INVITED PAPER

# OPEN WIRELESS ARCHITECTURE – THE CORE OF 4G MOBILE COMMUNICATIONS

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***Abstract***—*4G mobile communications should not focus only on data-rate increase and new air-interface, but should, instead, converge the advanced wireless mobile communications and high-speed wireless access systems into an OWA platform, which becomes the core of this emerging next-generation mobile technology. Based on this OWA model, 4G mobile will deliver the best business solutions to the wireless and mobile industries, such as cdma2000®/WLAN/GPRS and WCDMA/OFDM/WLAN three-in-one products.*

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## INTRODUCTION

Future wireless service will be characterized by global mobile access (terminal and personal mobility); high quality of service (full coverage, intelligibility, no drop, and no/lower call blocking and latency); and easy and simple access to multimedia voice, data, message, video, Worldwide Web, global positioning system (GPS), etc., services via a single user terminal.

From the user's perspective, this vision can be implemented by integrating these different evolving and emerging wireless access technologies into a common flexible and expandable platform to provide multiple possibilities for current and future services and applications within a single terminal. Fourth-generation (4G) mobile systems will mainly be characterized by a horizontal communication model, where different access technologies such as cellular, cordless, wireless local area network (WLAN), short-range wireless connectivity, and wired systems will be combined on a common platform to complement each other optimally for different service requirements and radio environments. This platform is technically called the converged broadband wireless platform or open wireless architecture (OWA).

OWA defines the open interfaces in wireless networks and systems, including the baseband signal processing parts, radio frequency (RF) parts, networking parts, and operating system (OS) and application parts, so that the system can support different industrial standards and integrate the various wireless networks into an open broadband platform. By comparison, software-defined radio (SDR) is simply a radio in which the operating parameters, including *inter alia* frequency range, modulation type, and output power limitations, can be set or altered by software. Therefore, SDR is just one of the OWA system's implemental modules.

OWA will eventually become the global industry-leading solution for integrating various wireless air-interfaces into one wireless open terminal where the same end equipment is flexible enough to work in the wireless access domain as well as in mobile cellular networks. As the mobile terminal (rather than the wireline phone) becomes the most important means of communication in the future, this single piece of equipment with a single number and multiple air-interfaces (powered by OWA) will undoubtedly dominate the wireless communication industry.

The April 2005 report of the Organisation for Economic Co-operation and Development (OECD) states that "As too many wireless systems come out every day, the current closed architecture and proprietary systems do not bode well for its success." The inference may be drawn that the OWA platform will drive future wireless and mobile communications.

4G mobile communications will focus mainly on OWA, as well as cost-effective and spectrum-efficient high-speed wireless mobile transmission. The third-generation (3G) system is suffering tremendously worldwide because it did not fundamentally improve the wireless architecture; making that architecture open is the final solution in the wireless industry.

## ABBREVIATIONS, ACRONYMS, AND TERMS

| | |
|---|---|
| 2G | second generation |
| 3G | third generation |
| 3G+ | beyond 3G |
| 3GPP™ | Third Generation Partnership Project |
| 4G | fourth generation |
| 4GMF | Fourth Generation Mobile Forum |
| AMC | adaptive modulation and coding |
| ARQ | automatic repeat request |
| ATM | asynchronous transfer mode |
| BTS | base transceiver station |
| CDMA | code division multiple access |
| C/I | carrier-to-interference (ratio) |
| DSP | digital signal processing |
| FFT | fast Fourier transform |
| FuTURE | (China) Future Technology of Ultra Radio Enhancement |
| GPRS | general packet radio service |
| GPS | global positioning system |
| GSM | global system for mobile communication |
| HDR | hardware-defined radio |
| HSDPA | high-speed downlink packet access |
| IF | intermediate frequency |
| IP | Internet Protocol |
| K4G | Korea 4G project |
| MAC | media access control |
| MIMO | multiple input, multiple output |
| mITF | mobile IT Forum |
| MOPS | million operations per second |
| NLOS | nonline of sight |
| OECD | Organisation for Economic Co-operation and Development |
| OFDM | orthogonal frequency division multiplexing |
| OFDMA | orthogonal frequency division multiple access |
| OS | operating system |
| OWA | open wireless architecture |
| QAM | quadrature amplitude modulation |
| QPSK | quadrature phase shift keying |
| RF | radio frequency |
| SDM | software-defined module |
| SDR | software-defined radio |
| SIG | signaling |
| SIP | silicon intellectual property |
| SMB | small/medium business |
| SOA | service-oriented architecture |
| SOI | service-oriented infrastructure |
| TCP | transmission control protocol |
| TD-SCDMA | time division synchronous CDMA |
| VMI | virtual machine interface |
| WLAN | wireless local area network |
| WCDMA | wideband CDMA |
| WiMAX | worldwide interoperability for microwave access |
| WWRF | Wireless World Research Forum |

## OPEN WIRELESS ARCHITECTURE

4G mobile communications based on OWA will ensure that a single terminal can seamlessly and automatically connect to local high-speed wireless access systems when the users are in locations where wireless access networks (WLAN, broadband wireless access, wireless local loop, HomeRF, wireless asynchronous transfer mode [ATM], etc.) are available. When users move to mobile zones (highway, beach, remote area, etc.), the same terminal will be able to automatically switch to wireless mobile networks (general packet radio service [GPRS], wideband code division multiple access [WCDMA], cdma2000®, time division synchronous CDMA (TD-SCDMA), etc.). Converged wireless communications can provide the following advantages:

- Increased spectrum efficiency
- Highest data-rate to the wireless terminal, for the most part
- Best network resource sharing and channel utilization
- Optimal management of service quality and multimedia applications

**Figure 1** shows the wireless evolution to 4G mobile communications based on the OWA platform, where 3G, WLAN, and other wireless access technologies converge into the 4G mobile platform to deliver the best infrastructure of mobile communications with optimal spectral efficiency and resource management. In fact, this OWA model has already been accepted by most wireless industries. The WCDMA/WLAN/Bluetooth™ three-in-one terminal, for example, is being designed in many companies.

Global 4G mobile research and development focuses on three types of OWA: adaptive modulation and coding (AMC); adaptive hybrid automatic repeat request (ARQ); and generic multiple input, multiple output (MIMO) and orthogonal frequency division multiplexing (OFDM).

### Adaptive Modulation and Coding

The principle of AMC is to change the modulation and coding format (transport format) in accordance with instantaneous variations in channel conditions, subject to system restrictions. AMC extends the system's ability to adapt to good channel conditions. Channel conditions should be estimated based on feedback from the receiver. For a system with AMC, users geographically close to the cell site are typically assigned higher order modulation with higher code rates (e.g., 64 quadrature amplitude modulation [QAM] with R=3/4 turbo codes). Users geographically close to the cell boundary, on the other hand, are assigned lower order modulation with lower code rates (e.g., quadrature phase shift keying [QPSK] with R=1/2 turbo codes).

AMC allows different data rates to be assigned to different users, depending on their channel conditions. Since channel conditions vary over time, the receiver collects a set of channel statistics, such as modulation and coding, signal bandwidth, signal power, training period, channel estimation filters, and automatic gain control, that are used by both the transmitter and the receiver to optimize system parameters.

### Adaptive Hybrid ARQ

A successful broadband wireless system must have an efficient co-designed media access control (MAC) layer for reliable link performance over the lossy wireless channel. The corresponding MAC is designed so that the transmission control protocol (TCP)/Internet Protocol (IP) layer sees the high quality link it expects. This is achieved by an ARQ mechanism, wherein the transmitter breaks up packets received from higher layers into smaller subpackets, which are transmitted sequentially. If a subpacket is received incorrectly, the transmitter is requested to retransmit it. ARQ is considered a mechanism for introducing time diversity into the system because of its capability to recover from noise, interference, and fades.

Through, for example, chase combining, adaptive hybrid ARQ shows significant gains over link adaptation alone. Adaptive hybrid ARQ self-optimizes and adjusts automatically to channel conditions without requiring frequent or

*Multiple antenna technologies enable high capacities suited for Internet and multimedia services and also dramatically increase range and reliability.*

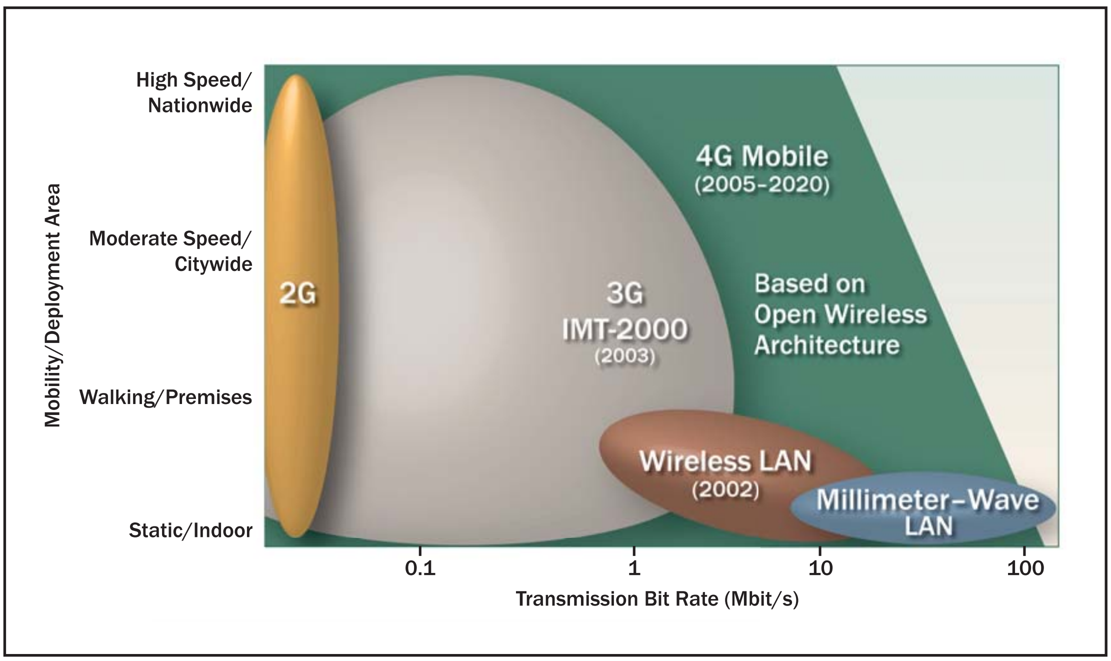


**Figure 1. Wireless Evolution to 4G Mobile Based on OWA**

highly accurate carrier-to-interference (C/I) measurements. It does this by adding redundancy only when needed and by saving failed transmission attempts to the receiver to help with future decoding. Furthermore, every transmission helps to increase the probability of packet success.

### Generic MIMO and OFDM

An increasing demand for high-performance 4G broadband wireless mobile service requires that multiple antennas be used at both the base station and subscriber ends. Multiple antenna technologies enable high capacities suited for Internet and multimedia services and also dramatically increase range and reliability. This design has emerged in response to the growing demand for broadband wireless Internet access. The challenge for broadband wireless access lies in providing a comparable quality of service at a cost similar to that of competing wireline technologies. The target frequency band for this system is 2 to 5 GHz due to favorable propagation characteristics and low RF equipment costs. The broadband channel is typically a nonline-of-sight (NLOS) channel and includes impairments such as time-selective and frequency-selective fading. Multiple antennas at the transmitter and receiver provide diversity in a fading environment. By employing multiple antennas, multiple spatial channels are created, making it unlikely that all channels fade simultaneously.

*OFDM is chosen over a single-carrier solution due to the lower complexity of equalizers for high delay spread channels or high data rates.*

OFDM is chosen over a single-carrier solution due to the lower complexity of equalizers for high delay spread channels or high data rates. A broadband signal is broken down into multiple narrowband carriers (tones), where each carrier is more robust to multipath. To maintain orthogonality among the tones, a cyclic prefix is added, the length of which is greater than the expected delay spread. With proper coding and interleaving across frequencies, multipath becomes an OFDM system advantage by yielding frequency diversity. OFDM can be implemented efficiently by using fast Fourier transforms (FFTs) at the transmitter and receiver. At the receiver, the FFT reduces the channel response into a multiplicative constant on a tone-by-tone basis. With MIMO, the channel response becomes a matrix. Because each tone can be equalized independently, the complexity of space-time equalizers is avoided. Multipath remains an advantage for a MIMO-OFDM system, since frequency selectivity caused by multipath improves the rank distribution of the channel matrices across frequency tones, thereby increasing capacity.

## OPEN BROADBAND WIRELESS CORE

The open wireless platform requires:

- Area- and power-efficient broadband signal processing for wideband wireless applications
- The highest industry channel density (million operations per second [MOPS] pooling) in flexible new base transceiver station (BTS) signal processing architectures
- BTS solutions scalable to higher clock rates and network capacity
- Waveform-specific processors that provide new architecture for platform reuse in terminals for multiservice capability
- Terminal solutions that achieve the highest computational efficiency for application with high flexibility
- Powerful, layered software architecture using the virtual machine programming concept

Key features of the open BTS modem include, but are not limited to:

- Multistandard air-interfaces
  - Global system for mobile communication (GSM), cdma2000, WCDMA, hardware-defined radio (HDR), TD-SCDMA, WLAN, OFDM, worldwide interoperability for microwave access (WiMAX)
  - Proprietary standards
- Highest channel density
  - Third Generation Partnership Project (3GPP™) channels, cdma2000 channels
  - OFDM channels
  - Ability to support multiple sectors on one chip
  - Growth from sectors-on-a-chip to BTS-on-a-chip or system-in-a-package
- Scalable data rates
  - Support from 8 kbps to 10 Mbps or higher
- Configurability to mix voice and data
  - Programmable allocation of channels
- IP-readiness
  - Direct interface via BTS IP backhaul
- Over-the-network programmability
  - Remote configurability from a network operations center

Key features of the open wireless terminal include:

- Multistandard air-interface
  - GSM, cdma2000, WCDMA, WLAN, Bluetooth™, OFDM, WiMAX
- Power efficiency
  - 100 MOPS/mW and more
- Scalable architecture
  - Beyond the 384 kbps, 2 Mbps, and 10 Mbps plateaus
- High-level modem virtual machine interface (VMI)
  - Simplified programming for each standard
  - Enhanced reuse across standards
- Integration across many platforms
  - No digital signal processing (DSP) and minimal microprocessor-dependent code
- Silicon intellectual property (SIP) cores
  - Initial engine optimization for beyond third generation (3G+)/4G applications

**Figure 2** shows the multistandard BTS engine for this OWA platform.

## OPEN BACKBONE NETWORK ACCESS PLATFORM

Recently developed access aggregation technologies allow a common access and transport network to bear subscriber traffic from multiple service providers. Separating access and transport from service accomplishes two things:

- It eliminates the burden of building out an access network, thereby reducing the barrier to entry for new service providers and improving the growth potential for existing service providers.
- It promotes technical and business efficiencies for access and transport enterprises due to economies of scale and the ability to resell that access infrastructure to multiple service providers.

New systems provide end-to-end direct IP connections for users by extending access aggregation architectures to mobile broadband access. Network and service providers can leverage existing equipment, tool, and content bases to support mobile broadband end users, while the end users experience the best of the wireless and wired worlds—the broadest range of applications and end-user devices, coupled with high data rates and the freedom to move.

*Spectral efficiency measures the ability of a wireless system to deliver a given amount of billable services in a given amount of radio spectrum.*

## SHARED SPECTRUM AND CAPACITY ENHANCEMENT

The spectral efficiency of wide-area wireless broadband systems can yield a system capacity that allows that efficiency to be delivered simultaneously to many users in a cell, reducing the cost of service delivery for this mass-market broadband service. These systems are optimized to exploit the full potential of adaptive antenna signal processing, thereby providing robust, high-speed connections for mobile users with a minimum of radio infrastructure.

The spectral efficiency of a radio system—the amount of information ("billable services") that can be delivered in a unit of spectrum—directly affects network economics and service quality. Spectrally efficient systems have the following characteristics:

- Reduced spectrum requirements, minimizing up-front capital expenses related to spectrum
- Reduced infrastructure requirements, minimizing capital and operating costs associated with base station sites, which

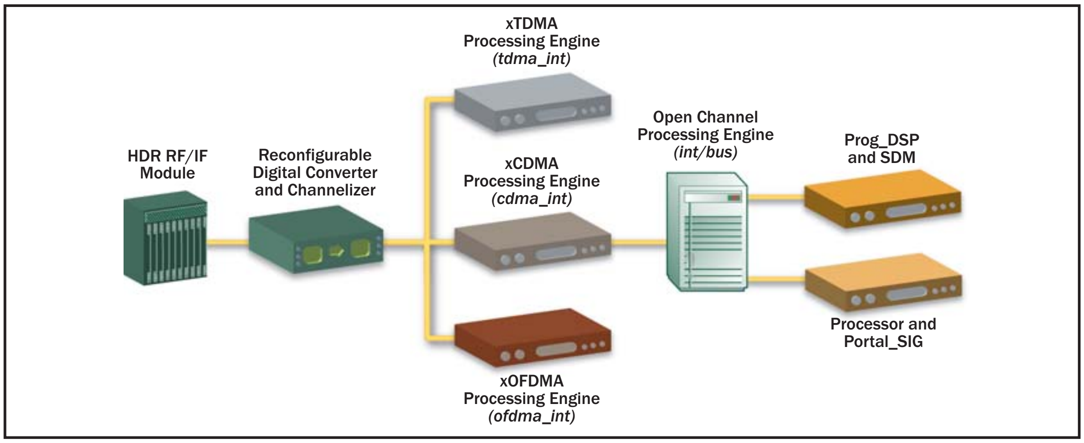


**Figure 2. Multistandard BTS Engine for the 4G OWA Platform**

- translates into reduced costs per subscriber and per covered population element
- High capacity, maximizing the system throughput and end-user experience, even under load

Spectrum acquisition is a key component of the cost structure of wireless systems, and two key features of spectrum have a great impact on that cost: the spectral efficiency of the wireless system and the type of spectrum required to implement the system. A fully capable and commercially viable mobile broadband system can operate in as little as 5 MHz of unpaired spectrum, with a total of 20 Mbps throughput per cell in that amount of spectrum.

*Given the current economic situation, many experts predict that 4G mobile may be developed much sooner than expected, especially if 3G takes too long to take off.*

Spectral efficiency measures the ability of a wireless system to deliver a given amount of billable services in a given amount of radio spectrum. In cellular radio systems, spectral efficiency is measured in bits/second/Hertz/cell (bps/Hz/cell). Many factors contribute to a system's spectral efficiency, including the modulation formats, air-interface "overhead" (signaling information other than user data), multiple access method, and usage model, among others. The quantities just mentioned all contribute to the bps/Hz dimensions of the unit. The appearance of a "per-cell" dimension may seem surprising, but the throughput of a particular cell's base station in a cellular network is almost always substantially less than that of a single cell in isolation. The reason is self-interference generated in the network, requiring the operator to allocate frequencies in blocks separated in space by one or more cells. This separation is represented by a reuse factor, where a lower number is indicative of a more efficient system.

For example, a mobile broadband system spectral efficiency of 4 bps/Hz/cell means that a mobile broadband radio network can use far fewer sites and far less spectrum to support a given mobile customer base than would be required with other technologies—and, hence, at greatly reduced capital and operating expenses. With 10 MHz of usable spectrum, for example, each mobile broadband base station would provide 40 Mbps of access capacity. In contrast, a second-generation (2G) or 3G system with a spectral efficiency of 0.1 bps/Hz/cell would provide only 1 Mbps of access capacity per cell in that same 10 MHz. In a capacity-limited rollout situation, a system with 2G- or 3G-like spectral efficiency would, therefore, require 40 times (4/0.1) the number of base stations as a wireless broadband system and have a correspondingly higher service delivery cost.

Actually, many countries are expecting that the service capacity and spectral efficiency of 3G technology will increase. Therefore, they are not demanding higher data-rate transmission, which, at present, is not the killer application.

The rollout of 3G and 4G technologies will be stunted unless wireless spectral efficiency improves. Consumer and enterprise adoption will depend on new wireless technologies providing significant new capabilities inexpensively and seamlessly.

## SERVICE-ORIENTED ARCHITECTURE AND OPEN OS PLATFORM

The success of future wireless communications will rely mainly on the services provided and the applications its users require, rather than on the underlying wireless transmission

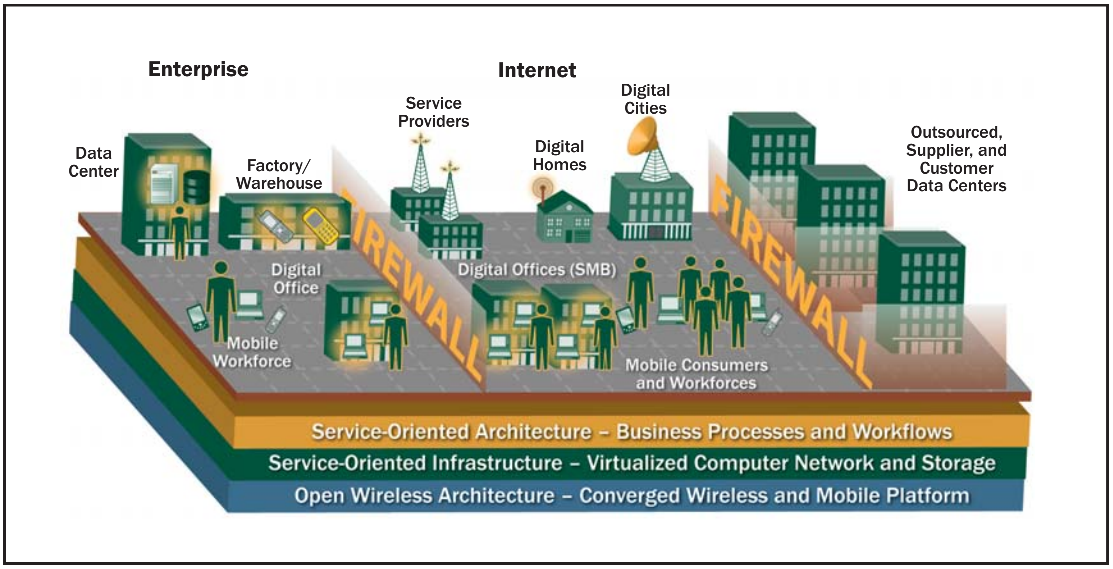


**Figure 3. Future Open Services Environment**

technologies. Users dislike the relatively uninteresting names of various wireless standards, e.g., IEEE 802.11, IEEE 802.16, and cdma2000, so service-oriented architecture (SOA) is extremely important for the system design and product development of future wireless communications.

To support this SOA platform, OWA must converge various radio transmission technologies onto an open system platform that incorporates the platforms for baseband processing, OS, RF, and infrastructure. This convergence will enable the future wireless terminal and base station to handle different communications needs with the same open equipment and same number—a truly unique and global personal communication identifier.

**Figure 3** shows the future open services environment. The OWA layer sits under the SOA layer and the service-oriented infrastructure (SOI) layer, and therefore is not transparent to the end users. This open environment is designed for the future wireless lifestyle of the year 2010 and beyond.

## OPEN DISTRIBUTED WIRELESS AD HOC NETWORKS

Experts doubt that the current path to 3G will succeed. Current 3G migratory paths involve gradually enhancing voice-centric, high-power, hierarchical networks with IP overlays. Air-interfaces may upgrade from GSM to WCDMA, or from CDMA to high-speed downlink packet access (HSDPA), but such RF adaptations do not address the underlying wireless network architecture issue. An additional concern is whether or not upgrading star networks will improve performance in a wireless environment as opposed to a wireline one.

However, low-powered, ad hoc, mesh-architected networks offer spectrally efficient, high performance solutions to this dilemma. In such peer-to-peer networks, end-user wireless handsets act as both end terminals and secure wireless routers that are part of the overall network infrastructure. Upstream and downstream transmissions "hop" through subscriber handsets and fixed wireless routers to reach network access points or other end terminals. Routing infrastructure, including handsets, uses intelligent routing capabilities to determine the "best path" for each transmission.

"Best path" routing must be defined as "least power." That is, network nodes must be able to calculate and update routing tables to send data packets through the paths with minimal power requirements. This is different from network nodes associating with the physically closest available infrastructure. Subscriber terminals do not "shout" at a centralized base station, but rather "whisper" to a nearby terminal, which, in turn, routes the transmission to its destination. Subscriber terminals cooperate, rather than compete, for spectrum. Spectrum reuse increases dramatically, while overall battery consumption and RF output within a community of subscribers are reduced. Simply put, additional users enhance rather than strain network capacity.

Thus, while the cellular handset can maintain only a 144 kbps link to the base station, the ad hoc mesh device can maintain a multi-megabit link without undue interference.

## CONCLUSIONS

Open standards are more than likely to prevail in the next decade. With strong economic growth in East Asia, including Korea, China, Japan, and neighboring countries, the 4G mobile system based on OWA (see **Figure 4**) will become the next wave in wireless communications. It is widely predicted that Asia-Pacific will be the major global hub of 4G mobile in the years to come. Already, more than 70 percent of the world's 4G research and development is based in this region, which reflects huge business opportunities and industrial potential in future wireless communications. Open standards will most certainly drive this new storm in the region's information and communication technology industry.


**Figure 4. Future OWA All-in-One 4G Terminal**

In the meantime, the Fourth Generation Mobile Forum (4GMF), Wireless World Research Forum (WWRF), mobile IT Forum (mITF), Korea 4G project (K4G), and China Future Technology of Ultra Radio Enhancement (FuTURE), among others, are all working diligently to promote this emerging 4G mobile development worldwide. Given the current economic situation, many experts predict that 4G mobile may be developed much sooner than expected, especially if 3G takes too long to take off. ■

## TRADEMARKS

**3GPP** is a trademark of the European Telecommunications Institute (ETSI) in France and other jurisdictions.

**Bluetooth** is a trademark owned by the Bluetooth Special Interest Group (SIG), USA.

**cdma2000** is a registered trademark of the Telecommunications Industry Association (TIA-USA).

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## BIOGRAPHY

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Professor Lu has been a guest editor for approximately 50 special issues on emerging wireless communications in IEEE, IEICE, ACM, CIC, and other major publications, and more than 150 of his papers have been published in major professional publications. In addition, he is a member of the editorial board of *IEEE Spectrum*, the flagship publication of the Institute of Electrical and Electronics Engineers.

Professor Lu has been a technical chairman for numerous IEEE conferences, including GLOBECOM'03, WCNC'02, VTC'03, and WWC'00-05, as well as a feature editor on topics relating to wireless technology for *IEEE Communications Magazine, IEEE Transactions on Wireless Communications* (formerly *J-SAC Wireless*), and other technology magazines. He is a frequent keynote and featured speaker at many global technical forums and is one of the world's prominent wireless pioneers. As the founding chairman of the prestigious World Wireless Congress, Global Mobile Congress, and Fourth Generation Mobile Forum, Professor Lu has been considered a distinguished and notable Chinese wireless expert overseas by various Chinese authorities since 1996.

Professor Lu received his PhD in Wireless Communications from the Technical University of Malaysia and Aachen University of Germany (joint program) and his MSc and BSc in Wireless Communications from Zhejing University in China. His post-doctorate studies were also in Wireless Communications at the German National Research Center for Information Technology.

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For more information about Professor Lu, visit his International Telecommunication Union personal home page (http://people.itu.int/~wlu/).