IMT-2000 Multi-band RFIC

Technology Reports

Mobile Terminal RF Circuit Technology for Increasing Capacity/Coverage and International Roaming

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Ever since the first mobile phones were introduced, the radio transceiver circuits in mobile terminals have continued to evolve in order to produce devices that are smaller and more lightweight, offer longer talk times, and have greater capacity and coverage. In the future, they will need to evolve further still with a view to the implementation of next-generation mobile phones. This article summarizes how this technology has developed, particularly with regard to the radio transceiver circuit technology of FOMA terminals, and describes the trends of future developments.

1. Introduction

The FOMA Third-Generation mobile phone service first started out in the 2 GHz band in October 2001. Later, in order to expand the service area efficiently in rural areas, services using the 800 MHz band were also started up in June 2005 (FOMA Plus-Area). More recently, new services using the 1.7 GHz band were introduced in June 2006 to accommodate the concentration of traffic in urban areas due to the increased number of subscribers to FOMA services, and the increased user traffic resulting from the switch-over to a flat-rate billing system. In June 2003, we also began offering an international roaming service to foreign travelers.

In these expanded FOMA services, a better user convenience can be provided if a single mobile terminal can communicate in all FOMA areas, and if users can carry on using the same mobile terminals when they go abroad. We therefore adapted to these band expansions by developing and marketing the FOMA 901iS series of dual band (2 GHz/800 MHz) mobile terminals, followed by the FOMA 902iS series of triple band (2 GHz/1.7 GHz/800 MHz) mobile terminals [1]. For international roaming, we have added various new models to our line-up since we first introduced the FOMA N900iG terminals equipped with Global System for Mobile communications (GSM)[2], and since the FOMA 905i series, these terminals have been provided with dual-mode (W-CDMA/GSM) capabilities as standard.

As these mobile terminals evolved, we continued to add new functions by incorporating the latest technology into the radio transceiver circuits so as not to affect the size trend of mobile terminals or their battery life. In the future, further progress will be needed to achieve the introduction and rapid uptake of Super 3G (Long Term Evolution (LTE)) standards [3].

This article clarifies the current situation regarding current frequency resources, and explains how radio transceiver circuit technology has evolved from the first FOMA services to the present state of the art. The technical issues and development trends of radio transceiver technology towards future Super 3G devices in the future are also discussed.

2. The Current Situation of Frequency Resources

The frequency allocation for IMT-2000 services was settled at the 1992 World Administrative Radio Conference (WARC-92), where it was decided that the 2 GHz band would be used worldwide. Three more bands were later added at the 2000 World Radiocommunication Conference (WRC-2000) — the 800/900 MHz band, 1.7-1.9 GHz band and the 2.5 GHz band. The WRC-2000 conference also defined Second-Generation mobile phone systems such as GSM/General Packet Radio Service (GPRS)/Enhanced Data rates for GSM Evolution (EDGE) for IMT-2000 standard, and fixed the current definition of IMT-2000.

To keep in step with these developments, the 2 GHz band was assigned at first for IMT-2000 services in Japan. Later, to improve frequency usage efficiency and make up for the lack of frequency resources caused by rapid growth in the number of mobile phone users [4], the 800 MHz and 1.5 GHz bands (hitherto assigned to services such as Personal Digital Cellular telecommunication system (PDC)[5]) were reconfigured for these services, and the 1.7 GHz band was also assigned as a new band. The use of these additional frequencies was made possible by IMT-2000.

Based on these domestic and international developments in frequency allocation, IMT-2000 is recognized as a world standard for mobile communication systems, and work is under way at the 3rd Generation Partnership Project (3GPP) to establish it as a technical specification. **Table 1** shows the frequency bands defined for Frequency Division Duplex (FDD)*1 systems as of December 2007 [6][7]. Although 14 bands are specified for GSM, only the four bands that are most frequently used worldwide are shown here. For W-CDMA, 11 bands are currently defined. **Figure 1** shows the frequency bands of Table 1 plotted on the frequency axis. By way of reference, this figure also shows the frequency bands used for Global Positioning System (GPS) and Wireless LAN (WLAN), which are two other capabilities that users look for

Table 1 3GPP frequencies

System	Band	Uplink frequency	Downlink frequency	TX-RX frequency separation	Region, Usage
W-CDMA	Band I	1,920 - 1,980 MHz	2,110 - 2,170 MHz	190 MHz	Global (Except North and South America)
	Band II	1,850 - 1,910 MHz	1,930 - 1,990 MHz	80 MHz	United States
	Band III	1,710 - 1,785 MHz	1,805 - 1,880 MHz	95 MHz	Europe
	Band IV	1,710 - 1,755 MHz	2,110 - 2,155 MHz	400 MHz	United States
	Band V	824 - 849 MHz	869 - 894 MHz	45 MHz	United States, U.S. roaming services
	Band VI	830 - 840 MHz	875 - 885 MHz	45 MHz	Japan, part of Band V
	Band VII	2,500 - 2,570 MHz	2,620 - 2,690 MHz	120 MHz	Europe, South Korea
	Band VIII	880 - 915 MHz	925 - 960 MHz	45 MHz	Europe
	Band IX	1,749.9 - 1,784.9 MHz	1,844.9 - 1,879.9 MHz	95 MHz	Japan, part of Band III
	Band X	1,710 - 1,770 MHz	2,110 - 2,170 MHz	400 MHz	United States
	Band XI	1,427.9 - 1,452.9 MHz	1,475.9 - 1,500.9 MHz	48 MHz	Japan
GSM	GSM850	824 - 849 MHz	869 - 894 MHz	45 MHz	Same as Band V
	GSM900	880 - 915 MHz	925 - 960 MHz	45 MHz	Same as Band VIII
	GSM1800	1,710 - 1,785 MHz	1,805 - 1,880 MHz	95 MHz	DCS band, same as Band III
	GSM1900	1,850 - 1,910 MHz	1,930 - 1,990 MHz	80 MHz	PCS band, same as Band II

: FOMA band (Bands I, VI, IX, XI)　: Roaming band (Band V, GSM850, GSM900, GSM1800, GSM1900)

*1 **FDD**: A bidirectional transmit/receive system. Different frequency bands are allocated to the uplink and downlink to enable simultaneous transmission and reception.

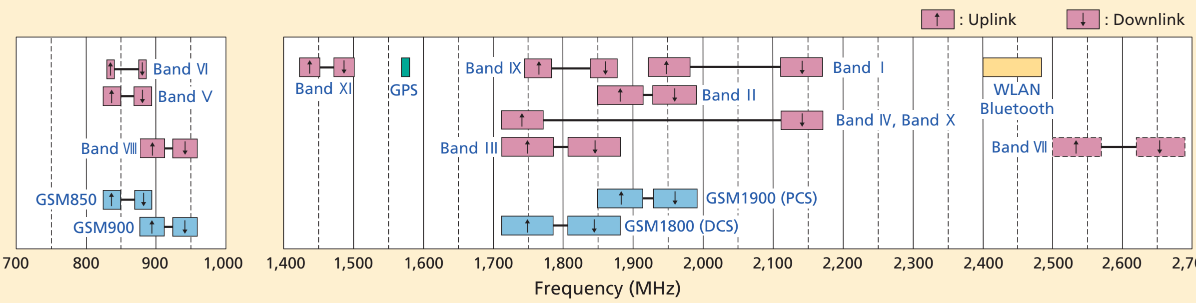

Figure 1 3GPP frequency bands

in mobile terminals. As you can see, the frequencies used in mobile terminals range from 800 MHz to 2.7 GHz, and are concentrated around the 800/900 MHz band and the 1.7-2.0 GHz band. However, there are currently no frequency bands that can be used in common worldwide, so a major design factor in the development of mobile terminals is thus the decision regarding which bands to support.

The state of development of the FOMA service area is shown in **Figure 2**. As this figure shows, NTT DOCOMO was licensed three frequency bands by the Ministry of Internal Affairs and Communications for W-CDMA applications — the 800 MHz, 1.7 GHz and 2 GHz bands. By using different frequency bands depending on region and application, we were able to develop FOMA services over a wide area. For foreign visitors, considering the practicalities of communicating from destinations throughout the world, we provided seamless roaming services using W-CDMA which is adopted by FOMA services, and GSM/GPRS which are available almost everywhere in the world.

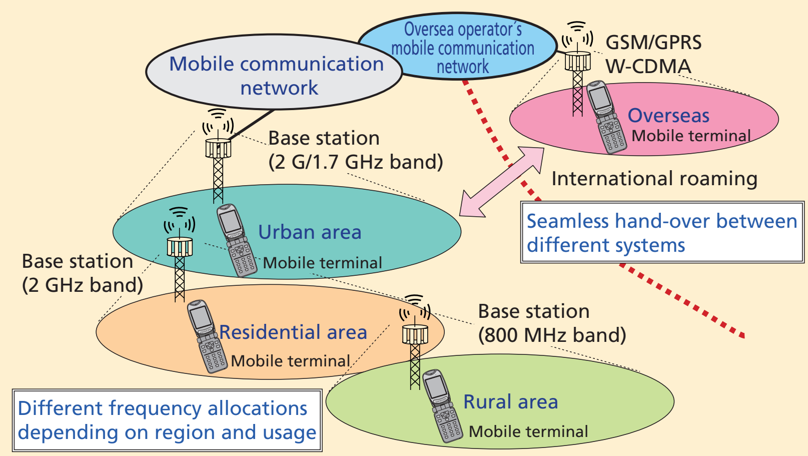

Figure 2 The state of development of FOMA service area

The basic specifications of a FOMA terminal are shown in **Table 2**. As this table shows, FOMA terminals are currently configured to work in up to three W-CDMA bands and up to four GSM/GPRS bands. The choice of frequency bands to include is made based on the product concept of the mobile terminal. Of the W-CDMA bands, Band I is used as a roaming band in Europe, South Korea and South East Asia. In the United States, Bands V and VI have almost identical arrangements, so a shared radio transceiver circuit is used for these two bands, and roaming is implemented by operating in Band V.

3. The Evolution of FOMA Radio Transceiver Circuits

In the radio transceiver circuits in mobile terminals, the latest RF circuit techniques [8][9] have been introduced as and when they appear in order to satisfy technical requirements and service demands. The evolution of radio transceiver circuit configurations from the

Table 2 Basic specifications of mobile terminal

Item	Specifications	
System	W-CDMA	GSM
Frequency bands	Band I Band VI (& Band V) Band IX	Low band : GSM850/900 High band : GSM1800 (DCS) / 1900 (PCS)
Access scheme	DS-CDMA	TDMA
Duplex scheme	FDD	FDD
Transmission rate	3.84 Mcps	270.833 kbit/s
Modulation scheme (data/spread)	Uplink: BPSK/HPSK Downlink: QPSK/QPSK	GMSK
Occupied bandwidth	5 MHz or less	200 kHz or less
Maximum output power	Class3 : +24 dBm	Low band: +33 dBm High band: +30 dBm
Spurious emissions	ITU-R Rec. SM.329-10	
	ACLR1 (5 MHz offset): – 33 dBc or less ACLR2 (10 MHz offset): – 43 dBc or less	±200 kHz: – 30 dBc or less ±400 kHz: – 60 dBc or less

ACLR : Adjacent Channel Leakage power Ratio
BPSK : Binary Phase Shift Keying
DCS : Digital Communication System 1800
GMSK : Gaussian filtered Minimum Shift Keying
HPSK : Hybrid Phase Shift Keying
ITU-R : International Telecommunication Union-Radiocommunication Sector
PCS : Personal Communications Service
QPSK : Quadrature Phase Shift Keying
TDMA : Time Division Multiple Access

earliest models to the latest state of the art is shown in **Figure 3**. This figure only shows the configuration of the transmitter units — the receiver units have undergone a similar evolution, which is omitted from the figure.

The first FOMA terminals were adapted from PDC technology, and thus their radio transceiver circuits were configured using a superheterodyne method (Fig. 3(a)). In this system, the signals are first orthogonally modulated at an intermediate frequency, and then transformed to a radio frequency band. An advantage of this method is that signal processing such as quadrature mod-

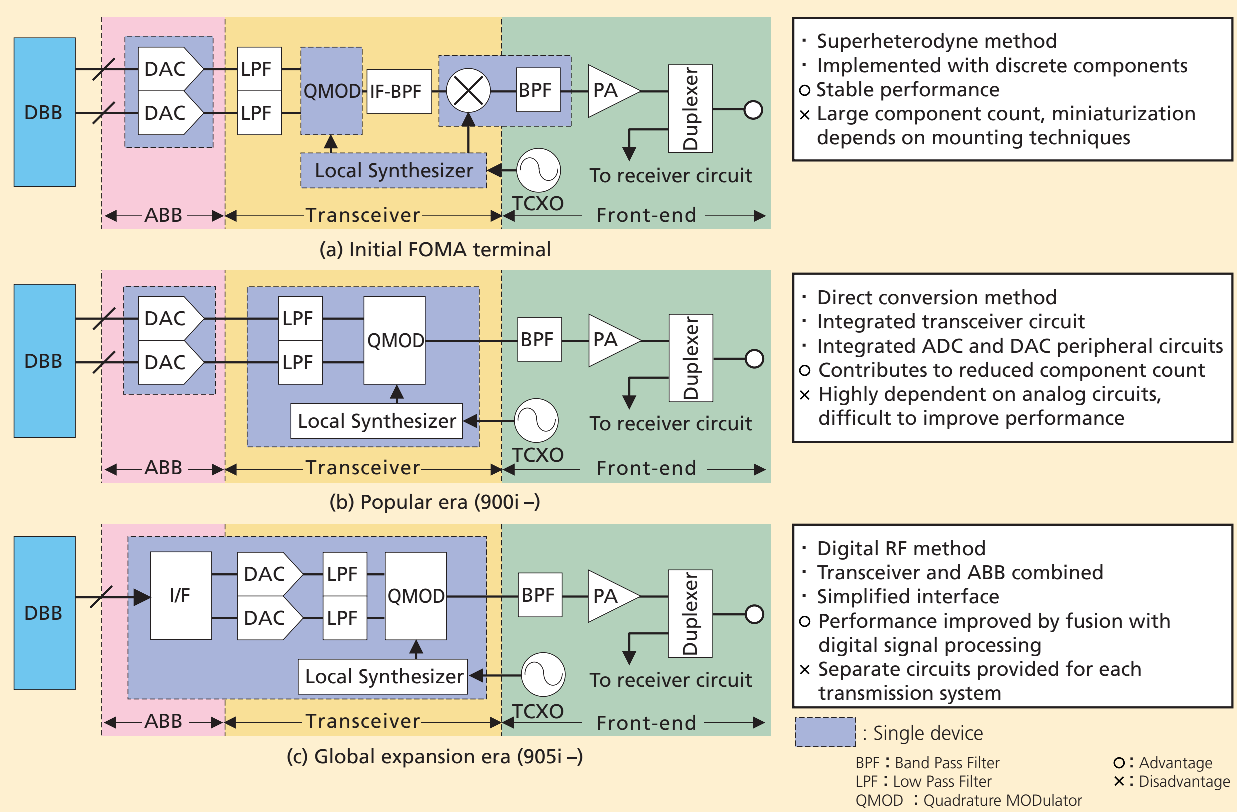

Figure 3 Evolution of radio transceiver circuit configuration

ulation and quadrature detection is performed in a low frequency range so that stable performance can be achieved. However, these circuits have large numbers of components and require Intermediate Frequency (IF) stage filters which are difficult to miniaturize, making it difficult to fit them inside mobile terminals. Consequently, the development of mobile terminals with this configuration reached its limit when targeting FOMA deployment.

In the FOMA 900i series and thereafter, this drawback was resolved by adopting a direct conversion (homodyne) method, where the baseband signals and radio frequency signals are subjected directly to quadrature modulation and quadrature detection. This eliminates the need for an IF stage filter, and since each transceiver needs only one synthesizer, the circuits can be miniaturized and integrated [10][11]. One reason why it became possible to adopt this technique is because of advances in analog semiconductor processing technologies such as SiGe-BiCMOS[*2], but the fact that the use of W-CDMA made it easier to implement direct receivers also had a part to play. The direct conversion method was originally adopted for GSM equipment, and contributed to reducing the size and cost of GSM terminals. However, the signal bandwidth of PDC is about ten times narrower than that of GSM, and it was particularly difficult to eliminate degradation factors due to distortion (secondary distortion) in direct receiver circuits. On the other hand, W-CDMA has a bandwidth at least ten times as wide as GSM, so there was no difficulty applying the techniques that had been established for GSM.

The 800 MHz and 1.7 GHz bands were added by optimizing the circuit based on this configuration (Fig. 3(b)) [1]. At the same time, due to developments in hybrid analog/digital IC technology[*3] during this period, it became possible to achieve integration of the Analog Base Band (ABB)[*4] unit [12].

Even more recently, the development of High Speed Packet Access (HSPA) has got up to speed, making it possible to obtain radio transceiver circuits with not only reduced size but also improved precision. On the other hand, it has become difficult to improve the Error Vector Magnitude (EVM)[*5] performance and interference robustness of the direct conversion method, which are highly dependent on analog circuitry. Studies are therefore still being conducted into the use of digital RF (Fig. 3(c)), which is being adopted in a growing number of cases. This method combines the functions of the direct conversion unit and ABB unit, but by substantially reviewing the way in which functions are partitioned to the analog and digital circuits, the performance of the transceiver can be improved by using digital signal processing to perform functions such as filtering, distortion compensation and gain control. Against the background of progress being made in the study of this technology, advances have also been made in semiconductor process technology for improving the performance of the Analog to Digital Converter (ADC) and Digital to Analog Converter (DAC) circuits. Specifically, the improved performance of the ADC and DAC has made it possible to implement high-precision signal processing using digital techniques while at the same time high-frequency analog and digital circuits can be mixed efficiently on one chip due to developments in RFCMOS technology[*6], and submicron semiconductor processes have made it possible to fabricate digital circuits (whose size is process-dependent) that are smaller than analog circuits performing the same function (whose size is more dependent on material constants). In the future, it is likely that radio transceiver circuit technology will progress based on these digital RF technologies.

Figure 4 shows the how the footprint of each part of the radio transceiver circuit for a single band has evolved. As explained above, we have been able to substantially reduce the radio transceiver circuit size due to advances in circuit construction. Meanwhile, the front-end parts have also become smaller due to miniaturization of the filter components and advances in module technology [13]. The end result is that the current circuit configuration is over 60% smaller than in the initial FOMA

*2 **SiGe-BiCMOS**: Semiconductor circuits consisting of BiCMOS gates made from Silicon (Si) doped with Germanium (Ge).

*3 **Hybrid analog/digital IC technology**: An IC fabrication technique where analog and digital circuits are implemented on the same package.

*4 **ABB**: The analog circuit that performs baseband processing. It mainly consists of an ADC and a DAC.

*5 **EVM**: A measure of signal precision, given by the difference in position between where a signal should be and the actual signal obtained after modulation and demodulation.

*6 **RFCMOS technology**: CMOS circuit technology used in the frequency bands for radio communication.

terminals. Consequently, even in the largest configuration shown in Table 2, the radio transceiver circuit can be built with a smaller footprint than the transceiver circuit of the FOMA 900i.

Figure 5 shows the configuration of the radio transceiver circuit that is expected to be used in the latest models. This figure shows a configuration based on information about forthcoming transceiver ICs released from Radio Frequency Integrated Circuit (RFIC) manufacturers. As this figure shows, configurations in which the W-CDMA and GSM circuits are combined will become the mainstream in the future. Furthermore, with regard to the interface between the transceiver IC and Digital Base Band (DBB), there is a trend towards adopting the DigRF3G[*7] industry standard [14], which is likely to result in further integration of circuit components.

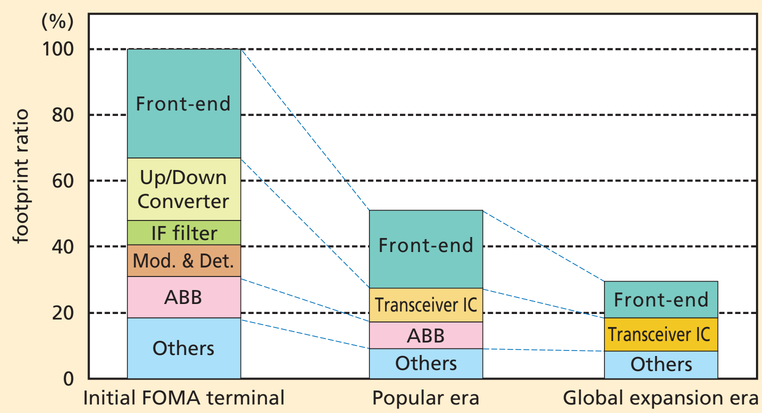

Figure 4 Changes in circuit footprint

4. Technical Issues of Radio Transceiver Circuits with Super 3G Implemented as Standard

Super 3G was developed by the 3GPP as the Long Term Evolution (LTE), and technical specifications [15] were released in December 2007. In the future, it is thought that this technology will undergo full-scale development for commercial systems. This chapter discusses the technical issues of implementing Super 3G in radio transceiver

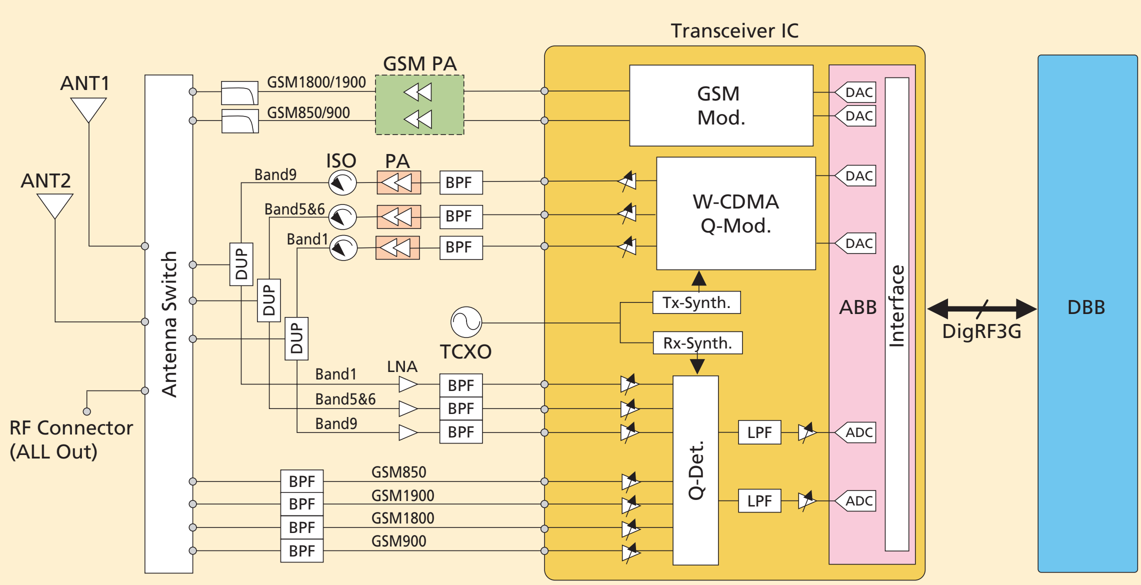

Figure 5 Radio transceiver circuit configuration for 2008 (projected)

*7 **DigRF3G**: A standard for digital interfaces between baseband processors and transceiver ICs in Third-Generation mobile phones, specified by an industry group called the Digital Interface Working Group.

circuits, and the development trends of commercial mobile terminals that are compatible with Super 3G.

4.1 Radio Transceiver Circuit Requirements

The basic specifications of a Super 3G mobile terminal are shown in **Table 3**. The technical concerns regarding the implementation of transmitter circuits with regard to the specifications shown in this table are as follows:

- Due to the adoption of SC-FDMA [16] and 16-Quadrature Amplitude Modulation (QAM)[*8], non-linear distortion causes pronounced degradation.
- Since W-CDMA is also present, the adjacent channel leakage power is specified without regard to bandwidth. This means that leakage has to be suppressed to lower levels than hitherto.
- Maximum Power Reduction (MPR) is specified as a measure for the relief of signals whose power level has a high Peak to Average Ratio (PAR), but since this leads to area limitations, it is desirable not to use this technique in practical operations.

In mobile terminals, it is also important to consider issues of heat generation and battery life. For these reasons, Super 3G transmitter circuits should be designed for improved linearity while maintaining high efficiency. With regard to such issues, we have so far managed to improve the performance of the Power Amplifier (PA). In the future, we will have to study the application of linearizing techniques [17].

The technical issues of the receiver circuit are discussed next.

- Wider bandwidth and higher precision

  To achieve the maximum downlink throughput (64 Quadrature Amplitude Modulation (64QAM)[*9], 20 MHz reception), it will be necessary to improve the receiver EVM and extend the receiver bandwidth.
- Improved blocking characteristics

  Since it coexists with earlier systems, it is necessary to maintain the blocking characteristics to interference irrespective of the system bandwidth.
- Compatibility with Multiple-Input Multiple-Output (MIMO)

  In frequency bands above 1 GHz (the frequencies to be applied are still under discussion), it is essential to incorporate a dual system receiver.

With regard to these issues, we must implement an ADC that is faster and more precise, and we must aim for reduced size and increased precision based on the digital RF techniques mentioned in Chapter 3.

Table 3 Basic specifications of Super 3G mobile terminal

Item		Specifications
Band used		Same as W-CDMA (see Table 1)
System bandwidth		Max 20 MHz
Duplex		FDD
TX	Access scheme	SC-FDMA
	Modulation scheme	QPSK, 16QAM
	Maximum output power	+23 dBm
	Occupied bandwidth	Variable in units of RB (=180 kHz)
RX	Access scheme	OFDMA
	Modulation scheme	QPSK, 16QAM, 64QAM
	Antenna branch	2 (under discussion for 1 GHz and below)
	Receiver bandwidth	Same as system bandwidth

OFDMA: Orthogonal Frequency Division Multiple Access
RB: Resource Block

4.2 Technical Issues Regarding the Standard Implementation

The future development of radio transceiver technology is shown in **Figure 6**. If Super 3G is to become widespread, it will be necessary to develop triple-mode (GSM/W-CDMA/LTE) terminals with LTE mode functions added to the W-CDMA and GSM functions. In Japan, there are plans to add more frequencies to cope with the trend towards increasing user traffic [18]. For

*8 **16QAM**: A digital modulation method that allows transmission of 4 bits of information simultaneously by assigning one value to each of 16 different combinations of amplitude and phase.

*9 **64QAM**: A digital modulation method that allows transmission of 6 bits of information simultaneously by assigning one value to each of 64 different combinations of amplitude and phase.

international roaming, it may also become necessary to add compatibility with frequencies that are used abroad, not only for GSM/W-CDMA but also for expanded EDGE/HSPA and LTE coverage. Consequently, radio transceiver circuits are tending to increase in size and complexity in terms of both frequency and functionality. Meanwhile, to produce mobile terminals that people want to purchase, it is essential to offer high quality products at low prices. In addition, to ensure that mobile terminals are brought onto the market in a timely fashion, there will probably also be a demand for further reductions in development time scales and increased flexibility of the radio functions offered by these terminals. To meet these conflicting demands, it is feared that the development burden of radio transceiver circuits will continue to grow in the future.

If we look at the new radio transceiver circuit configuration model shown in Fig. 5 from a different viewpoint, as explained in Chapter 3, it is expected that the size of transceiver units based on digital RF technology will naturally continue to decrease in the future as semiconductor processing technology advances into the deep submicron[*10] region. However, since the front-end units are equipped with separate RF components for each communication system and frequency band, they will require a larger number of components, making it difficult to meet demands for lower prices. Furthermore, the miniaturization of the individual constituent devices of the front-end unit is surpassing the limits of component mounting techniques, so further miniaturization is unlikely with current production methods.

This issue will have to be tackled in the future, and it will be necessary to develop so-called Software-Defined Radio (SDR)[*11] technology where the sharing of circuits between different systems is made possible by cutting down on frequency dependent components such as filters and isolators, even including structural modifications to the transceiver ICs. In SDR transceiver circuit technology, progress is being made in the study of the basic technology for each system [19]-[22], and in the future it will be essential to figure out how these technologies can be applied to the transceiver circuits of mobile terminals. But at the present stage, the technology for implementing a fully SDR mobile terminal has yet to be established, so it is not yet possible to eliminate all the frequency-dependent components (especially duplexers). It is therefore preferable to reduce costs by building platforms based on configurations in which the existence of these modules is taken as a precondition.

Figure 7 shows the configuration of an ideal radio transceiver circuit for a time when mobile terminals are built to conform with the Super 3G standard, based on an extension of these viewpoints. As this figure shows, a mobile terminal conforming to the Super 3G standard should be easy to produce by constructing it from four main components — a transmitter circuit that can adaptively control the transmitted signal, together with a multi-band/multi-mode PA, and main and sub front-end modules based on transceiver ICs — with the exception of the Temperature Compensated Xtal Oscillator (TCXO)[*12].

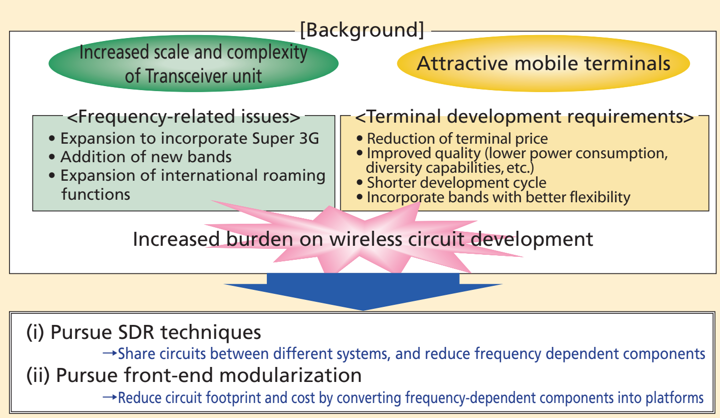

Figure 6 Future prospects of radio transceiver technology

*10 **Deep submicron**: A semiconductor process rule of 0.2 μm or less.

*11 **SDR**: Radio communication in which the RF operating parameters including, frequency range, modulation type, or output power can be set or altered by software, and/or the technique by which this is achieved.

*12 **TCXO**: A crystal oscillator equipped with a function for compensating the deviation of frequency with temperature.

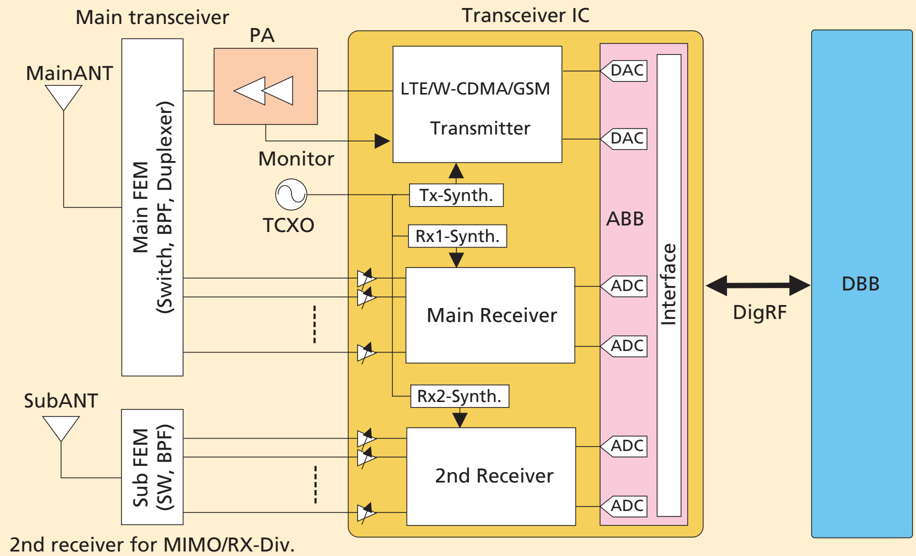

Figure 7 Radio transceiver unit configuration for next-generation mobile terminals

5. Conclusion

As mentioned above, along with the development of FOMA services, radio transceiver circuits have evolved to incorporate direct conversion instead of the superheterodyne method used for PDC, and their configuration has evolved to adopt digital RF technology. In the future, as mobile phones are produced with Super 3G available as standard, it will be necessary to continue making substantial improvements to the front-end parts. From this viewpoint, considering that it is a key point in the technical development of radio transceiver technology, we will study how to move ahead with modularization of the front-end with a view to introducing SDR based on digital RF technologies.

REFERENCES

[1] M. Koiwa et. al: "Multiband Mobile Terminal," NTT DoCoMo Technical Journal, Vol. 8, No. 2, pp. 31-38, Sep. 2006.

[2] S. Hagiwara et. al: "IMT/GSM Dual Mobile Terminal N900iG Supporting International Roaming," NTT DoCoMo Technical Journal, Vol. 7, No. 1, pp. 32-39, Jun. 2005.

[3] T. Nakamura et. al: "Super 3G Technology Trends/ Part 1: Super 3G Overview and Standardization Activities," NTT DoCoMo Technical Journal, Vol. 8, No. 2, pp. 52-56, Sep. 2006.

[4] Medium-term prospects of radio wave usage and the role of administration — A vision of radio wave policy (July 2003, Ministry of Internal Affairs and Communications Commission of Enquiry on Telecommunications, report materials of 7th consultation)

[5] K. Chiba et. al: "Special Article on Dual-band 800MHz/1.5GHz System: Mobile Terminals," NTT DoCoMo Technical Journal, Vol. 4, No. 1, pp. 14-19, Jun. 2002.

[6] 3GPP TS25.101 V8.0.0: "User Equipment (UE) radio transmission and reception (FDD)," Sep. 2007.

[7] 3GPP TS45.005 V7.7.0: "Radio transmission and reception," Sep. 2006.

[8] T. Nojima and Y. Yamao: "Wireless circuit technology for mobile communication," IEICE, chapter 3, 2007.

[9] B. Razavi: "RF Microelectronics," Prentice-Hall, 1998.

[10] S. Tanaka: "Circuit technologies for mobile communication transceivers," Trans. IEICE C, J89-C, pp. 622-640, Oct. 2006.

[11] W. Thomann, V. Thomas, R. Hagelauer and R. Weigel: "A Single-chip 75-GHz/0.35-µm SiGe BiCMOS W-CDMA Homodyne Transceiver for UMTS Mobiles," Proceeding of 2004 IEEE RFIC Symposium, Vol. 6-8, pp. 69-72, Jun. 2004.

[12] N. Aneha, M. Awaga, Y. Segawa, S. Taniguchi, Y. Satoh, H. Yoshizawa, H. Nakayama and K. Inoue: "Advanced Device Technologies for IMT-2000 Systems," Fujitsu Sci. Tech. J., 38.2, pp. 209-223, Dec. 2002.

[13] K. Chiba, M. Murata and T. Okada (Eds.): "Handset Component Technologies," CMC Publishing, Chapter 3, 2007 (In Japanese).

[14] DigRF Working Group: "Dual-Mode 2.5G/3G Baseband/RF IC Interface Standard Version 3.09"

[15] 3GPP TS36.101 V8.0.0: "Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (FDD)," Dec. 2007.

[16] S. Abeta et. al: "Super 3G Technology Trends/ Part 2: Research on Super 3G Technology," NTT DoCoMo Technical Journal, Vol. 8, No. 3, pp. 55-62, Dec. 2006.

[17] G. Norris, et. al: "Application of Digital Adaptive Pre-distortion to Mobile Wireless Devices," Proceedings of 2007 IEEE RFIC Symposium, pp. 247-250, Jun. 2007.

[18] Technical criteria for making effective use of radio waves in VHF/UHF bands (27 June 2007, Partial findings from Commission of Enquiry on Telecommunications, report materials of consultation No. 2022)

[19] T. Sowlati, D. Rozenblit, R. Pullela, M. Damgaard, E. McCarthy, K. Dongsoo, D. Ripley, F. Balteanu and I. Gheorghe: "Quad-Band GSM/GPRS/EDGE Polar Loop Transmitter," IEEE Journal of Sold-State Circuits, Vol. 39, No. 12, pp. 2179-2189, 2004.

[20] H. Okazaki et. al: "Band-Reconfigurable High-Efficiency Power Amplifier—900 MHz/ 1900 MHz Dual-Band PA Using MEMS Switches—," NTT DoCoMo Technical Journal, Vol. 7, No. 1, pp. 11-18, Jun. 2005.

[21] D. Jakonis, K. Folkesson, J. Dbrowski, P. Eriksson and C. Svensson: "A 2.4GHz RF Sampling Receiver Front-End 0.18-μm CMOS," IEEE Journal of Solid-State Circuits, Vol. 40, No. 6, pp. 1265-1277, Jun. 2005.

[22] S. Karvonen, T.A.D. Riley and J. Kostamovaara: "A CMOS Quadrature Charge-Domain Sampling Circuits with 66-dB SFDR Up to 100MHz," IEEE Transactions on Circuits and Systems 1, Vol. 52, No. 2, pp. 292-304, Feb. 2005.