Perspective Framework on the Fourth-Generation Mobile Communication Systems

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Abstract: **Emergence of the fourth generation mobile communication system (*4G system*) is now in its dawn. This article proposes a perspective framework on the 4G system, and discusses various kinds of system aspects and technological requirements in terms of novel service features, spectrum management, radio access technologies, wired access integration, core network, and mobile terminal. The focus of the article is to define the scope and features of the 4G system in an overall system/network viewpoint. From the foreseeable development trends, it is highly expected that whatever emerges in the 4G system will be some kind of constantly evolving and grand recursive concatenation of all the existing system/network developments.**

Index Terms: **Fourth-generation, mobile communications, CDMA, wireless multimedia.**

I. INTRODUCTION

The rapid growth of wireless networks and services, accelerated by the third-generation mobile communication system (in short, hereafter, *3G system*) research, is ushering in the era of the fourth-generation mobile communication system. Wireless communication systems are evolving to meet the ultimate goal, to allow 'anywhere, anytime, anything, by anyone' communication customized to a particular subscriber's preferences, location, and social behavior. To reach this goal, much effort is still underway.

Since the ITU (International Telecommunication Union) introduced the 3G concept called FPLMTS (Future Public Land Mobile Telecommunication Systems), it took about two decades until the 3G standard was established. The FPLMTS was first discussed at WARC MOB-87 in 1987, and frequency bands for the FPLMTS were decided at WARC-92 in 1992. In 1996, the 3G system was renamed from FPLMTS to IMT-2000 by the ITU-R. At that time, there were many candidate technologies for the 3G system, which were heavily debated among their proponents. The candidate technologies include cdma2000 (TIA), UTRA (ETSI), and WCDMA (ARIB). From 1997, the 3G standards have been primarily driven by two international standardization organizations - 3GPP (Third Generation Partnership Project) and 3GPP2 [1]–[3]. The 3GPP and 3GPP2 have made coordination and harmonization efforts aiming at a global IMT-2000 system. The 3GPP developed a standard based on WCDMA (wideband code division multiple access) and GSM-MAP, while the 3GPP2 established a standard based on cdma2000 and ANSI (American National Standards Institute) - 41.

As mentioned above, the 3G system development took a long time since its discussion of basic requirements for the 3G service. Therefore, it has little room to accommodate the recent changes such as the explosive growth of Internet and the demand for very high-speed data services. Although the 3G system is designed to support data rates up to 2Mbps, it is hard to provide such a speed to every single user in each cell. Also, highly demanded is the unified provision of various kinds of services including the ones provided by systems such as POTS (plain old telephone system), LAN (local area network), xDSL (digital subscriber line, x: S (symmetric), A (asymmetric), V (very high-speed), H (high-speed)), and 3G systems [4], [5]. Furthermore, the global roaming which is partially implemented in 3G system can not support the true global mobility of terminal, service, and subscriber.

In order to accommodate new needs of the subscribers, a great many efforts on a new wireless system (hereafter, we call it *4G system*) are being made in many countries and organizations including Japan, U.S.A, and ETSI (European Telecommunication Standards Institute). The NTT DoCoMo established a research team in 1998, while the ETSI has launched IST (Information Society Technologies) project to perform basic research for the 4G system. The 4G system can be described as over-the-horizon system. Although the new wireless system is currently called *'system beyond IMT-2000,'* the name is expected to be harmonized to the *'4G system'* in the near future. Since the research on the 4G system is in its very early stage, there are little results showing the perspective framework of 4G services and systems. As the 3G system was based on the 2G system, the 3G system will form a sound base for commercial take-off of the 4G system around 2010. The definition and identification of the 4G system entails new service features, new network types, new frequency bands, new air interfaces, and new terminals.

The previous studies on the 4G system have focused on the individual technology such as radio access technology, core network (CN), terminal implementation, etc. This article aims to shed some light on the overall framework of the 4G systems through suggestion and envisioning of a variety of system/network aspects. In this article, we propose a perspective framework of the 4G system in an overall system/network viewpoint. The focus of the article is to define and identify what the service feature, enabling radio access technology, wire-

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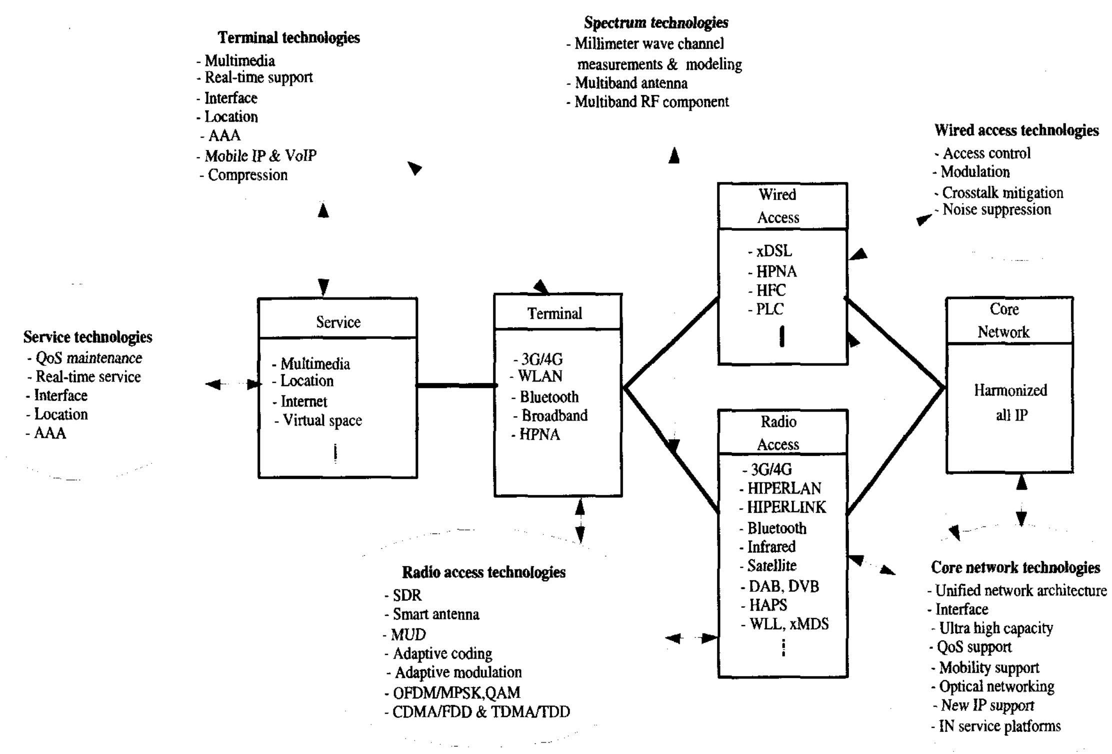

Fig. 1. Conceptual diagram of the 4G system.

less/wired network integration, operating spectrum, core network, and the mobile terminal will be in the 4G system. Finally, conclusions will be drawn suggesting the upcoming challenging issues for implementation of the 4G system.

II. CONCEPT OF 4G SYSTEM

Since the start of discussion on "system beyond IMT-2000" by ITU-R in 1999, the 4G system has been primarily triggered by a number of following factors:

- Rapid growth of mobile systems and services,
- Exponential spread of the internet and intranet,
- Emergence of nomadic computing,
- Convergence of communications and broadcasting,
- Deregulation and liberalization of telecommunications, and
- Openness and integration of different networks.

Our vision of the 4G system aims at:

- Seamless services across various types of fixed and wireless networks,
- Flexible access through reconfigurable terminal and innovative air interface,
- Integration and interoperation of various kinds of systems/networks,
- Service adaptation to the customers' needs through most available resources,
- Development of new spectrum fitted to expected services, and
- Creation of new market opportunities and jobs.

The 4G systems may be defined in various kinds of viewpoints such as services, operating spectrum, radio and wired access, core network, and mobile terminal. In this section, we describe a conceptual framework of the 4G system from these aspects. In Fig. 1, the conceptual diagram of the 4G system is depicted showing the relationship among system components and required technologies. Furthermore, the comparison between the 3G and the 4G systems is made in Table 1 from the various kinds of standpoints.

A. Service Aspects

The 4G system is usually described as a market (service) driven one while the 2G system is technology driven one. The 4G system will provide a new dimension of broadband capabilities. The users of the 4G system will be able to access high data rate services with guaranteed QoS (quality of service), and be independent of their geographical location and time, with a portable device such as laptop, palmtop, PDA (personal digital assistant), or PIC (personal intelligent communicator) [6]. The QoS required is typically associated with an acceptable delay, throughput, and perceptual parameters. It is hard to imagine that the 3G services will disappear when the 4G system is introduced. Rather, the 4G services will be based on a mix of services with a wide range of data rates and defined quality.

Table 1. Comparison between the 3G and 4G systems.

	Mobility			Quality	Operating Frequency Band	Roaming
	Low mobility	Low to medium mobility	High mobility			
3G system	2Mbps	384kbps	144kbps	Almost same as fixed	Around 2GH	Part of the word (partially global)
4G system	A few Mbps		More than a few Mbps	Same as fixed network	3 to 10 GHz	All over the word (global)

Wireless connectivity of the 4G system will enable access to such services in a variety of new environments. Compared to the 3G services, primary requirements of the 4G services are as follows:

- Mobile applications capable of interactively accessing, manipulating, and visualizing distributed multimedia information must be supported, and
- Corresponding transport/access networks must exhibit enhanced capabilities with respect to existing systems such as IS-95, W-CDMA, and other mobile systems to support the corresponding services.

The eventual goal of the 4G services is to provide the users with VHE (virtual home environment) in the sense that the users can be supported without any additional actions as if they are at home wherever they are located.

B. Spectrum Aspects

The radio spectrum has always been a critical issue whenever a new wireless system is introduced. In general, in order to achieve optimal system design and to exercise best engineering practices, extensive considerations should be taken in wireless systems deployment for each specific operating environment according to its propagation behavior. Now, analog and 2G digital cellular systems typically use 800MHz while the 3G system uses 2GHz bands. In developing the 4G system, the selection of frequency band is very important in that a sufficient amount of bandwidth should be allocated for high rate data provision. Since various kinds of wireless systems are now operating below 3GHz band, there may be a substantial collision with other systems if the 4G system is deployed below 3GHz band. Furthermore, if the 4G system is deployed over 10GHz band, serious level of attenuation during data transmission will be inevitable due to rain attenuation and fading. The cost of radio components should also be as cheap as possible. Especially, the cost of RF parts such as PA (power amplifier), LNA (low noise amplifier), PLL (phase locked loop) and mixer should be minimized for a cost-effective implementation of the 4G system. Considering the factors mentioned above, the candidate frequency of the 4G system is expected to be between 3GHz and 10GHz.

In the consideration of operating spectrum for the 4G system, the policies should also address the universally agreed rules dealing with the following questions:

- Who will use the limited spectrum available?
- What will be the technical characteristics such as channelization, power levels, and modulation?
- Which particular portion of spectrum will be allocated for the class of service?

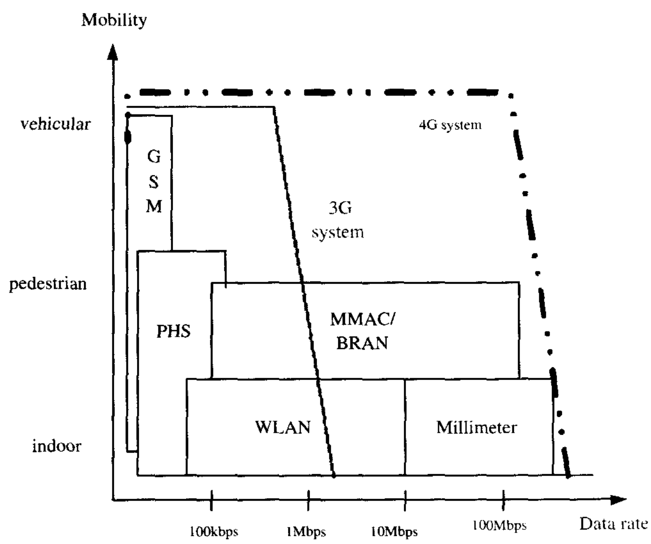

Fig. 2. Service coverage of 4G system.

C. Radio Access Aspects

In Fig. 2, the service coverage of the 4G system is depicted with respect to the mobility and data rate. The 4G system can support all the services available in the 2G and 3G systems as well as the 3G evolution (minor modification version of the 3G) system. The operational requirements of the radio access for the 4G systems include support of multiple data rates, simultaneous radio links, low power mode, multipath resistance, and high frequency agility. As was the case of the 3G system, the consensus toward a unique standard for the 4G system is expected to be a difficult one due to the heavy industrial competition among many countries. In this framework, the concept of software radio will surely provide a potential pragmatic solution by dynamically adapting to the radio environment in which it exists.

The radio access of the 4G system should support data rate up to a few hundred Mbps under various mobility environments, and entails a wide range of air interfaces. Each part of the radio access system should be flexible enough to adapt itself with high reconfigurability to the varying traffic load, channel environments, and service features [7]. Aiming at faster and more efficient transmission of high-speed data, the following techniques should be defined in a new paradigm:

- High spectrum/power efficiency (modulation/demodulation adaptive modulation),
- High reliability (channel coding, adaptive coding),
- High system capacity (smart antenna, multiuser detection, diversity, power control, multiple access/duplex),
- High flexibility (software defined radio), and

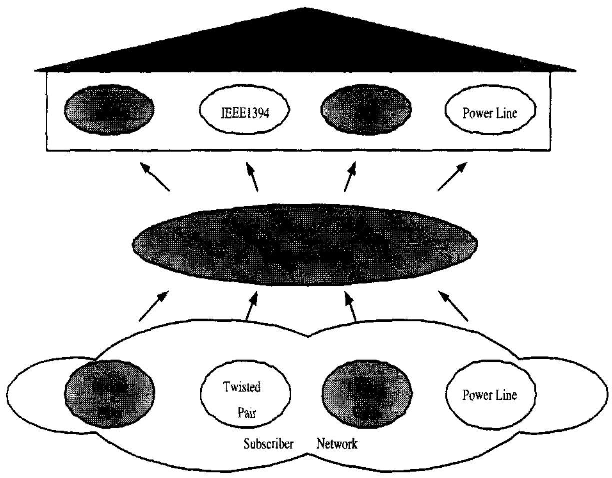

Fig. 3. Wired access network in the 4G network.

- High connectivity (handoff).

D. Wired Access Aspects

Communication network has been developed in the sequence of transport, subscriber, and home networks. Unlike the transport and subscriber networks which had been developed in a rather short period mainly by government and service providers, the various aspects of the home network, as the premise communication infrastructure of a new concept, are still under active discussion these days. The home network employs telephone line, UTP cable, and powerline as physical media while connecting HPNA (home phoneline networking alliance), IEEE1394, and fast Ethernet devices to the media.

The subscriber network has achieved technical maturity based on the DSL and HFC (hybrid fiber coaxial). However, the home network is still in a stalemate because there is no killer application, even though the office network was introduced by demand, and excited by Internet. Digitalization, with the Internet revolution and the spread of home digital devices, made it possible to connect information from the subscriber network to the home network. Through this kind of network, a lot of diverse services become available. Therefore, the 4G network should be able to build the end-to-end wired network connecting digital devices through subscriber and home networks. The wired access network of the 4G system will integrate diverse subscriber networks and home network, and provide high-speed multimedia service through the integrated network consisting of optical fiber, twisted pair, coaxial cable, PLC (powerline carrier), and home network.

Fig. 3. shows the conceptual diagram of integrated access network of the 4G network that provides IP and multimedia services [8]–[12]. The ideal solution of subscriber broadband network will be FTTH (fiber-to-the-home) that connects fiber to the home supplying almost unlimited bandwidth. However, the FTTH is not economical, and takes long time to replace conventional copper with fiber, so it is hard to consider this solution in the present. Alternative economic solution is FTTN (fiber-to-the-neighborhood) that includes FTTB (fiber-to-the-building), FTTC (fiber-to-the-curb), FTTCab (fiber-to-the-cabinet), and HFC. The FTTN uses fiber near to the subscriber, and employs conventional infrastructure as a final drop to supply high-speed access network. The candidate for the wired home network technologies will be HPNA, USB (universal serial bus), IEEE1394, PLC as well as the conventional Ethernet.

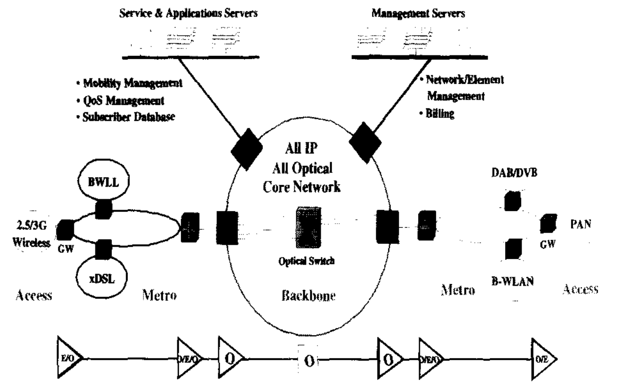

Fig. 4. Architecture of 4G core network. (*O: optical, E: electrical, GW: gateway, E/O: electrical-to-optical conversion, O/E: optical-to-electrical conversion)

E. Core Network Aspects

The first consideration in design of the 4G CN is the significant growth of data traffic, mainly driven by Internet-based services. Recently, the Internet is not considered as just a network, but it is emerging as a means of network and resource integration. Although the exact prediction on traffic statistics is impossible, what is clear at this moment is that the data traffic rather than the voice traffic will play a important role in the 4G CN.

The key open challenge for the 4G CN is its support for diverse access technologies such as PSTN (public switched telephone network), digital cellular networks, pager networks, and IP-based networks. Today's CN is based on a circuit-switched Signaling System No. 7 architecture. With the advent of the IP technology and tremendous demands on the data/voice traffic, the core network is evolving toward IP-based network. Keeping pace with these trends, the 4G CN should be designed to meet the following goals:

- Potential to access any network services,
- Easy adoption of service creation and customization,
- Scalability, availability, and fault tolerance,
- Extensibility, robustness, and personalization,
- Personal and service mobility, and
- Security, authentication, and privacy.

The 4G CN should guarantee the interworking of mobile and fixed networks so that it enables location- and terminal-independent access to a customized set of telecommunications services and seamless operation while in motion and/or roaming across different service provider domains. In addition, it should allow freedom in accessing and flexibility in invoking telecommunication services which can be ultimately achieved by:

- Personal mobility (enabling relocatable association between user subscription and actual terminal used),
- Terminal mobility (maintaining an established connection under both static and dynamic conditions), and
- Service mobility (enabling management of user service profiles).

Sample architecture of the 4G CN is shown in Fig. 4. It has become clear that the common traffic convergence layer in communication networks is going to be IP (internet protocol), because all forms of end-user communications practically make use of the IP protocol. Furthermore, since IP-based applications such as voice, video, and other multimedia applications are driving tremendous expansion, more amenable control and management solutions are required [13]. In parallel with the developments in IP technologies, significant advances are being made in optical component technologies, e.g., optical cross connector and optical switches.

The rapid growth of IP technology coupled with the large bandwidth yielded by optical network has sparkled a lot of efforts to bring the two technologies closer. There is an increasingly important need for designing a reliable control layer for optical networks with a focus on IP protocol internetworking. In all optical networks, packet-by-packet or cell-by-cell electrical routing processing is not performed in transit nodes, which minimizes the processing bottleneck. Pure optical domain will be restricted to long-haul network at the early stage of the 4G network, but it will be stretched out to the access network. Ideally, the optical domain may cover end-to-end services without any electric-optic conversion within the core network. The removal of electrical processing and the introduction of optical routing will yield a core transport node with vast throughput.

The distinguishing aspect in the CN architecture of the 4G system compared to the 3G system will be that the 4G CN should achieve seamless convergence of various types of wired and wireless access networks. As boundaries between the communications and broadcasting become blurred, those access networks encompass every available communication systems/networks such as xDSL, WLAN, WLL (wireless local loop), 2G/3G cellular network, DAB/DVB (digital audio/video broadcasting), satellite communication, ITS (intelligent transport system), intelligent logistics, remote surveillance, teleservice applications, location system, private multicast, distributed computers, and *ad-hoc* network. Therefore, the 4G CN should support the mobility and QoS among different access networks and a lot of IP related issues such as voice and/or multiservice over IP, IPv6, and mobile IP. In addition, the 4G access network is quite expected to be a dense aggregation of radio nodes controlled by a multitude of operators, and should be self-organizable (i.e., not requiring cell or frequency planning) in a dynamic network environment.

F. Mobile Terminal Aspects

The mobile terminal has to be capable of supporting various air interfaces and services to satisfy users' demand. Mobile terminal of the 4G system will have various kinds of characteristics such as high-speed data rate, broad bandwidth, various air interfaces and a variety of services, including support of QoS and user/terminal mobility. In order to support various air interfaces, the mobile terminal must guarantee software reconfigurability, which is achieved by software download. Software download will allow the reconfiguration of terminal, services and applications, and enable personalized services. Compared to the 3G mobile terminals, it is anticipated that the 4G terminals will have

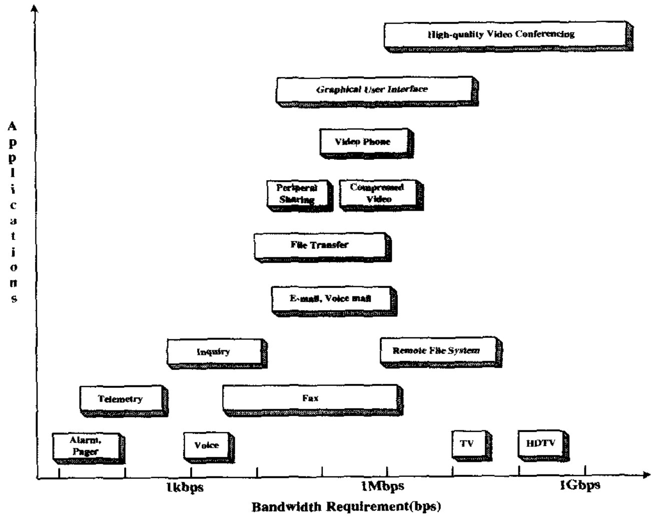

Fig. 5. Application bandwidth requirement for various kinds of services.

the following features:

- Higher interactivity (more comfortable interface between human and network worlds),
- Higher connectivity (networking with other wireless devices on *an ad hoc* basis),
- Multiple personalities (multiple functions such as cellular phone, pager, GPS locator, etc.),
  item Dynamic self-reconfigurability (adaptation to changing service requirements and network conditions),
- Enhanced security function (e.g., Fingerprint chip embedded), and
- Enhanced voice recognition function.

III. PROSPECTIVE KEY TECHNOLOGIES

Realization of the 4G system demands new technologies in the wide areas of system components. We describe the promising key technologies for the 4G system in terms of service, spectrum, radio and wired access, core network, and mobile terminal.

A. Novel Service Features

For the 4G system, we have identified the potential multimedia applications for a wireless user as shown in Table 2. The required bandwidth for various kinds of services is presented in Fig. 5. For instance, hospital bedside communications are used by doctors and nurses to access patient information, medical images, and teleconsulting. Also, this service should provide high definition image, file sharing, and video conferencing. Wireless virtual studio service will be used for TV studio, theater, congress counter, airport studio, and major sport events. This kind of service requires high-resolution video quality, extremely high reliability and availability, and continuous wireless channel claim. A consideration of killer application is always difficult, and often may turn out to be misleading. Therefore, we are not going to search for a specific application, but instead describe the requirements of wireless multimedia application.

High bandwidth and QoS support will be provided by new technologies such as wireless ATM or wireless LAN. As for

Table 2. Potential multimedia applications of the 4G system(1: applicable, blank: non-applicable).

	Video conferencing	Fast file/data transfer (Internet)	High resolution imaging	Real time audio/vidio	File sharing
Business Applications					
- Hospital bedside imaging	1		1		1
- Building-to-building	1	1		1	1
- Wireless virtual studio	1			1	
- Manufacturing/repair assistance	1	1	1		1
- Interactive design	1	1	1		1
- Tele-learning/Business TV	1	1		1	1
- Virtual reality		1		1	
Residential Applications					
- Wireless TV/audio	1	1		1	
- Wireless internet shopping		1		1	
- Videophone	1				

today, there are only few areas where bandwidth requirements drastically exceed the capacity of the current networks. The most important benefit of audio/video applications over traditional television broadcast is the possibility for users to choose the program (video on demand). Many trials are already in progress in this area. It can be seen that a wireless broadband technology could provide certain advantages over the traditional wired technology for this application

B. New Spectrum Management

The adoption of high frequency above 2GHz is essential in the 4G system. As the frequency band becomes higher, propagation loss increases and transmit power must be increased in order to support broadband multimedia traffic. The radio characteristics of high frequency above 2GHz have not well been investigated. Especially, the indoor propagation characteristics should be investigated since the most of high-speed data traffic will be generated in a static environment such as indoor buildings. For operation of the 4G system in a new spectrum, a new RF component technology should be developed for a low-cost production of the mobile terminal. In the development of RF components and modules, the implementation of multi-band and multi-mode functionalities will be critical to support legacy access networks such as the 2G/3G networks and WLAN. Also, the effect of radio waves above 2GHz on human body needs to be investigated to determine the permissible level of radiation.

In order to allow many streams of information to be delivered to the user in the most efficient manner, it is important to consider how the available spectrum will be used. One figure of merit relating to spectrum usage is *spectral efficiency* (often expressed in terms of bps/Hz/cell for the case of typical voice services). The spectrum efficiency allows many streams of information to be delivered in a most efficient way possible to the user. In selection of the operating spectrum for the 4G systems, the followings should be considered:

- Regulatory situation (Is the band allowed to be used?),
- Propagation characteristics (Is the attenuation and multipath behavior appropriate?), and
- Impact on system implementation (Is the system implementable with the state-of-the-art components of the antenna and transceiver?).

C. Radio Access Technologies

Towards the 4G system, many radio access technologies are now arising as promising solutions to enhance the spectrum efficiency and system capacity. In Table 3, the radio access technologies between the 2G, 3G, and 4G systems are summarized and compared.

C.1 Smart Antenna

A smart antenna consists of many antenna elements whose signals are processed adaptively in order to exploit the spatial dimension of the mobile radio channel. An adaptive antenna array has potential to provide designers with an extra dimension of SDMA (space-division-multiple-access) along with FDMA (frequency division multiple access), TDMA (time division multiple access), and CDMA in solving the problems related with the realization of the 4G system [14], [15]. It is widely accepted that an adaptive antenna array will offer potential solutions to a number of the key requirements since it provides many promising features such as high capacity, high spectrum efficiency, and more degrees of freedom to adjust cell coverage characteristics, leading to more efficient use of radio resources [16]. And, its particular configuration depends on the radio channel characteristics, terminal mobility, implementation complexity, capacity requirements, and environmental issues, etc. In the early commercial 3G system, the smart antenna may not be adopted, however, it may be employed in the 3G evolution system.

C.2 Multiuser Detection

The CDMA system performance may be degraded when the MAI (multiple access interference) becomes strong. The MAI from high-power users can significantly corrupt the received signals of low-power users, which is known as 'near-far problem.' To overcome the *near-far problem* and mitigate the MAI, concept of multiuser detection (MUD) (also called *"Interference Cancellation (IC)"*) has been proposed [17]. In spite of the superior performance of the optimum multiuser detector, its complexity is not acceptable in implementation of the system. The optimum multiuser detector is basically a maximum likelihood sequence detector consisting of a bank of matched filters followed by a Viterbi algorithm. To avoid prohibitive

Table 3. Comparison of radio access technologies among 2G, 3G, and 4G systems.

	2G System	2G System	2G System
Smartantenna	Not considered	(partially) expected	(strongly) promising
Multiuser detection	Not considered	(partially) expected	(strongly) promising
Software defined radio	Not considered	(partially) expected	(strongly) promising
Channel coding and error control	Convolutional	Convolutional/turbo Hybrid ARQ	Convolutional/turbo Adaptive coding Hybrid ARQ
Modulation	QPSK series (IS-95) GMSK (GSM)	QPSK series (3GPP) QPSK series (3GPP2)	Adaptive modulation (OFDM/MPSK, QAM)
Demodulation	Forward: coherent Reverse: noncoherent	Forward: coherent Reverse: coherent	Forward: coherent Reverse: coherent
Power control	Forward & Reverse	Forward & Reverse	Adaptive power control (Forward& Reverse)
Diversity	Rx diversity	Tx/Rx diversity	Space-time processing (Tx/Rx diversity)
Handoff	Soft/Softer handoff (Intra-system)	Soft/Softer handoff (Intra & inter system)	Soft/Softer handoff (Intra & inter system)
Multiple access/Duplex	CDMA/FDD (IS-95) TDMA/FDD (GSM) TDMA/TDD (PHS)	CDMA/FDD,TDD (3GPP, 3GPP2)	CDMA/FDD,TDD TDMA/FDD,TDD

computational complexity of the optimum MUD, many sub-optimal multiuser detectors have been proposed. The suboptimal detectors include decorrelating detector, multistage detector, neural-network based detector, successive interference cancellation (SIC) detector, parallel interference cancellation detector (PIC) detector, adaptive detector, and iterative detector, etc.

In the 4G system, the MUD is a very promising solution for improving receiver performance as well as system capacity and coverage in both uplink and downlink, while in the standardization of the 3G system, the MUD has not been actively discussed. In the uplink, interference estimation and subtraction based MUD appears to be the most promising one for practical implementation.

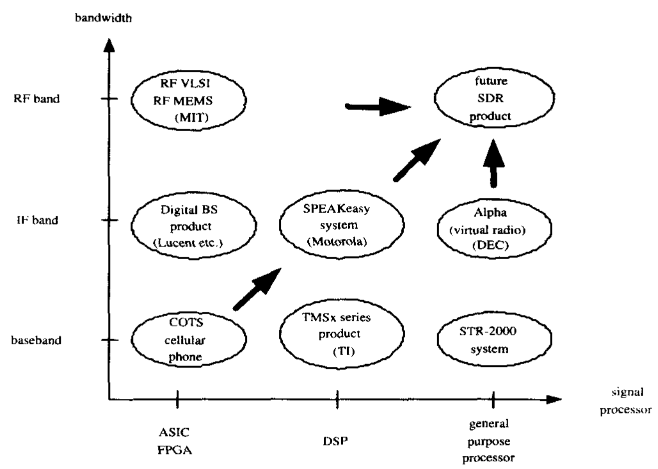

Fig. 6. Evolution of software defined radio.

C.3 Software Defined Radio

So far, the mobile communications world has witnessed the parallel emergence of a wide variety of radio standards throughout the world. The recent activities of the 3G standard such as the 3GPP and 3GPP2 have resulted in a growing interest in the field of multi-standard software defined radio (SDR) [18]. The SDR represents *'radio functionalities defined by software.'* The capability of processing a signal corresponding to a wide range of frequency bands and channel bandwidths in a cost-effective manner may also be a critical issue in the roadmap of the 4G system. The SDR provides a solution to this issue. The digital signal processing technology has led us to a point where it is feasible to change characteristics of a radio depending on the software loaded into it.

The SDR generalizes the primary functions of a radio system into a set of functional modules connected by information and control signals. It may have all the operating parameters defined in software rather than hardware, and would be extremely flexible with the following benefits in many commercial applications [19], [20]:

- Fully programmable,
- Multimode terminal,
- Easily adaptable to new signal processing technique, and
- Easily expandable for new services

One may expect that it is quite feasible to implement the necessary BS and terminal functionality in a simple programmable DSP device. The evolutionary path of the SDR and general block diagram of the SDR-based receiver are shown in Fig. 6 and Fig. 7, respectively. It really seems that the SDR can provide promising solutions for implementation of the 4G system as well as for that of the 3G system.

C.4 Channel Coding

There have been many channel coding schemes (such as RS code, BCH code, convolutional code, etc.) to improve performance of many kinds of systems by compensating channel distortion in wireless, optical, and magnetic channels. Recently, in the channel coding community, there has been a focus on turbo code (also termed *parallel concatenated convolutional code*) introduced in 1993 [21]. The substantial coding gain through turbo coding has been confirmed for a CDMA system in a wireless channel as well as in an AWGN channel.

The turbo code is a kind of concatenated convolutional code, and performs decoding in an iterative manner. The encoder is formed by concatenating two constituent codes in parallel and by separating the codes by the interleaver. This interleaver per-

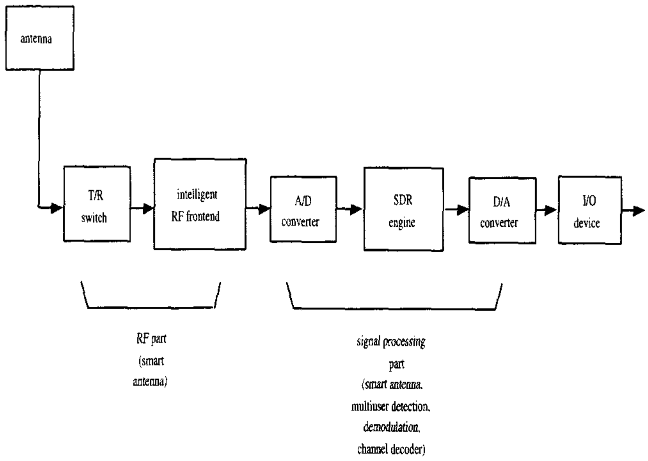

Fig. 7. General block diagram of SDR-based receiver.

mutes the information sequence and then uses this as the input to the second component encoder. It is well known that turbo coding performance is enhanced by increasing interleaver length, and its decoding complexity grows linearly, making the decoding of large block length possible. The decoding complexity of turbo code is proportional to the block length, the number of decoding iterations, and the constraint length of the constituent codes.

In the 2G systems, the convolutional code was primarily selected as the channel coding scheme, while in the 3G system, the convolutional and turbo codes have been alternatively employed for low and high rate data transmissions. In the 4G system, this kind of trend in the 3G system is expected to continue, however, the use of coded modulation and adaptive coding schemes may be challenging issues to improve spectrum efficiency and to adapt to changing channel conditions, respectively. In addition, for service applications which can tolerate delay, ARQ (automatic repeat request) can be applied for the error control in the MAC (medium access control) layer.

C.5 Tx/Rx Diversity

Diversity is a preventive way to mitigate fading effect, whereas power control combats against fading by controlling the transmit power. The diversity is useful in a full range of mobile speeds, and can reduce power rise effect. The diversity also requires smaller transmit power which results in capacity increase and less power consumption (which is important to the multimedia terminal). Up to now, many kinds of diversity combining techniques have been used independently or in a combined way, and they fall into the following categories: space, frequency, time, and polarization [22]. The diversity schemes include path diversity, receive antenna diversity, transmit diversity, and macro diversity.

Multi-carrier CDMA is well known as a kind of frequency diversity, and the interleaving as a kind of time diversity is effective for high-speed mobiles when combined with channel coding. Especially, the diversity techniques based on the use of multiple downlink transmit antennas have been adopted to exploit spatial and/or polarization decorrelations over multiple channels, and employing multiple antennas at both the base station transmitter and terminal receiver is actively being studied for high-speed downlink packet access.

So far, a number of transmit diversity techniques have been proposed for the downlink. It has been recognized that transmit diversity on the downlink can provide a means to achieve similar diversity gain as for the receiver diversity without complexity of extra receiver. In the 3G cdma2000 system, multicarrier transmit diversity has been proposed on its downlink configuration [1]. The major transmit diversity includes orthogonal transmit diversity, time switch transmit diversity, and selection diversity. In the 4G system, these kinds of transmit diversity will be surely considered for enhancement of the downlink performance.

C.6 Modulation/Demodulation

For multimedia services, high data rate transmissions should be guaranteed with a high QoS. In the 4G system, a high rate data up to a few hundred Mbps in a static user should be supported for transmissions of speech, fax, data, video, etc. This trend has motivated extensive research on modulation techniques with high spectral efficiency and efficient radio transmission techniques. One of the approaches is multicarrier transmission technique. In the multicarrier transmission technique, input data stream is divided into many substreams, each of which has a much lower bit rate. These substreams are modulated onto many subcarriers. The first system using multicarrier modulation was military HF (high frequency) radio links in the late 1950s and early 1960s. OFDM (orthogonal frequency division multiplexing) patented in the U.S.A. in 1970 is a special form of multicarrier modulation, and has densely spaced subcarriers with overlapping spectra of the modulating signal [23]. The OFDM technique was first employed for broadcasting applications of audio and video signals such DAB (digital audio broadcasting) or DVB (digital video broadcasting). In the OFDM technique, the steep bandpass filters to separate individual subcarriers are not required because OFDM time-domain waveforms are chosen such that mutual orthogonality is guaranteed even though spectra of each subcarrier may overlap. In a typical OFDM system, the single high data-rate stream is multiplexed into many parallel low data-rate steams, each of which is transmitted on an orthogonal subcarrier using an appropriate modulation format. When the number of subcarriers is sufficiently large and the bandwidth of each subcarrrier signal is very narrow compared to the coherence bandwidth of a channel, the fading characteristics on each subcarrier becomes frequency-nonselective (flat) fading.

In the 2G and 3G systems, the QPSK (phase shift keying) and GMSK series have been mainly employed as modulation formats [24]. However, in the 4G system, QAM (quadrature amplitude modulation) may be a strong candidate due to its high spectral efficiency as well as MPSK (M-ary PSK) series. The variable QAM and M-ary PSK can be alternatively selected according to the traffic and the channel conditions.

With the projected demand for multimedia services, the ability to provide spectrally efficient and flexible data rate access is one of the important design considerations of the 4G systems. One of the approaches to satisfy both of these requirements is to adapt the modulation and transmission power according to the instantaneous propagation conditions. This technique is called *adaptive modulation* which has been employed in many systems such as V.34 modem and two-way cable modem. The adaptive modulation can effectively improve BER (bit error rate) performance on radio channels which suffer from fading and shadowing.

C.7 Power Control

Power control is essential for the CDMA-based systems to keep the transmit power at a minimum level while satisfying the required QoS, and for maximizing the system performance by reducing unnecessary interference, and also lengthening the battery life. Typically, three types of power controls have been devised to combat near-far problem (path loss), shadowing, and fading: open-loop, closed-loop, and outer-loop power controls [25], [26]. Most of recent studies have focused on making power control faster and more accurate, and especially how to accommodate multi-rate and multi-QoS services. The closed-loop power control based on signal-to-interference ratio (SIR) attracts much interest even in downlink, and one more interesting issue is distributed power control as well as centralized control. It should be noted that the power control (particularly, closed-loop power control) which targets low-to-moderate mobile speeds, has a so-called *power-rise problem.*

To mitigate these shortcomings, diversity is widely used in the current and upcoming systems. In a wide sense, gating and DTX (discontinuous transmission) can be seen as another way of power control. In the 2G/3G system, the step size and frequency of power control are fixed once the propagation channel is identified, however, in the 4G system, they can be varied according to the channel propagation environments through enhanced channel estimation. This kind of technique is typically called *adaptive power control* and is a promising *approach for the 4G system implementation.*

C.8 Handoff

In a mobile cellular system, handoff is performed for link quality maintenance and for reducing interference in the system. For seamless networking of multiple interworking systems, handoff will be a very essential issue of the 4G system. In the 2G and 3G systems, the major handoff is the intra-network handoff based on physical layer characteristics such as signal strength, BER, range, etc [26]. However, in the 4G system, inter-network (inter-system) handoff may be a critical issue as well as the intra-network handoff. The handoff of the 4G system may demand the following features:

- Based on QoS and cost,
- Based on available spectrum,
- Dependent on higher (application) layer, and
- Dependent on different network legacies.

C.9 Multiple Access and Duplex

In the 2G systems, the TDMA and the CDMA have become primary multiple access techniques in the GSM and the IS -95 systems, respectively [24]. However, in the 3G systems, the CDMA has been widely adopted due to its many advantageous features over the TDMA. In the 4G system, it is highly expected that this trend will be maintained. However, the TDMA system can be a strong alternative in some applications such as the OFDM-based transmission environment, TDD (time division duplex) mode operation in a hot-spot cell, etc.

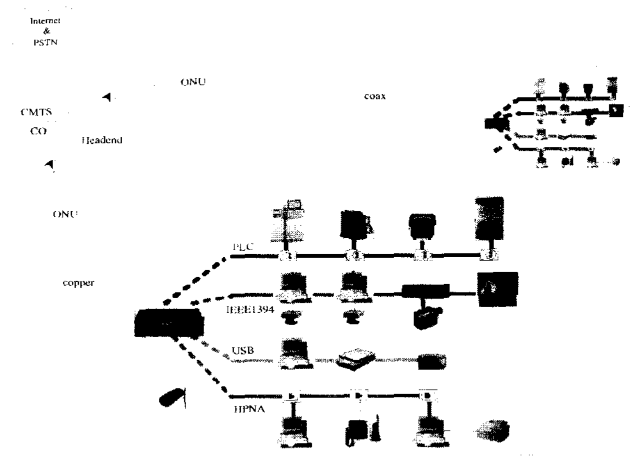

Fig. 8. Integration of wired subscriber network and home network.

Unlike voice communications, the primary service in the 4G system will be various kinds of multimedia applications in which system capacity is limited by the downlink traffic [27]. To cope with the problems caused by traffic imbalance between uplink and downlink, the TDD can be a viable solution in the sense that it permits one to allocate communication resources more flexibly compared to the FDD (frequency division duplex). One interesting feature of the TDD is that for a period of time, the channel impulse response is identical for the up and down links resulting in channel reciprocity [28]. The TDD systems are generally expected to be used for low-mobility applications such as indoor or picocell environments because the correlation between the up and down links degrades as the fading rate becomes higher. For an environment with the imbalance between uplink and downlink traffics, the CDMA and the OFDM/TDD may be strong candidates as the multiple access and duplex schemes for the 4G system.

D. *Wired Access Integration*

The wired access network of the 4G system will integrate wireline and cable subscribers and home networks. The subscriber networks using HFC and DSL will be integrated on the CO (central office) while the home network such as the HPNA, the IEEE1394, the USB (universal serial bus), and the PLC will be integrated on the HG (home gateway). The integrated structure of wired subscriber and home networks is shown in Fig. 8. The HFC is the network that uses conventional CATV (cable TV) network for the wired broadcasting service. The CPE (customer premise equipment) is connected to the network through the cable modem, and network side interface is CMTS (cable modem termination system) located in the CO. The xDSL transports voice and data through the different frequency bands. The CPE is connected to the network through the ADSL (asymmetric DSL), VDSL (very high-speed DSL) modem, and network side interface is DSLAM (DSL access multiplexer) located in the CO [29]. The HG including the HFC or the DSL subscriber modems can be connected to the subscriber network and the di-

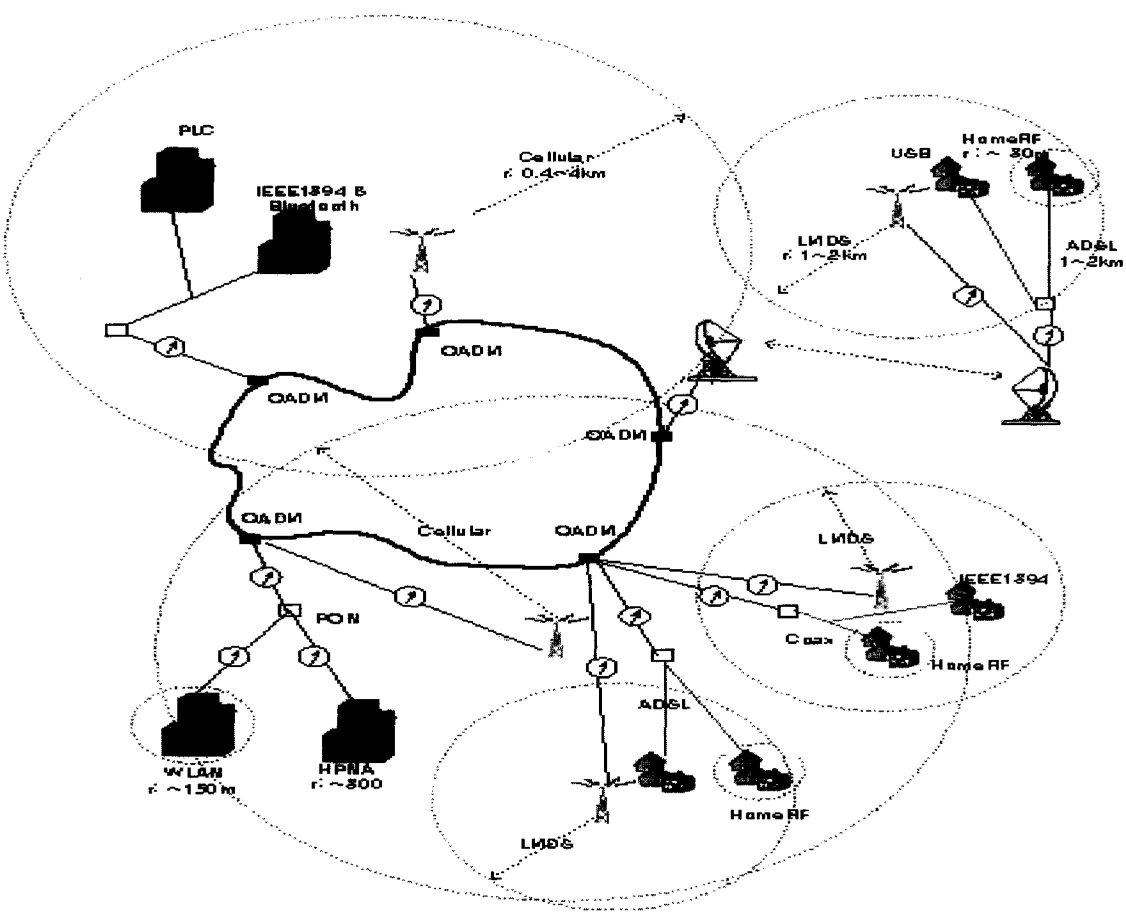

Fig. 9. Network configuration of wired and wireless integrated access network.

verse modules in a home network.

The main candidates for the home network include HPNA, USB, IEEE 1394, and PLC. The HPNA uses telephone line to connect home information and communication equipments. The USB can connect maximum 126 devices, and supports up to 6 hierarchies. The IEEE1394 supports both asynchronous and isochronous transmission, and provides unified standard for communication devices, computers, and AV devices. Primary attractions of the PLC are universal presence of electric wiring and ease of access through standardized wall-outlets. However, PLC is heavily affected by interference from various sources and attenuation during transmission exhibits unpredictable variations.

The possible candidates of subscriber and home networks are summarized and characterized in Table 4. The current various wired access technologies will be integrated with the wireless network as a part of the 4G network. The expected example of the 4G network configuration is shown in Fig. 9.

E. Core Network Evolution

There are plenty of key technologies to be developed for the 4G CN as shown in Table 5. The 4G CN architecture will be based on that of the 3G system. The standardized or to-be-standardized All-IP based network architecture models of 3GPP and 3GPP2 would contribute as the crucial components of the next generation CN. Furthermore, for the perfect global roaming between the two separate 3G CN standards, a single harmonized standard should be set out in the near future.

In considering the whole architecture of All-IP based 4G CN, more simple and unified IP backbone architecture has to be proposed. A good reference to this is a layered network approach separating the control, service, and access parts in the entire architecture. The backbone network should have full interfaces among the various access networks such as mobile (2G/3G), WLAN, WLL, xDSL, PAN (personal area network), DAB/DVB, etc [30]. And, the ultra high-speed communications may require the transmission network to be equipped with much bigger pipes, e.g., GSR/TSR (giga/tera-bit switch router), DWDM (dense wavelength division multiplexing), GbE/10GbE (giga/10 giga-bit Ethernet), etc. As the trunk capacity grows, the issue of maximizing the network reliability, in other words, the survivability to any network failures becomes more important. Also, the development of the IN (intelligent network) service platforms and NMS (network management system) controlling whole heterogeneous access networks would be another key elements in the 4G CN.

The future All-IP based CN could be characterized as an architecture according to the *'everything on IP'* philosophy. Therefore, all the voice and multi-service traffics will be provided by the IP carrier rather than existing circuit networks with development of the VoIP or Multi-service over IP technologies. And, most of the nodes or systems of the 4G CN will be developed not as the dedicated hardware but as IP based software. In

Table 4. Summary of candidate subscriber and home networks.

System		media	Access technology	Speed (Mbps)	range	modulation	frequency band(MHz)
HFC		Fiber/coax	Cable Access	30 ~ 50	-	64/ 256QAM	54 ~ 900[6]
FTTx	FTTCab	Fiber/copper	XDSL	1.5 ~ 2	5.4km	DMT,CAP	~ 1.1 [1.1]
	FTTC	Fiber/copper		6	3.6km		
	FTTB	Fiber/copper	XDSL	13 ~ 14	1.5km	DMT, DWMT	0.12 ~ 30
	FTTH	Fiber		26 ~ 28	1.0km	CAP, QAM	
				52 ~ 56	0.3km		
Home Network	HPNA	Copper	HPNA1.0	~ 1	0.15km	PPM	5.5 ~ 9.5[4]
			HPNA2.0	4 ~ 32	0.3km	PSK, FDQAM	4 ~ 10[6]
	PLC	Powerline	Powerline	1	0.3km	PSK, DSSS	-
				10		OFDM	
	USB	Cat5e	USB 1.1	12	30m	NRZI	-
			USB2.0	480			
	IEEE 1394	6/4wire	IEEE1394a	100~400	~ 4.5m	Data-Strobe	-
			IEEE1394b		~ 72m		
	Ethernet	UTP	802.3	10/100	100m	Manchester	-

Table 5. Key technologies for the 4G core network.

Architecture	Harmonized core network based on 3GPP and 3GPP2 All-IP standards
	Integration of various heterogeneous access networks
	Layered structures separating call/control/transport
IP transport	Metro/Long-haul IP optical networking: OADM/OXC, TSR, 10GbE
	Multi-protocol Label or Lambda Switching
	Dynamic resource/congestion management
	Higher reliability/survivability with fast restoration
IP routing	QoS provisioning for real-time IP multimedia services
	Seamless QoS adaptation to handoffs among heterogeneous networks
	IPv6, IP multicasting
Mobility	Inter-system seamless handoffs
	Micro/Macro mobility management
	Handoff based on required QoS and optimum use of spectrum
	Location management and services
	Evolved mobile IP

addition, the lack of the worldwide IPv4 address space will drive the future system to use a new version, IPv6. The IP multicast traffics should also be efficiently delivered in the 4G CN system. As more and more services become IP-based, we envision that the telephony-specific part of the cellular network will be less and less important. Eventually, the entire network infrastructure could be replaced with an IP-centric solution in the 4G CN.

Another peculiar element of the 4G CN functionality would include the mobility management, which requires more seamless handoff between heterogeneous access networks, dynamically adapting to the status of network bandwidth or spectrum usage. And, as more data and internet traffics flow into the domain of mobile communication network, the QoS provisioning issue would be the main focus in the planning and operation of the 4G CN. Without consideration of the QoS support technologies, the real-time multimedia services will frequently result in heavy traffic jams. Therefore, an efficient and effective strategy to dynamically manage the network resources has to be developed considering the varying traffic load, channel conditions, and service environments.

With the emergence of the optical layer in transport networks, the optical internetworking would be another key technology in establishing the 4G CN, which can provide maximum capacity with minimum cost for new applications such as the Internet, video and multimedia interaction, and advanced digital services. Ideally, the optical network will provide end-to-end services entirely in the optical domain, without ever converting signals into electrical format [31]. The challenge of designing optical networks increases with the introduction of optical cross-connects and add/drop multiplexers, which could dynamically change a signal path to travel across a physically different route. In the 4G CN, many applications are converged to IP, and these IP packets are transported via optical network which consists of optical add/drop multiplexer, optical cross-connector, optical amplifier, etc. The optical architectures discussed here make appreciable demands on optical hardware technology, and the optical performance sets fundamental limits on the node extent and the number of nodes that can be cascaded in one optical path.

F. Mobile Terminal Technology

Design of mobile terminals with low-power consumption has always been an interest in the wireless communication industry. It is well known that the improvements in power dissipation can be best attained through algorithmic and architectural innovations, guided by the knowledge of hardware and circuit properties through the advanced RF and integrated circuit technologies. One way to reduce power is to simply use components that consume less power in the storage, processing, display, and wireless communication units of the mobile terminal. Another way is to use components that can enter into low-power modes by temporarily reducing the speed or functionality. In the future design of the mobile terminal, the power reduction will be accomplished by software rather than by hardware technology.

In Fig. 10, the mobile terminal technology of the 4G terminal

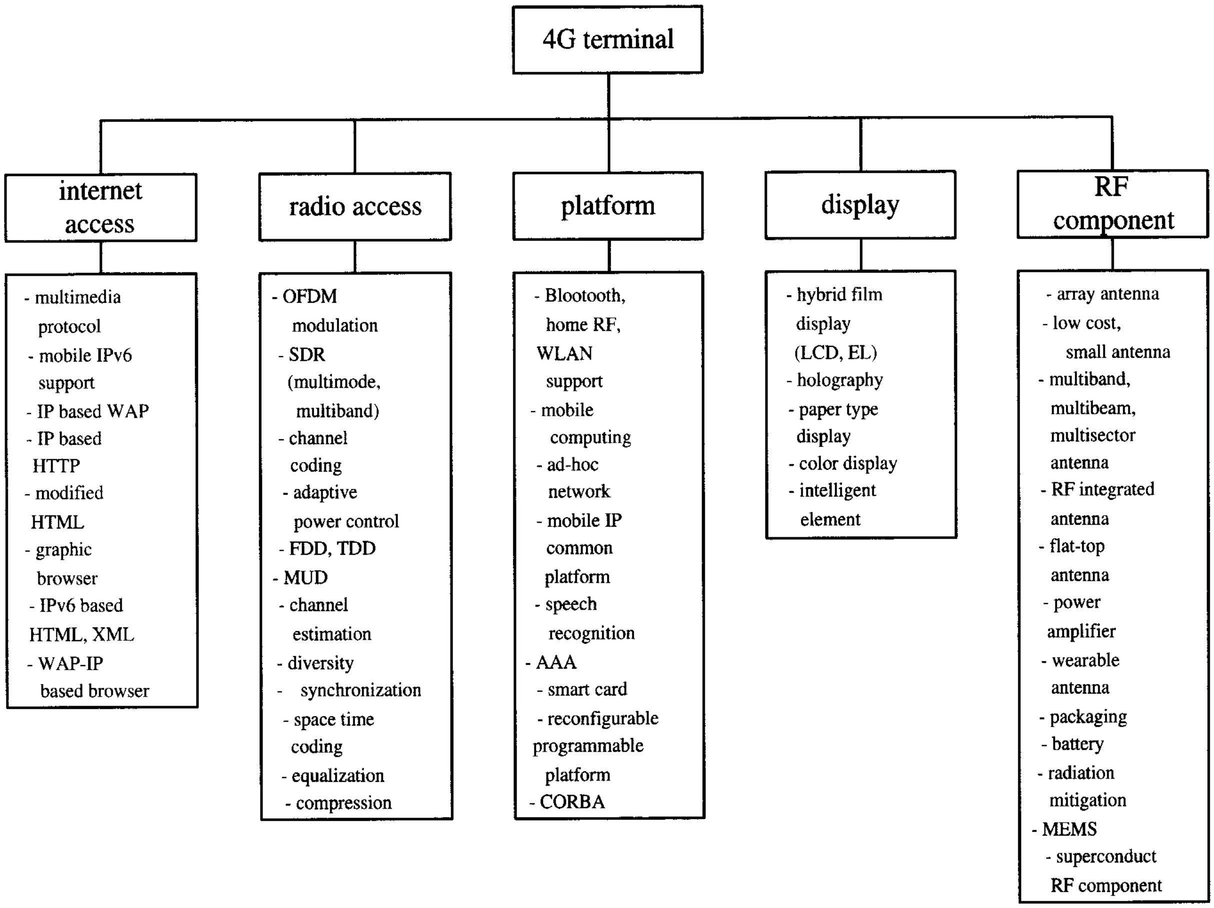

Fig. 10. Terminal technology for the 4G terminal.

is shown in terms of Intenet access, radio access, platform, display, and RF components. Since the future wireless terminals will be asked to integrate different kinds of traffic with different QoS, it is desirable that a lot of flexibility should be given to the mobile terminal. One of our visions to this mission is to apply *'terminal with knobs'* where the lower layers can be reached down by reprogramming according to its needs. In this manner, 'on demand' services can be served by best matching application requirements.

From the service aspects, the mobile terminal technology of the 4G system can be divided into three categories as follows:

- Multimedia technology
  - Moving picture technology such as MPEG (Moving Picture Experts Group)
  - Multimedia input/output interface technology
  - Various multimedia application service technology
  - Efficient compression technology
  - QoS Selection and providing technology base on channel environments
- Mobility technology
  - Support mobile-IP and VoIP
  - GPS (global positioning system) technology to support location service
  - Effective handover algorithm technology
  - Authentication/security technology to guarantee high safety
- User interface technology
  - Service and air interface selection technology
  - User interface reconfiguration technology
  - Interface technology between input/output devices and applications

Some of the listed contents may be overlapped with that of the 3G system. However, since the 4G system is fundamentally market (service) driven, the 4G terminal will be a kind of more enhanced, sophisticated, easy-to-handle one compared to the 3G terminal.

IV. CONCLUSIONS

In this article, we have defined and proposed the concepts and features of the 4G system, and discussed the required key technologies in terms of service, spectrum, radio and wired access, core network, and mobile terminal. The scope of topics dealt with in this article was extremely wide. Instead of adhering to a single topic, this article has discussed a number of topics with emphasis on the aspects and requirements in the context of the system, service, and core network. Since it was practically impossible to address all the facts about the above aspects, it was intended to initiate discussion on the 4G systems and networks.

The concepts and ideas in this article have just scratched the surface of the potentialities for the 4G system. We have a significant amount of future work ahead of us in more granular levels for implementation of the 4G system. A number of challenging issues listed below should be resolved:

- Development of innovative air interfaces,
- Channel modeling and measurements above 2GHz band for decision of operating bands,
- Deployment of layered network architecture,
- Development of multimode reconfigurable terminal/appliances,
- Management and integration of different networks/systems, and
- Generation of new services (business models).

We are now entering a new era in the development and evolution of the 4G systems which should meet the demanding requirements of a customer-based global market place. We also would like to point out that the 4G market opportunities demand substantial technological innovation for the adequate provisioning of personal/service mobility, ubiquitous coverage, robust communications, and high-capacity systems.

With recent breakthroughs in the component and system technologies as well as network and service technologies, the ubiquitous communication with anyone at anytime, anywhere through 4G system will surely be a reality. In the era of the 4G systems, as witnessed in the 3G system, the different world regions need to cooperate particularly in the field of standardization, regulation, and spectrum allocation to ensure widespread availability of advanced and affordable wireless services and applications. The national and regional borders should be more often transcended, and interconnection of the networks and interoperability of services should be highly encouraged with the objective of enhancement of quality of life in the ever-maturing information age.

V. APPENDIX

Abbreviations and Acronyms

AAA: authentication, authorization, and accounting
A/D: analog-to-digital
ARIB: association of radio industries and businesses
BER: bit error rate
BRAN: broadband radio access network
BWLL: broadband wireless local loop
CAP: carrierless amplitude phase
CMTS: cable modem termination system
CO: central office
CORBA: common object request broker architecture
COTS: commercial off the shelf
DAB: digital audio broadcasting
D/A: digital-to-analog
DEC: Digital Equipment Corporation
DMT: discrete multitone
DSL: digital Subscriber line (loop)
DSSS: direct sequence spread spectrum
DVB: digital video broadcasting
DWMT: discrete wavelet multitone
EL: electroluminescence
ETSI: European telecommunications standards institute
FDQAM: frequency diverse QAM
FPGA: field programmable gate array
GbE: giga bit Ethernet
GSM: global system for mobile telecommunications
HAPS: high altitude platform system
HTML: hyper text markup language
HTTP: hyper text transfer protocol
I/O: input/output
IP: Internet protocol
IPv6: Internet protocol version 6
LCD: liquid crystal display
LMDS: local multipoint distribution service
MEMS: micro electro-mechanical system
MMAC: multimedia mobile access communication
NRZI: non return to zero inversion
OADM: optical add and drop multiplexer
OFDM: orthogonal frequency division multiplexing
ONU: optical network unit
OXC: optical cross-connect
PHS: personal handyphone system
PON: passive optical network
PPM: pulse position modulation
PSK: phase shift keying
QAM: quadrature amplitude modulation
SDR: software defined radio
TI: Texas Instrument Inc.
TIA: telecommunication industry association
T/R: transmitter/receiver
TSR: terabit switch router
UTP: unshielded twisted pair
VLSI: very large scale integrated circuit
VoIP: voice over internet protocol
WAP: wireless application protocol
WARC: world administration radio conference
WLAN: wireless local area network
XML: extensible markup language

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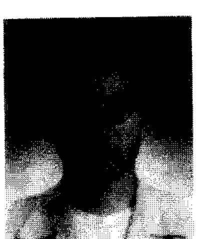

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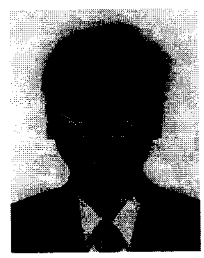

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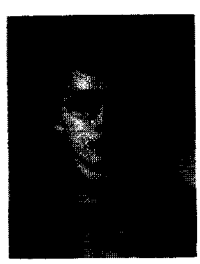

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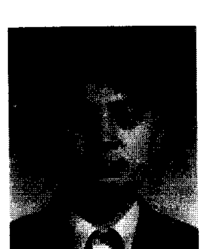

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