5G Radio Access: Requirements, Concept and Experimental Trials

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SUMMARY Currently, many operators worldwide are deploying Long Term Evolution (LTE) to provide much faster access with lower latency and higher efficiency than its predecessors 3G and 3.5G. Meanwhile, the service rollout of LTE-Advanced, which is an evolution of LTE and a “true 4G” mobile broadband, is being underway to further enhance LTE performance. However, the anticipated challenges of the next decade (2020s) are so tremendous and diverse that there is a vastly increased need for a new generation mobile communications system with even further enhanced capabilities and new functionalities, namely a fifth generation (5G) system. Envisioning the development of a 5G system by 2020, at DOCOMO we started studies on future radio access as early as 2010, just after the launch of LTE service. The aim at that time was to anticipate the future user needs and the requirements of 10 years later (2020s) in order to identify the right concept and radio access technologies for the next generation system. The identified 5G concept consists of an efficient integration of existing spectrum bands for current cellular mobile and future new spectrum bands including higher frequency bands, e.g., millimeter wave, with a set of spectrum specific and spectrum agnostic technologies. Since a few years ago, we have been conducting several proof-of-concept activities and investigations on our 5G concept and its key technologies, including the development of a 5G real-time simulator, experimental trials of a wide range of frequency bands and technologies and channel measurements for higher frequency bands. In this paper, we introduce an overview of our views on the requirements, concept and promising technologies for 5G radio access, in addition to our ongoing activities for paving the way toward the realization of 5G by 2020.

key words: next generation mobile communications system, 5G, 4G, LTE, LTE-advanced

1. Introduction

During the last few decades, mobile communications have significantly contributed to the economic and social developments of both developed and developing countries. Today, mobile communications form an indispensable part of the daily lives of millions of people in the world; a situation which is expected to continue and become even more undeniable in the future. In fact, more and more customers are expecting to have the same quality of experience from Internet applications anytime, anywhere, and through any means of connectivity. This expectation is now being better fulfilled as the gap of user experience between mobile and fixed environments becomes narrower and higher data rates are offered by mobile networks. In addition, there has been a rapid proliferation of high-specification handsets, smart-

phones in particular, and new mobile devices that support a wide range of applications and services. Image transfer and video streaming, as well as more cloud based services, such as cloud speech services, are reaching an increasing number of customers. These trends are expected to become even more pronounced in the 2020s and would expand to include new services and forms of communications. Examples of emerging services include tactile Internet, remote monitoring and real-time control of a wide variety of devices, which support machine type communications (MTC) and Internet of things (IoT). Obviously, such trends will impose unprecedentedly challenging and much diversified requirements on next generation mobile networks (5G).

From radio access perspective, 5G, compared to 4G, will need to be more massive and scalable to enable the support of a wider range of scenarios and services. 5G radio access needs to provide significant performance gains in system capacity, user data rates, the number of simultaneously connected devices and latency, which necessitates the pursuit of not a single but a set of directions of evolution for radio access technologies. From spectrum utilization point of view, in particular, the spectrum below 3 GHz is mostly utilized by existing systems. Therefore, it is crucial to extend the spectrum usage to the frequency bands higher than 3 GHz in order to ensure a sustainable system evolution. A key pillar of our 5G concept is the efficient integration of existing cellular bands and new spectrum bands over a wide range of frequency bands. In particular, 5G promising technologies for the integration of lower and higher frequency bands in addition to a set of spectrum specific and spectrum agnostic technologies are introduced. As a proof-of-concept, many activities are taking place including collaborations with world-wide vendors.

This paper presents an overview on 5G radio access including our views on 5G requirements, concept and promising technologies, in addition to our ongoing activities and experimental trials for paving the way toward the realization of 5G by 2020. The remainder of this paper is organized as follows. Section 2 describes the identified 5G requirements and the proposed technical concept. Section 3 discusses 5G promising technologies. In Sects. 4 and 5, as proof-of-concept, our ongoing activities related to the development of 5G real-time simulator and 5G experimental trials are introduced. Finally, Sect. 7 concludes the paper.

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Fig. 1 The five major targets for 5G.

2. 5G Requirements

Taking into account the recent market trends and services, the high-level targets which are most relevant to 5G are summarized in Fig. 1 and explained in the following.

➤ Higher System Capacity

Recently, it is reported that mobile data traffic in Japan has increased by a factor of 6.4 from 2011 to 2014, i.e., with a growth rate of 1.86 times per year [3]. If similar rates of growth continue in the future, the volume of mobile traffic in 2020s would be at least 1000-fold larger compared to 2010. Thus, 5G has to be able to manage traffic volumes of many orders of magnitude larger than today's networks. This is considered as the most important and challenging requirement for 5G. The target is set to achieve a 1000-fold system capacity per km² compared to that in 2010.

➤ Higher Data Rates

5G has to practically provide higher data rates than today's deployments. Also, considering the rapidly emerging trends of richer content and cloud services, 5G should target to provide higher data rate services along with more uniform quality of user experience (QoE) compared to LTE. The provision of a better and more uniform user experience can be achieved through the improvement of both the achievable data rate and fairness in user throughput. The target we set here is a 10-fold improvement in peak data rate and 100-fold increase in typical (user-experienced) throughput, targeting 1 Gbps experienced user throughput everywhere. Higher peak data rates will also continue to be important for new scenarios such as mobile backhauling for small cells and moving nodes.

➤ Support of Massive Connectivity

5G has to allow massive number of devices to be connected simultaneously to the network in order to support all-time connected cloud services even in a crowd and more machine type devices for IoT. The target is set to support a 100-fold increase in the number of simultaneously connected users compared to that in 2010 while still satisfying the QoE required in 5G era.

➤ Reduced RAN Latency

5G has to provide not only higher data rate, but also a user-plane latency of less than 1 ms over the radio access network (RAN), a large leap from LTE's 5 ms. This will enable future cloud services with almost "zero latency" and new services such as tactile Internet, augmented reality, and real-time and dynamic control for M2M systems. The low latency has to be achieved while still satisfying QoE required for such service applications; e.g., in terms of reliability and availability.

➤ Reduced Cost, Higher Energy Efficiency and Robustness Against Emergencies

5G has to provide increased capacity per unit network cost and be energy-efficient and resilient to natural disasters. This becomes particularly important as the future network will need to support diverse scenarios and services simultaneously with a consistent user experience. While cost and energy-efficiency requirements are not easy to quantify, they should be factored in as much as possible throughout the whole design of the 5G system.

3. 5G Concept

3.1 Definition of 5G Radio Access

Among the above mentioned 5G targets, 1000-fold system capacity per km² and 100-fold user-experienced data rate are viewed as the most challenging. This necessitates the pursuit of not a single but a set of directions of evolution for radio access technologies. In addition, there are two basic evolution paths that can be taken to support new system capabilities for 5G: 1) a step-by-step evolutionary path focusing on further LTE enhancements, or 2) a revolutionary path using a brand-new radio access technology (RAT) that may include major changes that are non-backward compatible with LTE. We believe that LTE/LTE-Advanced, well-optimized for existing cellular frequency bands, will continue to be improved in the future. As a result, 5G is more likely to be an efficient integration of both existing and new higher frequency bands, where the 5G system consists of a two-layer structure: a coverage layer and a capacity layer. The coverage layer uses existing lower frequency bands to provide basic coverage and mobility. The capacity layer uses new higher frequency bands to provide high data rate transmission as shown in Fig. 2. The coverage layer is basically supported by enhanced LTE RAT while the capacity layer is supported by a new RAT. The efficient integration of the coverage and capacity layers is enabled by the tight interworking, e.g., dual connectivity, between the enhanced LTE RAT and the new RAT, as illustrated in Fig. 2. Note that the new RAT may also support the coverage layer and replace or be used together with enhanced LTE RAT in case reasonable benefits are identified in the future.

5G will utilize a wider range of frequency bands with both frequency-optimized and frequency-agnostic radio ac-

Fig. 2 5G radio access concept.

Fig. 3 Scalable LTE numerology for new RAT.

cess technologies. In particular, new technologies for new spectrum bands can be non-backward compatible to LTE for further performance improvements. Meanwhile, backward compatibility is preferable for frequency-agnostic new technologies which are applicable to both existing spectrum bands as well as higher frequency bands. The most promising 5G frequency-optimized technologies (e.g., massive MIMO, NOMA, new RAT numerology) and frequency-agnostic radio access technologies (e.g., phantom cell, low-latency frame design) will be explained in the following.

3.2 New RAT Numerology and Waveforms

The new RAT explained earlier should provide significant gains for 5G to justify non-backward compatibility. In particular, it needs to offer higher data rates (greater than 10 Gbps) and be adapted to support wider bandwidth (several 100 MHz to GHz order) with a wider range of frequency bands. From numerology point of view, the new RAT should be designed to ensure robustness against phase noise, which is larger in higher frequency bands. One promising approach to achieve this is to scale LTE numerology to enable wider carrier spacing as shown in Fig. 3.

A new RAT based on scaled LTE numerology can also provide shorter transmission time interval (TTI) below 1 ms to achieve reduced latency. Furthermore, it would provide advantages based on commonality with LTE numerology such as efficient support of tight interworking (e.g., dual connectivity) between enhanced LTE RAT and the new RAT and less complex implementation for enhanced LTE RAT/new RAT dual-mode terminals. Note that a new RAT optimized for wider range of frequency bands may support spectrum below 6 GHz in addition to those above 6 GHz.

Regarding the new RAT waveform, orthogonal fre-

quency division multiplexing (OFDM)-like multi-carrier (MC) waveform would be the baseline also for 5G because of its high affinity with multiple-input multiple-output (MIMO) technologies and high spectrum efficiency in multipath fading environments. However, alternative advanced MC waveforms (e.g., filter bank MC (FBMC) and universal filtered MC (UFMC) [4]) can also be considered since such waveforms can localize the interference, which can be essential to flexibly support different use cases, topologies, communication links, and so on. Furthermore, single carrier (SC) waveform is also a promising candidate to provide good coverage even when extremely wider bandwidth transmissions (e.g., > 1 GHz) are introduced in higher frequency bands such as above 30 GHz. Thus, the waveform of choice would highly depend on the frequency band and bandwidth to be used and the coverage to be provided. Note that the new RAT should support a variety of scenarios such as device-to-device (D2D), wireless backhauling, multi-hop, etc. Thus, it would be desirable to have a RAT design with downlink and uplink symmetry as much as possible.

4. 5G Promising Technologies

The technologies viewed as the most promising for 5G are categorized and explained in the following.

- Integration of lower and higher frequency bands
  - Phantom cell concept (C/U plane split)
  - Flexible duplex and spectrum utilization
- Exploitation of higher frequency bands
  - Massive MIMO
- Further enhancements of lower frequency bands
  - Non-orthogonal multiple access (NOMA)

4.1 Phantom Cell

Network densification using small cells with low power nodes is a promising solution to cope with mobile traffic explosion, especially in high traffic areas (hot spot areas). To this end, an advanced Centralized RAN (Advanced C-RAN) architecture is developed for commercial launch in around 2015 [5]. Advanced C-RAN adopts the centralized network architecture with many branches of remote radio equipment (RRE) and utilizes LTE-Advanced carrier aggregation (CA) functionality between macro and small cell carriers. This CA functionality helps to maintain the basic connectivity and mobility under the macro cell coverage while small cells called “Add-on” cells achieve higher throughput performance and larger capacity. The advanced C-RAN architecture handles all processing for CA and handovers within a centralized baseband unit (BBU) at eNodeB, which drastically reduces the amount of signaling to the core network.

Meanwhile, we proposed the concept of “Phantom cell” in the 3GPP RAN workshop on Release 12 and onwards. The concept of the Phantom cell is based on a multi-layer network architecture, which splits the control

Fig. 4 Phantom cell architecture with C/U-plane splitting.

(C)-plane and the user data (U)-plane between macro cell and small cells using different frequency bands as shown in Fig. 4 [6]. The motivations and the major benefits of the Phantom cell architecture are similar to those of advanced C-RAN architecture for LTE-Advanced, which include enhanced capacity by small cells, easy deployment of higher frequency bands, and small cell deployment without impact on mobility management. However, the concept of Phantom cell architecture includes a wider range of advanced functionalities, such as inter-node aggregation, relaxed back-hauling and signaling requirements, and enhanced small cell discovery [7], [8]. Our 5G concept uses the Phantom cell architecture as the baseline, upon which to integrate future multi-layer networks using lower and higher frequency bands. As depicted in Fig. 4, the small cell handles traffic for high-throughput data sessions with the user (U-plane), while the macro cell controls C-plane signaling (e.g., radio resource control (RRC)). These macro and small cells form a master-slave relationship, through which the macro cell sends the control information relevant to the user connected to small cells. This architecture makes the small cells practically invisible to the users connected to them. For this reason, this type of small cells is called ‘Phantom cell’. In 3GPP LTE release 12, some aspects of the “Phantom cell” architecture were discussed and specified. The scenarios and requirements for LTE release 12 small cell enhancements are summarized in 3GPP TR 36.932 [9].

4.2 Flexible Duplex and Spectrum Utilization

A frequency-separated network deployment, where different frequency bands are individually assigned to different cell layers, may use different duplex schemes, i.e., frequency division duplex (FDD) and time division duplex (TDD), for lower and higher frequency bands. Therefore, it is desirable to support the Phantom cell solution irrespective of the duplex scheme used in either the lower or higher frequency bands. To this end, as shown in Fig. 5, the support of flexible duplex via the joint operation of FDD and TDD (or one-way link, i.e., downlink/uplink only) and/or opportunistic carrier selection for bands including unlicensed spectrum bands will be a key technology.

4.3 Massive MIMO

The use of massive MIMO technology in combination with a large number of antenna elements is a potential solution to

Fig. 5 Flexible duplex and spectrum utilization.

Fig. 6 Combined massive MIMO and Phantom cell.

exploit higher frequency bands (e.g., beyond 10 GHz) [6]. For high frequency bands, antenna elements can be miniaturized, and very large number of antenna elements can be co-located, and thus very narrow beams can be formed. We expect such massive MIMO will become essential in small cells at higher frequency bands because it will enable practical coverage for small cells and provide very high throughputs per unit area for high user density scenarios. For small cell deployments, a planar patch antenna of 20 cm in height and width would be typically used. When antenna elements are arranged on a square grid (horizontal and vertical dimensions) with half-wavelength spacing, it is possible to pack as many as 16 antennas at 3.5 GHz, 169 antennas at 10 GHz, and over 650 antennas at 20 GHz. For an assumed ideal beamforming gain, a two-dimensional mapping of antenna elements can in theory compensate for the path loss with a frequency factor of 20 dB/decade. However, massive antenna technologies have several technical issues that need to be resolved, such as how to achieve accurate beamforming, how to circumvent radio frequency (RF) impairments and how to provide control signaling for mobility and connectivity over highly directive links. We envisage macro-assisted small cells (i.e., Phantom cells) as a potential solution to the issue of coverage for common broadcast signals such as those used to provide system information, paging, and synchronization. Specifically, the beamforming gains of massive MIMO small cells would not be available to common broadcast signals, which would inherently and severely limit coverage of small cells. A very attractive alternative is to operate the massive MIMO small cells in conjunction with the “Phantom cell” architecture, whereby the common broadcast signals and control-plane signaling are provided by the macro cells, which operate at lower frequency bands, as shown in Fig. 6.

Macro-assisted operation offers many additional benefits, including efficient beam and point discovery and dynamic association by means of multi-beam precoded reference signals (RS) to achieve seamless physical-layer mo-

Fig. 7 NOMA concept.

bility. Macro-assisted operation in conjunction with a hierarchical RS structure can be very attractive. It can significantly reduce the overhead and the number of RS sequences to be simultaneously monitored by each user. For standalone modes, it would also be necessary to consider different designs.

4.4 Non-Orthogonal Multiple Access (NOMA)

NOMA is an intra-cell multi-user multiplexing scheme that utilizes an additional new domain, i.e., the power domain, which is not sufficiently utilized in previous 2G (TDMA: Time Division Multiple Access), 3G (CDMA: Code Division Multiple Access), and 4G (OFDMA: Orthogonal Frequency Domain Multiple Access) systems. For downlink NOMA in Fig. 7, non-orthogonality is intentionally introduced via power-domain user multiplexing either in time/frequency/code domains. User de-multiplexing is obtained through the allocation of large power difference between paired users at the transmitter side and the application of successive interference cancellation (SIC) at the receiver side. The channel gain (e.g., path-loss and received SINR) difference among multiple users is translated into multiplexing gains through superposition of the transmit signals of multiple users with large channel gain (path loss) difference in the power-domain. Although power sharing reduces the power allocated to each single user, both the users with high and low channel gains benefit from being scheduled more often and being assigned more bandwidth [10]. As a result, both system capacity and fairness can be improved. Furthermore, NOMA can support more simultaneous connections in either uplink or downlink, which is suitable to address the challenges related to massive connectivity for MTC.

In addition, NOMA performs user multiplexing without relying on the knowledge of the transmitter of the instantaneous channel state information (CSI) of each user. It is expected, therefore, to achieve robust performance even in high mobility scenarios and for backhauling for moving networks. Also, NOMA captures well the evolution of processing capabilities of user devices, generally following Moore's law, by relying on more advanced receivers such as SIC. In fact, network-assisted interference cancellation and sup-

Table 1 Technology evolution from 4G to 5G.

Requirements	LTE (Release 8)	LTE-A (Release 10-12)	5G potential technologies
Higher system capacity & higher user data rate	Spectrum efficiency	- OFDM waveform - MIMO diversity & multiplexing - Frequency-domain scheduling	- Higher-order MIMO - Multiuser MIMO & coordinated multi-point transmission and reception (CoMP) - Advanced receiver
	Bandwidth extension	Flexible bandwidth (up to 20 MHz)	Carrier aggregation (up to 100 MHz)
	Network densification	-	- HetNet & C/U-plane split (Phantom cell) - Small cell discovery & on/off functionality
Reduced latency	1 ms TTI	-	- 0.1 ms-order TTI and very fast retransmissions - Enhanced random access
Massive device connectivity	-	- MTC enhancements - D2D communications	- Flexible waveform for various use cases and MTC - NOMA for small packet transmission - New network architecture
Energy saving & cost reduction	-	Small cell discovery & on/off functionality	- Efficient cell/beam discovery for higher frequency bands - Lean carrier design or more dynamic cell on/off

pression (NAICS) including SIC was studied and specified in LTE Release 12 [11]. So far, we studied both system-level performance of NOMA and its enabling technologies for both downlink and uplink [12], [13].

4.5 Technical Evolution

The evolution of key radio access technologies from LTE to 5G with their mapping to the 5G requirements is summarized in Table 1.

5. 5G Proof-of-Concept Activities

5.1 5G Real-Time Simulator

In DOCOMO, we started studies on 5G requirements, concept, and candidate technologies as early as 2010 [14], [15]. Since 2012, we have been developing a real-time simulator to evaluate and demonstrate the 5G concept and the gains of candidate radio access technologies under different setups and for various use cases.

In the real-time simulator of Shinjuku area in Tokyo of Fig. 8, a 7-macro cell model is assumed where each macro cell has three sectors. Vertical plane launch (VPL) ray tracing method is applied to emulate real propagation environment of Shinjuku area in Tokyo, Japan. The baseline system consists of LTE-based macro cells using 20 MHz bandwidth at 2 GHz. Each macro cell uses two transmit antennas. For evaluating the performance of network densification and higher frequency bands, 12 small cells are deployed per each macro cell sector. Each small cell uses 1 GHz bandwidth at 20 GHz. The number of transmit antennas per small cell is 64. Massive MIMO with rank adaptation and dynamic switching between single user and multi-user MIMO are applied to improve both cell coverage and spectrum efficiency. Hermitian precoding is applied in order to compensate for the path-loss by beamforming gains and also improve the spectrum efficiency of small cells. The number of receive antennas at the terminal is 4 at both 2 GHz and 20 GHz. Proportional fairness (PF) scheduling is applied

Fig. 8 DOCOMO's 5G real-time simulator (Use case: Dense urban area, Shinjuku, Tokyo).

Fig. 9 DOCOMO's 5G real-time simulator (Use case: Ultra-dense scenario, Stadium).

for multi-user scheduling. For 1 GHz bandwidth, the system and user throughputs are calculated over 20 MHz bandwidth then scaled to 1 GHz. Under these assumptions, the compound gains of introducing network densification using small cells (12 small cells per sector), bandwidth extension in higher frequency bands (1 GHz bandwidth at 20 GHz for small cells) and massive MIMO using very large number of antennas at small cells (64 antenna elements per small cell), on the top of the LTE macro cell layer, are demonstrated. We showed that more than a thousand-fold increase in the system capacity (compared to a macro-only LTE deployment using 20 MHz bandwidth at 2 GHz) can be achieved using 5G technologies. Furthermore, more than 90% of users are shown to be able to achieve data rates in excess of 1 Gbps in the simulated 5G network.

In addition, as another representative example of an ultra-dense deployment environment, the real-time simulator was extended to the stadium use case where a very large number of users are connected to the network as shown in Fig. 9. ITU outdoor UMi LOS (Line Of Sight) model is used to model the channel from the transmit antennas at small cells to the receive antennas at user terminal. Over an evaluation area of $142\text{ m} \times 71\text{ m}$ which has 14,000 users (population density of about 1.4 million/km^2), and 10% (i.e., 1,400) of users being assumed active, with LTE (20 MHz @ 2 GHz, 4×4 SU-MIMO) and 16 small cells arranged over a grid of $30\text{ m} \times 18\text{ m}$ on the ceiling of the stadium, the data rate of

Table 2 Noma testbed radio link parameters.

Carrier Frequency	3.9 GHz
Bandwidth per user	NOMA: 5.4 MHz, OFDMA: 2.7 MHz
Number of subcarriers	1200
Subcarrier spacing	15 kHz
Subframe length	1.0 ms
Symbol length	Effective data: 66.67 ms + CP: 4.69 ms
Modulation	QPSK, 16QAM, 64QAM
Antenna configuration	2×2 SU-MIMO (Open-loop MIMO: TM3)
Channel model	1-path Rayleigh fading
Encoding and decoding	Turbo coding (Constraint length: 4 bits) / Max-Log-MAP decoding (6 iterations)
Receiver	MMSE + SIC
Type of SIC receivers	Codeword level SIC (CWIC)

each user is a few Mbps, while for 5G (1 GHz @ 20 GHz, 128×4 SU-MIMO) with 64 small cells on the ceiling (on a grid of $15\text{ m} \times 9\text{ m}$), the user data rate can be boosted to more than 100 Mbps for more than 90% of the users.

5.2 5G Experimental Trials

Efforts to materialize our 5G concept through field experiments have also been taking place since a few years. In the following, we introduce some of our ongoing experiments for both lower and higher frequency bands.

➤ NOMA experiments at lower frequency bands

We developed a NOMA testbed in order to confirm NOMA performance with real SIC receiver taking into account hardware (RF) impairments such as EVM (error vector magnitude) and the number of quantization bits of analog/digital (A/D) converter, etc. The testbed parameters are summarized in Table 2 where the LTE Release 8 frame structure being adopted and channel estimation is based on CRS (Cell-specific reference signal). We assume we have two UEs. For MIMO transmission LTE TM (Transmission Mode)-3 is utilized for open-loop 2-by-2 single user MIMO transmission. At the transmitter side, for each UE data, Turbo encoding, data modulation and multiplication by precoding vector are applied, then the precoded signal of the two UEs is superposed according to a predefined power ratio ($\text{UE \#1:UE \#2} = P_1:P_2$, $P_1 + P_2 = 1.0$, $P_1 < P_2$), then goes through D/A converter before up conversion to the carrier frequency of 3.9 GHz and transmission from two antennas. At the receiver side, two receive antennas are used to receive the RF signal, which is down-converted then goes through a 16-bit A/D converter. At the cell-center UE (UE #1), CWIC (Codeword level SIC) is applied. After channel estimation based on CRS, UE #1 decodes the signal of UE #2 using Max-Log-MAP algorithm for turbo decoding (6 iterations), then re-encodes using turbo encoder and modulates in order to generate UE #2 signal replica, which is subtracted from UE #1 received signal. At the cell-edge UE (UE #2), no SIC is applied and the decoding is applied directly since the power ratio of UE #2 is higher than that of UE #1. Both UEs apply MMSE (Minimum mean squared error) based stream separation.

Fig. 10 NOMA test-bed.

Using the fading emulator, for simplicity we set each link of the 2-by-2 MIMO channel to a 1-path channel with maximum Doppler frequency of 0.15 Hz. In Fig. 10, we compared the user throughput of UE #1 (green color) with NOMA and SIC applied (29 Mbps) and with OFDMA applied (18 Mbps). For UE #1, NOMA gains compared to OFDMA are about 61%. These gains are obtained when the SNR of UE #1 is set to 33 dB and that of UE #2 to 0 dB while we set MCS (Modulation and Coding Scheme) of UE #1 to 64QAM (coding rate of 0.51), and UE #2 to QPSK (coding rate of 0.49). The transmit rank of UE #1 is set to 2 and that of UE #2 to 1. For UE #2 the cell-edge user (pink color), the same rate is set for both OFDMA and NOMA. NOMA gains are the result of enabling 3 layer transmission using a 2-by-2 MIMO channel and still being able to use twice the bandwidth compared to OFDMA.

➤ 10 Gbps transmission experiments at 11 GHz

In December 2012, the world first 10 Gbps packet transmission was successfully tested in the field in outdoor mobile environments using 8×16 MIMO-OFDM transmission system with 400 MHz bandwidth on a 11 GHz frequency band [16]. In the experiments, the transmission power per antenna was 25 dBm and 10 Gbps transmission was achieved by spatially multiplexing 8 streams using 64QAM, $R = 3/4$ for the modulation and coding scheme. The maximum number of iterations in turbo detection is set to two and for each iterative processing, there were six iterations for turbo decoding.

Figure 11 depicts the throughput performances which were calculated from the received signal measured in the outdoor transmission experiment by off-line processing over the experiment course in Ishigaki City, Japan. Between 10 m and 20 m, and 100 m and 120 m, a throughput greater than 10 Gbps is achieved successfully.

However, these field experiments do not include some key 5G technologies such as massive-antenna beamforming to boost coverage and overcome the amplifier power limitation [17], low latency radio interface design, control signaling and initial access technologies. Furthermore, much

Fig. 11 Measured throughput performance.

Fig. 12 Measurement routes in Tokyo area.

wider range of frequency bands, e.g. mm-wave, and wider bandwidths would need to be investigated for the 5G radio access.

➤ Channel measurements at higher frequency bands

Radio propagation characteristics have been mainly investigated in UHF and low-SHF bands. Therefore, the propagation characteristics in high-SHF (over 6 GHz) and EHF bands need to be clarified in order to enable a good design of the 5G radio access. Basically, the higher is the frequency, the larger is the path loss. Thus, to understand the fundamental frequency dependency of path loss in urban micro-cell (UMi) environment, we have conducted measurements in Tokyo, Japan as shown in Fig. 12.

We mounted the sleeve antennas as Base station (BS) antenna on the bucket of a bucket car and set to a height of 10 m, and then transmitted continuous waves (CWs) for six frequency bands (0.8, 2.2, 4.7, 8.45, 26, 37 GHz). On the Mobile station (MS) side, the six sleeve antennas were mounted on the roof top of a measurement wagon, and CWs for the six frequency bands were received while moving along the measurement routes.

Figure 13 shows the median values for each route and each frequency band. Path loss exponents for frequency are about 1.8 for LOS, 2.3 for NLOS1, 2.1 for NLOS2 and 2.2 for NLOS3. This means that frequency dependency is almost equal to that of free space.

In order to estimate the performance of massive MIMO and beam-forming in practical environments, it is essential

Fig. 13 Frequency dependency of path loss in UMi environment.

Fig. 14 Massive array antennas.

to clarify the temporal and spatial channel characteristics and model them. Thus, we developed a channel sounder with 20 GHz band and massive-array-antenna that have 256 antenna elements as shown in Fig. 14. By using this as BS antenna, the performance of massive-MIMO can be evaluated. Currently, we are verifying the performance of our sounder, and further measurements of the channel properties in practical environments are planned.

On the other hand, in order to model the propagation characteristics with high accuracy, propagation mechanisms need to be well understood. Figure 15 shows the main phenomena which we see as key for higher frequency propagation. Characteristics of rain attenuation and vegetation loss have been already clarified in the high SHF and EHF bands [18], [19].

However, the shadowing effect (or loss) of human body and the scattering effect on rough surface have not yet been understood well enough [20]. This remains as one of our future works.

➤ Other Ongoing Experimental trials

Additional experimental trials of emerging 5G mobile technologies are also taking place in collaboration with other mobile technology vendors [21], [22]. A wide range of technologies is under investigation as summarized in Fig. 16. The technologies under trial include new candidate waveforms, coordination of ultra-dense small cells, radio interface design and massive MIMO [23]–[27].

Fig. 15 Key propagation phenomena at higher frequency bands.

6. Conclusion

5G will need to meet very challenging requirements and cover a wide range of services and scenarios. The evolution path and the system concept of the 5G radio access are quite important for the successful migration from LTE-Advanced to 5G and the effective integration of key radio access technologies. In the proposed evolution concept toward 5G, we emphasized on the importance of the efficient integration of lower and higher frequency bands to meet the future challenges. Also, we explained our views on New RAT and its relationship with 5G radio access. In addition, we introduced a set of 5G radio access technologies identified as the most promising for improving system performance in both lower and higher frequency bands. Our ongoing proof-of-concept activities, ranging from 5G real time simulator to experimental trials and channel measurements are also explained. Although not covered in this paper, the network architecture should also support the evolution toward 5G [28]. In particular, built-in scalability and flexibility of the core network are required to support a wider range of quality of services and a massive number of nodes and devices.

Currently, 5G related discussions are ongoing in the ITU-R Study Group 5 Working Party 5D (WP 5D), such as the development of a new Recommendation on “IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond”. Studies on 5G have gained interest worldwide as also evidenced by the acceleration of efforts by governmental entities and several research bodies from both academia and industry, e.g., METIS project in Europe, the ARIB 2020 and Beyond Ad Hoc (20B AH) group and 5G Mobile Communications Promotion Forum (5GMF) in Japan, NGMN alliance, and other initiatives. In 3GPP, standardization of 5G is expected to gain real momentum starting from LTE Release 14 and 15. In particular, in order to meet 5G first commercialization by 2020, 5G discussions need to be started by the end of 2015 in order to enable the specification of 5G initial functionalities by the end of 2018. The standardization of more 5G functionalities are to be continued later on taking into account the newly identified frequency bands at the world radio conference of 2019 (WRC19).

Fig. 16 5G experimental trials. (MA: multiple access, BF: beamforming, SC: single carrier).

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