Special Articles on Technology Supporting Large-capacity and High-efficiency Communication in the Flat-rate Era

Key Wireless Technologies for Future High-speed and Large-capacity Communications

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Although future mobile systems are expected to support much higher speeds and larger capacities, technologies are needed to compensate various difficulties associated with the use of high frequencies and wide bandwidths. In this article, we describe state-of-the-art research activities with regard to the key technologies for realizing future high-speed and large-capacity wireless systems.

1. Introduction

As mobile communication technology develops, peak transmission speeds are more or less doubling every year. However, transmission speeds in fixed networks are roughly five years ahead of mobile communication networks, and it is thought that demands for higher speed and larger capacity will continue into the future (**Figure 1**).

Advances are also being made with regard to antennas and wireless circuits, allowing simplifications to be made to the placement of base stations while increasing system performance, such as shared techniques compatible with multi-band operation of FOMA systems (800 MHz, 1.7 GHz and 2 GHz bands).

As a future system, the requirements are already up to 1 Gbit/s with the use of new and higher frequency bands. In the future, this will make it necessary not only to use frequency more efficiently, but also to develop technologies such as advanced antenna technology and circuit technology that is better adapted to multi-band transmission.

In this article we describe the enhancement of Multiple-Input Multiple-Output (MIMO)*1 technology based on cooperative transmission among remote base stations that offers improved frequency usage as a key technology for the future mobile systems. We also describe base station and mobile terminal antenna technology, and with regard to Radio Frequency (RF) circuit technologies for mobile communications, we describe trends in highly efficient multi-band Power Amplifiers (PAs) for mobile terminals and linear PAs for base stations.

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*1 **MIMO**: A wireless communication technique that utilizes multiple paths between multiple antennas at the transmitting and receiving ends to exploit spatial propagation properties, causing the capacity of wireless links to increase in proportion with the number of antennas.

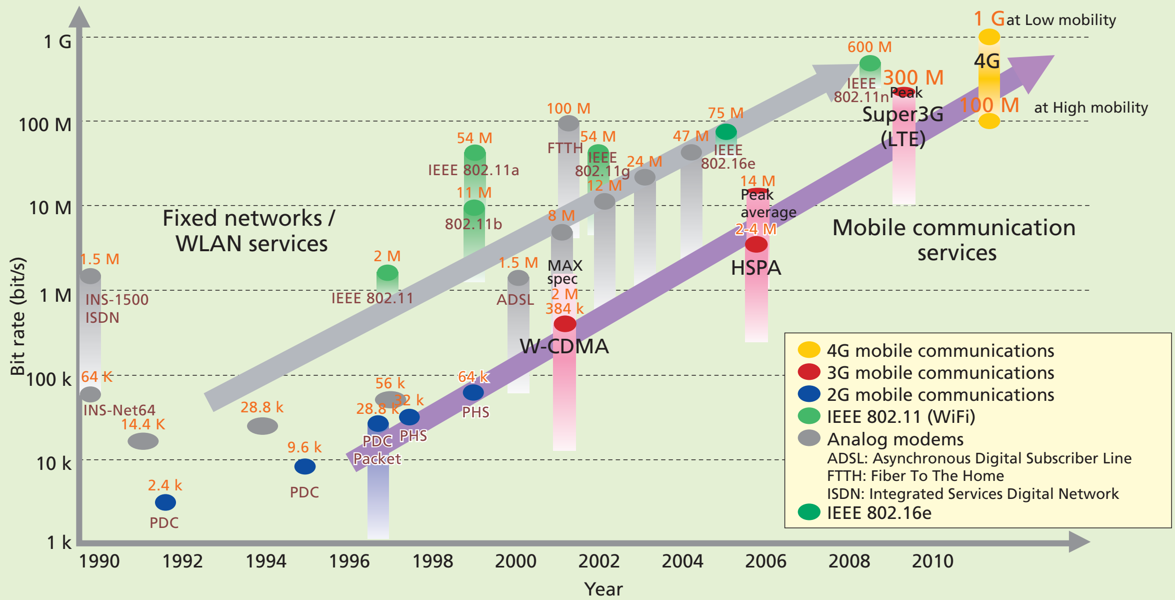

Figure 1 The increasing speed of mobile communications

2. Requirements and Issues of Future High-speed Large-capacity Communications

It is envisaged that the future mobile systems, such as IMT-Advanced[*2] (Fourth-Generation (4G)) will adopt high frequency bands such as 3–4 GHz, where the propagation losses are approximately 3.5–6 dB larger than in Third-Generation (3G) mobile communication systems (2 GHz band) [2]. To achieve further increases in data transmission speeds, the frequency bands are expected to be at most 100 MHz or so, and thus if we assume that an existing system, such as, Super 3G (Long Term Evolution (LTE))[*3] system with a bandwidth of 1.25–20 MHz [3][4] is simply applied to operation at higher frequency bands and wider bandwidths, then the required additional link budget[*4] is at least 3.5 dB, or in some cases more than 10 dB (**Table 1**).

Key technologies for overcoming such technology trends are described below.

3. Wireless Signal Processing Technology

In cellular environments, a factor that reduces throughput at cell edges and sector boundaries is co-channel interference between cells or sectors.

To control interference between cells and sectors, Second-Generation (2G) Personal Digital Cellular (PDC) systems used different frequencies (exploiting frequency orthogonality), while 3G W-CDMA systems used different spreading codes (exploiting code orthogonality). For Super 3G (LTE) systems, low-period Fractional Frequency Reuse (FFR) based on an Over-

Table 1 Link budget for future mobile communications

System / Loss factor	3G	Beyond 3G	Link budget difference
Propagation	2 GHz band	3 - 4 GHz band	3 GHz band: Approx. 3.5 dB 4 GHz band: Approx. 6 dB
Transmission bandwidth	1.25 - 20 MHz	20 - 100 MHz	Expansion from 20 MHz to 100 MHz: 7 dB Expansion from 5 MHz to 100 MHz: 13 dB

*2 **IMT-Advanced**: The Fourth-Generation mobile communications, which is being studied by International Telecommunication Union (ITU-R) as the system to follow Third-Generation mobile communications (IMT-2000). It is targeted at achieving 100 Mbit/s data transmission in high mobility situations, and 1 Gbit/s in nomadic environments.

*3 **LTE**: An expansion (long-term evolution) of 3G technology which is being studied by the 3GPP. Synonymous with 3.9G or NTT DOCOMO's Super 3G proposal.

*4 **Link budget**: A design criterion for the allocation of average power levels between base stations and mobile terminals. This is used for calculating cell radius from various wireless parameters such as transmitter power, frequency and receiver sensitivity.

Load Indicator (OLI) has been investigated, and is able to reduce interference between cells [5][6]. There are a wide variety of other techniques, including transmission power control, beamforming,[*5] soft hand-offs[*6] and frequency reuse,[*7] and there are many practical examples such as low-period frequency hopping in Global System for Mobile communications (GSM) [7] and research efforts such as Reuse Partitioning (RP) [8][9].

Attempts have also been made to use MIMO for the orthogonalization of wireless resources among base stations. MIMO is a technique for implementing spatial multiplexing, so it is possible to achieve orthogonalization of wireless resources among distributed base station antennas, and it is possible to achieve higher system throughput than a non-cooperative MIMO system (**Figure. 2**) [10]–[16].

1) SU-MIMO and MU-MIMO

Multi User-MIMO (MU-MIMO) with Dirty Paper Coding (DPC)[*8] and Single User-MIMO (SU-MIMO) have the same upper limit of achievable capacity when the total number of receiving antennas is the same, but MU-MIMO has the ability to reduce antenna correlation and can be expected to improve the average capacity through the multi-user diversity effect (**Figure 3**).

Although MU-MIMO requires information on the transmission channel (Channel State Information (CSI)) at the transmitting side, it is expected to be suitable for improving the average capacity in situations where it is difficult to incorporate many antennas into mobile terminals.

2) MU-MIMO Cooperative Transmission among Base Stations

By decentralizing the placement of base station antennas, it is possible to increase the angular spread of incoming waves and improve the spatial multiplexing characteristics. It should also be possible to reduce the number of antennas per base station, leading to benefits in terms of implementation and operation.

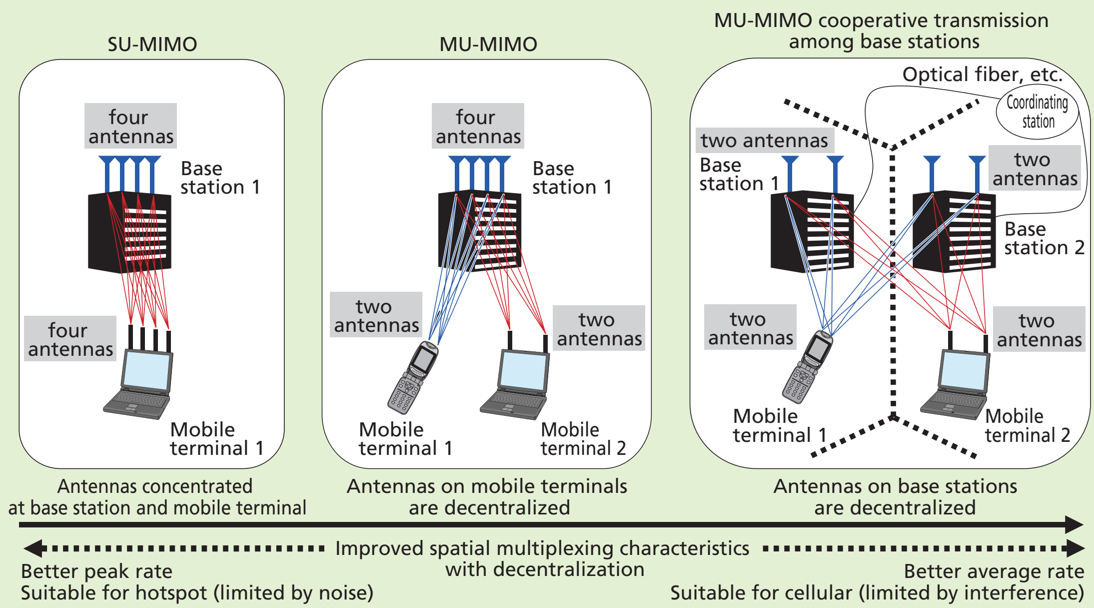

Figure 2 From SU-MIMO/MU-MIMO to MU-MIMO cooperative transmission among base stations

*5 **Beamforming**: A technique for increasing or decreasing the gain of antennas in a specific direction by controlling the phase of multiple antennas to form a directional pattern of the antennas.

*6 **Soft hand-off**: A hand-off technique characterized in that when a mobile terminal moves between multiple base stations, it establishes simultaneous wireless links to multiple base stations. The use of soft hand-off has the effect of reducing the link loss period during hand-offs and improving the received signal quality at cell edges.

*7 **Frequency reuse**: A technique for reducing interference between cells by splitting the available frequencies between multiple groups and having adjacent base stations use different frequency groups.

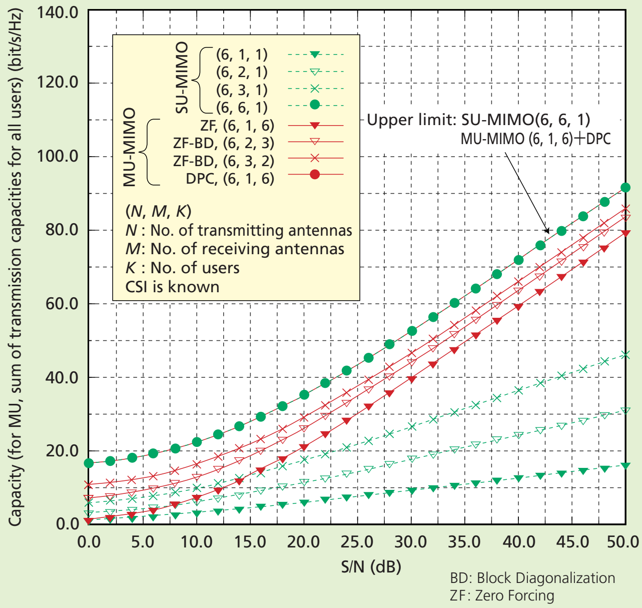

Figure 3 Capacity of SU-MIMO and MU-MIMO

3) Scenarios for the Application of MU-MIMO Cooperative Transmission among Base Stations

When MU-MIMO cooperative transmission among base stations is applied to existing mobile communication systems, it is necessary to exchange large amounts of information for signal processing among multiple base stations, making the sort of cooperation between multiple base stations shown in **Figure 4**(c) impractical. On the other hand, it is of course easy to implement cooperation inside the base stations (between sectors) as shown in Fig. 4(a), but by adopting the optical feeder [17] configuration widely used in FOMA networks, it should be possi-

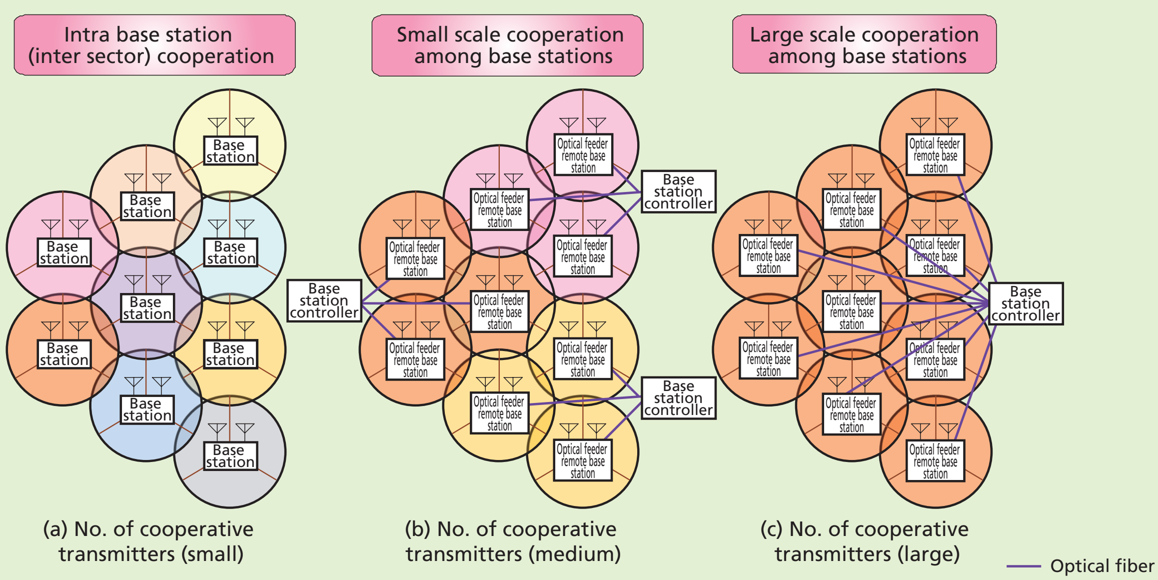

Figure 4 Scenarios for the application of MU-MIMO cooperative transmission among base stations

*8 **DPC**: A coding technique that cancels out interference. In DPC, interference compensation processing is performed in the transmitter so as to cancel out the interference at the receiving end. To do this, the transmitting side must have information about the interference signals at the receiving end in addition to the signal to be transmitted.

ble to bring about cooperation by grouping small numbers of base stations into clusters as shown in Fig. 4(b).

As an example of a study where MU-MIMO cooperative transmission among base stations is performed by clustering limited numbers of base stations together, when cooperation was performed among seven base stations, the Signal to Interference plus Noise Ratio (SINR) was shown to improve by approximately 5 dB in the median for users at the boundary of the central cell [18].

4. Antenna Technology

4.1 Base Station Antennas

Figure 5 shows the technical issues of antennas for the implementation of high-speed transmission. At high frequency bands, the propagation losses and losses in the feed network become greater, making it necessary to increase the antenna gain and/or reduce the feed network losses. Increasing the antenna gain makes the antenna pattern more directional, and necessitates the use of an adaptive antenna array*9 to track the mobile terminals. The effectiveness of applying adaptive antenna arrays to mobile communication systems has been reported in many studies, including some conducted by NTT DOCOMO [19][20]. For future systems, it will also be important to address issues such as adaptation to wideband communications and appropriate methods for the selection of diversity combining, adaptive beam forming and MIMO transmission functions.

To reduce losses in the antenna feed network, an active antenna configuration has been proposed where active elements such as the amplifier are integrated into the antenna. This configuration has been put into practice in equipment such as satellite broadcast receiver antennas. If this configuration is applied to the base station receiver equipment of a cellular system, it should make a large contribution to reducing the power consumption and transmission power of mobile terminals. Having applied an active antenna configuration to the base station antenna, we are continuing with investigations into issues such as adding filter functions to the antenna in order to realize a configuration that is easier to produce based on a systematic consideration of the performance of the circuitry and antenna [21].

4.2 Mobile Terminal Antennas

Since mobile terminals are required to provide multi-antenna transmission and a wide variety of functions such as One Seg TV reception and wireless IC card compatibility, reducing the antenna volume by such means as sharing antennas between multiple systems is an important consideration. Also, particularly in multi-antenna transmission, it is important to improve the antenna performance and establish antenna performance evaluation techniques that take into account the propagation environment, the state of actual usage of the antenna, and the overall wireless transmission performance. NTT DOCOMO has therefore been actively investigating appropriate antenna arrangements

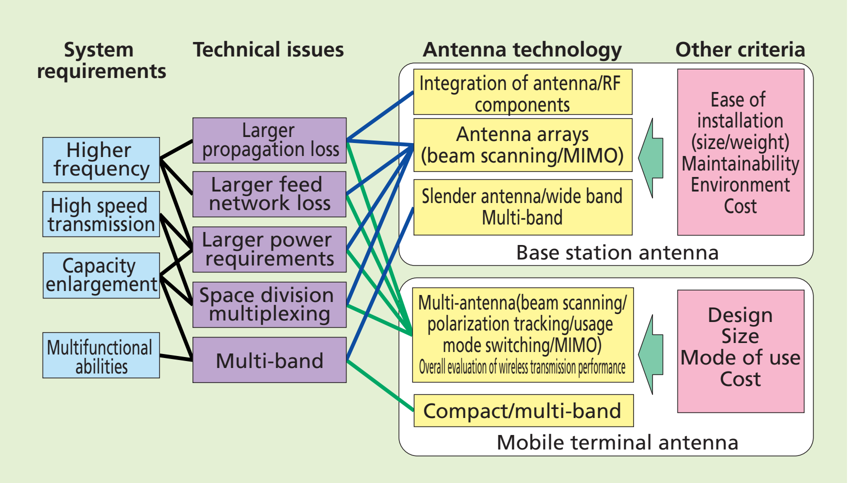

Figure 5 Technical issues of antennas for achieving higher transmission speeds

*9 **Adaptive antenna array**: An antenna that consists of multiple antenna elements and can adaptively change its antenna pattern by applying different weightings to the signals transmitted and received by each element. The pattern formation is generally achieved by adopting a digital beamforming configuration which uses digital signal processing to apply weights to the signals at each element for a digital baseband signal.

for mobile terminals and performance evaluation methods that take actual usage conditions into consideration [22]–[26].

5. RF Circuit Technology

A PA is an important device in RF circuits for mobile communications. Two major issues to consider for future mobile communications are the design of mobile terminal PAs for multi-band operation, and the establishment of methods for configuring linear PAs for base stations that have high nonlinear distortion compensation capabilities and are capable of highly efficient operation.

5.1 Designing Mobile Terminal PAs for Multi-band Operation

With regard to the RF circuit section of mobile terminals, current FOMA terminals attain multi-band operation by independently installing circuits for predetermined frequency bands (the 800 MHz, 1.7 GHz and 2 GHz bands) [27]. However, this approach cannot be used for even greater numbers of bands because the mobile terminals would become larger and less portable. Practical approaches to achieving multi-band operation with a single RF circuit include broadband operation and the use of variable reactance devices.*10 Micro ElectroMechanical Systems (MEMS) switches [28][29], which are based on MEMS technology*11, have attracted much attention recently because they have low distortion characteristics and can provide both low insertion loss in the on-state and high isolation*12 in the off-state even at radio frequencies. At NTT DOCOMO, we are investigating a multi-band PA configuration by making the most of the advantages of MEMS switches [30]. **Figure 6** shows an example of the prototype quad-band 1-W class PA module that uses MEMS switches to operate in the 900 MHz, 1.5 GHz, 2 GHz and 2.6 GHz bands [31]. With regard to the identically numbered MEMS switches on the input and output sides, switching on numbers 1, 2 and 3 respectively causes the PA to operate in the 900 MHz, 1.5 GHz and 2 GHz bands respectively. If all the switches are turned off, the PA operates in the 2.6 GHz band. From a practical viewpoint, there still remain technical issues to be solved for multi-band operation of the PA such as achieving further miniaturization, establishing a nonlinear distortion compensation scheme, and reducing the power consumption during transmitter power control.

5.2 Establishing a Method for the Configuration of Linear PAs for Base Stations

In the configuration of linear PAs for base stations, it is necessary to operate the PA with high efficiency while effectively compensating nonlinear distortion generated by the PA. In the FOMA system, from the viewpoint of reducing power consumption and its affinity with the modulation and demodulation units (digital signal processing), we adopted a Digital Pre-Distorter (DPD)*13 as a nonlinear distortion compensation method. From the viewpoint of efficient operation, attention has been focused on Doherty amplifiers,*14 and a configuration that combines a Doherty amplifier with a DPD has been proposed [32][33]. A method for operating close to the PA saturation point has also been investigated.

It is necessary to improve the compensation capability of the DPD because frequency-dependent nonlinear distortion (which is difficult to compensate with a conventional DPD) is generated if the PA is operated in the vicinity of the saturation point for the purpose of high-efficiency operation. At NTT DOCOMO, we have proposed a

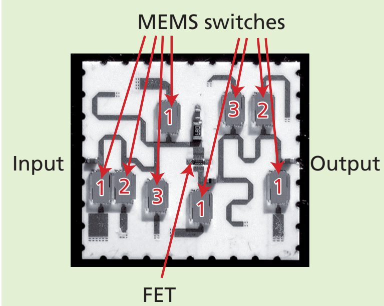

Figure 6 A multi-band PA using RF-MEMS switches
(a 4-band 1-W class PA module)

*10 **Variable reactance device**: Reactance is a physical value related to the Root Mean Square (RMS) values of voltage and current across a coil or capacitor in an AC circuit, like resistance in a DC circuit. Reactance is treated separately from resistance because it does not consume electrical power. A variable reactance device is an element whose reactance value can be changed, a typical example being a varactor diode.

*11 **MEMS technology**: MEMS are tiny devices consisting of sensors, actuators and electrical circuits formed by the same processes as integrated circuits. MEMS technology is the semiconductor fabrication technology used in the production of MEMS, which systematically combines technologies such as electrical circuit technology and mechanical processing technology.

new DPD that can achieve this [34], and we are evaluating the combination of the DPD with a Doherty amplifier [35] and with a class-B PA[*15] [36]. **Figure 7** shows an example of the nonlinear distortion compensation performance of the proposed DPD. For further improvements in the performance of linear PAs for base stations, we are investigating other techniques such as envelope-tracking configuration that adaptively controls the bias point of the PA based on the envelope of the input signal supplied to the PA [37].

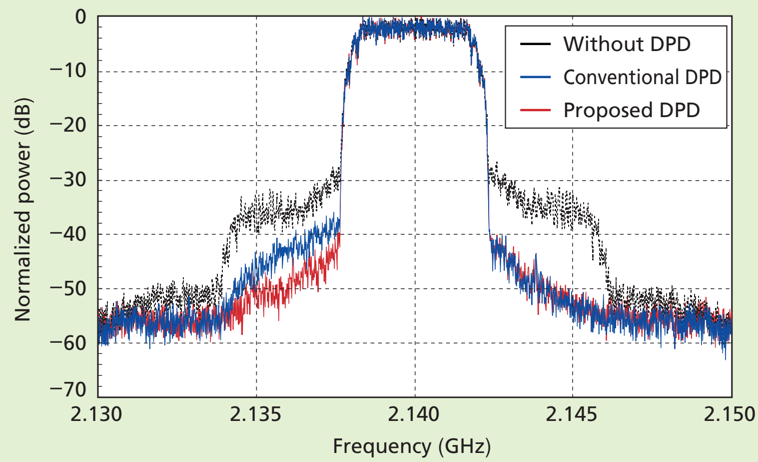

Figure 7 Example of nonlinear distortion compensation characteristics obtained using 2-GHz band QPSK modulated signal

6. Conclusion

In this article, we have described the trends in key wireless technologies to support the high-speed and large-capacity mobile communication systems of the future. We have also clarified various trends, such as technology for extending the capabilities of MIMO technology and improving system throughput while controlling interference between base stations, technology for improving the capabilities of base station and mobile terminal antennas, and technology for designing PAs for multi-band operation and improving their performance. We have also clarified the technical issues of these trends.

In the future, we plan to resolve these issues and to further investigate the application of this technology to real systems.

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*12 **High isolation**: Isolation is a measure of the degree of how well signals are separated from each other, and in the case of a switch it refers to the amount of signal leakage that occurs when the switch is off. As the degree of isolation increases, this signal leakage becomes smaller, so a high-isolation switch has particularly good characteristics.

*13 **DPD**: Pre-distorter is a method for compensating nonlinear distortion generated by a power amplifier, which involves predicting the nonlinear distortion caused by the power amplifier, and applying a signal to the power amplifier with characteristics that are opposite to this distortion. A digital pre-distorter performs this process by digital signal processing.

*14 **Doherty amplifier**: An amplifier consisting of a carrier amplifier and a peak amplifier in a parallel configuration. Depending on the input signal level applied to the Doherty amplifier, the gain characteristics of the carrier amplifier and peak amplifier are used with the aim of achieving highly efficient amplifier operation over a wide range of input signal levels.

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*15 **Class-B PA**: A type of power amplifier configuration where the PA is configured so that only half the cycle of the input signal is amplified. The maximum efficiency of a class B PA is about 78%, so amplifiers of this type are used in high-power amplification circuits.