Research and Developments of Software-Defined Radio Technologies in Japan

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ABSTRACT

Software-defined radio technologies are attractive for future mobile communication systems because of reconfigurable and multimode operation capabilities. The reconfigurable feature is useful for enhancing functions of equipment without replacing hardware. Multimode operation is essential for future wireless terminals because a number of wireless communication standards will still coexist. Recently, research efforts on SDR have become very active in Japan, and various kinds of SDR prototypes have been developed. This article introduces the trends of Japanese wireless communication systems and the role of SDR technologies for the future wireless systems. R&D activities for the SDR in the field of academia and industry are also presented including examples of SDR prototypes.

INTRODUCTION

The third generation (3G) of mobile communication systems, International Mobile Telecommunications 2000 (IMT-2000), is scheduled to start service in Japan in October,2001 for higher quality and variable transmission speed for multimedia information. Researchers' interest is moving beyond 3G, to multimedia mobile access communication (MMAC) system in Japan as well as in the U.S. national information infrastructure (U-NII) and broadband radio access network (BRAN) in Europe. In fact, various systems coexist with different standards in mobile communication and wireless LAN. In transition between 2G and 3G mobile cellular systems there coexist many different standards such as Personal Digital Communication System (PDC), Global System for Mobile Communications (GSM), IS-95, Personal Handyphone System (PHS), DECT, EDGE, GPRS, IMT-2000, cdma2000, and so on. However, their interoperability has not been completely ensured in both a handset and a base station yet. Although IMT-2000 was designed in order to make a single global standard, minor differences still remain. In wireless LANs, there are standards — IEEE802.11b (ARIB-STD33), IEEE802.11a (ARIB STD-T71), and HBRAN (ARIB STD-T70) — but widely varying wireless LANs using direct sequence (DS), frequency hopping (FH), orthogonal frequency-division multiplexing (OFDM), and other technologies coexist; some of them seem to be de facto standards, such as Bluetooth. Their different specifications result in less interoperability among them. In particular, Japanese customers are used to mobile wireless access to the Internet with a handset such as i-mode of NTT DoCoMo, wireless connection in intelligent transport systems (ITS) such as GPS car navigation, and dedicated short-range communications (DSRC) including electric toll collection (ETC) and intervehicle communications (IVC). To satisfy such demands, many manufacturers in Japan have been developing various wireless systems with different specifications. However, radio frequency resource is limited in practice, coexisting systems tend to interfere each other, and sometimes too much wireless equipment needs space in a vehicle. Therefore, a software-defined radio (SDR) system with multimode and multifunctional capability is urgently needed in Japan. The Software Radio Study Group was formed in December 1998 by the Institute of Electrical, Information, and Communications Engineers (IEICE) of Japan in order to promote R&D in the field of SDR or reconfigurable radio systems. Several companies and laboratories have developed prototypes of multimode transceivers using SDR components.

This article introduces present and future wireless communication systems in Japan and the expectations for SDR technology in future mobile communications. Research results for SDR in academia and industry are presented. Configurations and features of seven kinds of SDR prototypes made by laboratories and companies are also described.

Wireless Communications Systems in Japan

As in other countries, there exist a number of standards for wireless communications systems in Japan, such as those for cellular, wireless LAN, and cordless telephone shown in Table 1. Three international standard mobile communications systems — PDC, cdmaOne, and PHS — are active in Japan. The number of subscribers is 66 million, and the penetration rate is about 55 percent of the population. PDC and cdmaOne are so-called cellular systems, and PHS is a kind of microcell system. PDC and cdmaOne systems provide nationwide services. PHS systems do not cover rural areas but closed areas such as subway stations and underground shopping malls where cellular services (PDC and cdmaOne) are unavailable. Thus, the cellular systems and PHS complement each other in the coverage aspect. NTT DoCoMo provides a dual-band (800 MHz/1.9 GHz) and dual-mode (PDC/PHS) portable phone called Doccimo. Doccimo users can make and receive calls almost everywhere, such as in rural, urban, and underground environments, utilizing this complementary characteristic of the two systems.

i-mode service was implemented in the PDC system using packet transmission channels. Many young people enjoy i-mode for exchanging e-mails with their friends; 20 million people became i-mode subscribers within two years! The newest i-mode terminal has the capability to download Java application programs. Currently, most of the programs are games, but many new kinds of services are expected through downloading various application programs.

NTT DoCoMo provided a new service including subscriber location information. The PDC terminal is connected to equipment with a GPS function and large display. The user can get various information, such as restaurants and hotels close to the user's location. It is more convenient if these functions (cellular, GPS, and display) are combined in one terminal.

Three cellular operators got licenses for IMT-2000 services in Japan. Commercial service will begin within 2001–2002 by using either wideband code-division multiple access (W-CDMA) or cdma2000 technology. These operators will provide nationwide services. It may be helpful for avoiding huge initial investment to the infrastructure if dual-mode terminals were applied during introductory stage.

Since the price of 2.4 GHz band wireless LAN is going down, it will become popular for home use like cordless phones. A higher-speed (30 Mb/s) wireless LAN, MMAC, has been standardized in Japan. The air interface specification of the MMAC is the same as HBRAN developed in Europe and IEEE 802.11 in the United States.

System		Frequency bands
Cellular	PDC & cdmaOne PHS (microcell)	800 MHz & 1.5 GHz 1.9 GHz
Wirless LAN	IEEE802.11 MMAC Altair (Motorola)	2.4 GHz (ISM band) 5.15–5.25 GHz 19 GHz
Pager	NTT and POCSAG	250 MHz
Cordless phone	Analog	250/400 MHz

Table 1. *Current wireless communications systems in Japan.*

Research on systems beyond IMT-2000, or the fourth generation (4G), has started in Japan. The major objectives are:

- High-speed transmission (downlink: 20 Mb/s in an average cell area)
- Next-generation Internet support (IPv6, quality of service — QoS, Mobile IP)
- High capacity (more than 10 times that of IMT-2000)
- Providing seamless services with fixed and private networks
- Utilize higher frequencies (microwave: 3–10 GHz)
- Lower system cost (1/10 of IMT-2000)

The toughest technical problem is ultra-high-speed transmission in the higher frequency band. Cell radius becomes smaller according to the increase in propagation loss and transmission bit rate under the limited RF output power. 4G may be applicable in urban areas where cell radius is relatively small, but it is quite difficult to cover rural areas where large cells or a number of small cells are required, resulting in higher investment. One solution to this problem is to utilize a 3G radio access network in rural areas. This means that 4G mobile terminals must be dual-mode (4G and 3G), and SDR becomes useful.

Seamless means that whenever the user makes a call, he/she can use the best communication system at that location. Best means, for instance, cheapest, highest speed, and/or most reliable. If the user is in a house, wireless LAN or fixed telephone may be the best communication system; outdoors, only a cellular system can provide services. In this case, communication terminals must have a multimode function.

The Role of SDR in Wireless Communication Systems

Reconfigurability

Although most existing mobile phone terminals do not have reconfigurability, it will become very important for future systems. Table 2 predicts the required reconfigurable functions for mobile stations and base stations. There are three layers in the operation of mobile and base stations. An application layer corresponds to the time period after the call is set up. Anybody can make, download, and run application programs. The newest PDC terminals have this function. The programs are written in Java. Most current programs are games, but in the future various software will

Usually hardware equipment must be replaced when new functions are added to the base stations. SDR's ability to be reconfigured solves this problem.

	Mobile station	Base station	Et cetera
Application layer	Applications programs (games, user encryption, e-commerce, etc.) Games in Java (PDC MS) QoS (quality, bit rate)	–	Programming is opened for third parties, downloaded by users
Middle layer	Authentication, encryption	Bug fix	Programmed only by manufacturers
	Baseband SDR Call control, mobility, and radio resource management (Multiple access (TDMA/CDMA, handover, location registration, frequency assignment, etc.)		Approval is necessary
	PDC/PHS dual mode not by SDR High-speed channel (64 kb/s) added (PHS)		Downloadable by users with some restrictions
Physical layer	Modulation Scheme and Bitrate,		
	RF SDR Output frequency range and channel separation, output power, antenna pattern		License is necessary

Table 2. *Reconfigurable functions (examples). Underlined: functions already implemented in existing systems.*

developed, such as for user-specific encryption, e-commerce, customized agent functions, and so on. This cannot be used to reconfigure mobile terminal operation, but is important for providing new services.

Call control, mobility, and radio resource management functions are included in a middle layer. Since these functions are different among mobile communication systems, reconfigurable capability is useful for multimode operation terminals. Programming and downloading of the software for these functions should be allowed only for terminal manufacturers, but not for users or third-party software companies because it is very important to keep up the quality and reliability of communication systems. Special downloading procedures must be considered for protecting against illegal use of this capability.

Baseband SDR technology is applicable for the middle layer. In PHS base stations, a time-division multiplexed (TDM) time slot assignment function was reconfigured. Original data communication was 32 kb/s, but additional 64 kb/s service was provided using two time slots simultaneously by reconfiguring the base station software. No hardware was replaced.

The physical layer means wireless circuits. Output frequency, power, antenna gain, and modulation are classified in this layer. Reconfiguring this layer needs government. Baseband SDR functions of the physical layer have already been realized by existing technologies, such as high-speed analog-to-digital (A/D) conversion and DSP; however, much more effort is necessary for development of the RF functions, such as variable frequency/bandwidth filters and ultra wideband amplifiers.

Although the user can download the software of the middle and physical layers, there must be strict limitations so as not to download unapproved programs. Licensing, approval, and protection from illegal use are new issues of the reconfigurability of mobile terminals.

MULTIMODE OPERATION

Table 3 shows where multimode functions are applicable. In Japan, there are two kinds of 2G systems: PDC and cdmaOne. Furthermore, two kinds of 3G systems, W-CDMA and cdma2000, will be applied for commercial services soon. Since these systems provide nationwide service, there will be no demand for multimode/band terminals among these systems. Dual-mode terminals for W-CDMA and cdma2000 are not necessary for domestic applications. However, those who want to utilize 3G services, both in Japan and abroad, need dual-mode terminals.

As for the 4G systems, multi-mode terminals might be essential. As mentioned above, the 4G service area will be limited within urban area at least introductory stage. In order to provide nationwide service, 3G/4G dual mode terminals are essential.

SDR is useful from the viewpoint of saving infrastructure cost. For instance, suppose that one system is good at covering outdoor area and another is suitable for indoors; coverage can be expanded without additional investment in either system if the systems cooperate and dual-mode terminals become available.

BUG FIX AND PERFORMANCE ENHANCEMENT

Cellular systems have become large communications infrastructures, and the number of the mobile terminals is huge. If a software bug is found in the base stations or mobile stations, it is considerably costly to repair. Nowadays some of the software for base stations is downloadable, so the problem may not be as serious. However, debug is impossible for mobile terminals after they are sold. Recalls for software bugs of mobile terminals have already happened in Japan. SDR may solve this problem.

Usually hardware equipment must be replaced when new functions are added to the base stations. SDR's ability to be reconfigured solves this problem. This feature was already realized in Japan in the PHS as mentioned before. When a 64 kb/s channel was added, no hardware was replaced; only software was changed in the base stations.

Requirements for SDR in the Mobile Communication Systems

High-speed and low-power-dissipation baseband SDR components are necessary. As for RF SDR components, wideband and/or tunable characteristics are required. Existing portable phones are very compact, with long battery life and low cost. These performances are required even when SDR technologies are applied.

Since size and weight of PDA-type terminals may not be as serious as for telephone-type terminals, it may easier to introduce SDR technologies for PDA type multimedia terminals rather than the telephone type terminals.

The power dissipation is not as much of a problem problem for the applications to base stations as the size and weight conditions.

Since SDR terminals have capabilities to transmit any kind of frequency, power, and spectrum within specified range, illegal use causes serious interference to other wireless systems. Protection from illegal use is the most important issue.

Systems	Feature	Commonality	Frequency range
PDS+PHS	G Already exists	N FDD/TDD	800 M/1.5 G/1.9 G
PDC+GPS	G Already exists	N TDMA/SS	800 M/1.5 G
PDC+3G	? Both cover nationwide	N TDMA/CDMA	800 M/1.5 G/2 G
3G+4G	G Complementary	? CDMA/?	2 G/3–10 G
3G+2.4G LAN	G Seamless coverage	G CDMA/SS	2 G/2.4 G
4G+MMAC	G Seamless coverage	? OFDM/?	5.2 G/3–10 G
3G+4G+MMAC	G Seamless coverage	N CDMA/OFDM/?	2 G/5.2 G/3–10 G

Table 3. *Examples of multimode terminals. G: good; N: not good.*

The SDR Situation in Japan

The Motivating Force for SDR

In order to respond to demands for SDR, IEICE Software Radio Technical Group (SR-TG) has been organized and are active as follows. After IEICE SR-TG was formed in December 1998, the first technical committee meeting took place on January 27, 1999. Following that, five technical meetings were held over two years, and panel sessions were organized at IEICE annual symposia and IEEE international conferences, such as PIMRC '99 in Osaka and IEEE VTC 2000-Spring in Tokyo (http://www.ieice.or.jp/cs/jpn/sr). Since starting in 1999, numerous regular technical presentations and invited talks have been made at IEICE SR-TG technical meetings, occasionally in conjunction with the SDR Forum (http://www.sdrforum.org). IEICE SR-TG has published a special issue on SDR in the English edition of *IEICE Transactions on Communications* (June 2000) and will do another special issue in the Japanese edition in July 2001. In addition, various SDR prototypes have been developed and theoretical research has been ongoing at universities and research organizations.

Research Trends in SDR

SDR is a broad concept including all-digital transceivers and software-based adaptability for multiple purposes and applications in multiple environments. An SDR transceiver is generally defined as a transmitter and a receiver implemented by such SDR techniques that can adaptively process and control RF analog hardware with software in digital circuits. It should be a multipurpose transceiver which is applicable to all or multiple purposes, and an adaptive transceiver which can learn and adapt to all or a wide variety of transmission and channel environments with software. Such a concept of SDR is quite attractive, but its implementation is not easy because there are still a lot of problems which must be overcome. Moreover, SDR is an enabling technology for designing and implementing devices that are capable of downloading or programming their hardware architecture and functionality remotely.

IEICE SR-TG has been covering various subjects in a field of SDR such as architectures, devises, algorithms, description languages, and application programming interfaces (APIs) for achieving reconfigurability and downloadability in an SDR system [1–3]. R&D for SDR in Japan tends to focus on wireless hardware rather than software architecture because most researchers in SDR come from wireless, electrical, or electronics engineering backgrounds.

A wireless communications system typically consists of several hardware modules such as an antenna, a multiband RF converter, an IF band filter, an A/D converter (ADC), a D/A converter (DAC), a baseband processor, (e.g., DSP, field programmable gate array, FPGA, application-specific integrated circuit, ASIC). For a feasible SDR system, such a structure still has several problems. Several major themes discussed at IEICE TG-SR technical conferences and related workshops are as follows.

Baseband Processing: To achieve reconfigurability and programability for broadband signals, higher-speed signal processing is required. Even if high-speed DSP is prepared for, it is difficult to do real-time processing. On the other hand, if FPGA is employed with a hardware description language (HDL), FPGA is used to achieve mostly real-time processing and HDL as high-efficiency coding, but HDL tends to require a large-scale circuit. Since FPGA is designed to be general composition, it takes several times larger circuits scale than necessary logic numbers. To solve these problems, optimum combinations of DSP and FPGA multiprocessor structures have been presented in IEICE conferences.

ADC and DAC: Power consumption in ADC and baseband circuits is a major problem in a mobile terminal using a battery. The speedup of ADC leads to an increase in consumption of

Most types of DC's use complex mixers to output IQ basedband signals, while a multi-port junction type of DC produced by SONY can reduce power consumption for wider band signals.

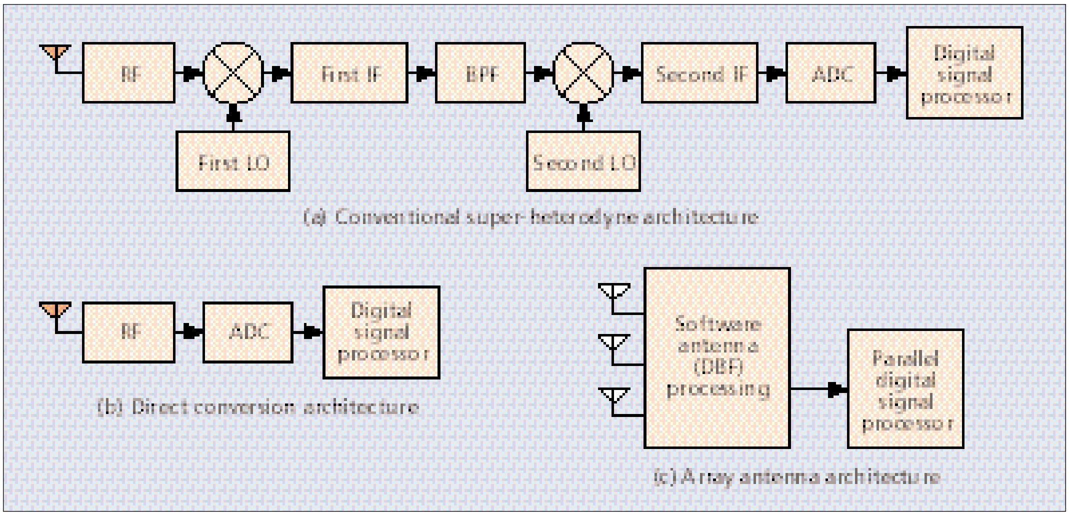

Figure 1. *Various configurations for software-defined radio systems (receiver side).*

electric current while the complication of the digital circuit causes the same problem. To reduce sampling rate and bit modification of ADC, quadrature sampling, which can reduce the rate by using two ADCs for IQ channels, and bandpass sampling for band-limited IF signals have been presented. On the other hand, an architecture for an extremely fast sampling ADC has been invented using superconductive devices, and its feasibility has been improved.

Direct Converter: Conventional wireless communication systems typically have a double superheterodyne architecture which consists of RF, IF, and basedband modules as in Fig. 1a. However, IF modules tend to restrict reconfigurability due to nonlinearity and high power consumption. To avoid IF modules like Fig. 1b, various types of direct converters (DCs) have been proposed. DCs can directly convert RF signals down to baseband or very low frequency IF signals. Most types of DCs use complex mixers to output IQ basedband signals, while a multiport junction type of DC produced by Sony can reduce power consumption for wider-band signals. Figure 2 shows classification of hardware architectures of receivers in terms of downconversion schemes.

Smart Antenna: In order to carry out a single hardware system available for multiple standards,

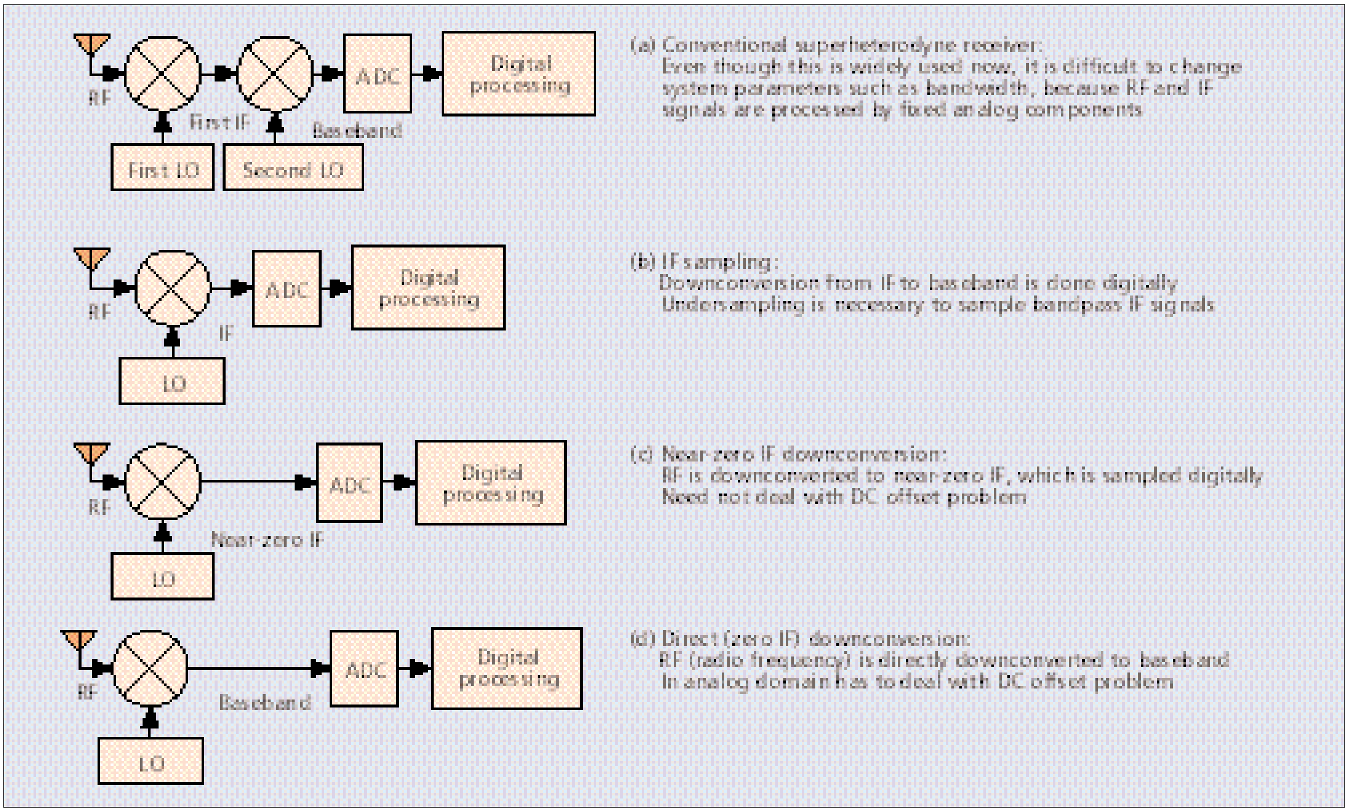

Figure 2. *Types of down conversion in receiver.*

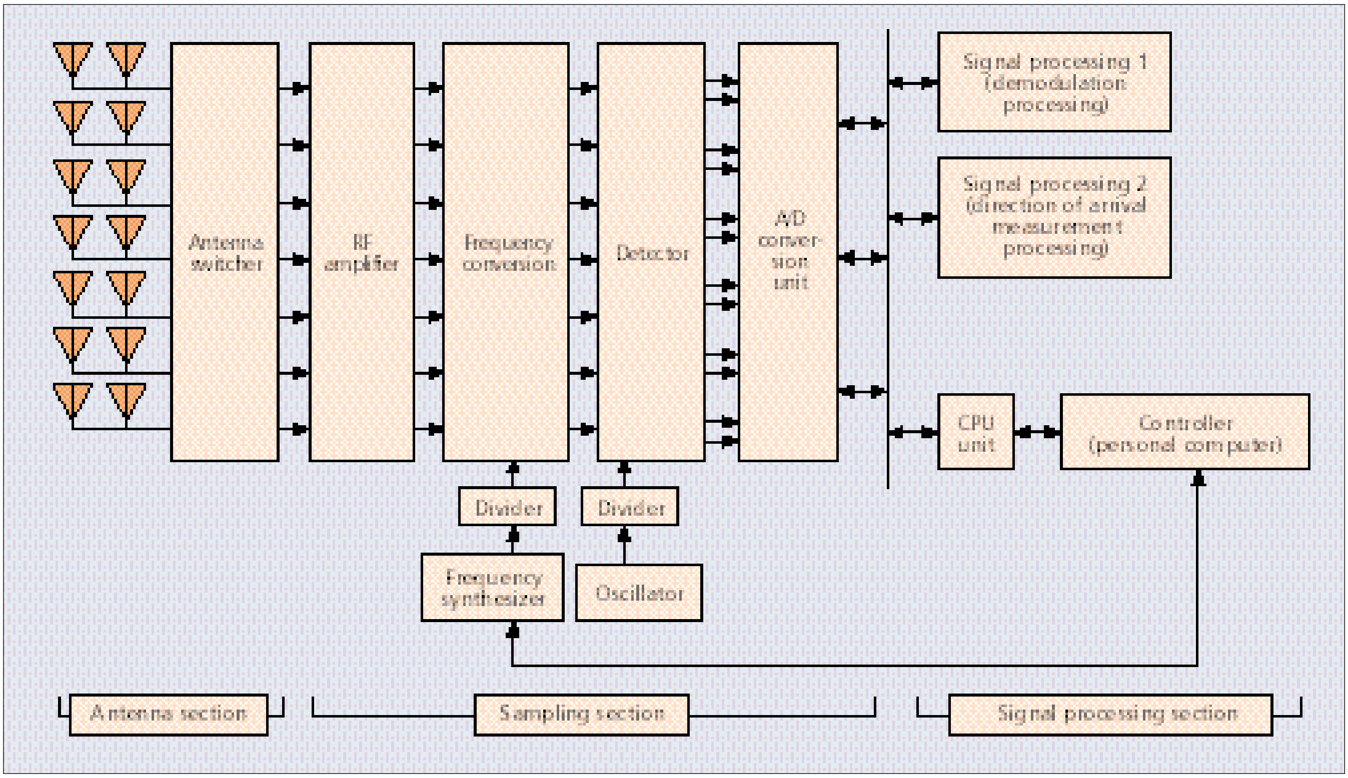

Figure 3. *A block diagram of the prototype SDR receiver for ARIB.*

an antenna and an RF circuit require robust and wideband performance. However, a wideband RF circuit leads to increase of circuit current and nonlinearity of ADC. A baseband circuit has been implemented in digital and adaptively controlled with software, while an RF circuit is still analog with less adaptability. In particular, an antenna must be very hardware-dependent, and hence is a bottleneck when a fully reconfigurable system is carried out. Therefore, an antenna with more adaptability is required to realize an SDR system. Novel structures and algorithms for an adaptive array antenna with software control (i.e., a software antenna) have been proposed in Japanese academia and industry [4, 5].

Other Topics: SDR in Japan stimulates a lot of related research such as adaptive coding/decoding, and adaptive modulation/demodulation in which channel coding and modulation schemes can be adaptively changed to optimize QoS in transmission according to channel conditions and required services. In particular, various schemes to identify modulation and coding schemes used in the transmitter have been presented. Download methods have been proposed to ensure security and authentication of downloaded information. Hardware/software codesign is also an important subject in which a system description language should be designed to code with a high level of language without being conscious of software vs. hardware.

Not only these technical discussions but also regulatory activities are ongoing, in particular a new concept of type approval or its alternative regulation for reconfigurable hardware systems, because an innovation in regulation is necessary for mass production of commercial wireless systems maintaining QoS and avoiding illegal use.

SDR Prototypes in Japan

In order to clarify the feasibility of SDR, several organizations have developed prototype SDR as the first step in SDR application studies in Japan. Targets of those studies are to verify the feasibility of SDR functions.

A study group concerned with the development of the software receiver was established with the Association of Radio Industries and Businesses (ARIB) [6, 7]. In the period from 1996 to 1998 this study group investigated not only the successful development of terminals commonly usable in various systems, but also radio monitoring equipment that can cope with an ever increasingly complex radio wave environment. As one of the application examples, a prototype model was manufactured and evaluated. The specifications for the functional model were discussed and the prototype was manufactured as a typical example for evaluation of the software receiver. Among the applications of the software receiver, radio monitoring especially requires many functions, including direction of arrival estimation, interference wave suppression, and radio wave characteristic measurement. For this reason, its specifications were defined, giving major consideration to this radio monitoring application. The functions the prototype successfully offers are:

- Multimode, multirate demodulation
- Direction of arrival estimation
- Interference wave suppression
- Radio wave characteristic measurement
- Software download

The main prototype specifications are RF frequency bands of 27 MHz, 900 MHz, and 2 GHz, 6-element circular antenna array, bit rate of 8–32

The experimental prototype can realize three real telecommunication systems: PHS with 384 kb/s, GPS with 50 bit/s (1.023 Mchip/s), and ETC systems with 1.024 Mbit/s as Service mode.

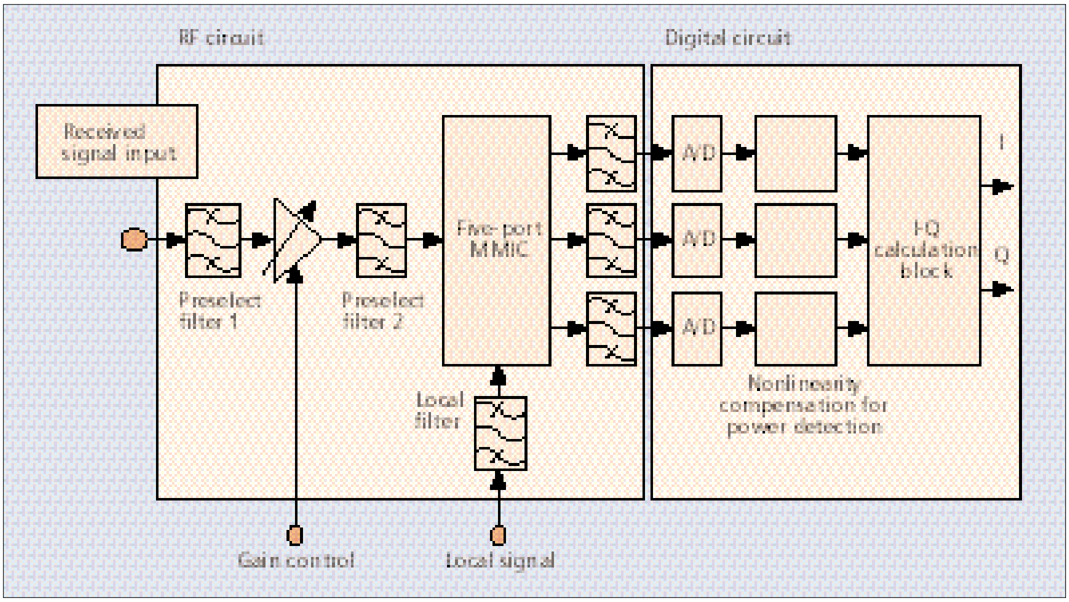

Figure 4. *A block diagram of Sony CSL's SDR platform (SOPRANO).*

kb/s, modulation methods of binary phase shift keying (BPSK), quadrature PSK (QPSK), π/4-QPSK, Gaussian minimum shift keying (GMSK), FM and AM, direction of arrival (DOA) estimation method using multiple signal classification (MUSIC), interference suppression function, and so on. A block diagram of the prototype is shown in Fig. 3.

Communications Research Laboratory (CRL) of the Ministry of Posts and Telecommunications (MPT) has proposed a configuration method for an SDR system in order to overcome these problems in the full-download-type SDR system. In the proposed method, basic telecommunication component blocks have already been implemented in digital signal processing hardware such as DSP and/or FPGA. As for each block, the specification is not fixed but programmable and changeable easily by downloading external parameters. For example, for the filter block the download parameter is only the filter coefficient, and for the coding block the download is carried out with only a parameter of the equation of generation polynomial. Only by changing the external parameters required can telecommunication systems be reconfigured. The SDR system is a parameter-controlled-type SDR system. In order to show the effectiveness of proposed SDR system, an experimental prototype was developed and its transmission performance was evaluated [8]. The experimental prototype can realize three real telecommunication systems: PHS with 384 kb/s, GPS with 50 b/s (1.023 Mchip/s) and ETC systems with 1.024 Mb/s service mode. Moreover, in user mode, it is possible for a user to freely conduct several modulation schemes of GMSK, π/4-QPSK, BPSK, and QPSK. As for PHS and GPS, the antennas of two systems are integrated into one antenna because the frequency utilized in GPS (1.5 GHz band) is quite close to PHS (1.9 GHz band). And the external parameters, needed to change the system, are supplied from a notebook computer connected to the experimental prototype by a 10 Base-T Ethernet cable.

Sony Computer Science Laboratories has proposed an SDR platform called Software Programmable and Hardware Reconfigurable Architecture for Networks (SOPRANO) [9]. It is capable of handling multiband and multimode radio standards for such applications as wireless LANs and cellular phone systems, whose carrier frequency ranges from 500 MHz to 9 GHz, applicable modulation schemes of BPSK, QPSK, 8-PSK, 16-array quadrature amplitude modulation (16-QAM), and 64-QAM, and bandwidth of 15 MHz. The proposed platform consists of a reconfigurable digital circuit, ADCs, DACs, and a low-power wideband analog component called a multiport junction monolithic microwave integrated circuit (MMIC) for direct converting radio signals to baseband signals. The configuration of SOPRANO is shown in Fig. 4. The flexible digital hardware and analog RF components are capable of handling multiband and multimode radio signals. The digital platform can handle various wireless schemes by reconfiguring the hardware. A new design methodology accepts hardware description in C language, whose hardware architecture is synthesized by optimizing its hardware resource and scheduling. The C program is translated to HDL, which is then converted to a network of electronic components by a synthesis tool. The network is then mapped to an FPGA. The demonstration software running on the FPGA is capable of processing several millions samples per second in real time. The receiver MMIC is based on the linear operation of the device, and related nonlinear effects may be omitted. The power level of the local oscillator (LO) is much smaller than in the classical approach. Therefore, the DC offset problems may be overcome. Moreover, the proposed DC receiver is able to support a wide band that is more demanding for conventional I/Q receivers. The received signal passes through preselect filter circuits, and the gain-controlled low noise amplifier (LNA), and is then fed to the proposed five-port-junction MMIC. The out-

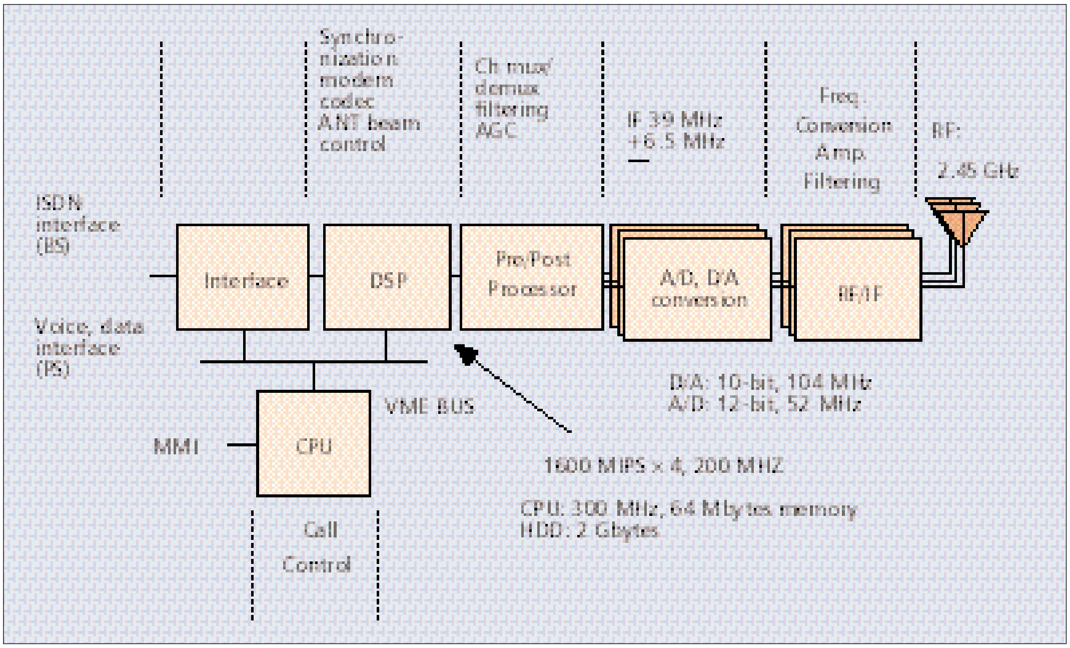

Figure 5. *The configuration of NTT's prototype SDR station.*

put of the MMIC is A/D converted and fed to the DSP part. In this part, the nonlinearity is compensated for, and the in-phase (I) and the quadrature (Q) values of the signal are calculated from the three output voltages of the MMIC.

NTT has developed an SDR prototype base station and personal station for various types of cellular systems [10]. The main prototype specifications are RF frequency band of 2.45 GHz, bandwidth of 13 MHz, three-branch antenna and RF/IF circuits, bit rate up to 1 Mb/s, modulation modes of BPSK, QPSK, π/4-QPSK, GMSK, and 16-QAM, and a sampling scheme of IF under sampling. A block diagram of NTT's SDR prototype system is shown in Fig. 5. It is composed of RF/IF circuits, ADCs and DACs, pre/post-processors, a CPU, an interface circuit, and DSP parts. The CPU, DSPs, and an interface circuit are connected with a 32-bit VME bus. The base station offers an integrated services digital network (ISDN) interface, while the personal stations have voice and bearer communication interfaces. The pre/post-processors, which handle multiple access and waveform shaping, are employed to reduce DSP loads. In the receiving process, the 39 ± 6.5 MHz IF signal is A/D converted using 12-bit quantization with 52 MHz resolution. The preprocessor undersamples the IF signal, and a channel signal is digitally downconverted, filtered, and fed to the DSPs. In the transmitting process, the reshaped and channel multiplexed baseband signal is upsampled with a 10-bit resolution DAC using 10-bit quantization at 104 MHz. The signal is zero-stuffed before D/A conversion to improve the aperture effect due to the imperfection of the pulses. Four commercially available 1600 mega instructions per second (MIPS) DSPs (offering 6400 MIPS) are mounted on the same board. The loads of the transmission function are relatively simple compared to those of the receiving function. Thus, basically one DSP is assigned to the transmission side and three DSPs to the receiving side. Task programs performing modulation and demodulation, codec, and adaptive array control are loaded onto the DSPs. Those programs communicate with the program on the CPU through the macro interface. The CPU handles communication control and system management. The developed prototype can operate in PHS mode and/or lower-bit-rate mode comparable to the cellular system.

Toshiba has investigated the broadband and flexible receiver for the handheld SDR [11]. The proposed SDR architecture is based on the direct conversion and low intermediate frequency (low-IF) principle with digital channel filtering, which provides the receiver with flexibility for the multistandard application. This architecture also enables ADC activation essentially in baseband or low frequency so that the clock jitter, which services as an important subject in the well-known IF sampling method, can be reduced. Basic performance of the proposed architecture has been confirmed by the experimental prototype. Basic performance of the proposed SDR prototype using direct conversion has been confirmed in the experimental mode. The major hardware specifications are $\lambda/2$ Dipole TX (transmission) antenna and Microstrip RX (reception) antenna, 5 MHz A/D sampling, with 14-bit resolution and so forth.

NEC and Anritsu have developed and evaluated a software receiver that could accommodate future needs [12]. As the first step in making the receiver practicable, modulation mode classification algorithms were studied. As the next step, an adaptive receiver that is the evolution type of the software receiver has been developed. The adaptive receiver analyzes the communication signal of an unknown parameter, and is the environment adaptive type receiver for automatic extraction and automatic demodulation of the signal parameters. The modulation method identification algorithm using the analysis techniques of envelope analysis, symbol radius distribution characteristic analysis,

The output of the MMIC is A/D converted and fed to the DSP processing part. In this part, the nonlinearity is compensated for, and the in-phase (I) and the quadrature (Q) values of the signal are calculated from the three output voltages of the MMIC.

The adaptive receiver analyzes the communication signal of an unknown parameter, and it is the environment adaptive type receiver that performs an automatic extraction and automatic demodulation of the signal parameters.

and phase difference histogram analysis between adjacent symbols were proposed and the experimental results reported. The major parameters of the prototype receiver are demodulation modes of AM, FM, FSK, MSK, GMSK, BPSK, QPSK, $\pi/4$-QPSK, 8-PSK, and 16-QAM, access types of time-division multiple access (TDMA) and single channel per carrier (SCPC), symbol rate up to 10 Msymbol/s, speech codec for adaptive differential pulse code modulation (ADPCM), and the continuous variable slope delta modulation (CVSD-DM) sampling method of IF undersampling.

Hitachi Kokusai Electric has developed a prototype which provides compatibility with the typical types of waveform for both digital and analog modulation as well as full duplex for the study of technical issues such as DSP, RF signal processing, software download, and software adaptability. The under (bandpass) sampling scheme was employed for the receiver of the prototype. From evaluation tests it was recognized that the developed prototype presents better characteristics than conventional radio equipment for each type of waveform in both digital and analog modulation. The major parameters of the prototype are IF frequency of 455 kHz–100 MHz, modulation modes of FSK, BPSK, QPSK, 16QAM, AM, FM, and single sideband (SSB) access type of simplex/two-way, and sampling resolution of 16/14 bits, etc.

Toyo Communication Equipment and Tohoku Electric Power Co. have developed a software radio prototype for the radio base station. A design method of SDR including RF section has been proposed and its usefulness confirmed by experiment. It can handle $\pi/4$-QPSK and FM modulated signals. The major parameters of the prototype are RF frequency of 370–380 MHz, modulation modes of$\pi/4$-QPSK, QPSK, BPSK, FSK, and FM, four simultaneous TX/RX channels, TX/RX channel bandwidth of 1.25 MHz/650 kHz, and sampling resolution of 12 bits with 40 MHz sampling rate.

Conclusion

The current status of Japanese mobile communication systems and the expectations for SDR technology are presented. Activities of the Software Radio Study Group and prototypes of SDR transceivers are also introduced.

According to the expansion of mobile communications, the number of standards increases and operational frequency bands extend from UHF to microwave. No system meets all users' requirements, and people subscribe for several mobile terminals. In such a case, SDR may be very effective for user convenience. People can select better systems for tariff, transmission speed, and quality wherever he/she makes a call, such as in a house or vehicle.

SDR is useful for cost saving in enhancing the system performance or functions since it is not necessary to replace hardware.

SDR has many advantages for future mobile communication systems. The success of SDR depends on the progress of hardware technology, such as high-speed and low-power-consumption DSP and ADC/DAC, tunable and low loss filter, ultra wideband power amplifier. Furthermore, the standardization is also important regarding interfacing both among functional modules and between software and hardware.

In the 2G and 3G mobile communication systems, higher-layer functions, such as part of layers 2 and 3 and applications, are already software-based and programmable. In order to realize next-generation mobile communication systems beyond IMT-2000 (4G), we have to realize seamless, flexible, and adaptive wireless equipment including physical layer (layer 1) programmability. SDR technology is one of the most promising ways to meet the requirement for mobile communications in new era.

Although this article has overviewed trends of technologies for SDR, modification of radio regulation has also been reviewed in order to make commercial SDR products more feasible. The Ministry of Public Management, Home Affairs, Posts and Telecommunications (the former MPT) in Japan has initiated its related activities.

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Feature Topic on
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In the course of the accelerated contention of wireless technologies with wired technologies, broadband wireless service has become a reality, and wireless Internet is attainable. However, Quality of Service and cost remain as deficiencies of wireless systems. Despite the freedom of mobility, in the data arena, wireless technologies have enjoyed limited popularity to speak of. The true advantage of mobility in the context of broadband services is exemplified by the capability to deliver location specific services to the mobile user. Expanding the user's range of sight through the fog, and around the corner, as well as increasing the user's visibility to those around him, are among the objectives.

This feature topic issue will address the state-of-the-art of proposals and research activities toward the next generation broadband wireless networks and how these networks can provide global seamless roaming between heterogeneous wireless, satellite, and wired networks. Introduction of the interworking units (IWU) between networks of different standards (2G, 3G, and 4G) and between satellite and terrestrial wireless networks could be considered as the main issue in these networks. The next generation broadband wireless networks will provide new services to users such as Internet connectivity and navigation through satellite and terrestrial networks with perceived level of quality and at an affordable cost.

The feature topic issue looks at different technologies, different protocols, and different network architectures that will be supported in the next generation broadband wireless networks. The choice between IP-based and ATM-based technologies for wireless networks, optimum integration between satellite and terrestrial networks, and solutions for medium access protocols, routing, location management, handoff management, QoS management, error control, and interoperability are going to be explored for the next generation broadband wireless networks in this feature topic issue. The feature topic in particular aims to gather state-of-the-art of the activities in defining new services and applications for the next generation broadband wireless networks with emphasis on satellite-based and navigation services.

The articles for this Feature Topic issue will be solicited through an open call-for-papers and invitation to the experts in the field from industry and academia. Suggested topics for this FT issue include but not limited to:

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- Transport and navigation services in next generation wireless networks
- Geocasting, nearcasting, multicasting for wireless networks
- Terrestrial and satellite-based solutions to navigation and global positioning
- Interoperability between broadband terrestrial and satellite networks
- Ad hoc networking
- Global roaming between heterogeneous wireless networks
- QoS management and QoS provisioning in next generation wireless networks
- Next generation wireless network and ethnic and health implications
- Optimum choice of orbit height for integrated broadband satellite networks

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