Digital Cellular—Its Roots and Its Future

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Invited Paper

Cellular started in the early 1980's by using analog technologies. Research in voice coding, modulation, and channel coding resulted in second-generation cellular based on digital technologies, which were introduced in the early 1990's. These were all based on advanced time division multiple access technology, resulting in better capacity and lower cost. Today, these digital technologies—based on the global system for mobility, digital Advanced Mobile Phone System, and personal digital cellular—have more than 100 million subscribers worldwide.

The next step is to introduce wide-band packet services for wireless Internet up to 2 Mb/s. These so-called third-generation systems (Universal Mobile Telecommunications Services, IMT2000) are planned to be introduced in the early 2000's.

Keywords— *CDMA, equalization, frequency hopping, GSM, IMT2000, multipath delay spread, packet radio, TDMA, UMTS.*

I. THE PAST

A. History

When the cellular mobile phone arrived in the early 1980's, it was a turning point in telecommunications. Adding radio access to the core telephone network meant that for the first time in history, the concept of a telephone's being at a fixed point in the network was no longer valid. Equally, the concept of a telephone number's indicating a fixed geographical location also had to be reconsidered.

First-generation analog cellular systems were followed in the early 1990's by second-generation digital technologies that allow much larger numbers of mobile subscribers to be supported within a given frequency allocation, provide better voice quality, and permit a range of value-added services, such as data.

The first automatic cellular system started operation in the early 1980's and was based on well-proven analog frequency modulation (FM) technology. Systems like Nordic Mobile Telephony in Scandinavia and Advanced Mobile Phone System (AMPS) in the United States used very similar bandwidth (25 and 30 kHz, respectively) that had already been in use in land mobile radio for decades.

Research of digital cellular had started in the 1970's, primarily focused on narrow-band frequency division multiple access (FDMA) systems with similar bandwidth as the analog FM systems. Research was focused on three areas:

- spectral efficient constant envelope modulation;
- channel coding combined with interleaving to combat Rayleigh fading;
- low-rate voice coders.

One of the earliest full digital FDMA experimental systems is shown in Fig. 1. It was presented in [1] using 25-kHz channels with advanced channel coding. Using soft decoding, it was possible to achieve better spectrum efficiency than analog FM.

B. GSM and Narrow-Band Time Division Multiple Access (TDMA)

In 1982, a 900-MHz spectrum allocation was made by the Conference Europeene des Postes et Telecommunication for all European countries. It was aimed for a second-generation pan-European cellular system.

It was recognized that a digital solution would offer not only improved capacity but also possibilities to offer secure voice and new data-transmission capabilities.

TDMA was identified as a possibility to reduce the cost of base stations, since many users then could share the same radio transceiver. TDMA also had even better spectrum efficiency performance than FDMA. One important reason was that frequency hopping (FH) easily could be introduced. The FH combined with interleaved channel coding implied that the impact of slow Rayleigh fading for portable users was eliminated (see Fig. 2). Furthermore, with FH, the interference from other cells was smeared out, which further improved the frequency reuse. A 300-kHz narrow-band TDMA system was developed in 1985 [2]. Reuse plans with somewhere between three and nine frequency groups were shown to be possible in [2], giving capacity improvements of more than three times compared to the analog system, where 21 frequency groups normally are needed.

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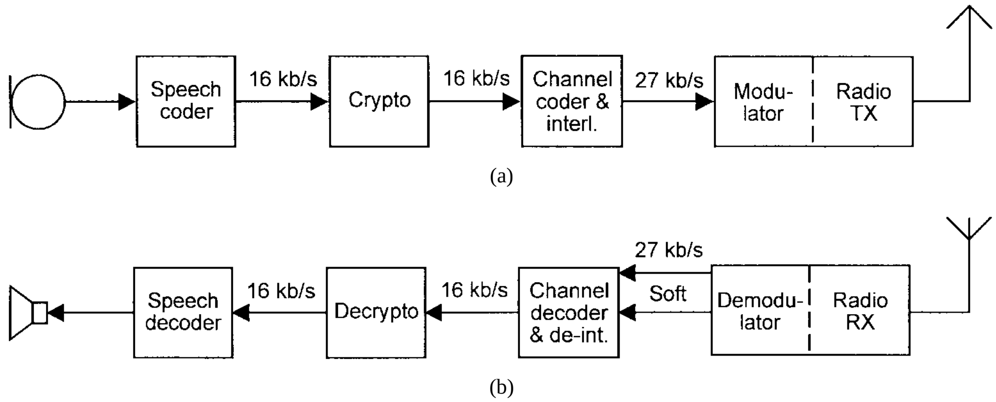

Fig. 1. Block diagram of the coded digital system for 25-kHz FDMA channels.

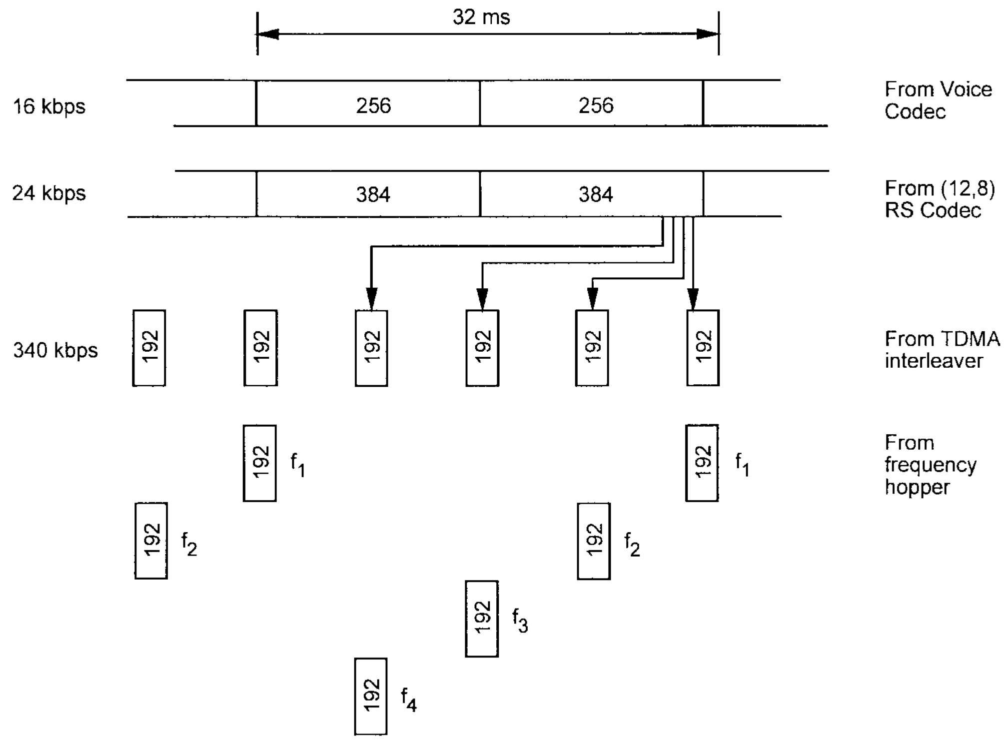

Fig. 2. Coding and hopping technique. Code symbols from a (12,8) Reed–Solomon code are distributed over four TDMA slots with the frequency hopping.

TDMA also meant that a new type of handoff mechanism could be introduced. This was the so-called mobile assisted handoff method, in which the mobile stations measured signal quality from other base stations in the time interval between receive and transmit bursts. This reduced the network signalling load to such an extent that very small cells—microcells—could be introduced.

TDMA was first experimented with in Japan [3] in 1982. However, it was found that delay spread due to multipath propagation completely destroyed performance in urban areas. Similar results were also experienced in Sweden in 1984, as reported in [4].

The solution was to introduce an adaptive equalizer [4], [5] to combat the multipath. It was found that with a well-defined adaptive equalizer, it was in fact possible to utilize multipath to improve performance compared to Rayleigh fading. This is illustrated in Fig. 3, taken from the results of [4]. Notice that bit-error-rate performance is improved as delay spread increases (up to a certain level), while without equalization, performance is degraded as delay spread is increased.

After extensive testing, narrow-band TDMA with 200-kHz channel spacing was finally chosen in 1987 for the pan-European GSM standard. Each 200-kHz TDMA carrier can handle eight full-rate voice calls at 13 kbps each or 16 half-rate voice calls. Other technologies were also tested, such as wide-band TDMA (6 MHz) and code division multiple access (CDMA) (1.25 MHz), but they were rejected.

In 1989, narrow-band TDMA was also selected as the digital standard in the United States and Japan. In the former, a 30-kHz bandwidth was selected in order to be com-

Table 1 Summary of Standards

	Europe (GSM)	North America (TIA IS 136)	Japan (MPT)
Access method	TDMA	TDMA	TDMA
Carrier spacing	200 kHz	30 kHz	25 kHz
Slots/carrier	8 (16)	3 (6)	3 (6)
Modulation	GMSK	QPSK	QPSK
Channel code	convolutional	convolutional	convolutional
Voice bit rate	13 kbps	8 kbps	6,8 kbps
Deployed in frequency bands	900 MHz 1800 MHz 1900 MHz	800 MHz 1900 MHz	700 MHz 1500 MHz
Number of subscribers (1997)	70 million	6 million	25 million

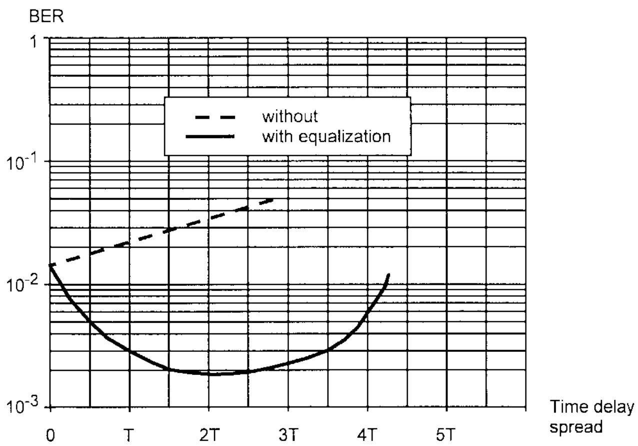

Fig. 3. Performance with and without equalization in a TDMA system.

patible to AMPS. This was standardized by the Telecommunications Industry Association (TIA) and is called digital (D)-AMPS. Each 30-kHz carrier can handle three voice calls, each at 8 kbps. In Japan, a similar standard called personal digital cellular (PDC) was selected based on a 25-kHz channel.

Table 1 gives a summary of these standards. In the United States, a second digital standard (IS-95) based on CDMA (1.25 MHz) was later (1992) adopted as well by TIA.

II. TODAY

Digital cellular has become a real success, with almost 100 million subscribers worldwide. That number is increasing at a rate that will result in more than 500 million subscribers in the digital systems in the year 2001. The vast majority are in the global system for mobility (GSM), which today is deployed in more than 110 countries. GSM has become much more than a pan-European system. GSM service is available in the major Asian countries, including China, India, and all Southeast Asian countries, as well as in all major U.S. cities. PDC in Japan has become a success, with more than 25 million subscribers.

At the same time, it is interesting to note that low-tier digital cordless systems, such as digital enhanced cordless telecommunications and the personal handyphone system, have not been as much of a success as digital cellular. The lesson from this is basically that people want to have coverage. In other words, when you are wireless, you do not want to be limited but want the freedom to be able to use the mobile phone wherever you are.

Cellular phones are today small pocket devices with weights below 100 g—a dramatic development compared to the fact that ten years ago, virtually all mobile phones were mounted in cars.

Cellular can offer very high capacity in city areas. User density of 400 erlangs per km^2 is achieved today [6] in dense urban areas, e.g., Hong Kong.

III. THE FUTURE

A. Services

The next significant development in wireless communications will be enhancements to the radio interface so that true multimedia services at high bit rates can be delivered.

Digital wireless networks will be developed to support bit rates up to 384 kbps, and further up to 2 Mbps.

Now it is becoming clear that a wireless terminal is potentially a generic platform for a whole range of communication services involving voice, data, video, and images. Network operators recognize that in competitive markets, the real revenue-earning opportunities lie not so much in offering simple voice connections but in offering more sophisticated services to subscribers.

At the same time, use of Internet services has risen in a similar way as mobile telephony (see Fig. 4). As these two communications developments converge, they will create the next major trend: mobile multimedia services.

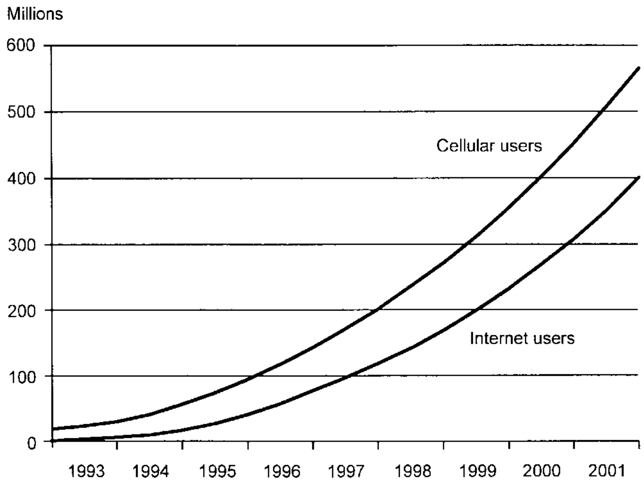

Fig. 4. Mobile telephone and Internet users.

It is now very natural to take this new step for the wireless industry. The first analog cellular services started around 1981, and the second-generation digital (GSM, D-AMPS, PDC) technology started in 1991. Third-generation wireless multimedia services can be expected around 2001.

The tremendous growth of Internet usage is the main driver for third-generation wireless. Text, audio, and images (also moving) will be the natural content, i.e., multimedia, for the user. It is clear that in these types of applications, the demand for high peak bit rates, with short time duration, is quite high. It is a highly packet-oriented application, with high demand at active periods and no demand while inactive (reading/looking). Bit rates of a few hundred kilobits per second will be required.

Circuit-oriented applications, requiring high bit rates (100 kbit/s and more), will probably be very difficult to motivate, as opposed to high-rate packet-oriented applications, such as Internet access. It is much more appealing to pay for "number of bits" than for "bandwidth." One application is video. With Internet stream technologies, however, video can be transmitted over a packet network.

It is very important to distinguish the services in coverage area, i.e., is wide-area coverage supported or is it just local coverage, e.g., indoor. Cellular systems such as GSM are optimized for wide-area coverage, giving bit rates around 100 kbit/s. On the other hand, wireless local-area networks can give very high bit rates but with very limited coverage.

B. Technology for UMTS and IMT2000

Standardization is ongoing for third-generation systems in the European Telecommunication Standardization Institute (ETSI), under the project name Universal Mobile Telecommunication Systems (UMTS) and in the International Telecommunications Union (ITU), where it is called IMT2000. Already, the same 2-GHz frequency band has been allocated in Europe and Asia for these third-generation systems. With the vast footprint of GSM networks, it seems natural that the UMTS/IMT2000 services will draw on GSM network technology.

Going forward, GSM will continue to evolve to meet demands for high data rates through two complementary developments. The first development, known as GSM phase 2+, will evolve the current air interface to include high bit rates for wide-area coverage through so-called high-speed circuit-switched data and packet-switched data through general packet radio service that will provide data rates up to 115 kbps. Operators can implement high-speed data in line with their market opportunities while enjoying full compatibility with their existing network. Furthermore, GSM will be able to give up to a 384-kbps user data rate within the existing TDMA format. An enhanced modulation method is the enabler for this increase in data rate, which is particularly suitable for limited-area coverage, e.g., cities.

A very similar development is also seen for the D-AMPS (IS136) digital standard—it will be possible to provide user data rates up to 384 kbps.

Following the successful standardization process for GSM, European research started in the late 1980's to develop the UMTS air interface standard. This new air interface standard, together with an evolved GSM core network, will form a UMTS/IMT2000 standard. As seen in Fig. 5, the core network is retained with its network signaling parts, etc.

UMTS aims to deliver wide-area/high-mobility data rates of 384 kbps, and up to 2 Mbps for local-area/low-mobility coverage. To reach this level of throughput, two air interfaces will coexist: the evolved GSM and the new UMTS interface.

Using dual-mode GSM/UMTS global handsets—with GSM providing coverage and UMTS delivering new functionality—operators will be able fully to leverage additional wide-band services in their GSM networks with full service transparency across the enormous GSM worldwide presence.

The 2-GHz frequency band (the 1920–1980 MHz band, paired with 2110–2170 MHz) was allocated at the 1992 World Administrative Radio Conference for third-generation UMTS/IMT2000 services in Europe and Asia. European and Asian standards bodies are also increasing their collaboration on third-generation standards.

C. Wide-Band CDMA

In January 1998, ETSI decided to base the UMTS standard on a new wide-band (W)CDMA technology using 5-MHz wide-band radio carriers. This WCDMA radio-access technology supports instant access to wireless multimedia optimized for packet-switched data. This is a totally new approach to CDMA technology and inherently different from previously proposed narrow-band CDMA systems such as IS95, which was primarily designed for voice communication.

The same WCDMA technology has also been chosen by NTT DoCoMo and the Japanese standardization organization ARIB. This means that a common UMTS/IMT2000 standard for the 2-GHz ITU frequency band is becoming a reality based on WCDMA according to the ETSI/ARIB standard.

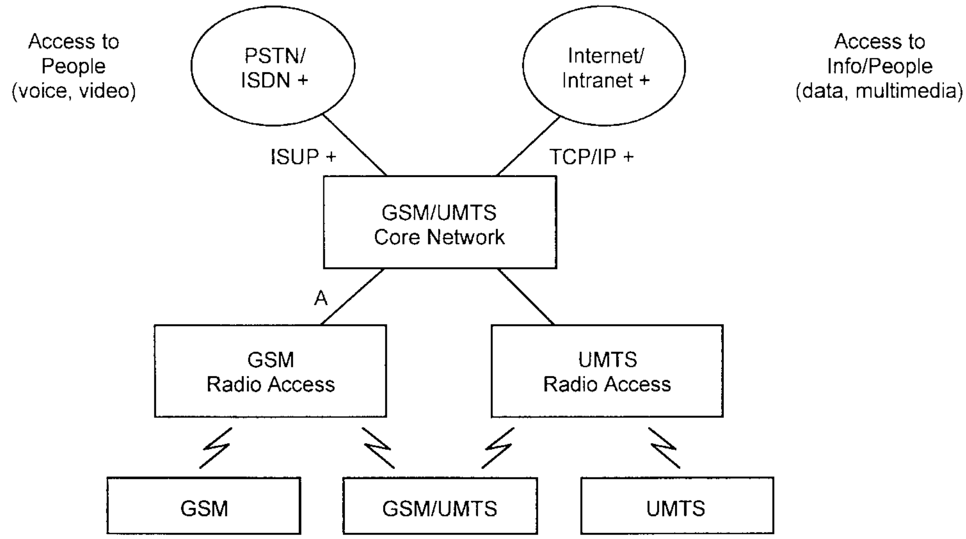

Fig. 5. Evolution to UMTS/IMT2000 in a GSM environment.

WCDMA is designed to meet high-bit-rate data requirements for superior radio coverage. In fact, high-speed packet-data services are truly optimized in the wide-band spectrum, as some advanced multimedia services cannot be delivered over narrow-band systems.

Europe has conducted research in this area since 1989, focusing on WCDMA. The European Union project named CODIT (1992–1995) confirmed that WCDMA is an efficient technology for the transmission of high-speed data, including text and graphics, and video. An advanced WCDMA air interface, optimized for service flexibility, was defined by the CODIT project. Based on this concept, Ericsson developed a 5-MHz WCDMA testbed and began multimedia tests in 1996.

The tests have shown that CDMA becomes a more attractive technology when it is wideband. A 5-MHz bandwidth allows high-data-rate services but in addition, the performance is optimized.

Improved capacity and coverage are additional benefits of WCDMA because wideband exploits multipath propagation more efficiently than narrow-band CDMA systems.

The WCDMA system under development will operate with better sensitivity than narrow-band CDMA systems due to the wider coherence bandwidth and because coherent demodulation and fast power control are applied in both the uplink and the downlink. This results in a lower receiver threshold, which improves both capacity and coverage. Capacity gains of an approximate factor of two, compared to narrow-band CDMA, can be achieved in urban and suburban environments. Given the traffic density of downtown Tokyo, improved capacity is critical to delivering a wireless multimedia system.

It will also offer additional capacity advantages because the system allows adaptive antenna arrays and for handoff between different radio frequencies. Operators can employ a technique called hierarchical cell structure to create a layered cell system to handle densely trafficked areas and achieve greatly increased capacity.

The UMTS/IMT2000 standard will also incorporate the latest asynchronous transfer mode (ATM) minicell transmission protocol—known as ATM adaption layer 2 (AAL2). The protocol will be used for the transmission between the radio base stations and the mobile switching center through the base-station controllers.

Standardized in early 1997 by the ATM Forum, AAL2 permits information to be transmitted more efficiently and with less delay. The minicell technology is being used in combination with other adaptation layers such as AAL5 for packet data.

IV. Summary

While no one can predict the future, it is certain that in less than five years' time, at the start of the twenty-first century, the way the world communicates will be vastly different from now. Not least, the speed of mobile multimedia communications and the accessibility of mobile multimedia are two such key changes.

During the late 1990's, the coming convergence of the telecommunications, information technology (IT), and media industries has become obvious. In the twenty-first century, business users and consumers will view the two services—telecommunications and IT—as one product.

Nations that have previously been cut off from means of global communication will join the world's conversations. Two key driving forces are the evolution of today's world-leading mobile communications technologies and the coming of third-generation wide-band solutions optimized for multimedia.

The Internet and corporate intranets will be accessible from portable wireless devices that incorporate the facility of a personal digital assistant with the use of a mobile phone.

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Jan Uddenfeldt (Member, IEEE), for a biography, see this issue, p. 1306.