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Radio Access Technologies for Fifth Generation Mobile Communications System: Review of Recent Research and Developments in Japan

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SUMMARY As the demand for higher transmission rates and spectral efficiency is steadily increasing, the research and development of novel mobile communication systems has gained momentum. This paper focuses on providing a comprehensive survey of research and development activities on fifth generation mobile communication systems in Japan. We try to survey a vast area of wireless communication systems and the developments that led to future 5G systems.

key words: *fifth generation mobile communication systems, higher frequency band, massive MIMO, C-Plane/U-Plane splitting, C-RAN*

1. Introduction

With the tremendous growth in wireless data traffic and mobile services, fifth generation (5G) mobile communication systems have gained considerable interest from academia, industry, and standards bodies. Among various technological aspects related to 5G mobile communication systems, a survey article [1] covers research and development activities for 5G reported in the IEICE technical committee on radio communication systems (RCS), in which nearly 400 papers are presented every year. The IEICE RCS offers academic open discussion to 5G researchers in operators, vendors, and universities in Japan. Unlike IEEE Standards Association, IEICE RCS does not have standardization activity. In this survey paper, we expand its scope to include major published papers in Japan. And also, references are updated.

The traffic increasing rate of the mobile communication systems in Japan is around 50% per year [2]. This increasing rate leads to 1000 folded traffic within 20 years. Therefore, one of the main objectives of 5G mobile communication systems should, not only offer more traffic capacity, but also support emerging applications described in Sect. 2.

As the key for the success of 5G, most of the researchers emphasize the technical aspect of the use of higher frequency bands. This is the most important issue to be covered by R&D activities. Throughout this article, we describe in-depth survey of recent progress on cutting-edge technologies intended to contribute toward 5G, especially the technologies for higher frequency bands are highlighted.

The remainder of this paper is organized as follows. We first present definition of 5G in Sect. 2. Section 3 covers heterogeneous networks and radio access network architectures. Section 4 introduces technical studies for 5G frequency bands. Section 5 describes multi-antenna technologies. Advanced modulation and multiple access schemes are presented in Sect. 6. In Sect. 7, challenges to further enhance coverage and services are given. Section 8 summarizes proof-of-concept activities. Finally, Sect. 9 presents the conclusions of this paper.

2. Definition of 5G

Currently, the service rollout of long term evolution (LTE)-Advanced "true 4G" is being underway to further enhance LTE performance. However, anticipated challenges of the next decade (2020s) are so tremendous and diverse that there is a vastly increased need for a 5G mobile communications system with even further enhanced capabilities and new functionalities.

5G use cases, requirements, concept, and radio access technologies (RATs) are being discussed by many operators and vendors worldwide [3]–[6], and especially in Japan, "Association of Radio Industries and Businesses (ARIB) 2020 and Beyond Ad Hoc" organization has summarized them [7], [8]. In [8], 5G will enhance socio-economic satisfaction for existing services. 5G provides more efficient and safer transportation, home security and remote control of

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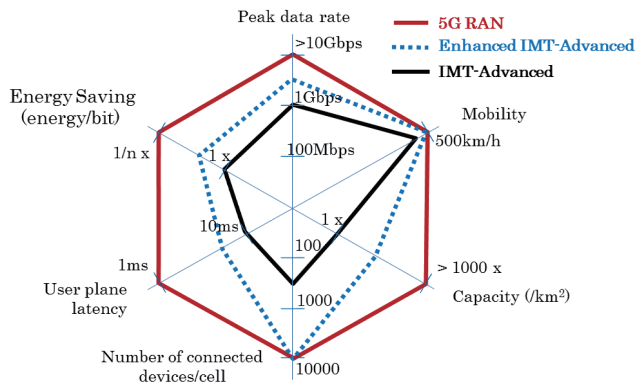

Fig. 1 Maximum system capabilities of 5G RAN [7].

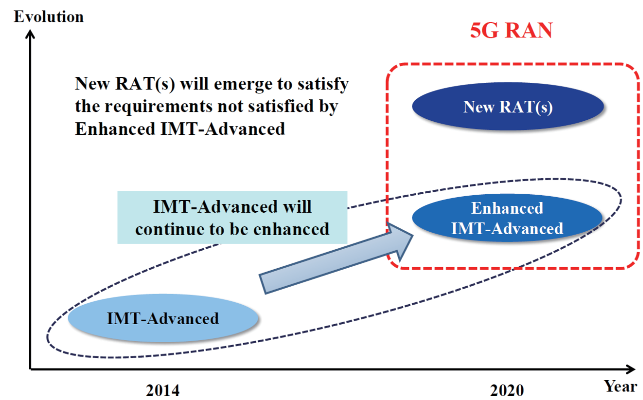

Fig. 2 Definition of 5G [7].

consumer electronics, collision avoidance and rescue from distress and accidents, and prediction technology for disaster using massive sensors. These services support machine type communications (MTC) and Internet of things (IoT) with massive connectivity and ultra reliability. Distance learning, virtual experience, remote medical examination, and richer contents such as multiuser ultra-high-definition teleconferences, videos, music, and books are also experienced by users in 5G. In addition to the enhancement of user satisfaction for existing services, 5G induces completely new use cases. Smart citizen services realize knowledge creation and activity support. Shared experience provides virtual and perceptual touches with fidelity, reality and tactile sense. Automatic information sharing in proximity assists communication between unacquainted persons. In the 5G era, such new applications and services are expected to emerge to satisfy diverse needs and requirements of users. In [7]and [8], 5G radio access network (RAN) needs to provide significant performance gains in system capacity (> 1000×), peak data rates (> 10 Gbps), the number of simultaneously connected devices, and latency as shown in Fig. 1. 5G RAN consists of New RAT(s) and Enhanced IMT-Advanced (LTE-Advanced), and New RAT(s) will emerge to satisfy the requirements not satisfied by Enhanced IMT-Advanced that is a further enhancement of IMT-Advanced as shown in Fig. 2.

In order to ensure a sustainable system evolution, it is crucial to extend the spectrum usage to the frequency bands higher than currently used frequency bands. To this end, 5G will efficiently integrate new spectrum bands over a wide range of frequency bands. One example of 5G promising technologies for the integration of lower and higher frequency bands is control (C)-plane and user data (U)-plane split over the radio access [3], [9]. For exploitation of higher frequency bands such as centimeter wave and millimeter wave, massive MIMO, which employs very large number of antenna elements, is one promising technology for the 5G RAN [3]–[5], [7], [9].

On the other hand, [10] presented the Ministry's efforts along with 'The 5G Roadmap' contained in the interim report of 'Radio Policy Vision Council' toward realizing 5G around 2020. Note that 5G activities in "2020 and Beyond Ad Hoc" are continued by "Fifth Generation Mobile Communications Promotion Forum (5GMF)" [2].

3. 5G Architecture

3.1 Heterogeneous Network

A promising concept for the 5G RAN architecture is introduced [5], [11]–[15]. As shown in Fig. 3, 5G RAN is generally perceived as a heterogeneous network employing different RATs, that combines with Enhanced IMT-Advanced using the existing cellular frequency bands and New RAT(s) using higher frequency bands with wider bandwidth as an enabler of more advanced capabilities. The anticipated future traffic growth is so tremendous that, besides further spectrum efficiency enhancements, there is a vastly increased need for further network densification with small cells, and utilization of higher and wider frequency bands. Figure 4 shows these promising approaches for increasing network capacity introduced in [11]. The rest of this section mainly focuses on heterogeneous network structure with different cell sizes and different frequency bands. The technical studies for spectrum expansion with higher and wider frequency bands are introduced in Sect. 4. Those of spectrum efficiency improvement, such as multi-antenna technologies, advanced modulation and multiple access schemes, are introduced in Sect. 5 and Sect. 6, respectively.

From the view points of increasing network capacity and improving Quality of Experience (QoE), network densification based on heterogeneous cell deployment using different cell sizes, in which small-cell base stations (BSs) with a low transmission power are overlaid at the hot spot area (local area) of a wide area covered by macro-cell BS with a high transmission power, is a very important approach for 5G RAN as well as 4G RAN i.e., LTE-Advanced. This is because the heterogeneous cell deployment enables network densification without the change of the macro-cell coverage. Note that co-channel inter-cell interference (ICI) from macro cells to small cells is unavoidable when the same car-

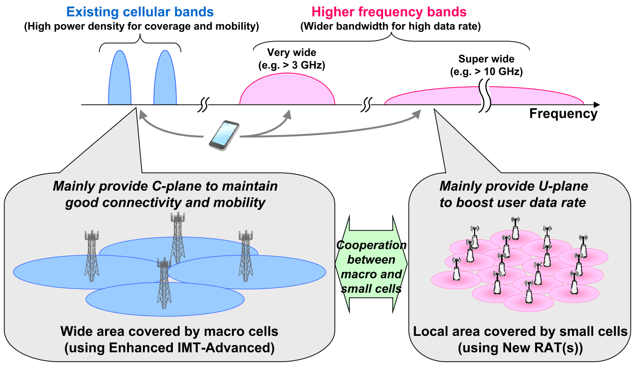

Fig. 3 A promising concept of heterogeneous network for 5G RAN [11].

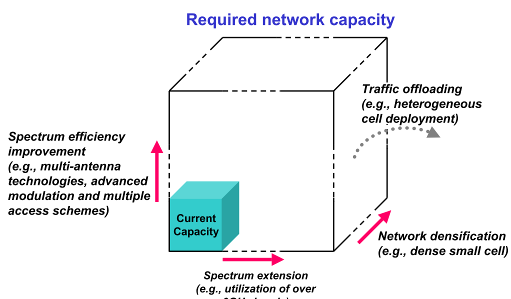

Fig. 4 Promising approaches for increasing network capacity [11].

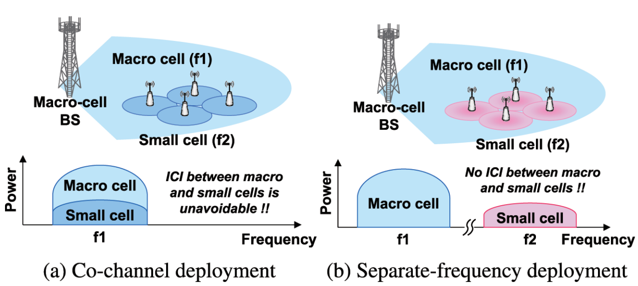

Fig. 5 Heterogeneous cell deployment scenarios [17].

rier frequency is applied between macro and small cells, as shown in Fig. 5(a). On the other hand, when the different carrier frequencies are applied between them, the ICI is easily avoidable, as shown in Fig. 5(b).

In the heterogeneous cell deployment, however, there is a lack of connectivity and mobility in small cell area, when small cells using higher frequency bands are high-densely overlaid over existing macro cells in lower frequency bands as shown in Fig. 5(b). In order to solve this issue, a new network concept with C-plane/U-plane split configuration, called Phantom-cell, is also proposed [11]. Figure 6 shows the concept of Phantom-cell using C-plane/U-plane split. The Phantom-cell concept is very reasonable for the following reasons. In the Phantom-cell concept, the C-plane is mainly provided by macro-cells in a lower frequency band to maintain good connectivity and mobility. On the other hand, U-plane is mainly provided by small-cells using higher frequency bands with wider bandwidth in order

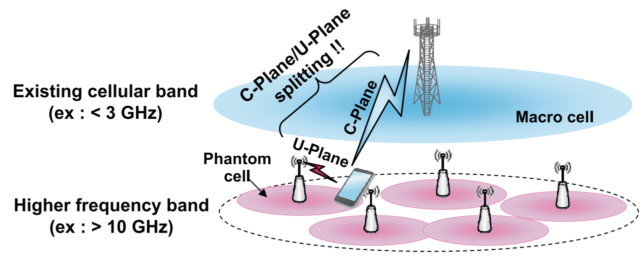

Fig. 6 C-plane / U-plane split and Phantom cell [11].

to boost the user data rate. Therefore, it is a promising approach for 5G RAN developments to establish heterogeneous network technologies using different RATs and different cell sizes with different carrier frequency based on C-plane/U-plane split. A development of heterogeneous network technologies based on C-plane/U-plane split is also introduced in order to realize 5G RAN [12].

In heterogeneous networks for 5G RAN using a huge number of small cells, efficient small-cell operation techniques, such as ICI mitigation among small cells, cell-discovery, cell-selection, and self-organizing networks (SON), are also very important. Since the highly dense small-cells increase residual ICI among small-cells due to common signals constantly transmitted from all BSs, the residual ICI degrades the user throughput. In order to solve this issue, the concept of small-cell On/Off operation, in which small-cell BSs without user-data traffic stop most of common signals so as to decrease the residual ICI, is introduced [16], [17]. The small-cell On/Off operation is also effective to reduce power consumption for heterogeneous networks with dense small-cells. A highly energy-efficient small-cell BS On/Off switching algorithm with the aim of balancing traffic load and energy consumption is proposed [18]. On the other hand, the performance degradation problem on small-cell discovery in high-density small-cell environments is revealed [19], [20], and a small-cell discovery improvement scheme is introduced when applying the small-cell On/Off operation in the case that small-cell BSs synchronize to macro-cell BSs in time domain [17], [21]. SON algorithms for heterogeneous cell deployment scenarios are proposed in order to operate high-density small cells efficiently [22], [23]. In [22] and [23], automatic neighbor relation (ANR), mobility robust optimization (MRO), and coverage and capacity optimization (CCO) are introduced.

3.2 RAN Architecture

In order to reduce the operating cost of heterogeneous network using a huge number of small cells, use of a centralized- (or cloud-) RAN (C-RAN) architecture has attracted attention [14]. Figure 7 shows the typical C-RAN architecture. C-RAN consists of a center unit (CU), fronthaul links and remote radio units (RRUs). CU carries out the layer 1, layer 2 and layer 3 processing. Specifically, layer 1 processing includes digital baseband modulation. Layer 2 is composed of media access control (MAC), radio link con-

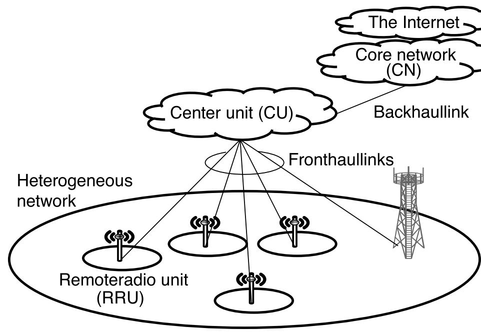

Fig. 7 Typical C-RAN architecture.

trol (RLC) and packet data convergence protocol (PDCP) layer. Layer 3 is composed of radio resource control (RRC) layer. RRU transmits/receives radio signals. Since CU and RRUs work in close cooperation, it becomes easy to introduce new technologies to enhance network capability. One of the new technologies is coordinated multi point transmission/reception (CoMP). C-RAN architecture and CoMP are very compatible because the information for the coordinated cells can be treated in CU. Coordinated beamforming (CB), which is one of CoMP schemes, was studied for ultra-high-density small cell [24]. In CB, precoding weights for transmission antennas are selected so as to avoid ICI. By applying CB, it was possible to achieve network capacity in proportion to the ultra-high-density of small cell.

In C-RAN architecture, fronthaul links require higher data rate and lower latency as radio data rate is higher [25]. In order to address these requirements, there are two approaches. One approach is to enhance data compression scheme for fronthaul links; the other approach is to revise C-RAN architecture to alleviate the requirements of fronthaul links. As the former approach, an enhanced data compression scheme was proposed [26]. The data compression scheme minimized the performance degradation with reducing the latency increase due to data compression/extension. As the latter approach, layer2(L2)-C-RAN architecture was proposed [27]. In L2-C-RAN architecture, the function of processing on layer1 is transferred from CU to RRU.

Similar to fronthaul links, an enhancement of backhaul links was proposed for group mobility issue [28]. Group mobility issue is performance degradation due to concentration of control load. The proposal is to introduce moving cells, which are installed inside the moving object such as bus and train, and to apply massive MIMO to backhaul links. It was reported that the proposal was feasible in terms of backhaul link capacity and amount of control signal.

4. Technical Studies for 5G Frequency Bands

In order to provide throughput of over 10 Gbps, in addition to 4–6 GHz bands, new bands over 6 GHz, referred to as higher frequency bands, are required. Technical problems and solutions related to usage of the higher frequency bands are described in this section.

For 5G, wide frequency bands from 4 GHz to 100 GHz have been well studied. In [29], low-SHF band (–8.4 GHz) are evaluated with the time-spatial propagation model. In [30], high-SHF band (6–30 GHz) and EHF band (30–60 GHz) are introduced as promising bands, and vegetation loss, human body shadowing, and scattering effect on rough surface are some of loss inducing elements in the aforementioned bands. On MIMO aspects, a multi-path angular spread is receiving much more attention and results from several measurement campaigns demonstrate rich multipath angular spread and effectiveness of MIMO transmission in the following conditions: outdoor-to-indoor in 2.2 GHz [31], indoor measurements in 3.35 GHz [32], outdoor measurements in 11 GHz [33] and 44 GHz [34].

In higher frequency bands, high gain antennas with high directivity are effective to overcome the severe path loss effect. Massive MIMO technology is a promising one mentioned in Sect. 5.

Also, rain attenuation in higher frequency bands becomes much severe and its effects are well evaluated [35]. In addition, studies on user's hand shadowing effect against the mobile terminal are other issues [36]. [37] evaluates performance of the prototype with two 4-elements array antennas in order to avoid this effect. Furthermore, [38] shows the effectiveness with an antenna-sharing cooperation among mobile terminals, which can multiply the number of antenna elements virtually.

Thanks to these research activities, a cost-effective base station with large number of antennas is realized. Moreover, the distance between the base station and the mobile terminal can be extended to several tens of meters and more. As a result, an environmentally friendly 5G system in higher frequency bands can be realized with the reduced number of base stations.

5. Multi-Antenna Technologies

Multi-antenna technologies are mandatory technologies in 5G wireless systems to increase spectral efficiency. Since frequency resource is highly limited, spectral efficiency is expected to be mainly improved by spatial reuse.

Multi-user multi-input multi-output (MU-MIMO) can achieve MIMO transmission by regarding the multiple users as the virtual large scale array antenna system. Nonlinear precoding MU-MIMO is promising to increase system capacity [39], [40]. However, the transmission performance seriously degrades due to inter-user-interference (IUI) caused by low channel state information (CSI) accuracy. [41] proposes IUI suppression scheme for nonlinear MU-MIMO. In the receiver, perturbation vector is temporarily estimated through spatial linear filtering and then maximum likelihood detection (MLD) with sphere decoding is applied for the filtered signal space. [42] proposes THP scheme minimizing the influence of noise enhancement at the receivers by placing the diagonal weighted filters at both transmitter side and receiver side with square root.

Beamforming using adaptive antenna array (AAA) is a significant technique for flexible cell design. Various beam-controlling technologies including beam search [43], beam transition [44], and coordinated beamforming [24] are studied. Full-dimensional MIMO (FD-MIMO), also known as three-dimensional MIMO (3D-MIMO) or vertical MIMO, is a new beamforming paradigm in cellular systems. Spatial multiplexing gains will be obtained by exploiting not only horizontal dimension but also the vertical dimension. [45] reports that the throughput of FD-MIMO is 30% larger than the legacy MIMO in cumulative distribution function (CDF) 50% from the field experiment for 4–by–2 MU–MIMO transmission. Link-adaptable non-linear precoder for FD-MIMO is studied in [46].

Massive MIMO is also a key technology for 5G wireless systems. Base station with huge number of transmit/receive antennas will realize sharper beamforming, wider coverage expansion, and higher order spatial division multiplexing. With the massive MIMO technologies, [47] and [48] investigate a novel mobile communication system. [49] proposes a massive MIMO system applied in line-of-sight (LOS) link to establish a wireless entrance MU-MIMO system. Since direct wave is dominant and stable in LOS environment, coherent combining of desired signal is achieved without frequent CSI update. IUI is fortunately suppressed without null-steering since interference waves are randomly combined thanks to massive antennas property. Another efficient IUI suppression technique with massive MIMO is null-space extension [50], which uses some spatial degrees of freedom to expand the dimension of the null space with current and past CSIs. The complexity of MIMO algorithms grows significantly with the number of antennas. Cost-effective solutions for base stations with large number of antenna elements are also important research topics: hybrid massive MIMO systems with fixed and adaptive analog beams are investigated in [44], [51], [52], respectively, which provide beam-space MIMO processing with the number of spatial-multiplexing streams. Other practical issue for massive MIMO is computational complexity for detection at the receiver. Belief propagation (BP) algorithm based signal detection technique [53], that passes likelihood between antenna nodes, is an attractive approach to reduce the complexity proportional to the second power of the number of antenna elements. Antenna calibration regarding the difference of each radio frequency (RF) circuit on antenna is the other practical issue for realizing massive MIMO. [54] and [55] propose antenna calibration schemes for implicit feedback downlink beamforming exploiting uplink CSI. On the other hand [56] proposes an antenna calibration scheme for explicit feedback beamforming.

Mobile station like small smart-phone may have a limitation for the number of installed antennas due to its form factor. Overloaded MIMO, that permits the more signal streams multiplexing than receive antennas, is an approach to achieve much higher speed transmission for downlink without huge number of reception antennas. Joint detection and decoding for repetition-coded overloaded MIMO-OFDM is proposed in [57]. The transmitted signal stream is encoded by a repetition code and the spatially multiplexed signals are jointly decoded after joint MLD in the receiver. Various receiver structures with idea of virtual channels for overloaded MIMO is introduced in [58]. It achieves superior performance to MIMO linear detectors with much lower computational complexity than MLD receivers.

MIMO transmission can be jointly used with other transmission technologies. [59] and [60] evaluated MIMO with non-orthogonal multiple access technology mentioned in Sect. 6.

6. Advanced Modulation and Multiple Access Schemes

Considering 5G, further enhancement to achieve significant gains in capacity and system throughput performance is a high priority requirement. Non-orthogonal multiple access (NOMA) has been attracting much attention as a candidate multiple access scheme for future radio access network systems. In NOMA, multiple signals for different users are superimposed before transmission on common resources. At the receiver, successive interference cancellation (SIC) is applied in order to reduce the inter-user interference caused by the non-orthogonally multiplexing. NOMA can be applied to both downlink and uplink [61]–[65].

In NOMA, the signals are assigned different power levels to facilitate reception at the receiver and therefore, not only channel dependent scheduling, which is commonly used in 4G, but also pairing of multiplexed users and multi-user power allocation should also be considered for further enhancement of user throughput. For downlink, the performance of NOMA using various user pairing and multi-user power allocation schemes are studied in [61], [62]. In [62], pre-defined user grouping and fixed per-group power allocation is proposed to reduce the overhead associated with power allocation signaling while maintaining a hefty portion of NOMA gains. The complexity reduced proportional fair scheduling method for NOMA is proposed in [63]. It was shown that by searching only the user combinations that are worth non-orthogonally-multiplexing, the number of the user combinations to be searched can be significantly reduced while keeping almost identical average and cell-edge throughput performance compared with conventional exhaustive search method. Similar to downlink NOMA, resource allocation, user grouping, and power allocation issues are studied in [64], [65] for uplink single-carrier frequency division multiple access (SC-FDMA).

NOMA is also beneficial for the reliable readiness communication, which is one of key applications of 5G. By simultaneously transmitting own message by spectrum sharing on the basis of NOMA from plural nodes, the latency can be shorter. Resource management methods are proposed in [66] to suppress the impact of interference.

The researches on NOMA above are mostly based on traditional orthogonal frequency division multiplexing (OFDM) waveform design. On the other hand, new waveform has also been attracting much attention in recent year as one of the key enabling technologies for 5G. New waveform research is also undergoing a paradigm shift from orthogonal to non-orthogonal design approach [67]. Faster-than-Nyquist (FTN) transmission and filter bank multi carrier (FBMC) transmission are considered as examples of candidate non-orthogonal transmission schemes for future systems that could improve the spectrum efficiency by increasing the data rate. For both FTN and FBMC, channel estimation is one of the key technical issues as classical channel estimation schemes used for OFDM cannot be applied in a straightforward manner due to presence of interference caused by the relaxation of the orthogonality. Channel estimation methods are studied in [68] for FTN and in [69] for FBMC.

A well-known simultaneous transmission and reception (STR) or full duplex transmission can also enhance the spectral efficiency (theoretically double the spectral efficiency), and is expected to be realized in 5G. An STR scheme utilizing MIMO spatial modulation, in which the unselected antenna is used as a reception antenna of STR, is proposed in [70]. Development of self-interference cancellation technique is proposed in [71].

7. Challenges to Further Enhance Coverage and Services

In 5G system, it is considered that technologies which are not currently implemented are to be developed and to be included as much as possible. Some topics of these technologies are introduced in this section.

The proximity service, defined as a concept to improve user experiences and resource utilization by taking advantage of users' proximity, becomes more important in recent mobile communications. By the proximity communication using location information, the large effects such as coverage expansion, latency reduction, spectral efficiency improvement, and provision of social networking service, are expected. Device to device (D2D) communication is quite suitable for those proximity services and has already been discussed in 3GPP standardization. Because it is planned that the cellular uplink resource is shared with the D2D link, the interference mitigation between cellular uplink and D2D link, and between D2D links is essential. To realize it, a random resource allocation scheme to suppress the interference for D2D throughput enhancement is proposed [72]. Furthermore, a transmit power control scheme with interference-aware adaptive transmission modes in D2D is proposed and its improvement on system capacity is shown [73]. Before D2D communication, the D2D discovery process is always needed, and it is shown that the discovery resource enhancement and the intermittent transmission from D2D terminal improves the discovery performance [74]. The demands for D2D communication is growing and the commercial use will be started in the initial stage of 5G. This technology is connected to machine to machine (M2M) communication of Internet of things (IoT). M2M is a rather genetic term in which a machine automatically connects communication networks each other, and is also called as machine type communication (MTC). In general, M2M includes D2D. In 5G M2M communications, there are some requirements such as massive connectivity, eco M2M, reliable M2M, that include huge demands of home smart meter and autonomous driving.

On the other hand, the utilization of satellite communication is also considered in 5G. To deploy services in isolated areas such as mountainous region and ocean, the satellite communication is efficient. In addition, when the terrestrial network is down by a natural disaster, the satellite communication becomes quite important communication method. Because of this effectiveness and importance, the cooperation of terrestrial and satellite systems has been discussed in ITU-R standardization [75]. For the disaster case, a simultaneous short-message communication with million terminals based on spread spectrum - code division multiple access (SS-CDMA) using satellite is proposed [76]. There are two schemes for terrestrial-satellite cooperation, indirect and direct communications. In the indirect scheme, a terrestrial base station has the satellite backhaul and forwards the connection to terminals [77]. In the direct scheme, the terrestrial terminal directly connects to the satellite basestation [78]. In addition to that, there are two types in the direct scheme, the common wireless interface between terrestrial and satellite systems, and the different interfaces with dual mode chip in mobile terminal. If the satellite system can synchronize the terrestrial system, the satellite cell can be accommodated as a super macro cell of 5G, and the 5G system will be further evolved.

8. Proof of Concept

Several proof-of-concept activities and investigations on the 5G concept and RATs in Japan have been introduced [34], [79]–[83], [84] and are summarized in Table 1. In [79], the world first 10 Gbps transmission experiment was reported in outdoor mobile environments using 8×16 MIMO system with 400 MHz bandwidth in 11 GHz frequency band. Furthermore, [80] presented the experimental trial and its concept for a new radio interface design in 15 GHz frequency band, and [81] investigated other experimental trial for the 5G millimeter-wave radio access with super wideband single carrier (SC) transmission. In addition, to verify the potential of massive MIMO beamforming in sub-6 GHz frequency band, [82] described a fundamental transmission experiment using time-domain beamforming by over-100 antenna elements. [83] introduced preliminary results of the 28 GHz band experimental trial using analog RF beam-

Table 1 5G proof-of-concept activities.

Ref. No.	Technical issues	Frequency (bandwidth)
[3], [79]	Super high bit rate MIMO	11 GHz (400 MHz)
[80] , [84]	Radio interface design	15 GHz (400 MHz)
[81] , [84]	Millimeter-wave SC radio access	73 GHz (1 GHz)
[82]	Time-domain beamforming	5 GHz (100 MHz)
[83]	RF beamforming in BS and UE	28 GHz (800 MHz)
[34]	Hybrid beamforming	44 GHz (100 MHz)

forming in both the BS and user equipment (UE), and [34] showed the potential of massive MIMO hybrid (analog-digital) beamforming for 5G ultra high capacity by exploiting 44 GHz band propagation measurement results. [84] also described massive MIMO experimental trials briefly.

9. Conclusion

With the increasing demand for mobile data communications, higher frequency bands are gaining importance. This paper surveys recent research and development activities in Japan related to 5G mobile communication systems. Those are creating new paths to "5G World" especially on higher frequency bands. As the result of sophisticated integration of these innovative technologies, 5G systems will provide pleasant services for users with unprecedented capacity, higher throughput, and less latency.

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