DOCOMO 5G White Paper

5G Radio Access: Requirements, Concept and Technologies

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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. Currently, many operators worldwide are deploying Long Term Evolution (LTE) to offer faster access with lower latency and higher efficiency than its predecessors 3G and 3.5G. LTE-Advanced, which is an evolution of LTE and a "true 4G" mobile broadband, is under development and its initial service rollout is expected by 2015. Amid such a situation, the anticipated challenges of the future are so tremendous that there is a vastly increased need for a new mobile communications system with even further enhanced capabilities, namely a fifth generation (5G) system. Envisioning the development of a 5G system, NTT DOCOMO (hereinafter referred to as "DOCOMO") started studies on future radio access (FRA) as early as 2010. The aim is to identify the future needs and requirements of 2020 and beyond and identify the right system concept and radio access technologies to address them. Today, several experimental trials with world-leading vendors are ongoing. The goal is to provide an initial 5G deployment in time for the Tokyo 2020 Olympic Games. This document provides DOCOMO's views on the drivers and requirements, the evolution concept, and potential candidate solutions for realizing DOCOMO's 5G radio access targeting 2020 and beyond.

2. General Trends and Requirements

2.1. Recent market trends and mobile services

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, smartphones 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 will become even more pronounced in the future. The following are the two most significant trends in mobile services as also illustrated in Figure 1.

(1) Everything will be connected by wireless to enable monitoring and collection of information and control of devices. Examples of emerging services include remote monitoring and real-time control of a wide variety of devices, which support machine-to-machine (M2M) services and Internet of things (IoT), such as connected cars, connected homes, moving robots and sensors.

(2) Wireless services will become more extensive and enriched through richer content being delivered in real-time and with safety and lifeline communications being ensured. Examples of such emerging services (which may use new types of mobile devices) include high resolution video streaming (4K), tactile Internet, media rich social network services, augmented reality, and road safety.

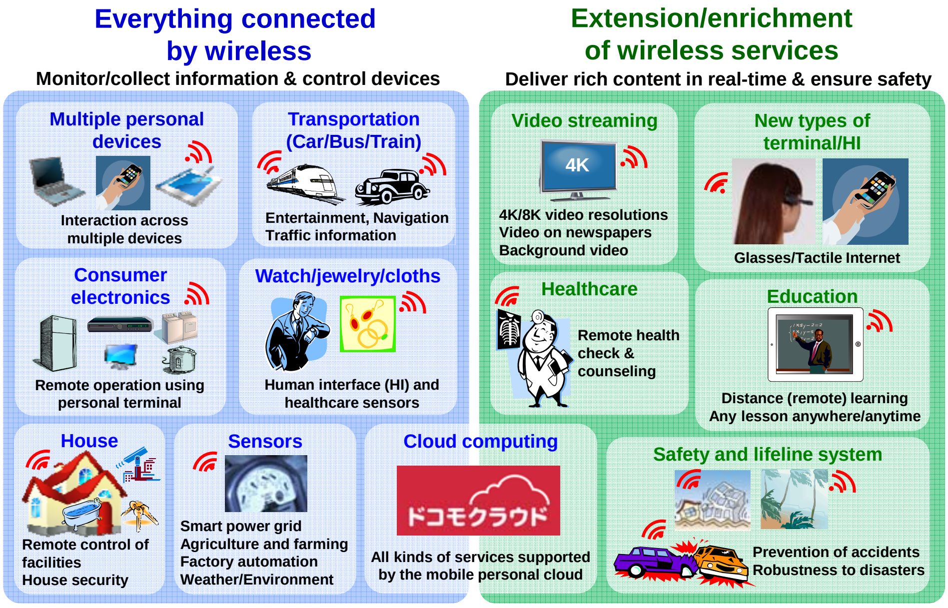


Figure 1 – Major market/service trends toward 2020 and beyond.

Given these trends, the traffic growths observed currently on the mobile operators' networks will continue in the years to come. The mobile data traffic grew 45 times from 2008 to 2013 and is projected by many to grow 24 times from 2010 to 2015 [1][2]. The latter corresponds to a compound annual growth rate (CAGR) of almost 1.9. On DOCOMO network in Japan, mobile data traffic almost doubled during 2010 and is expected to increase by a factor of 12 from 2011 to 2015 [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.

On the other hand, services will be more diversified in the future. As shown in Figure 1, a wide range of services will be provided over the mobile network, ranging from small packet services (e.g., low data rate M2M services and real-time remote control) to richer content services (e.g., high-definition video streaming, augmented reality (AR), and tactile internet). In addition, data traffic over today's networks is not evenly distributed; it is becoming extremely high in super dense areas (hot spot areas), such as stations, shopping malls, and stadiums where large number of users generates huge volumes of traffic. Therefore, besides the huge growth of total traffic, there will be more variations in the traffic volume, depending on the time, location, application, and type of device.

2.2. 5G requirements

Despite the advances made in the design and evolution of 4G cellular networks, new market trends are imposing unprecedentedly challenging requirements which are driving us further to the necessity of a 5G mobile network. The high-level targets most relevant to DOCOMO 5G are summarized in Figure 2.

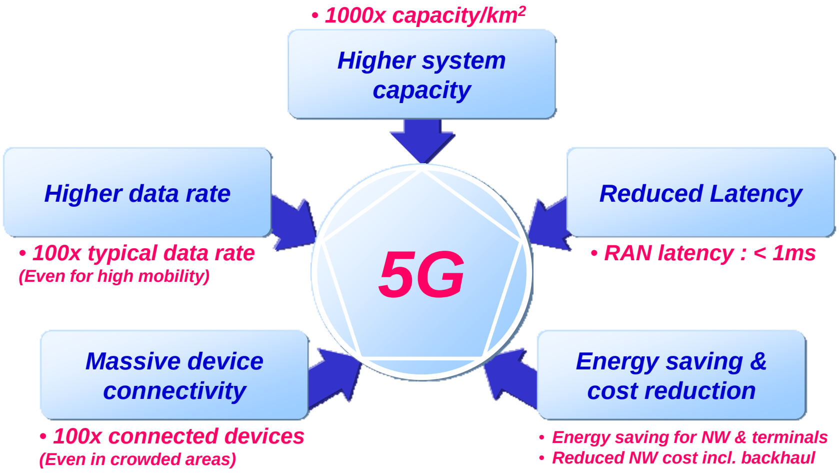


Figure 2 – DOCOMO's 5G targets.

- **Higher system capacity:** 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 future networks. Our target is to achieve a 1000-fold system capacity per km^2 compared to LTE.

- **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 DOCOMO sets here is a 10-fold improvement in peak data rate and 100-fold increase in user-experienced throughput, targeting 1Gbps experienced user throughput everywhere. Higher peak data rates will also become important for new scenarios such as mobile backhauling for 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 and more machine type devices for IoT. Our target is to achieve a 100-fold increase in the number of simultaneously connected users compared to LTE.

- **Reduced RAN latency:** 5G has to provide not only higher data rate, but also a user-plane latency of less than 1ms over the radio access network (RAN), a large leap from LTE's 5ms. 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.

- **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 environments and services simultaneously. For example, the spectrum to be used will be more diverse, ranging from low to high and narrow to wide frequency bands. In addition, the future network will have an increased density through development of more small cells. While these requirements are not easy to quantify, they should be factored in as much as possible throughout the whole design aspects of the 5G system.

3. 5G Evolution Concept

3.1. Directions of evolution

5G, compared to 4G, needs to be more massive and scalable to enable a wider range of scenarios and services. In particular, the 5G radio access needs to provide significant performance gains in system capacity and user data rates. Specifically, it is necessary to meet the very challenging targets of 1000-fold system capacity per km^2 and Gbps-order user-experienced data rate. This necessitates the pursuit of not a single but a set of directions of evolution for radio access technologies. Figure 3 illustrates the three directions of technological evolution DOCOMO has identified necessary, which are collectively called "The Cube". This includes: spectrum efficiency, spectrum extension, and network densification. All of which will be of great importance in the design of the 5G system. In particular, the requirements of significant enhancements in system capacity and user-experienced data rates can only be met by massive improvements in all these three directions. Additionally, traffic offloading to other systems such as WiFi is also expected to continue in the future. The key radio access technologies identified for the directions of evolution toward 5G will be explained in Chapter 4.

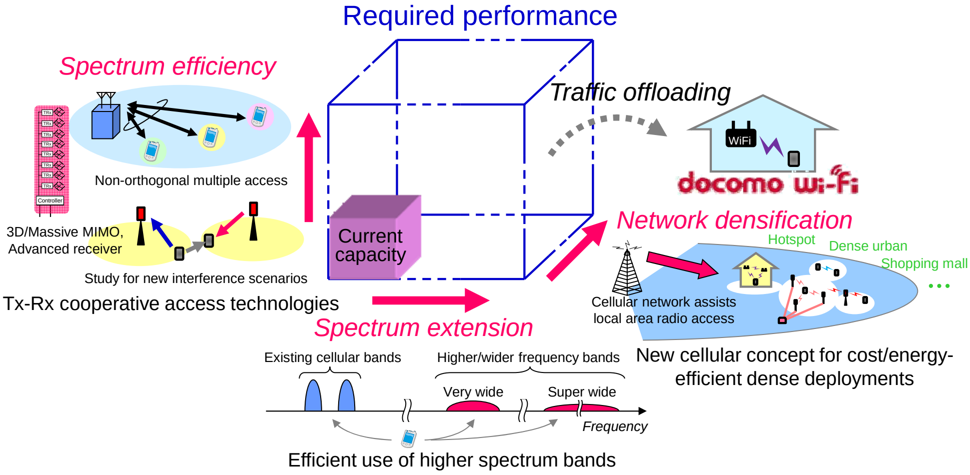
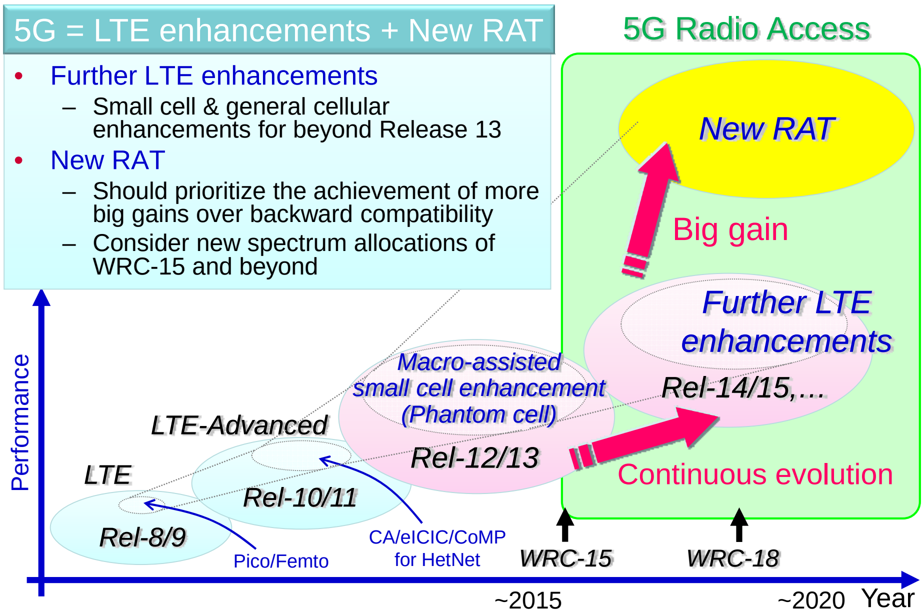


Figure 3 – Directions of evolution: "The Cube".

3.2. Evolution paths

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. DOCOMO believes that LTE/LTE-Advanced, well-optimized for existing lower frequency bands, will continue to be improved in the future. LTE/LTE-Advanced could even be further enhanced to cover some of the 5G system capabilities, such as massive connectivity and reduced latency. However, the challenges of achieving significant gains in capacity and user-experienced data rate will require a significant leap in spectrum efficiency, spectrum extension, and network densification and LTE/LTE-Advanced and their enhancements alone are unlikely to accomplish.

From spectrum utilization point of view, the spectrum below 3GHz is mostly utilized by existing systems. To ensure sustainable system evolution, therefore, it is crucial to extend the spectrum usage to the frequency bands higher than 3GHz. The utilization of higher frequency bands will enable higher data rates (maybe also lower latency) by using wider bandwidths. The transmissions over higher and wider bandwidths would require new numerology and waveform designs (e.g., subcarrier spacing and frame structure). For higher frequency bands, e.g., beyond 10GHz, the current 4G system (LTE/LTE-Advanced radio interface) would not be an optimum solution because it has been optimized for the existing cellular bands, i.e., around 2GHz. Thus, the use of higher frequency bands requires a new RAT that is able to achieve big gains compared to LTE/LTE-Advanced enhancements. Therefore, DOCOMO considers 5G radio access as a combination of a new RAT specifically designed for higher frequency bands and LTE/LTE-Advanced enhancements, as illustrated in Figure 4. The new RAT should be equipped with the capability of tight interworking with LTE/LTE-Advanced so that it can be deployed together with LTE/LTE-Advanced enhancements within the 5G radio access.



CA: Carrier Aggregation eICIC: enhanced Inter-cell Interference Coordination
CoMP: Coordinated Multi Point transmission/reception HetNet: Heterogeneous Network
WRC: World Radio Conference

Figure 4 – Evolution paths toward 5G.

3.3. 5G radio access concept

In order to support the 5G evolution path shown in Figure 4, a key pillar of DOCOMO's 5G concept is the efficient integration of both lower and higher frequency bands. Higher frequency bands can open up opportunities for wider spectrum; however, they have coverage limitations because of higher path loss. In addition, it is difficult to deploy higher frequency bands on existing network infrastructure due to either space limitations on the site or cost issues arising from the need to alter the already established infrastructure. These conditions have led DOCOMO to envision a 5G radio access system with the following features. The system has a two-layer structure that consists of 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 Figure 5. The coverage layer is supported by enhanced LTE RAT while the capacity layer is supported by a new RAT dedicated to higher frequency bands. The efficient integration of the coverage and capacity layers is enabled by the tight interworking (dual connectivity) between the enhanced LTE RAT and the new RAT.

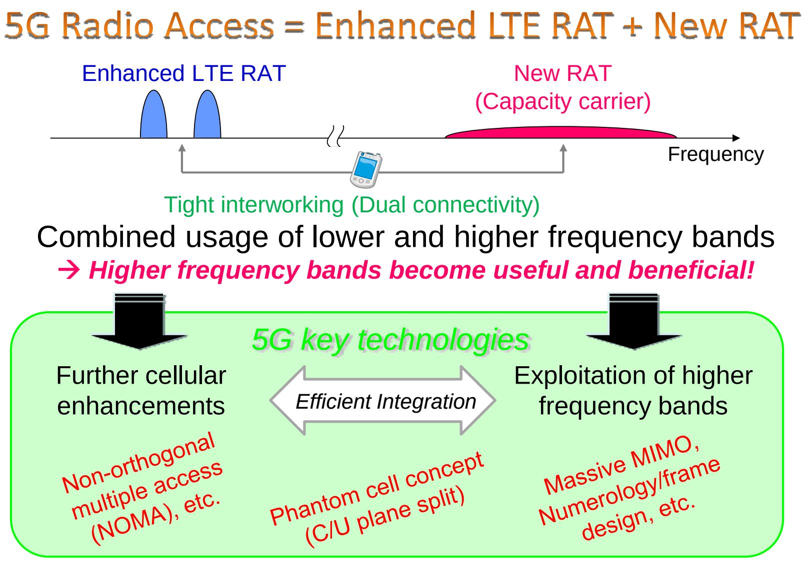


Figure 5 – DOCOMO's 5G radio access concept.

The key radio access technologies to enable DOCOMO's 5G radio access concept are as follows:

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

4. 5G Technical Components

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, DOCOMO is developing advanced Centralized RAN (Advanced C-RAN) architecture (see Figure 6), for commercial launch in around 2015 [4].

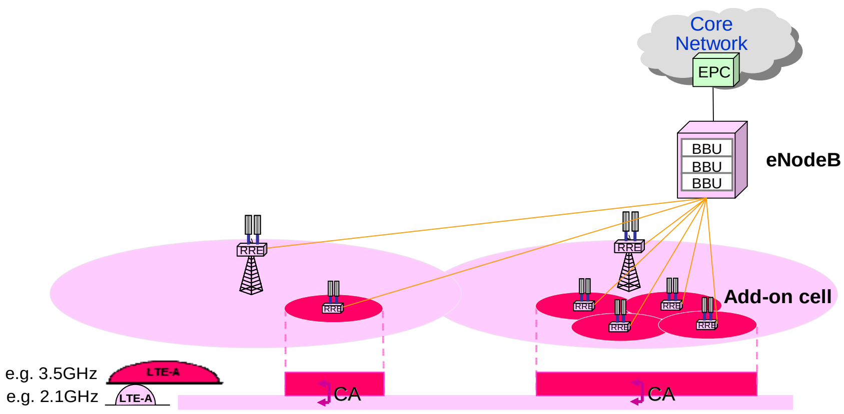


Figure 6 – DOCOMO's advanced C-RAN architecture.

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, DOCOMO 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 (C)-plane and the user data (U)-plane between macro cell and small cells using different frequency bands as shown in Figure 7 [5]. 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 backhauling and signaling requirements, and enhanced small cell discovery [6][7]. DOCOMO's 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 Figure 9, the small cell handles traffic for high-throughput data sessions with the user (U-plane), while the macro cellular layer 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 user connected to them. That is why this type of small cells is called 'Phantom Cell'.

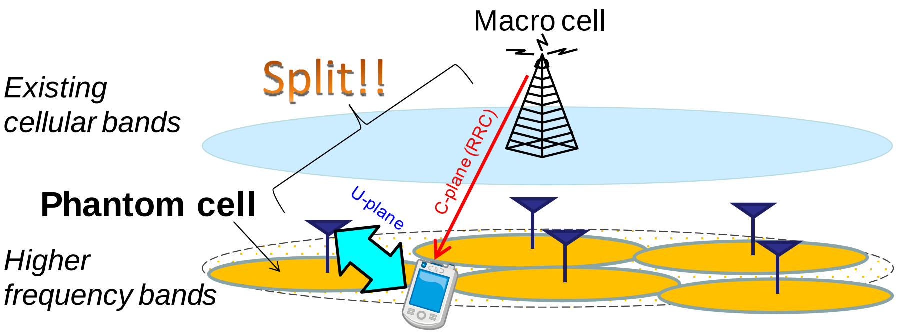


Figure 7 – Phantom cell architecture with C/U-plane splitting.

3GPP has an ongoing discussion to include some aspects of the "Phantom cell" architecture in LTE Release 12 small cell enhancements. The scenarios and requirements for Release 12 small cell enhancements are summarized in 3GPP TR 36.932.

4.2. Flexible duplex

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 whichever duplex scheme is used in either the lower or higher frequency bands. To this end, the support of flexible duplex via the joint operation of FDD & 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. Numerology and waveform design

The new RAT should provide significant gains for 5G. In particular, it needs to offer higher data rates (greater than 10Gbps) and be adapted to support wider bandwidth (several 100MHz to GHz order) at higher 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. A promising approach to achieve this is to scale LTE numerology to enable wider carrier spacing (see Figure 8). A new RAT based on scaled LTE numerology can also provide shorter transmission time interval (TTI) below 1ms 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.

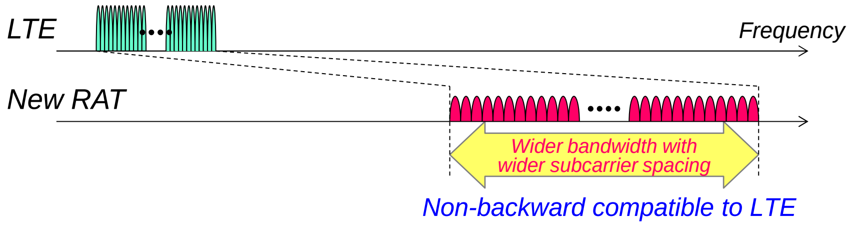


Figure 8 – Scalable LTE numerology for new RAT.

On the other hand, the new RAT should support a variety of scenarios (device-to-device (D2D), wireless backhauling, multi-hop, etc.). Thus, it would be desirable to have a RAT design with downlink and uplink symmetry. In addition, regarding signal waveform, orthogonal frequency division multiplexing (OFDM) would be the baseline because of its high affinity with multiple-input multiple-output (MIMO) technology and high performance in multi-path fading environments. Some alternatives such as single carrier waveform or other advanced multi-carrier waveform (e.g., filter bank multi carrier (FBMC)) can also be used to prioritize coverage and support much higher/wider frequency bands and new scenarios. Especially, single carrier waveform is a promising candidate to provide good coverage even when wider bandwidth transmissions (e.g., > 1GHz) are introduced in higher frequency bands. Thus, the waveform of choice would highly depend on the frequency band and bandwidth to be used and the coverage to be provided. Examples of potential bandwidth and signal waveform for new RAT are illustrated in Figure 9.

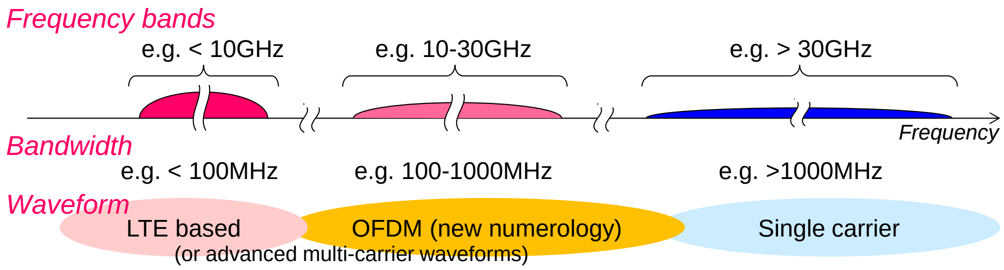


Figure 9 – Potential bandwidth and signal waveform for new RAT.

4.4. Massive MIMO

The use of massive MIMO technology in combination with a large number of antenna elements is a potential solution to exploit higher frequency bands (e.g., beyond 10GHz) [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. DOCOMO expects 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 (see Figure 10). For small cell deployments, a planar patch antenna of 20cm 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 3.5GHz, 169 antennas at 10GHz, and over 650 antennas at 20GHz. 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.

Figure 10 – Massive MIMO using very large number of antenna elements in small cells at higher frequency bands.

Nevertheless, 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. DOCOMO envisages 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 (see Figure 11).

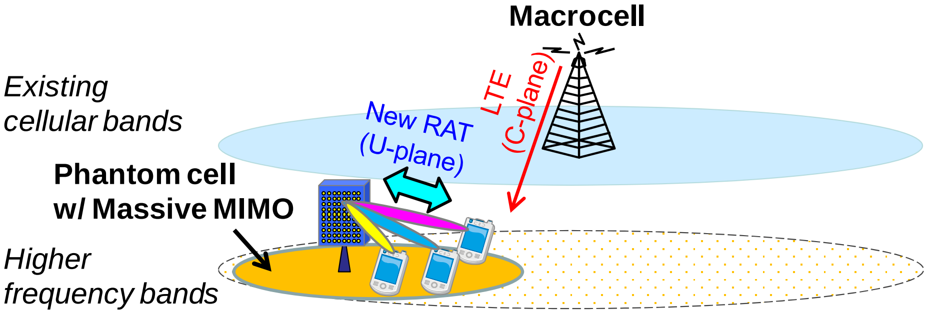


Figure 11 – Combined massive MIMO and Phantom cell.

Macro-assisted operation offers many additional benefits, including efficient beam and point discovery and association by means of multi-beam precoded reference signals (RS). 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. Many aspects related to the operation of massive MIMO are under active investigations.

4.5. 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, non-orthogonality is intentionally introduced via power-domain user multiplexing either in time/frequency/code domains (see Figure

12). 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 [8]. As a result, both system capacity and fairness can be improved. Furthermore, NOMA can support more simultaneous connections, which is suitable to address the challenges related to massive connectivity.

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 receiver processing schemes such as SIC. In the same spirit, but for the purpose of inter-cell interference mitigation, discussions on network-assisted interference cancellation and suppression (NAICS) including SIC are underway for LTE Release 12. In the future, NOMA can be introduced as LTE/LTE-Advanced enhancements in lower frequency bands.

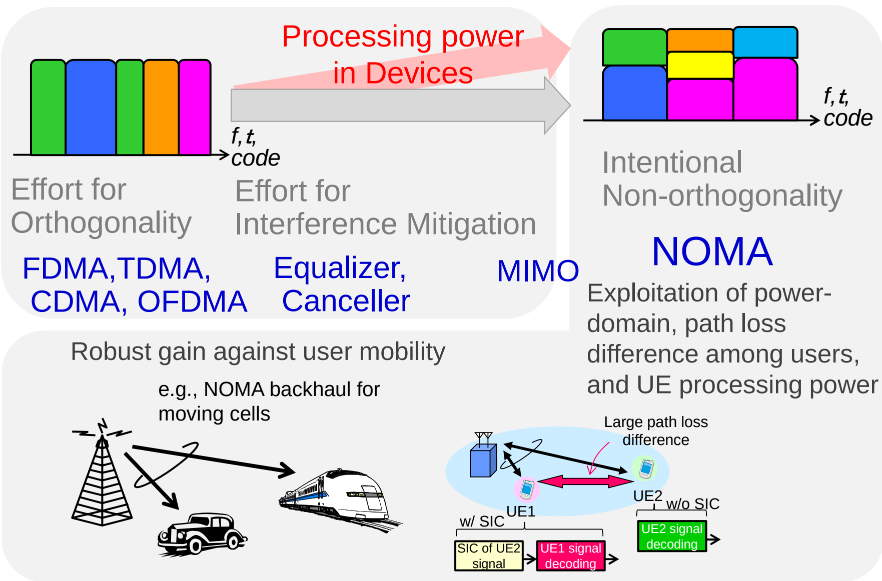
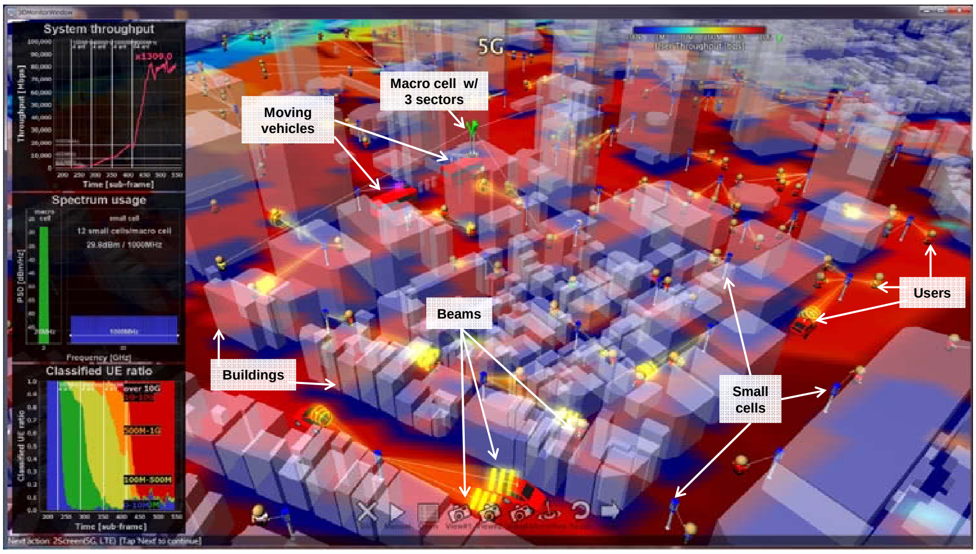


Figure 12 – NOMA for intentional intra-cell non-orthogonality.

5. 5G Activities

5.1. 5G real-time simulator and field experiments

DOCOMO started studies on 5G requirements, concept, and candidate key technologies as early as 2010. Since 2012, it has been developing a real-time simulator to evaluate and demonstrate its 5G radio access concept and the gains of candidate radio access technologies. Using the real-time simulator as depicted in Figure 13, DOCOMO showed that more than a thousand-fold increase in the system capacity (compared to a macro-only LTE deployment using 20MHz bandwidth at 2GHz) can be achieved using 5G technologies. Furthermore, more than 90% of users are shown to be able to achieve data rates in excess of 1Gbps in the simulated 5G network. This is realized by introducing network densification using small cells (12 small cells per sector), bandwidth extension in higher frequency bands (1GHz bandwidth at 20GHz 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. As a result, it is confirmed that outdoor small cell deployments combined with spectrum extension and massive MIMO are indeed an effective approach to boosting the system capacity and user-experienced throughput.



A 7-macro cell model is assumed where each macro cell has three sectors. Ray tracing is applied to emulate real propagation environment of Shinjuku area in Tokyo, Japan. The baseline system consists of LTE-based macro cells using 20MHz bandwidth at 2GHz. 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 1GHz bandwidth at 20GHz. 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 is 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 2GHz and 20GHz.

Figure 13 – DOCOMO's 5G real-time simulator.

On the other hand, efforts to materialize DOCOMO's 5G concept through field experiments are also taking place. In December 2012, DOCOMO successfully tested in the field, its world's first uplink packet transmission at a rate of 10Gbps for outdoor mobile radio access. This experiment, which was jointly conducted with the Tokyo Institute of Technology [9], was also the world's first outdoor field experiment to test frequency bands above 10GHz for mobile radio access. In May 2014, DOCOMO announced about its plans to conduct further experimental trials of emerging 5G mobile technologies with six world-leading mobile technology vendors: Alcatel-Lucent, Ericsson, Fujitsu, NEC, Nokia and Samsung [10]. The experimental trials with the vendors aim to confirm the potential of 5G mobile technologies to exploit frequency bands above 6GHz and realize very high system capacity per unit area. Furthermore, DOCOMO will test new radio technologies to support diverse types of applications including M2M services.

5.2. **5G related pre-standardization activities**

5G related discussions are ongoing in the ITU-R Study Group 5 Working Party 5D (WP5D), 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 evidenced by the acceleration of efforts by governmental entities and several research bodies from both academia and industry. Many special sessions are also being held on the topic of 5G in international conferences. DOCOMO is actively contributing to 5G related global pre-standardization activities through the METIS project in Europe, the ARIB 2020 and Beyond Ad Hoc (20B AH) group in Japan, NGMN alliance, and other initiatives.

6. Summary

5G will need to meet very challenging requirements and cover a wide range of scenarios and services. 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, DOCOMO emphasizes on the importance of the efficient integration of lower and higher frequency bands to meet the challenges of achieving 1000-fold increase in the system capacity and 100-fold increase in the typical data rate. In addition, DOCOMO has introduced a set of 5G radio access technologies identified as the most promising for improving system performance in both lower and higher frequency bands. Further technical studies, field experiments, and pre-standardization consensus building will be required in the next steps. Furthermore, the whole network architecture should also support the evolution toward the 5G radio access. 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. Standardization of 5G is expected to gain real momentum starting from LTE Release 14 and 15. Going forward, DOCOMO will continue to actively research 5G to further contribute to the technical advancement and global proliferation of mobile communications.

7. References

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