this will reverse and become quite common in the surrounding environment. This is like a structure, with wavelength lowered by one magnitude, being stuck on a flat object. Our clothing textiles are about 50 microns and even THz waves, when based around 100 GHz to 300 GHz, will succumb to such a relationship, so I expect and anticipate that when coherent THz is implemented, there will be more reactions like a butterfly wing looking beautiful under light. This is only my personal interest, and I don't expect the aesthetics of butterfly wings will have much practicality, but it maybe something fun to look forward to.

The influence of wind has been researched by a standardization organization called APT (Asia-Pacific Telecommunity.*5 Slide 31, shows their report.



Slide 31

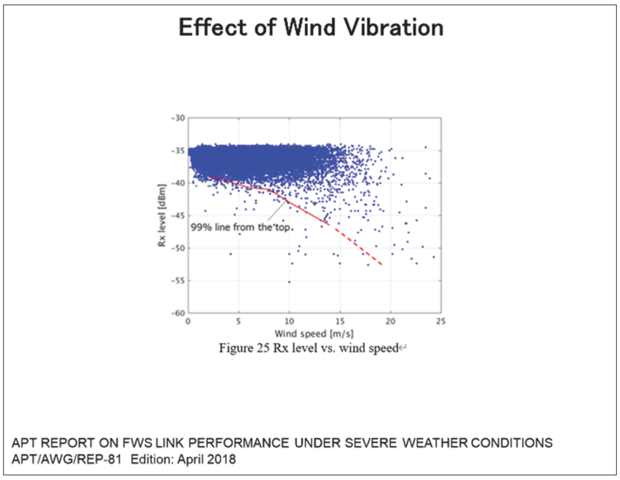
It checks the correlation at link performance by placing an E band device for measuring wind. Slide 32 shows the relationship between wind and angle.



Slide 32

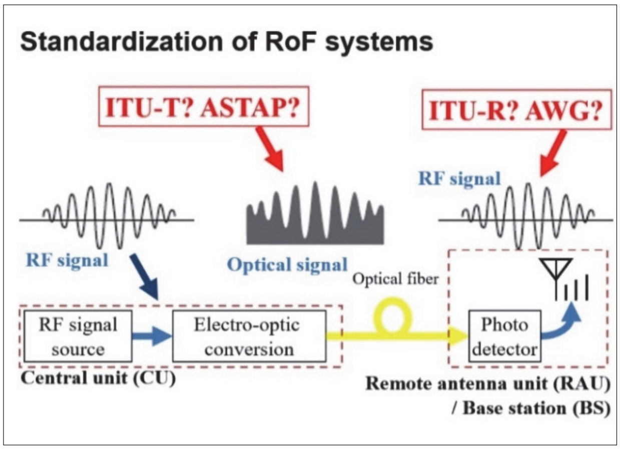
It is projected that when the wind velocity is 20 m/s, the angle will be about 0.4°. For a 99.999% availability, it has to withstand a wind velocity of about 20 m/s. The losses at 0.4° can be calculated using antenna patterns where a margin of about 4 dB is necessary. Right now, a recommendation for this is being prepared.

Slide 33 shows the details on the effect of short time periods.



Slide 33

Now I would like to talk about standardization.



Slide 34

We are in the active process of standardization with various help from Anritsu. As of today, the standardization of FoR has become recognized, but in the initial stages this was quite difficult to progress. Operational silos are not only a problem in Japan but is something global. Obviously, the organization culture between a radio-wave regulation authority and optic research facility is different. This difference in culture is something inevitable, but what's concerning is which organization will be in charge of standardizing FoR systems.

Despite, standardization needs a division of labor. One point of this will be a search for a method of collaboration without causing confusion. In addition, when RoFs are networked, I expect radio-wave management will become increasingly difficult. For example, when including a complete digital channel within a fiber using WDM, replacing the parts controlling the digital section may affect radio-wave quality. The question is what to do then. Currently, FoR systems are standalone. For example, for the system at Narita International Airport, it is a matter of being granted permission by the entire system. However, the real problem is how to grant permission when accessing the network. Botching the job and creating too much interference is a problem, but the reverse of trying to avoid the interference could raise voices for dynamic network use. In summary, networks, seems to inherently internalize these troublesome phenomena.

*5: APT (Asia-Pacific Telecommunity): Regional organization aiming to complete, facilitate, and effectively managed the Asia Pacific telecommunication networking project.

5 Conclusions

Finally, I want to tell you what will happen from now on and what you should use.

The first question when talking about 6G is "what do use it for?" This is my personal opinion based on my experience, but it feels like there is never enough capacity in the current situation for communication with other people. This lecture is much the same, but it doesn't show on our faces! There are even some people who say we should return as quickly as possible to all online teaching at universities. It seems like there are some merits from the students' side because it would be possible to rewind and watch lectures over without even going to university.

But from the teacher's side being unable to see students' faces is difficult. I think it depends on the teacher, but it's good to be able to adjust the lecture while watching the faces of people listening to it. When teaching, we see various types of students, like those who are mostly asleep, or have only just got up, or are awake all the time. If I do three or four lectures, since I get to know each personality somehow, and I can adjust the level of the lecture when I glance at the students and get the feeling that at least a student who should be following has attended the lecture. When I see the student and lecture content "click", I don't need to ask, "how about you?" This is when I realize that it's the students who make the class. Looking at the faces of people listening to this lecture, perhaps I should have adjusted the contents more to people's expectations!

In fact, from the teaching side, massive amounts of information are necessary and maybe even 8K hi-definition would be insufficient. We should create a system that is able to show students suddenly paying attention. For students, displaying documents occupying nearly their whole screen is sufficient for receiving information if the teacher glances at them occasionally. However, this is never enough to create a class. Maybe entertainers feel the same way.

When I talk offline after having finished a conference, for an instant, I see who is there and imagine what kind of theme is carried on. Despite using the various available tools, it always feels as if the information is insufficient, making it necessary to increase the amount of information more and yet more.

As has been said already, 6G is an important key for autonomous driving and health applications.

Perhaps it is content-based management (CBM) for infrastructure? Its importance is in fixing what is broken. I always test this when speaking positively. Since the testing is continuous rather than periodic, it's like a world where car inspections are not necessary, for example. When wanting to do such a thing, it is necessary to handle huge volumes of information. In my previous example about the radio-astronomy laboratory, we were monitoring, measuring and testing ourselves.

If 6G were used in this type of field, it is said that the number of base stations would exceed the world population! Perhaps this won't happen in an era when radio waves are as close as the nearest light from a lamppost. However, it may be necessary for researchers and developers to at least aim for this. If we don't, I think it is unlikely that the telecommunications world will develop and install new hardware.

This ends my talk—thank you for listening.

References

1) GSMA, Research Report, Mobile backhaul options Spectrum analysis and recommendations, September 2018

Lecturer Biography

Tetsuya Kawanishi

1992	Graduated in electronic engineering from Faculty of Engineering, Kyoto University
1994	Awarded master's degree in electronic engineering from Postgraduate School of Engineering, Kyoto University
1994—1995	Researcher at Matsushita Denki in process technology R&D laboratories
1997	Awarded doctorate in electronic engineering from Postgraduate School of Engineering, Kyoto University
1997—1998	Researcher at Venture Business Laboratory, Kyoto University
1998—2015	Researcher at Communications Research Laboratory (now National R&D Agency; National Institute of Information and Communications Technology)
2015—present	Professor at Waseda University

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