Wireless Mobile Communications at the Start of the 21st Century

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ABSTRACT

At the start of the 21st century, the wireless mobile markets are witnessing unprecedented growth fueled by an information explosion and a technology revolution. In the radio frequency arena, the trend is to move from narrowband to wideband with a family of standards tailored to a variety of application needs. Many enabling technologies including wideband code-division multiple access, software-defined radio, intelligent antennas, and digital processing devices are greatly improving the spectral efficiency of third-generation systems. In the mobile network area, the trend is to move from traditional circuit-switched systems to packet-switched programmable networks that integrate both voice and packet services, and eventually evolve toward an all-IP network. Furthermore, accompanied by wireless mobile location technology, wireless mobile Internet is expected to revolutionize the services that can be provided to consumers in the right place and at the right time. Wireless mobile communications may not only complement the well-established wireline network; it may also become a serious competitor in years to come. In this article we briefly review the history of the wireless mobile communications, examine the current progress in standards and technologies, and discuss possible trends for wireless mobile solutions.

THE HISTORY OF WIRELESS MOBILE COMMUNICATIONS

Halfway through the 20th century, after the invention of two-way radio communications at the beginning of the century, the key foundations of wireless mobile systems were invented in Bell Laboratories. The concept is to reuse the same limited radio frequency (RF) in a group of cells arranged in a cellular structure to serve an unlimited number of users. Furthermore, calls are systematically handed off from one cell to another to accommodate vehicle mobility from cell to cell. It is interesting to observe that these seemingly simple ideas have since revolutionized wireless communications and led to a multibillion dollar industry.

The first-generation cellular wireless mobile systems were analog and were based on frequency-division multiplex (FDM) technology. Limited to the technologies of that time, most phones were large, placed in a briefcase-sized case, and permanently installed in a vehicle. Based on the number of vehicles that might need a phone and the number of people who could afford to pay, it was once projected by some that the cellular industry would only see limited growth. Indeed, the growth of cellular subscribers was moderate before the 1980s, as can be seen from Fig. 1.

By the end of the '80s, however, advances in semiconductor technologies provided a vital boost to the cellular mobile industry. Using application-specific integrated circuits (ASICs), the size of the phone shrank to a small handset. It turned out that this small technical evolution led to a major revolution for the cellular mobile industry for at least two reasons. First, the industry's consumer base was changed from the number of vehicles to the number of people, which is a much larger base. Second, the function of the phones was also changed from being able to call from a vehicle to being able to call from anywhere. This greatly increased people's desire to have a phone and therefore significantly increased the penetration rate. Figure 1 shows the phone size evolution in terms of the reduction in number of ICs in the handset and its correspondence with subscriber growth.

The second boost for the cellular industry came from the introduction of the second-generation (2G) digital technology standards, including Global System for Mobile Communications (GSM, previously known as Groupe Spéciale Mobile), IS-136 (time-division multiple access, TDMA), IS-95 (code-division multiple access, CDMA), and Personal Digital Cellular (PDC). Digital technology has not only improved voice quality and services, but more important, significantly reduced the cost of handset and infrastructure systems, leading to further acceleration of the industry's growth since the mid-1990s, as can also be seen from Fig. 1.

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Moving forward to the 21st century, further acceleration of growth is widely anticipated. Soon, third-generation (3G) systems will be deployed. While 3G systems will significantly improve the spectral efficiency and possibly the cost of the system, a more profound feature is the significant improvement of its data and multimedia capabilities. While this feature seems to be a mere evolution from a technical viewpoint, its potential lies in the promotion of communications not only from person to person, but also from person to machine and from machine to machine. Similar to the expansion from vehicles to people in 2G systems, this expansion is hoped to lead to a significant increase in the user base, since the number of machines can be an order of magnitude larger than the number of people.

In addition to the possible user base expansion, growth will also be further fueled by the significant increase of the user penetration rate. Increasingly, more functions are being built into the wireless mobile handset. One example is the combination of the phone with the personal digital assistant (PDA). This combination, with a user-friendly interface, can greatly improve convenience for a user over that provided by a wireline phone. When further combined with improved voice quality, reliability, multiple functionality, and "reasonable air price," it can indeed become a serious competitor to the wireline phone system.

Frequency Spectrum

As discussed above, both the subscriber base and subscriber penetration rate are expected to grow significantly in time. The combined growth rate is expected to be much faster than can be achieved only through the spectral efficiency improvement of various new technologies. Consequently, new spectrum in addition to that of the traditional cellular band (800–900 MHz) needs to be allocated for 3G systems to accommodate the exponential growth. To make the global roaming of wireless communications easier, frequencies in similar bands worldwide have been proposed by the International Telecommunication Union (ITU). Unfortunately, the allocated frequency bands are not necessarily aligned from country to country.

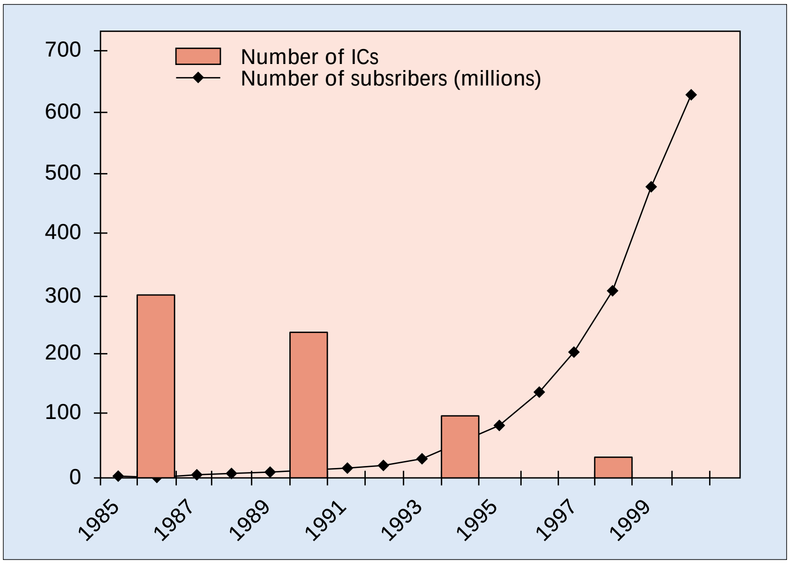

Figure 1. *Subscriber growth and IC reduction in mobile terminals.*

For instance, frequencies in the 1900–2000 MHz in the United States are already allocated for personal communications systems (PCS) used by 2G systems. Figure 2 provides an overview of the spectrum allocations worldwide for cellular, PCS, and International Mobile Telecommunications in 2000 (IMT2000). From Fig. 2, it is evident that wireless handset will need to operate in different frequency bands in order to roam from country to country.

While various frequency bands have been allocated in different countries around the world, how each service provider obtains the corresponding frequency bands varies from country to country. Some countries distribute the frequency band by auction; others distribute it through a process of selection known as a "beauty contest." Figure 3 gives the approximate timeframe for spectrum awards of a selected number of countries.

Wireless Mobile Standards

In order to promote global roaming, the ITU started the IMT-2000 initiative that proposes worldwide recommendations for terrestrial and

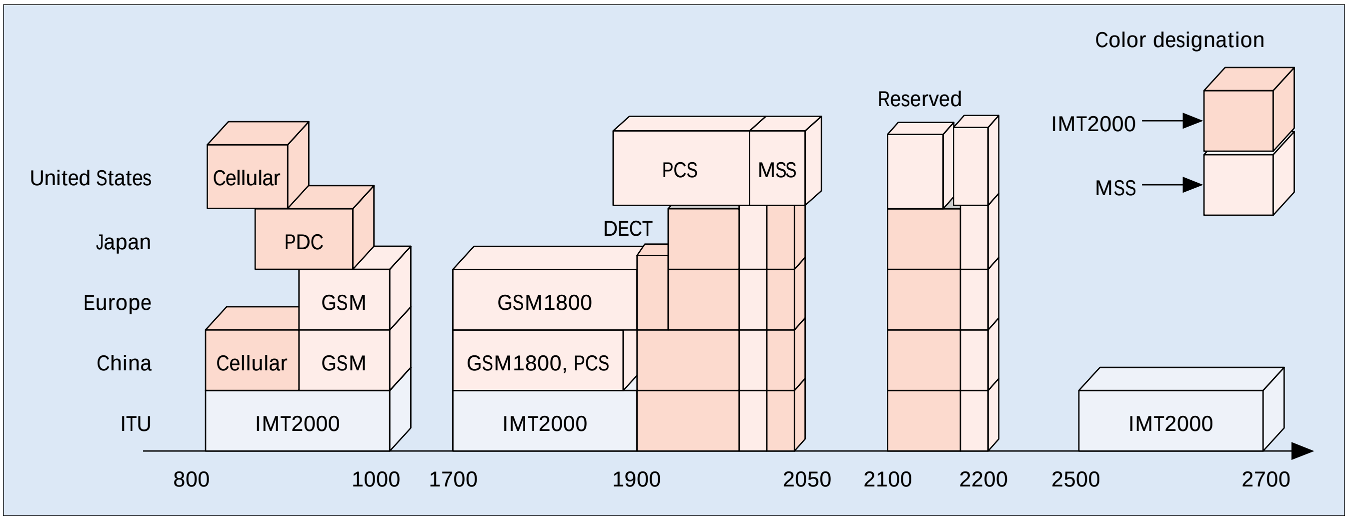

Figure 2. *RF spectrum allocation in major regions.*

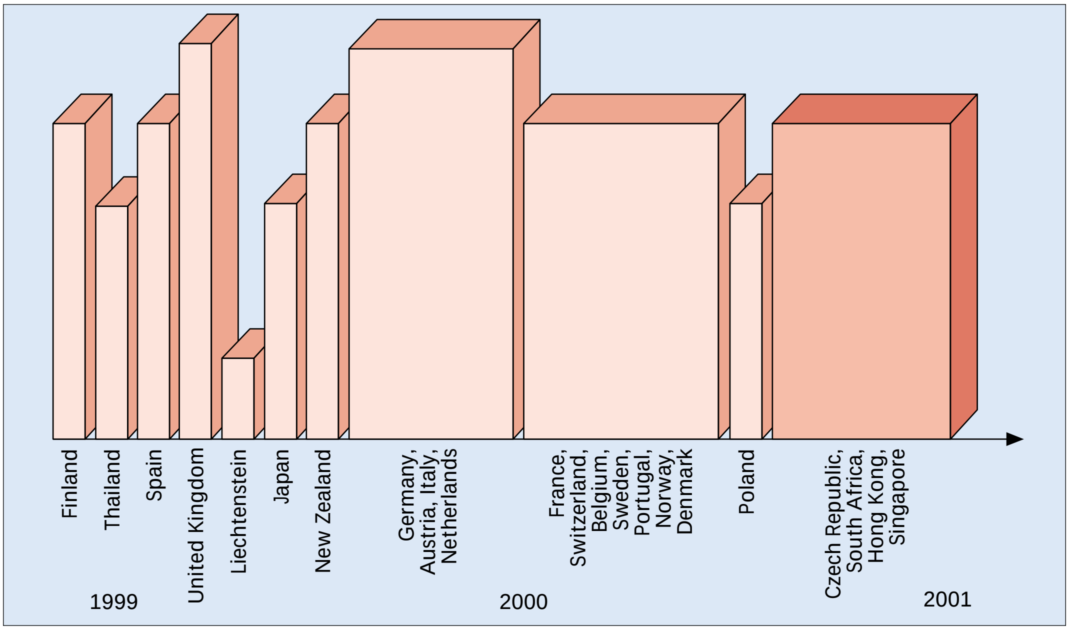

Figure 3. *A timeline for new wireless licenses.*

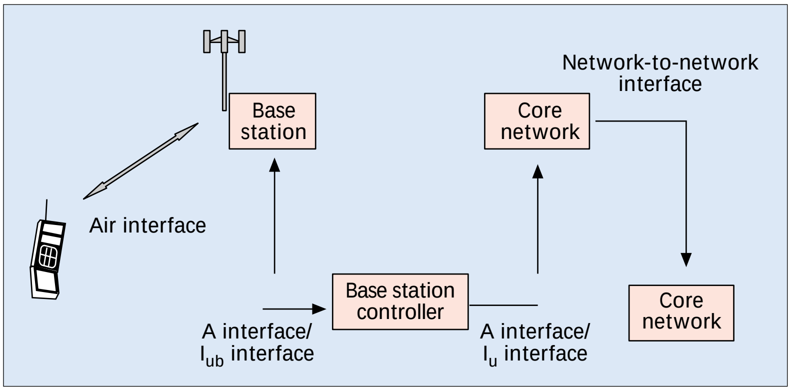

Figure 4. *Wireless mobile system interface definition.*

satellite communications systems. For wireless mobile communications, various interface definitions are shown in Fig. 4.

While it was initially hoped that a unique air interface standard would be desirable worldwide, reality soon led to the realization that a family of systems would be needed to cover a wide range of services and requirements from different regions of the world. This was a result of the acknowledgment that 3G systems would need to evolve from the existing 2G systems, which are based on different technologies and air interface standards including GSM, CDMA, and TDMA. In addition to the difference in various air interfaces, there are also two major regional network standards: GSM-MAP and ANSI-41.

For most 2G systems based on GSM or TDMA standards, the evolution to 3G is planned through the Enhanced Data for GSM Evolution (EDGE) standard. For new "green field" service providers, the Universal Mobile Telecommunications System (UMTS) will most likely be used and is based on wideband CDMA (W-CDMA) technology. W-CDMA systems will utilize 5 MHz of bandwidth in each link direction using frequency-division duplex (FDD). For systems based on IS-95 CDMA technology, the evolution will be based on the cdma2000 standard, IS-2000. The initial implementation of cdma2000 will utilize 1.25 MHz bandwidth in each link direction to ensure full compatibility with the current 2G CDMA systems, with a possible migration path to 5 MHz systems. Figure 5 shows the approximate market shares in 2000 based on different technologies.

To facilitate the rapid development of 3G wireless mobile standards, two programs were launched to deal with the UMTS and cdma2000 standardization. They are the Third Generation Partnership Projects, identified as 3GPP for UMTS and 3GPP2 for cdma2000. Currently, 3GPP is supported by the Standards Committee T1 organization of the United States and the European Telecommunications Standards Institute (ETSI) of Europe, whereas 3GPP2 is supported by the Telecommunications Industry Association (TIA) from the United States. In addition, both 3GPP and 3GPP2 are supported by China Wireless Telecommunications Standards (CWTS), the Association of Radio Industry Board (ARIB) and Telecommunications Technology Council (TTC), both of Japan, and the Telecommunications Technology Association (TTA) of Korea.

While a family of air interface standards will be specified for 3G systems, the ITU has decided not to specify the protocols to be used within the core network. This is intended to allow the two major network standards, GSM-MAP and ANSI-41, to evolve independently according to market needs. The ITU will specify the protocols to be used between the core networks, known as the *network-to-network interface* (NNI), so that calls can roam between cells connected to the two different networks.

Given the selection of possible 3G air interface standards such as EDGE, UMTS, and cdma2000 connected to either the GSM-MAP or ANSI-41 network, many different infrastructure systems supporting different standards will need to be manufactured and deployed, possibly using different frequency bands, depending on the service providers and the corresponding countries. This presents a dilemma for handsets as well because each handset will need to support different standards when roaming between service providers and countries. One technique thought to have the potential to solve this dilemma is software-defined radio (SDR). With this technique, only one infrastructure hardware system would need to be developed. The difference in frequency bands and technology standards would be implemented by loading different software into the system. The same technique can also be applied to the handset. A person visiting different countries supporting different standards will only need to carry one handset, with different software loaded into the handset when needed.

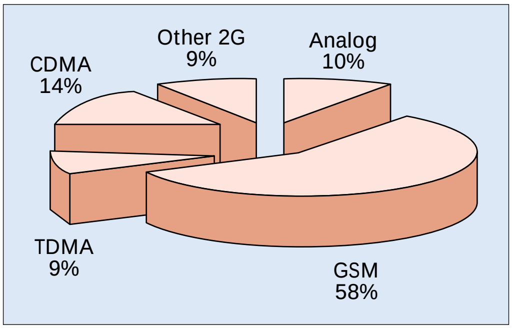

Figure 5. *Estimated market shares of 1G and 2G wireless mobile systems in 2000.*

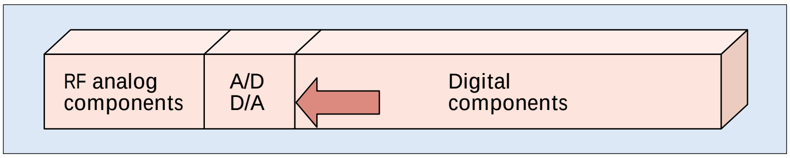

Figure 6. *A high-level view of a general radio system.*

SOFTWARE-DEFINED RADIO

From the discussions above, it is clearly desirable to have a system that can operate on different standards and in different frequency bands. This approach becomes possible because of the rapid progress in semiconductor and digital technologies. More specifically:

- The advances in analog-to-digital (A/D) and D/A conversions have made it possible to directly convert signals closer to the antenna at high speed with adequate dynamic range. This reduces the radio components needed and greatly facilitates digital implementation, as shown in Fig. 6.
- With the signals converted to digital in the very early stages of the system at high speed, a wideband radio approach can be adopted that provides inherent flexibility to support different standards which operate with different frequency bandwidths.
- The rapid growth in the use of general-purpose digital signal processing (DSP) and field programmable gate array (FPGA) chips makes it commercially viable to manufacture general-purpose programmable devices at low cost. Furthermore, the speed of these devices using software or firmware implementation is now adequate, and its performance can be comparable to that of a hardware implementation.

In addition to the advantage of being able to support different standards with a unified platform and hardware, SDR also has the following possible benefits:

- Many commercial digital architecture and software protocol stacks are already available and can be used to further reduce the cost and the time to market.
- It will be much easier to introduce new services and features with software upgrades. This approach is especially attractive for the rapidly growing wireless industry because both end-user needs and standards continue to evolve.
- The implemented system can easily be tailored to specific customer needs for both mass and niche markets.
- It provides flexibility to optimize the system performance over time and reduces new system deployment risks.

While the SDR approach has many attractive features as listed above, its wide acceptance is not necessarily guaranteed at this stage. It still faces strong competition from the standard-specific implementations using ASICs. For the infrastructure systems, different service providers may only need system equipment supporting a particular standard. Although implementation using ASICs is likely to result in a longer time to market, it can potentially be manufactured at a lower cost at present because the equipment is made specifically for a particular standard with a minimum overhead of hardware and software.

Another concern for the implementation of SDR is the rapid progress in the semiconductor and communications technologies. Currently the speed of processors and DSP chips increases significantly every year or two. This rapid increase is consumed by new wireless standards and features as soon as it is available. While theoretically systems implemented by SDR only need to make software upgrades as time goes by, practically the system hardware may need to be redesigned and changed periodically due to the obsolescence of processors and DSP chips. Therefore, some of the advantages of SDR may not be realized due to the instability of the hardware, similar to the hardware-software relationship in the PC market.

For handset implementation, the future is also not necessarily clear. While many world travelers would like to have a handset that supports different standards depending on where they travel, a significant number of wireless subscribers may be satisfied with a handset supporting a particular wireless standard selected by a corresponding country or service provider. Therefore, implementation using ASICs can be attractive in terms of low cost for that population. Furthermore, one important consideration for any wireless handset is

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its battery life. Currently, the power consumption of ASIC implementation can be made much smaller than that of DSPs and FPGAs. Implementation using ASICs is likely to result in handsets with a smaller size as well. Therefore, many obstacles must be overcome before SDR can become a popular choice for handset implementation.

Based on the above observations, a more likely scenario in the near future is a mix of ASIC and SDR implementation. As time passes, the percentage of software-defined components may increase.

Geolocation and Related Applications

When a call is made through a landline telephone, the caller's telephone number and location can be identified through the call processing signaling. This feature has been used for caller identification (ID) and emergency call applications (E911). Similarly, the geographical location, or geolocation, of a wireless caller can be determined by various means. Unlike the landline case, however, wireless geolocation technology is also considered a key enabling technology, because it has great potential to promote many other related applications that could significantly increase the wireless user base through people-to-machine and machine-to-machine communications. While some obvious applications of geolocation technology include mobile map service and identification of mobile location for emergency calls, it is the many other e-commerce applications that are expected to satisfy users' changing needs depending on particular locations.

There are two types of geolocation techniques, one based on the network and the other on the handset. In network-based solutions, the geolocation information is generally estimated through the timing, arrival angle, and strength of the signals received from the handset. Typically, the received signals from the same handset at different base stations are compared to determine the exact handset location through triangulation techniques.

Handset-based techniques are mainly based on satellite signals using the Global Positioning System (GPS). While initially the GPS was mainly for military applications and its commercial use was prohibitively expensive, the recent rapid and massive commercialization of GPS applications have made cost-effective implementations possible.

When examining the above two types of techniques, each has limitations when used alone. For network-based techniques, the accuracy of the estimation is usually limited by the accuracy of the received signals. For handset-based GPS approaches, the limitation lies in the fact that accurate estimation will require the reception of several GPS satellites, which might not be possible in many circumstances, including indoors and in narrow metropolitan areas with surrounding high-rises. Consequently, an approach using a combination of GPS and network-based techniques known as *assisted GPS* has been proposed.

Intelligent Antennas

Due to the continued rapid growth of wireless mobile applications, more system capacity is needed as well as the identification of new frequency bands. Intelligent antennas are a promising technique that can significantly increase system capacity. Current narrow beam proposals include two techniques: the steered-beam and switched-beam approaches.

The steered-beam approach utilizes phased-array antennas, with multiple columns of antenna elements in pairs or equally spaced. The phased-array elements are used in the antenna to create a narrower beam directed only to the intended mobile on the forward link. This beam is then steered with the mobile as it moves. Forward link transmit diversity can be provided as part of the intelligent antenna solution. In this case, the total gain will be the combination of the gains from transmit diversity and the aperture due to reduction of the antenna beam relative to the corresponding sector antenna beam.

The switched-beam approach differs from the steered-beam approach in at least two ways. First, the aperture of the antenna in the switched-beam approach is fixed to a fraction of the sector, whereas that in the steered-beam case is adaptive depending on channel condition. Second, instead of being adaptively steered with the mobile users as it moves, the system simply switches from one antenna beam to another.

In addition to the above narrow beam techniques, adaptive processing algorithms can also be used to process signals from multiple antenna columns to take advantage of optimal combining of the relatively incoherent diversity and relatively coherent phased-array antenna columns. The corresponding gain of this technique over conventional antennas will be especially large when there are a limited number of high-speed data mobiles mixed with voice users, since the adaptive processing algorithm can significantly reduce the identified interference from high-rate mobile data.

Beyond the above intelligent antenna techniques, an even more powerful technique was proposed by Bell Laboratories, known as Bell-Labs Layered Space Time (BLAST) technology. BLAST technology establishes multiple parallel and simultaneous channels that operate in the same frequency band without increasing the total transmitted power. The result is that the capacity of both the forward and reverse links can be increased by an order of magnitude over other techniques.

Superconductor, TTLNA, and Multi-User Detection

In addition to the intelligent antenna techniques that can improve both forward and reverse links of wireless mobile systems, techniques exist that can greatly improve reverse link performance. Superconductor, tower-top electronics, and multi-user detection belong to this category.

In many wireless mobile systems, the coverage radius of a cell is limited by the handset maximum transmit power and base station thermal noise strength, known as the *noise figure*.

Since the handset transmit power will determine the battery life, it is desirable to limit the maximum handset transmit power. Consequently, the reduction of the system noise figure becomes important for coverage improvement. The current state of the art results in a noise figure in the 4–5 dB range in most wireless mobile systems. Utilizing a superconductor device or low noise amplifier on top of a tower at the antenna, the noise figure can be reduced by a few dB, resulting in a larger coverage radius. Currently, the tower-top low noise amplifier (TTLNA) is beginning to be accepted with increased improvement in reliability and size of the device, whereas the superconductor device is not yet widely adopted. Its wide acceptance will largely depend on improvement in the cost, reliability, and size of the device. Furthermore, it faces stiff competition from the TTLNA, since the TTLNA approach appears able to compensate for much of the loss due to the noise figure at lower cost and with higher reliability.

In an urban environment, many wireless mobile systems are limited by capacity, not coverage. In this case, a multi-user detection technique can be used. This approach is based on the observation that the capacity of a base station in many cases is limited by the co-channel interference generated by other users in the same cell using the same frequency. When a user with strong signal strength has been received and detected, it can be subtracted from the aggregate signals received at the base station before another user's signal can be detected, since the signal from the detected user causes co-channel user interference to the still undetected user.

Once the signal from the second user is detected, it can be subtracted from the aggregate received signal to detect the first user again for further detection improvement. Clearly this process can be iterated to improve signal detection. While the above discussion provides high-level ideas of how multi-user detection works, many techniques exist that either detect one user at a time or detect all users simultaneously. Currently, multi-user detection is still in the laboratory research stage. Its wide acceptance will depend on improvement of processing speed and forward link capacity, since the need for reverse link capacity improvement will be limited if the corresponding capacity on the forward link cannot be achieved.

WIRELESS INTERNET

If anyone has any doubt about the potential of wireless Internet, they need only look at the iMode service provided by the Japanese service provider NTT DoCoMo. In only about 15 months, DoCoMo built its iMode service into a popular wireless experience serving nearly 7 million users. The iMode phone uses 19.2 kb/s data rate to access the network for everything from reserving karaoke service to downloading music.

Currently, a large amount of information exists in the Internet that can meet very diverse needs. This is clearly a good match for mobile wireless users while traveling from place to place. It has been projected that most handsets will be equipped with Wireless Application Protocol (WAP) and Wireless Java in a few years for wireless Internet applications. When Internet information can be delivered wirelessly according to handset geolocation information, it becomes even more valuable and convenient.

To deliver an Internet connection wirelessly, good packet-switched networks are desired. This raises the question as to whether voice over IP will be feasible and an all-IP wireless network possible for efficient delivery of both voice and data once data traffic is comparable to or more than voice. In 3G systems, packet-switched data channels will be available for efficient data delivery. However, an all-wireless IP network for both voice and data may not be widespread for the air interface of wireless mobile applications in the near future. This is because the IP protocols have a large amount of overhead that will reduce spectral efficiency when used for voice applications. It may also suffer intolerable delays because bandwidths for wireless mobile applications are still limited and sometimes expensive to obtain.

For the interface between the base station and the network, or the air interface for fixed wireless and others, an all-IP network will be feasible. However, the conversion is likely to be through asynchronous transfer mode (ATM) before transition to an all-IP network. ATM implementation will guarantee quality delivery of both voice and data, and allow the additional time needed to perfect the IP network and build up the needed bandwidth. Once large bandwidth is secured, an all-IP network can be implemented to delivers both voice and data across different networks.

Currently, voice is transmitted through circuit-switched mobile switching centers (MSCs), whereas data are likely transmitted through routers, bypassing the MSCs. A single softswitch will likely replace separate MSCs and routers in the future. The integration of voice and data delivery will reduce network costs and promote unified operation, administration, and maintenance (OAM).

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COMPETING NETWORKS AND TECHNOLOGIES

In addition to wireless mobile communication technologies, many other wireless and wireline technologies exist that will complement and compete with wireless mobile technology. Some of the major alternative wireless technologies include fixed wireless, broadband wireless such as LMDS and MMDS, and satellite.

Fixed wireless had been projected to become a multibillion dollar industry in the past, but most projections have been overly optimistic so far. Technically speaking, the fixed wireless environment is quite different from the mobile environment. Without the mobility requirement, narrow-beam antennas with high gains can be used that greatly improve coverage and reduce power amplifier cost. Since no handoff is needed, the system architecture can be greatly simplified. All the above raised the hope that fixed wireless systems could be implemented much more cheaply than wireless mobile systems and be able to compete effectively with wireline solutions as well.

However, it appears that success so far is lim-

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ited. One difficulty lies in the strong competition from wireless mobile systems. As long as the main application continues to be voice, there is nothing to prevent wireless mobile systems from being used for fixed wireless. After all, everyone would prefer a handset without a cord. Furthermore, the cost savings from the possible system design simplifications requires volume comparable to that of mobile wireless systems. This proved difficult to achieve initially because wireless mobile systems have already had mass market production for many years. In addition, installation of fixed wireless also proved to be costly and time-onsuming if narrow beam antennas are used. Several fixed wireless voice solutions have already been killed in their infancy because they cannot compete in cost and deployment speed with the mature mass wireless mobile solutions.

Point-to-point and point-to-multipoint solutions using LMDS and MMDS are other alternatives for wireless solutions. However, competition to the wireless mobile solution in voice application may also be limited. Due to the high frequency band allocated for these applications, the system operation often requires line of sight (LOS). Furthermore, microwave components are still expensive, resulting in high costs for equipment. Therefore, the LMDS and MMDS solutions may initially provide trunk service for the small office/home office (SOHO). The initial subscribers in these markets are much fewer than in the wireless mobile markets.

With the fiasco of the Iridium project, the competition for voice applications between satellite and wireless mobile technologies appears to be over. While technically feasible, the cost of satellite communications for voice is much higher with today's state of the art. Any future satellite voice solutions are likely to target high-end users and see a limited market base. Based on the above observations, it appears that wireless mobile technology will remain the technology of choice for wireless voice applications for years to come.

With the rapid growth of data applications, however, the competition from the above alternative wireless solutions will be renewed. Consider the fixed wireless solution; it has the potential to provide much higher spectral efficiency in terms of bits per hertz using narrow beam antennas in the fixed environment. This can be attractive for indoor wireless applications where moderately high-speed transmission is desired for mixed voice and data traffic. Furthermore, both LMDS and satellite solutions can deliver much higher data rates due to their available wide bandwidth. Therefore, strong competition is expected from all the above alternative wireless solutions for data applications.

Conclusions

With less than 50 years of commercial history, wireless mobile communications have already changed the way people communicate with each other. While the progress has been impressive, much more is yet to come that will revolutionize communications as we know it, leading eventually to communicating with anyone or any device at anyplace and any time.

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