A Study on Extreme Wideband 6G Radio Access Technologies for Achieving 100 Gbps Data Rate in Higher Frequency Bands

Satoshi Suyama†, Senior Member, Tatsuki Okuyama†, Member, Yoshihisa Kishiyama†, Senior Member, Satoshi Nagata†, Member, and Takahiro Asai†, Senior Member

SUMMARY  In sixth-generation (6G) mobile communication system, it is expected that extreme high data rate communication with a peak data rate over 100 Gbps should be provided by exploiting higher frequency bands in addition to millimeter-wave bands such as 28 GHz. The higher frequency bands are assumed to be millimeter wave and terahertz wave where the extreme wider bandwidth is available compared with 5G, and hence 6G needs to promote research and development to exploit so-called terahertz wave targeting the frequency from 100 GHz to 300 GHz. In the terahertz wave, there are fundamental issues that rectinearity and pathloss are higher than those in the 28 GHz band. In order to solve these issues, it is very important to clarify channel characteristics of the terahertz wave and establish a channel model, to advance 6G radio access technologies suitable for the terahertz wave based on the channel model, and to develop radio-frequency device technologies for such higher frequency bands. This paper introduces a direction of studies on 6G radio access technologies to explore the higher frequency bands and technical issues on the device technologies, and then basic computer simulations in 100 Gbps transmission using 100 GHz band clarify a potential of extreme high data rate over 100 Gbps.

key words: sixth generation mobile communication system, radio access technology, millimeter wave, terahertz wave, extreme high data rate

1. Introduction

Commercial services of the fifth-generation (5G) mobile communication system were globally introduced, and in Japan, the commercial service launched in March 2020. Equally, new problems faced by 5G and expectation toward further enhancement of 5G, so-called “5G evolution” appear. DOCOMO started a study on requirements for 5G evolution and beyond 5G (6G) from 2017 [1], and has already released DOCOMO’s white paper that describes (i) directions of evolution, (ii) requirements and use cases, and (iii) technological enhancement and study areas on 5G evolution and 6G in addition to its concept video in January 2020 [2], [3]. And then the white paper has been updated as revision 2.0 based on the further studies in July 2020 [4]. 6G is an innovative infrastructure to support future society and industry in the 2030s and aims to provide required extreme performances such as extreme high data rate and capacity, extreme coverage, extreme low energy and cost, extreme low latency, extreme high reliability, and extreme massive connectivity. Worldwide competition in research and development of 6G has launched. In Japan, the Ministry of Internal Affairs and Communications (MIC) has been holding “Beyond 5G Promotion Strategy Roundtable” and the recommendations from the roundtable and MIC’s “Beyond 5G Promotion Strategy -Roadmap towards 6G-” has been released [5], and it is expected that specific 6G research and development projects that Japanese government leads will start in the near future. Additionally, as one of Japanese academic society activities, an online panel session BP-1 “Future Prospects and Direction of Evolution for 6G -We Co-create 6G-” was held in IEICE Society Conference in September 2020, gathering more than 400 participants, and seven invited talks on recent 6G studies and interesting panel discussion were performed (for example, [6]).

In Japan, 3.7 GHz, 4.5 GHz, and 28 GHz bands were assigned to the 5G commercial services, and a higher data rate can be provided in especially the 28 GHz band where the wider bandwidth of 400 MHz is employed compared to the sub 6 GHz bands. On the other hand, Federal Communications Commission (FCC) in United States announced to open new frequency bands between 95 GHz and 3 THz for 6G experimental trials [7], and currently, there is an increasing momentum to exploit the higher frequency bands than 5G toward 6G.

In order to provide extreme high data-rate communications over 100 Gbps in 6G, this paper assumes to exploit so-called terahertz wave targeting the frequency bands from 100 GHz to 300 GHz where much wider bandwidth is available compared with 5G. Hence, this paper introduces a direction of studies on 6G radio access technologies to explore the higher frequency bands and some technical issues on radio-frequency (RF) device technologies. In addition, a potential of extreme high data rate over 100 Gbps is clarified by basic computer simulations that achieve 100 Gbps data rate in the 100 GHz band.

The rest of this paper is organized as follows. Section 2 describes NTT DOCOMO’s 6G concept including requirements for 6G radio access. In Sect. 3, 6G spectrum extension, a concept of 6G radio access technologies, and related wireless technologies for 6G are introduced briefly. Section 4 considers some technical issues on RF device technologies, and then, in Sect. 5, simulation results of 100 Gbps transmission using the 100 GHz band are shown. Finally, we conclude this paper in Sect. 6.

† The authors are with NTT DOCOMO, INC., Yokosuka-shi, 239-8536 Japan.

a) E-mail: satoshi.suyama.rd@nttdocomo.com

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2. 6G Concept

At present, with the popularization of big data and artificial intelligence (AI), cyber-physical fusion has attracted much attention and become heightened [8]. As shown in Fig. 1, AI reproduces the real world in cyberspace and emulates it beyond the constraints of the real world, so that future prediction and new knowledge can be discovered. Various values and solutions such as the solution to social problems can be offered by utilizing this in services in the real world. A role of wireless communications in the cyber-physical fusion/system is assumed to include high capacity and low latency transmission of real world images and sensing information, and feedback to the real world (actuate) through high reliability and low latency control signaling. Therefore, in order to realize the advanced cyber-physical fusion in the 2030s, wireless communications with extreme performance, "6G" is absolutely essential.

Figure 2 shows NTT DOCOMO’s view on extreme-performance requirements for 6G that realizes the above world-view [4]. 6G assumes use cases that require extreme performances that even 5G cannot achieve, as well as new combinations of requirements that do not fall into the three categories of 5G: enhanced mobile broadband (eMBB), ultra-reliable and low latency communication (URLLC), and massive machine type communication (mMTC).

Through further improvements in communication speed, by 6G with “extreme high-data-rate and high-capacity communications” exceeding 100 Gbps, it is considered that new sensory services equal to or exceeding actual sensory quality can be actualized. In addition, 6G aims to develop “extreme coverage extension” that can be used in all kinds of places, including the sky, sea, and space, which are not covered by current mobile communication systems. For example, further expansion of activity environments for humans and machines and the creation of new industries are expected. This expansion is also expected to be applied to future use cases such as flying cars and space travel. “Extreme low power consumption and cost reduction” for network and terminal devices will be important requirements in 6G, when future extension of the high frequency bands to millimeter wave and terahertz wave and deployment of the denser network and massive terminal devices are considered. In order to actualize services in real-time and be highly interactive, an always stable end-to-end (E2E) low latency “extreme low latency” is also a basic requirement for 6G, and concretely, an approximately 1 ms or less E2E latency is considered as the target value. In many industrial use cases, the wireless communication of control information with high reliability is an important requirement, and “extreme high-reliable communication” in 6G is expected to realize higher level of reliability and security than 5G. A larger number of IoT devices are expected to spread further in the 6G era, and “extreme massive connectivity” that can support 10 million devices per square km is required. In addition, the mobile communication network itself is expected to evolve to have functions for sensing the real world such as high-precise positioning with the error of a centimeter or less and object detection around the terminal devices by using radio waves. In fact, the requirements for 6G will be determined for international standardization.

3. 6G Radio Access Technologies for Higher Frequency Bands

3.1 Overview of 5G Spectrum Extension

As shown in Fig. 3, 5G supports frequency bands up to 52.6 GHz and it is considered that the frequency bands will be extended up to almost 90 GHz in the future. In NTT DOCOMO’s initial studies on the extension of the higher frequency band toward 5G, starting with a 10 Gbps experiment using 400 MHz bandwidth in 11 GHz band [9], the following concepts and studies of 5G radio access technology including basic technical elements have been introduced [10]–[14]: (i) a massive multiple-input multiple-output (MIMO) technology to increase coverage without increasing a transmission power based on the results of the 10 Gbps experiment, (ii) massive MIMO simulations with 256 antenna elements to verify 20 Gbps in 20 GHz band in consideration of the year 2020, (iii) channel measurement in the higher frequency bands and technical issues on massive MIMO implementation, (iv) a beam searching method to transmit an index related to each beam by beamforming (BF) with multiple pre-fixed angles, (v) a method to set the sampling frequency to a power of two times of 4G to realize scalable radio frame length, and so on.
Moreover, NTT DOCOMO has promoted a large number of 5G experimental trials with world-leading vendors to verify a variety of potentials of the massive MIMO technologies in candidate higher frequency bands for 5G as follows [14]. In the low super high frequency (SHF) (3–6 GHz) bands, a fully digital BF technology for multiuser MIMO has been evaluated by using experimental equipment in addition to distributed MIMO. In the high SHF (6–30 GHz) bands, especially 15 GHz and 28 GHz bands, analog BF and hybrid BF technologies and beam tracking capability for high-speed mobility have been checked by the 5G experimental trials. Moreover, in the extremely high frequency (EHF) bands, NTT DOCOMO has verified the potential of millimeter-wave analog BF technology using a lens antenna in 39 GHz and 70 GHz bands.

### 3.2 New Spectrum Extension for 6G

Toward 6G, as mentioned above, the FCC in United States recommends to exploit the higher frequency bands from 95 GHz to 3 THz than 5G. Since the terahertz waves handle a significantly wider signal bandwidth than 5G, the extreme high data rate communication exceeding 100 Gbps is being considered.

The terahertz wave has fundamental technological problems that the radio waves do not fly far, because the rectilinearity and pathloss of the terahertz wave are higher than those of the conventional millimeter wave. Thus, measuring terahertz-wave propagation characteristics in real environments and establishing channel models based on the measurement results, and high-precision propagation simulation methods are needed for 6G [15]–[17]. Measurements of building shadowing, human blockage, and scattering from building rough surface up to 150 GHz have been conducted [16], [17]. On the other hand, in order to realize the 6G systems early and at low cost, a rapid development of the RF device technologies for such high frequency bands is also important.

#### 3.3 Concept of 6G Radio Access Technologies

Figure 4 shows a concept of 6G radio access technologies that considers both “extreme high data rate/capacity” thanks to such the new spectrum extension and “extreme coverage extension” including the sky, sea, and space areas mentioned in Sect. 2. Although these two requirements are the different directivity of the evolution in terms of the frequency bands and coverage, a common technical issue exists in the meaning of the region where the power efficiency become more important in comparison with the spectrum efficiency. Hence, it is ideal that common radio access technologies can be applied to 6G only by changing their parameters. Also, in this region, the signal waveform of single carrier (SC) becomes dominant in comparison with orthogonal frequency division multiplexing (OFDM), and the importance of high power-efficiency radio access may increase, as an application area of the radio access technologies including integrated access and backhaul (IAB) expands in the future.

Note that depending on both the imperfection of frequency characteristics of terahertz-wave RF devices and the relationship between the signal bandwidth and the spectrum efficiency to realize 100 Gbps, remarkably high performance and manufacturing accuracy are required for the RF devices. Additionally, in removing the imperfection of the RF devices by digital signal processing, extreme wideband SC has a large impact on baseband (BB) processing systems, especially digital-to-analog converter (DAC) and analog-to-digital converter (ADC). In order to relax these requirements, the implementation of multiband (multicarrier) radio access is a realistic solution, and it is important to optimally design introduced signal waveform and some parameters of the radio access technologies including integrated access and backhaul (IAB) expands in the future.

In present 4G and 5G radio access networks, a coordinated and fixed network topology that covers the area by using the base stations (BSs) deployed by a mobile operator is mainstream. Meanwhile, when maintenance of the coverage and improvement of the connectivity in the higher frequency bands are considered, high-density network configuration in which optimum path selection and transmit diversity/diversity reception are carried out by cooperating multiple BS antennas around the mobile station (MS) is ideal. In order to realize this, a spatially distributed and overlapped network topology, “new radio network topology” is necessary, which intentionally makes coverage with multiple connection paths, increases line of sight (LOS) probability for the higher frequency bands, and assists new network capabilities such as wireless sensing and wireless power sup-
ply. Note that a fundamental problem of how to achieve this at the low cost exists and the cost-effective solution will be one that does not use conventional BS antennas. In the new radio network topology, there are investigations such as utilization of existing objects such as street/traffic lighting, signboards, vending machines, and window glass for the BS antennas. Integration of sensors and communication antennas, advanced repeater and IAB for the higher frequency bands, intelligent reflecting surface (IRS) that can dynamically control reflection intensity and directivity, cooperation between terminal devices, MS-like moving BSs, and uplink-only-receiving antennas, etc. [4].

Recently, NTT DOCOMO has conducted some experimental trials on new radio network topology for 5G evolution and 6G to verify the potential of metamaterial reflector and transparent dynamic metasurface as the IRS technologies and the feasibility evaluation of 28 GHz-band BS connection/cooperation in high-mobility environments [18]–[22]. Specifically, the world’s first 28 GHz-band experimental trial on an actual Shinkansen running at a speed of 283 km/h in Japan has been carried out by successful consecutive BS connection among the three BSs [21]. In [22], to improve 28 GHz-band transmission performances in high-mobility environments, it has been shown that the BS cooperation technology with high-density two BSs and fully digital BF can expand coverage that achieves almost peak throughput 1.4 times in comparison with the non-cooperation in an outdoor experimental trial where one MS runs at a speed of 120 km/h. In the near future, an outdoor experimental trial with high-density three BSs and two MSs will be performed to verify the effectiveness of the BS cooperation technology in such high-mobility environments.

Even in 6G, further enhancement of massive MIMO technology is an important topic, and it is expected that the enhanced massive MIMO can handle the larger numbers of antenna elements and streams for the MIMO spatial multiplexing. In addition, combination of massive MIMO with distributed antenna deployment and new radio network topology, “distributed MIMO” is one of the promising technologies in the higher frequency bands, which has been introduced in detail including the latest research results [23].

Furthermore, as networks and devices in 6G become highly intelligent by an advanced AI technology, it is effective to utilize various image and sensing information obtained from non-wireless technologies such as cameras and sensors for radio control and radio resource management in the mobile communication systems. For example, it is real-time measurement, analysis, prediction of radio propagation environments in the millimeter wave and terahertz wave. Propagation channel parameters are extracted by absorbing both propagation data and high-precision position information measured at BSs and MSs into the network and analyzing them as big data by AI. Next, an actual propagation channel is predicted by building a channel model based on these parameters and high-precision propagation simulation in the cyberspace. And then, by anticipating time-variant dynamically changing mobile communication environments based on the predicted propagation channel, it is expected to carry out flexible, dynamic beam control and optimum path selection in the new radio network topology, to maintain required transmission quality and performance by selecting or combining appropriate frequency bands, and to perform intelligent switching with other integrated cooperative radio technologies.

4. Technical Issues on RF Device Technologies in Higher Frequency Bands

As device technology in the higher frequency bands of the millimeter wave and terahertz wave, it is necessary to realize the BB processing system which can deal with further extreme wideband, namely, digital signal processing circuit, DAC, and ADC in low cost and low power consumption. Also, antennas, filters, power/low noise amplifiers, mixers, local oscillators, etc. operating in the higher frequency bands exceeding 100 GHz must be developed to cope with the massive antenna elements of massive MIMO, and in addition to high performance and high integration of RF circuits, it is necessary to be able to manufacture semiconductor devices at a level of performance and cost that can be used in actual commercial services. Since the wiring loss is so large in the higher frequency bands, the configuration of the chip and integrated circuit (IC) and an implementation method that connects the RF devices to the antenna elements are also major problems. Optimizing a balance between the performance improvement of the RF devices themselves and the performance compensation (calibration) assisted by the digital signal processing as shown in Fig. 5 is assumed to be a research subject, considering the migration of future semiconductor manufacturing technology, etc., and it is also a technical issue even in 6G whether compound or silicon semiconductors should be adopted [4]. Moreover, miniaturization, low power consumption, and high heat radiation of RF/BB semiconductor ICs are also required, when those developed RF/BB ICs are applied into the terminal devices, and realization of an RF circuit corresponding to multiband and its miniaturization are also large subjects on the premise of carrier aggregation in the millimeter wave and terahertz wave.

![Configuration example of massive MIMO transmitter](image_url)

Fig. 5 Massive MIMO transmitter with digital assist.
5. Performance Evaluation of 100 Gbps Radio Access in Higher Frequency Bands

5.1 Simulation Specifications

Basic computer simulations evaluate the performances of 6G 100 GHz-band 100 Gbps transmission. This paper employs joint processing of fixed analog BF and channel state information (CSI)-based precoding, called FBCP (fixed BF and CSI-based precoding) as a hybrid BF scheme combining analog BF and digital precoding [24]. FBCP first performs a beam search for a predetermined angle in the analog BF, and an $N_T \times L$ BF weight matrix $W$ is determined based on the maximum received power criterion, where $N_T$ and $L$ are the number of BS antenna elements and the number of beams in the hybrid BF, respectively. Note that the resolution of angle in the beam search of the analog BF was optimized to one degree (deg.) by the simulation. Next, FBCP calculates a weight matrix for digital precoding by using an equivalent channel matrix $HW$ when applying the analog BF, where $H$ is an $N_R \times N_T$ channel matrix and $N_R$ is the number of MS antenna elements. FBCP can achieve excellent transmission performances, while the computational complexity is drastically reduced compared with the fully digital BF.

Table 1 shows simulation specifications. The performances of 5G are also evaluated in addition to 6G. The center frequency $f_c$ was set to 28 GHz and 100 GHz for 5G and 6G, respectively. The bandwidth per CC of 6G was made to be eight times of 5G, and subcarrier interval of 6G was 480 kHz which is also eight times of 5G. Thus, a total bandwidth $B = 400$ MHz for 5G with 4CCs and $B = 6.4$ GHz for 6G with 8CCs, which is 16 times of 5G. In order to extract the full performance of MIMO transmission by the digital precoding, this paper employed OFDM as 5G and 6G radio access, and time slots in time division duplex (TDD) were all assigned to downlink (DL), in other words, the ratio of time slots in DL and uplink (UL) (TDD ratio) was 10 to 0. In 6G, $N_T$ is set to 256, 1024, and 4096, and $N_R$ is made to be a planar array equivalent to 256 elements in which 16 uniform planar arrays with 16 elements and half-wavelength interval are arranged at 3.5-wavelength interval so as to have the same aperture size as the 5G MS antenna with 16 elements and one-wavelength interval. Note that the simulations in 6G were carried out by 16-element uniform planar array with 3.5-wavelength interval, and $12 \text{ dB}$ was considered as an additional BF gain of MS in evaluating coverage performances. The number of beams, $L$ is set to 16, for example, in the case of $N_T = 4096$, a subarray of 16 elements in the horizontal direction and 16 elements in the vertical one generates one beam. The number of streams $M$ is set to 16 for 5G and 4 and 8 for 6G. From the sets of modulation schemes and coding rates shown in Table 1, this simulation employed adaptive modulation and coding (AMC) using the set with the highest throughput according to the average signal-to-noise power ratio (SNR) of each stream. When the transmission efficiency considering pilot insertion loss, etc. is 0.8, the maximum throughput becomes 28.96 Gbps in 5G, 115.85 Gbps and 231.70 Gbps in 6G with $M = 4$ and $M = 8$, respectively. It is assumed that in the 100 GHz band, the MIMO multiplexing of eight streams is expected to be not easy in the single-user MIMO, while it can be realized by combining distributed MIMO and polarization multiplexing. Since the UL throughput is expected to become important in 6G, $M = 8$, which can allocate the TDD ratio to the UL to some extent, is a more realistic setting.

5.2 Throughput Performances with Average SNR

Figure 6 shows DL throughput performances in 5G and 6G for the average received SNR. Here, SNR represents the ratio of signal power per stream to noise power at the receive antenna. From this figure, the average SNR that can achieve 100 Gbps in 6G with $N_T = 256, 1024,$ and $4096$ is 17.5 dB, 12.0 dB, and 8.0 dB, respectively. As the number of BS antenna elements $N_T$ increases, the BF gain improves, however, in the case of $N_T = 4096$, the BF gain decreases with the expansion of antenna aperture size. 6G with $N_T = 4096$ and $M = 4$ can achieve 100 Gbps at the average SNR of 18.0 dB. The spectrum efficiency in 6G with $M = 8$ is half of that in 5G, while even in case of $N_T = 256$, the effect of increasing the bandwidth $B$ by 16 is large, which shows that higher throughput can be achieved compared with 5G. From these evaluation results, it was shown that the extreme wideband 6G radio access can provide extreme higher data-rate communications for 5G.
5.3 Coverage Performances

By calculating the received SNR based on the link budget, the coverage performances of 6G radio access using the center frequency of 100 GHz are evaluated. Ground heights of BS and MS antenna arrays are defined as \( h_{BS} \) and \( h_{MS} \), respectively, and let \( d_{2D} \) and \( d_{3D} \) denote a ground distance and a linear distance between BS and MS, respectively. When the total transmission power is \( P_T \) (dBm), the pathloss is \( L_P \) (dB), the noise power density is \( N_{PD} \) (dBm/Hz), and the noise figure is \( N_f \) (dB), the received SNR \( \Gamma \) (dB) is expressed as

\[
\Gamma = P_T + G_{BS} + G_{MS} - L_P - (N_{PD} + 10 \log_{10} B + N_f),
\]

where \( G_{BS} \) and \( G_{MS} \) denote antenna (element) gains of BS and MS, respectively. Here, in consideration of the fact that the rectilinearity of 100 GHz is higher than that of 28 GHz, the pathloss equation in the LOS environment of a rural area is used, and \( L_P \) is given by [25]

\[
L_P = \begin{cases} 
PL_{LOS,1} & (10 < d_{2D} \leq d_{BP}) \\
PL_{LOS,2} & (d_{BP} < d_{2D} < 10000) 
\end{cases}
\]

where \( PL_{LOS,1} \), \( PL_{LOS,2} \), and \( d_{BP} \) are expressed by the following equations:

\[
PL_{LOS,1} = 20 \log_{10}(40 \pi d_{3D} f_c / 3) + \min(0.03 h_{1/2}, 10) \log_{10}(d_{3D}) - \min(0.044 h_{1/2}, 14.77) + 0.002 d_{3D} \log_{10}(h),
\]

\[
PL_{LOS,2} = 20 \log_{10}(40 \pi d_{3D} f_c / 3) + \min(0.03 h_{1/2}, 10) \log_{10}(d_{BP}) - \min(0.044 h_{1/2}, 14.77) + 0.002 d_{BP} \log_{10}(h) + 40 \log_{10}(d_{3D} / d_{BP})
\]

\[
d_{BP} = 2 \pi h_{BS} h_{MS} / \lambda,
\]

where \( \lambda \) is the wavelength, and \( h \) is the average building height. Note that \( f_c \) in Eqs. (3) and (4) should be entered in GHz. From Eq. (3), it can be seen that under the same condition except for \( f_c \), the pathloss \( PL_{LOS,1} \) in 6G increases by approximately 11 dB compared with 5G. In this evaluation, it was assumed that \( h_{BS} = h_{MS} = 3.0 \text{ m}, \lambda = 25 \text{ m}, \) and \( G_{BS} = G_{MS} = 3 \text{ dBi} \), and 6G considered 12 dB as the additional BF gain of MS.

Figure 7 shows the throughput for the distance \( d_{2D} \) from the BS as coverage performances. As a reference, the coverage performance of 5G with \( f_c = 28 \text{ GHz} \) is also shown. Note that \( L_P \) in Eq. (2) is not defined for \( d_{2D} \) of less than or equal to 10 m [25] while this paper employed \( PL_{LOS,1} \) as \( L_P \) for \( d_{2D} \) of less than or equal to 10 m in this performance evaluation. Although this paper evaluated 5G only in the 28 GHz band, coverage performances in the 4.5 GHz band have been shown in [26].

From this figure, the throughput of 6G with \( f_c = 100 \text{ GHz} \) decreases as the distance increases, and 6G can achieve the throughput of 100 Gbps up to the distance of 35 m for \( M = 4 \) and 60 m for \( M = 8 \). The results of \( M = 4 \) and \( M = 8 \) become closer as the distance increases. This is because the MIMO spatial multiplexing is performed under the condition that the total transmission power is constant, so that the transmission power per stream of \( M = 4 \) is twice that of \( M = 8 \). In comparison with 5G, 6G can achieve the throughput of approximately 60 Gbps even in the distance of 100 m by exploiting the extreme wideband of 6.4 GHz despite the larger pathloss, and it is proven that almost 13 times higher throughput than 5G can be achieved.

6. Conclusion

This paper introduced the extreme high data rate communications over 100 Gbps as one of six requirements for 6G, and clarified the demand of the new 6G spectrum to extend the targeting frequency to so-called terahertz wave such as 100 GHz bands where much wider bandwidth is available compared with 5G. This paper also studied a concept of 6G radio access technologies for such higher frequency bands and investigated some technical issues on RF device technologies for 6G. In addition, to verify the potential of over-100 Gbps transmission using the 100 GHz band, the computer simulations showed that the 6G radio access can
achieve over-100 Gbps throughput when the distance from BS is within 60 m by exploiting the 6.4-GHz extreme wide bandwidth and eight-stream multiplexing with 4096 antenna elements.

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References


Satoshi Suyama received the B.S. degree in electrical and electronic engineering, the M.S. degree in information processing, and the Dr.Eng. degree in communications and integrated systems, all from Tokyo Institute of Technology, Tokyo, Japan, in 1999, 2001, and 2010, respectively. From 2001 to 2013, he was an Assistant Professor in the Department of Communications and Integrated Systems at the Tokyo Institute of Technology. He has been engaged in research on OFDM mobile communications systems and applications of the adaptive signal processing, including turbo equalization, interference cancellation, and channel estimation. Since April 2013, he has joined NTT DOCOMO, INC. and has been involved in research and development of 5G mobile communications systems. He is currently Manager of 6G Laboratories in NTT DOCOMO. He received the Best Paper Prize from the European Wireless Technology Conference (EuWiT) in 2009, Best Paper Award from International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC) in 2016, and the Paper Award from IEICE in 2012. He is a member of IEICE and IEEE.
Tatsuki Okuyama received the B.E. degree in electrical, electronic and information engineering, M.E. and Ph.D. degrees in information and communications technology, all from Osaka University, Osaka, Japan in 2012, 2014, and 2019, respectively. Since April 2014, he has been with NTT DOCOMO, INC. He has been engaged in research on Massive MIMO systems, including distributed MIMO and digital signal processing to suppress interference among users for downlink and uplink, for fifth generation mobile communications system. He received the Young Researchers’ Award from IEICE in 2017. He is a member of IEICE.

Yoshihisa Kishiyama received his B.E., M.E., and Dr. Eng. Degrees from Hokkaido University, Sapporo, Japan in 1998, 2000, 2010, respectively. In 2000, he joined NTT DOCOMO, INC. He has been involved in research and development for 4G/5G mobile broadband technologies and physical layer standardization in 3GPP. He is currently Manager of 6G Laboratories in NTT DOCOMO. His current research interests include 6G radio access concept and key technologies. He was a recipient of the International Telecommunication Union (ITU) Association of Japan Award in 2012.

Satoshi Nagata received his M.S. degree from Tokyo Institute of Technology, Tokyo, Japan, in 2003. In 2003, he joined NTT DOCOMO, INC. He has been involved in research and development for 4G/5G mobile broadband technologies and physical layer standardization in 3GPP. He had contributed to 3GPP TSG-RAN WG1 as a vice chairman and chairman. He is currently a chairman of 3GPP TSG-RAN WG1. He is currently Manager of 6G Laboratories in NTT DOCOMO. He was a recipient of the International Telecommunication Union (ITU) Association of Japan Award in 2015.

Takahiro Asai received the B.E. and M.E. degrees in electrical and electronics engineering, and Ph.D. degree in communications and computer engineering from Kyoto University, Kyoto, Japan, in 1995, 1997, and 2008, respectively. In 1997, he joined NTT Mobile Communications Network, Inc. (currently, NTT DOCOMO, INC.). Since joining NTT Mobile Communications Network, Inc., he has been engaged in the research of signal processing for mobile radio communication. He is a member of IEEE and IEICE.