INVITED ARTICLE

WIRELESS COMMUNICATIONS: PAST EVENTS AND A FUTURE PERSPECTIVE

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Wireless communications has emerged as one of the largest sectors of the telecommunications industry, evolving from a niche business in the last decade to one of the most promising areas for growth in the 21st century. This article explores some of the key technological advances and approaches that are now emerging as core components for wireless solutions of the future.

INTRODUCTION: A BRIEF LOOK AT THE PAST DECADE

The 1990s were a period of tumultuous growth for the wireless communications industry, and few could have predicted the rapid rise of many of today's key players that chose "winning" approaches and technologies. Likewise, there were some amazing and startling failures in the wireless sector, despite the brilliant engineering and technological efforts that went into their formations.

One of the most successful wireless communications technologies of the previous decade was Code Division Multiple Access (CDMA), pioneered by Qualcomm, Inc. Qualcomm introduced its CDMA concept for mobile radio in 1990, at a time when the U.S. cellular industry was selecting its first digital mobile telephone standard [1, 2].

To appreciate the growth of the wireless sector, it is worth noting that in 1990 there were only 10 million cell phone subscribers worldwide, mostly using analog FM (first-generation) technology. Today there are approximately 700 million subscribers, and this is expected to increase to more than two billion subscribers in the 2006-2007 time frame. In China alone, more than 15 million cell phone subscribers are being added each month, more than the cumulative number of wireless subscribers that existed throughout the entire world in 1991 [3].

Just prior to Qualcomm's introduction of its wideband digital CDMA mobile radio standard in 1990, now known as IS-95, the U.S. cellular industry was poised to select TDMA (which became IS-136) as the digital successor to the analog AMPS standard. The European community had already adopted GSM for its own pan-European digital cellular standard a couple of years earlier, and Japan's popular second-generation digital TDMA standard, PDC (Pacific Digital Cellular), was introduced shortly after IS-136's acceptance in the U.S. As cellular telephone service caught on with consumers, governments across the world auctioned additional spectrum (the Personal Communications Services, or PCS spectrum) to allow new competitors to support even more cellular telephone subscribers. The PCS spectrum auctions of the mid-1990s created a vast increase in frequencies for cellular telephone providers across the globe, thereby providing the proving ground for the second generation of cellular technology (2G, the first generation of *digital* modulation technologies).

While the pioneering design of GSM, which included international billing, short messaging features, and network-level interoperability, now enjoys the lead in today's global wireless market, it is also evident that wireless CDMA was a breakthrough technology, offering increased wireless capacity by increasing channel bandwidth and moving complexity in the handset to low-cost baseband signal processing circuits. All proposed third-generation wireless standards (except for EDGE) use some form of CDMA (Fig. 1), and the number of subscribers using the major second-generation technologies (Fig. 2) clearly show CDMA and GSM as the two leading worldwide technology standards. In fact, within the past year major wireless carriers in Japan and the U.S. announced they were abandoning IS-136/PDC technology in favor of newer third-generation standards that have a core wideband CDMA component. While CDMA was an example of a breakthrough technology of the past decade, there were many other brilliant system concepts that ultimately failed.

The vision of anytime, anywhere communications was championed by two companies that ultimately declared bankruptcy, although both companies were ahead of their time. Iridium (and companies like it) attempted to provide satellite-based wireless communications throughout the globe, using cellular telephone concepts from space, whereas Metricom attempted to provide a nationwide service of always-on data in metropolitan areas using Internet Protocol connectivity over a large network of low-power devices operating in unlicensed spectrum.

In the case of Iridium, the cost to build and

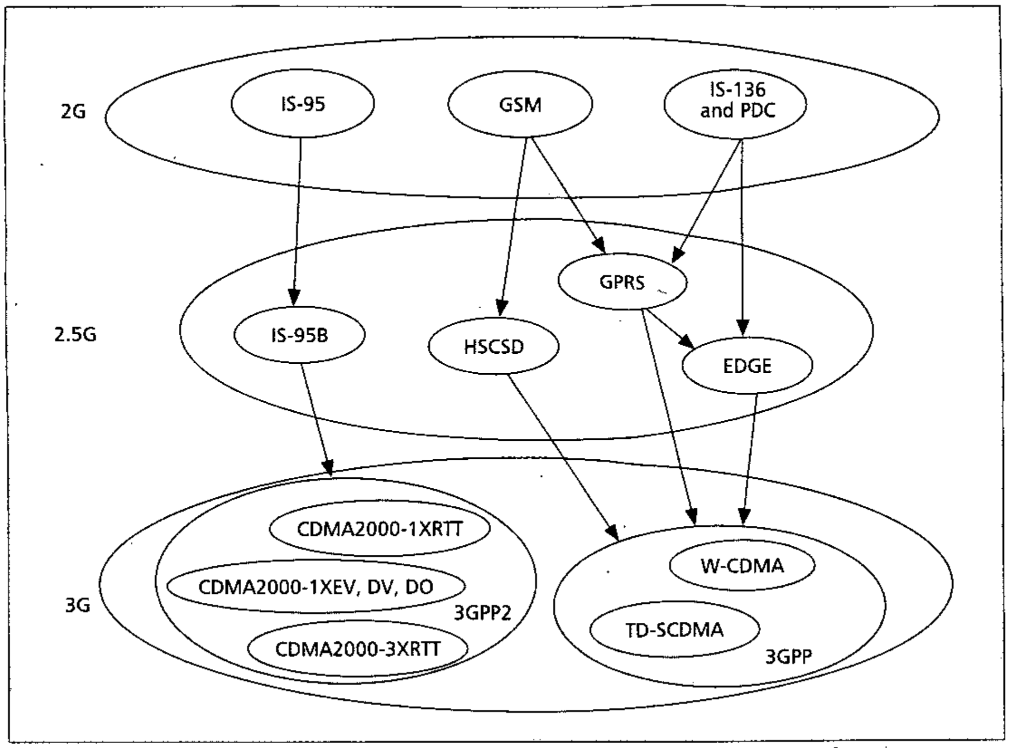

FIGURE 1. *Cellular/PCS technologies and their evolution to 3G. The "alphabet soup" of wireless standards continues into the third generation of cellular phones. First-generation analog FM systems of the 1980s gave way to second-generation (2G) standards in the 1990s. Today, 2.5G standards are being rolled out, and 3G is in its infancy, waiting for better economic conditions [3, p. 31].*

deploy a complete network of medium earth orbit (MEO) satellites and ground stations was enormous, in the many billions of dollars, and the relatively slow early-adoption rate of customers made it impossible to pay back the debt service for the initial infrastructure quickly enough. Pricing of the now defunct worldwide space-based global roaming telecommunications service hovered around $US3 per minute, making it prohibitively expensive for the mass consumer market. Nevertheless, the technological breakthroughs pioneered by Iridium in space-based handoffs, spot-beam antenna technology, power-efficient engineering, handset engineering, and network management were truly extraordinary.

Metricom pioneered the vision of always-on tetherless network access, and offered the first glimpse at ubiquitous wireless Internet access for users on the move. Metricom successfully deployed its Ricochet packet-based wireless data service in many metropolitan areas, providing its customers with 64-128 kb/s peak data throughput (and even greater in some cities) by using the license-free ISM bands and an extensive network of radio repeaters, relay stations, and network servers. The Ricochet infrastructure was installed on thousands of buildings, lamp posts, and broadcast towers in select cities, and provided high quality data access and Internet for mobile and portable users of personal computers. Metricom was ahead of its time, as it built and operated one of the first examples of an ad hoc wireless network for packet-based data access, years ahead of the 2.5G cellular/PCS technologies that are just now rolling out their medium and high data rate solutions. Ultimately, Metricom was forced to file for bankruptcy in 2001, unable to justify the mounting debt incurred from aggressive build-out plans. The network infrastructure and subscriber equipment were costly, and subscribers were slow to adopt the service.

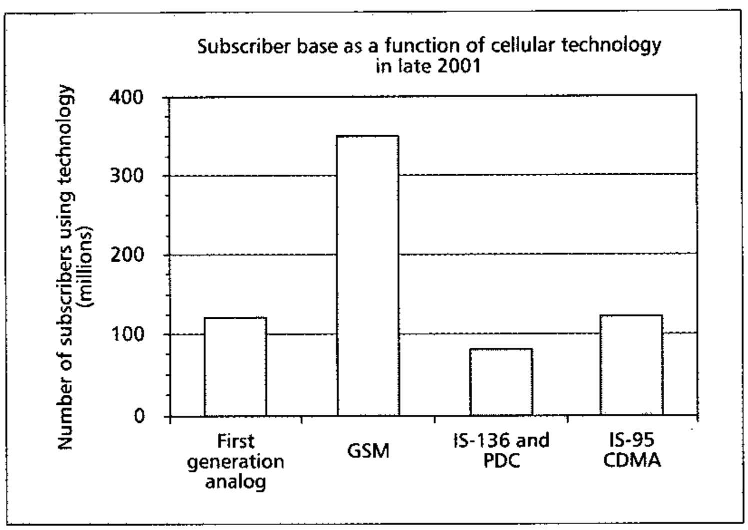

FIGURE 2. *Number of subscribers of key wireless technologies in late 2001 [3, p. 27].*

Perhaps most importantly, we must consider the Internet, which was not even part of the wireless industry's thinking through most of the 1990s. The Internet, and the widespread demand for always-on access to data, is sure to be a major driver for the wireless industry in the coming years.

Another company with an exciting public wireless Internet vision was Mobilestar, best known for its public WLAN access deployed in Starbucks coffee shops throughout the world. Voicestream Wireless recently purchased the assets of Mobilestar and may be exploring WLAN service as an augmentation to its conventional PCS wireless business.

There are many other examples of both successes and failures in the past decade. The Wireless Local Area Network (WLAN) industry, for example, is an exciting and emerging bright spot for enterprise networking within and between buildings through the use of unlicensed frequencies, whereas the collapse of several promising wireless competitive local exchange carriers (W-CLECs) and wireless Internet Service Providers (W-ISPs) are further examples of businesses that were ahead of their time (and which may someday stage a comeback with the IEEE 802.16 wireless Metropolitan Area Network standard), or who faced difficult or expensive access to the incumbent carrier's customers, in addition to brutal capital market conditions.

As we enter the 21st century, the telecommunications industry is undergoing an economic depression. Access to capital has been extremely difficult and valuations of several telecommunication companies have sunk by 90 percent or more in the past 18 months. Thousands of companies have either been forced to file for bankruptcy, or have jettisoned slow-growth or money losing businesses in order to survive. Many of our colleagues, some of the leading contributors to the wireless field, are out of work or are seeking jobs elsewhere. While many new technologies abound, those that are now successful were implemented at a time when capital was readily available and governments throughout the world provided spectrum for broad adoption of new services. The availability of PCS spectrum throughout the world, for example, created the opportunity for companies such as Qualcomm to gain a foothold in the worldwide market based on their CDMA concept. On the flip side, the U.S. Telecommunications Act of 1996 promised a competitive landscape that proved to be financially untenable for most new entrants, after all.

What Lies Ahead in Technological Advances?

As we consider what may influence the wireless technology landscape in the coming decade, we know that quite often the past is prologue. The winning technologies will require a new or existing spectrum allocation to allow them to be readily adopted. There must be access to capital, meaning that it is most likely that well heeled competitors and deep-pocketed incumbents will be involved in some way in breakthrough advances. Perhaps most importantly, we must consider the Internet, which was not even part of the wireless industry's thinking through most of the 1990s. The Internet, and the widespread demand for always-on access to data, is sure to be a major driver for the wireless industry in the coming years [4].

The fact that the Internet is now universally popular suggests that someday wireless networks will be made to behave in a fashion similar to today's packet-based networks and computing devices, just as early cell phones were made to emulate the functionality of wired phones. Ad hoc networking, where users and routers move randomly throughout a network, is growing as an important research field and represents a technology that is in its early stages but which promises to extend portable access and improve emergency communications. To date, wireless networks have been designed with distinct approaches at the lowest and highest levels of the OSI network-layer model, with the view that base stations are fixed in position with unlimited access to bandwidth. Ad hoc networks of the future, however, will merge immediate knowledge of the physical and MAC layers with adaptive strategies at the higher-level networking layers, so that future networks can be rapidly optimized for performance at specific instances of time, using resources and connection points that may be moving or limited in bandwidth.

In today's conventional wireless networks, where the network access points are fixed and connected to broadband backbones, the quest for greater data rates, as evidenced by the WLAN industry's move to IEEE 802.11a/g 54 Mb/s data rates, suggests that where data is concerned, more is better, especially in and around homes and buildings. A number of exciting technologies in this area are evolving, and promise to make a large impact on the wireless landscape in the coming decade. Ultra Wide Band (UWB), which was just recently approved by the FCC for a number of communications and sensing applications [5], is an intriguing signaling method that relies on the fabrication of ultra-short baseband pulses that have enormous bandwidths, on the order of several GHz. Unlike conventional wireless systems that upconvert baseband signals to radio frequency (RF) carriers, UWB can be used at baseband and can be thought of as a baseband transmission scheme that happens to propagate at RF frequencies. UWB has been demonstrated to provide reliable data rates exceeding 100 Mb/s within buildings, with extremely low power spectral densities.

Another exciting development, particularly applicable to home or campus wireless distribution, is the commercialization of Orthogonal Frequency Division Multiplexing (OFDM). OFDM offers multiple access and signal processing benefits that have not been available in previous modulation methods, and allows wireless networks to pack high spectral efficiency into relatively small spectrum bandwidths, similar to how Digital Subscriber Line (DSL) technology allows high data rates to be passed through low-bandwidth copper cables. IEEE 802.16 point-to-multipoint MAN wireless networks certainly could provide tetherless broadband access in the local loop, and are already doing so in developing nations [3].

New discoveries in the 1990s have shown us how to exploit the spatial dimension of wireless channels through the use of multiple antennas at the transmitter and receiver, where significant gains in either energy efficiency or (more importantly, perhaps) spectral efficiency can be obtained. Pioneering work showed that the theoretical data rates obtained with such systems in an independent Rayleigh scattering environment increases linearly with the number of antennas [6, 7] and these rates approach 90 percent of the theoretical maximum Shannon capacity. New space-time methods have been shown to offer more than an order of magnitude of increase in spectral efficiency over today's modulation and coding techniques used in current WLANs and cell phone systems, and these methods hold promise for wireless networks of the future. As an example, Lucent's V-BLAST laboratory prototype system was demonstrated to provide spectral efficiencies of 20–40 bps/Hz at average signal-to-noise ratio ranging from 24 to 34 dB in an indoor environment [8], and potential capacities on the order of 60–70 bps/Hz were demonstrated at 30 dB SNR using 16 antennas at both the transmitter and receiver [9].

We now explore in more detail some of the exciting technologies listed above, and postulate how they may be deployed in networks of the future. Some of these new technologies will require new spectrum allocations in order to succeed, and some may exploit already congested spectrum through the promise of greater capacity. Yet some of these ideas may still be ahead of their time, and may need to wait another decade or so to gain widespread acceptance.

Indoor Access: The Wireless Frontier

It is only when sitting, studying, or concentrating that we, as human beings, are most able to use large bandwidths, and this activity happens primarily inside buildings. Just like watching a movie or television, the absorption of data is primarily a passive activity, occurring at home or at work while we sit or stand in a pseudo-stationary position. Yet the entire wireless industry, as we know it today, was originally developed for mobile voice users, for people traveling in cars between home and work, before the Internet was even available to the public.

Internet usage has exploded due to consumer and business adoptions inside buildings using fixed connectivity provided by Internet service providers (ISPs) who team with the local exchange carrier, a long distance company, or cable company to gain access to each home. By stark contrast, wireless carriers have spent huge amounts of capital to purchase spectrum licenses and to deploy infrastructure for outdoor mobile coverage, and have historically had difficulty penetrating their signal into buildings or homes. Furthermore, all current second-generation digital wireless technologies were developed with a voice-centric architecture, before the widespread acceptance of the Internet, leaving all wireless carriers vulnerable to each other and to alternative providers who can provide reliable voice and data service into buildings.

The battle for indoor wireless access, where broadband data will be most needed and wanted, is shaping up to be one of the most important industry issues in the coming decade. Cellular and PCS operators desperately need third-generation Web-centric wireless equipment that can provide Internet-like capabilities in the hands of its consumers inside buildings, as much to reduce subscriber churn as to offer new services, yet most carriers do not have existing infrastructure to provide indoor coverage or capacity reliably for *today's* more primitive cellular technology. This offers an opening for a new type of competitor that can exploit the availability of low-cost, license free wireless LAN (WLAN) equipment.

By using the existing wired Ethernet infrastructure within a building or campus, WLANs are being deployed rapidly and inexpensively today, providing tetherless computer access with data rates over an order of magnitude than those promised by much more expensive 3G cellular equipment. As Voice over IP technology is improved, it is conceivable that WLANs could offer mobile/portable wireless service that integrates phone-like features with Internet access throughout a campus without any reliance upon the cellular infrastructure.

Today many early-stage companies are looking at ways to integrate 2.5G and 3G cellular technology with WLAN technology, in order to provide coverage and capacity distribution systems for any carrier who wishes to penetrate campuses or buildings. Phones are now being built that combine WLAN and cellular capabilities within them, as a way to ensure connectivity for either type of indoor service.

Dual-mode chipsets for cellular mobile and WLAN are already becoming available from Nokia and other sources [10, 11], and Intel and Microsoft, two titans steeped in software and semiconductors, recently announced a joint venture to make a new generation of cell phone [12]. Where in-building wireless connectivity is concerned, WLANs and their existing, widely installed IP-based wired network infrastructure, may soon become a serious contender to the radio-centric cellular/PCS carriers of today who are just now seriously addressing the need for connectivity and capacity inside buildings. Moreover, WLANs are extending to campus-sized areas and in outdoor venues such as tourist attractions and airports.

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Multiple Access: The Universal Acceptance of CDMA

Code Division Multiple Access (CDMA) allows multiple users to share the same spectrum through the use of distinct codes that appear like noise to unintended receivers, and which are easily processed at baseband for the intended receiver. The introduction of CDMA seemed to polarize service providers and network system designers. On the one side were those who saw CDMA as a revolutionary technology that would increase cellular capacity by an order of magnitude. On the other side were the skeptics who saw CDMA as being incredibly complex, and not even viable. While CDMA did not immediately realize a 10-fold capacity increase over first-generation analog cellular, it has slowly won over skeptics and is the clear winner in the battle of technologies, having emerged as the dominant technology in third-generation cellular standard-

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ization (Fig. 1). Further, CDMA techniques have also been adopted for many consumer appliances that operate in unlicensed bands, such as WLANs and cordless phone systems. Early indications are that Ultra Wideband technology may also rely on CDMA for multiple access, thereby completing the domination of CDMA as a wireless technology.

CDMA Successes

CDMA is based on spread spectrum transmission schemes originally developed for the military due to their resistance to jamming and low probability of intercept (i.e., relatively low power spectral density). These properties, combined with the inherent resistance to multipath, make CDMA beneficial for commercial wireless networks. The noise-like properties of spread spectrum signals allow CDMA to provide several key advantages over competing TDMA technology. CDMA is superior because the interference caused to co-channel users behaves like Additive White Gaussian Noise (AWGN), which is the most benign form of interference. Specifically, the noise-like interference allows the system design to be based on *average* interference conditions as opposed to worst-case conditions, thereby allowing nearby transmitters to use the same carrier frequency (universal frequency reuse). Further, CDMA allows more efficient statistical multiplexing of simultaneous users by taking advantage of voice activity and universal frequency reuse leads to soft handoff which provides large-scale diversity advantage in cellular systems [13].

A second area in which CDMA technologies excel is in its applications to wireless local area networks (WLANs). Due to the propensity of WLANs to cover small areas and to be uncoordinated with other WLANs, the networks are restricted to unlicensed bands. To allow uncoordinated networks to share the same frequency band, spread spectrum multiple access must be exploited, since it results in noise-like interference that increases the number of users that can be supported by the system. The unlicensed bands for WLANs have fostered the widespread use and acceptance of CDMA throughout the world, as exemplified by the IEEE 802.11b WLAN standard.

CDMA Challenges

In the early days of CDMA cellular systems, it was widely believed that the IS-95 uplink, with its asynchronous transmission, would be the bottleneck in system capacity. However, experience has shown that the downlink is typically the system bottleneck. In the uplink, power control for each mobile user ensures that, at the base station, each user has approximately the same signal level. However, in the downlink there are a smaller number of unequally-powered signals, not conforming well to the assumption that each signal should look like AWGN to all other signals, arriving at a particular mobile station from the co-channel base stations. This effect, combined with the lack of sufficient channel diversity in slow fading, non-handoff scenarios, has caused lower capacities to be experienced in the downlink. Third-generation CDMA networks are mitigating this problem by adding fast power control and transmit diversity to the downlink. Adding fast power control reduces the variability of the received signal strength in slow to moderate fading conditions. This, along with transmit diversity, significantly reduces the required power for slow-fading conditions (typically the worst case on the IS-95 downlink) and was found to even the capacities of the two links. It is generally believed that future networks will be highly asymmetric, with much larger capacity requirements necessary on the downlink (for Web browsing), although consumer devices such as streaming-video camcorders may challenge this assumption. Thus, given the uncertainty of data usage, it remains unclear how CDMA will handle significantly larger data rates on the downlink in the presence of symmetric frequency allocations. A further challenge to CDMA is the efficient implementation of packet data service.

In an attempt to solve both of these issues, a data-only version of 3G CDMA emerged for the *cdma2000* family of standards called *cdma2000 1xEV-DO* (*EVolution — Data Only*). It is also known as CDMA High Data Rate or HDR, and some challenges remain. First, HDR is a packet system and therefore cannot easily support voice services until Voice over IP (VoIP) over wireless is mature. Hence, separate carriers are needed for voice and data. Second, while HDR is significantly more efficient at serving packet data then previous versions of CDMA were, it looks less and less like CDMA. While the uplink remains relatively unchanged from *cdma2000*, the downlink serves users in time-multiplexed mode rather than in code-multiplexed mode. When combined with low spreading gains (due to high data rates in a 1.25MHz band), the downlink physical layer may suffer from inefficiencies that were alleviated in CDMA.

The first challenge to HDR is currently being met by parallel groups within 3GPP and 3GPP2. 3GPP2 is attempting to combine voice and data efficiently on a single carrier by evolving *cdma2000* to the *1xEV-DV* (EVolution — Data and Voice) standard. Similar efforts are taking place in 3GPP under the name of High Speed Data Packet Access or HSDPA. Both systems improve the data efficiency of CDMA by implementing a shared downlink packet channel, high-order adaptive modulation, hybrid ARQ schemes, and fast packet scheduling. Tantivy Communications, of Melbourne, FL, has developed an alternative approach to packet-based CDMA that also exploits the wireless channel using phased-array antennas.

A key issue surrounding a practical deployment limitation of CDMA has been its performance inside buildings, where the multipath delay spread is much smaller than in outdoor settings. Originally designed for the early large-cell systems of the 1990s, Qualcomm's IS-95 used only 1.25 MHz bandwidth and a 1.2288 Mc/s chipping rate. Historically, this bandwidth decision was based on the fact that the early-adopter carriers were originally only willing to allocate 10 percent of their 12.5 MHz U.S. cellular spectrum band for CDMA trials. The CDMA Rake receiver is, therefore, only able to exploit and distinguish multipath that exceeds a single chip duration, or about 800 nanoseconds. For multipath delays less than 800 ns, a CDMA signal begins to fade the same as a conventional narrowband signal. Thus, indoor deployments of CDMA (where delay spreads are typically only 100-200 ns at most) must either use a link budget that accounts for typical Rayleigh or Ricean fading (10 dB or more of fading headroom), or "phantom" multipath must be induced within the buildings by adding propagation delays in a distributed antenna system (DAS). In addition, a GPS clock is needed for each CDMA base station, and it is often difficult to bring such a clock signal into a large building. New fiber-based distribution systems, however, allow the entire cellular/PCS spectrum to be transmitted into buildings from an external or roof mounted base station, and microcells located outside of buildings are able to provide coverage into buildings with sufficient time diversity in the channel. It is worth noting that 3G CDMA systems have greater bandwidths, allowing the spreading code to have more multipath diversity benefit inside buildings.

The success or failure of the above listed attempts to improve CDMA will surely influence the design of fourth-generation wireless networks, and may determine the future of CDMA. Some of today's 4G thinking considers OFDM as the physical layer of choice, as opposed to direct sequence spread spectrum. CDMA versions of OFDM are certainly possible (e.g., Multi-Carrier CDMA) and may be considered for 4G. Another alternative is to return to the roots of spread spectrum and attempt to achieve high data rates while still achieving low power spectral density through an Ultra Wideband physical layer [14] as discussed subsequently.

Wireless Data Rates: Up, Up, and Away!

The next decade will finally see high-speed wireless data come to maturity. A key to making this a reality will be spectral efficiencies that are an order of magnitude greater than what we see today. At the physical layer, three technologies will play a role in achieving these efficiencies: Orthogonal Frequency Division Multiplexing, Space-Time Architectures, and Ultra Wideband communications.

Orthogonal Frequency Division Multiplexing (OFDM) and Multicarrier Communications

Orthogonal Frequency Division Multiplexing (OFDM) is a special form of multicarrier transmission where a single high-speed data stream is transmitted over a number of lower-rate subcarriers. While the concept of parallel data transmission and OFDM can be traced back to the late 1950s [15], its initial use was in several high-frequency military systems in the 1960s such as KINEPLEX [15] and KATHRYN [16]. The discrete fourier transform implementation of OFDM and early patents on the subject were pioneers in the early 1970s [17, 18, 19]. Today, OFDM is a strong candidate for commercial high-speed broadband wireless communications, due to recent advances in very-large-scale-integration (VLSI) technology that make high-speed, large-size fast Fourier transform (FFT) chips commercially viable. In addition, OFDM technology possesses a number of unique features that makes it an attractive choice for high-speed broadband wireless communications:

- OFDM is robust against multipath fading and intersymbol interference because the symbol duration increases for the lower-rate parallel subcarriers. (For a given delay spread, the implementation complexity of an OFDM receiver is considerably simpler than that of a single carrier with an equalizer.)
- OFDM allows for an efficient use of the available radio frequency (RF) spectrum through the use of adaptive modulation and power allocation across the subcarriers that are matched to slowly varying channel conditions using programmable digital signal processors, thereby enabling bandwidth-on-demand technology and higher spectral efficiency.
- OFDM is robust against narrowband interference since narrowband interference only affects a small fraction of the subcarriers.
- Unlike other competing broadband access technologies, OFDM does not require contiguous bandwidth for operation.
- OFDM makes single-frequency networks possible, which is particularly attractive for broadcasting applications.

In fact, over the past decade OFDM has been exploited for wideband data communications over mobile radio FM channels, high-bit-rate digital subscriber lines (HDSL) up to 1.6 Mb/s, asymmetric digital subscriber lines (ADSL) up to 6 Mb/s, very-high-speed subscriber lines (VDSL) up to 100 Mb/s, digital audio broadcasting, and digital video broadcasting. More recently, OFDM has been accepted for new wireless local area network standards which include IEEE 802.11a and IEEE 802.11g, providing data rates up to 54 Mb/s in the 5 GHz range, as well as for high performance local area networks such as HIPERLAN/2 and others in ETSI-BRAN. OFDM has also been proposed for IEEE 802.16 MAN and integrated services digital broadcasting (ISDB-T) equipment.

Coded-OFDM (COFDM) technology is also being considered for the digital television (DTV) terrestrial broadcasting standard by the Federal Communications Commission (FCC) as an alternative to the already adopted digital trellis-coded 8-T VSB (8-VSB) modulation for conveying approximately 19.3 Mb/s MPEG transport packets using a 6 MHz channel. The transition period to DTV in the United States is scheduled to end on December 31, 2006, and the broadcasters are expected to return to the government a portion of the spectrum currently used for analog stations. The proponents of COFDM technology are urging the FCC to allow broadcasters to use it because of its robustness in urban environments, compatibility with DTV in other countries, and appeal in the marketplace for development of DTV.

Current trends suggest that OFDM will be the modulation of choice for fourth-generation broadband multimedia wireless communication systems. However, there are several hurdles that

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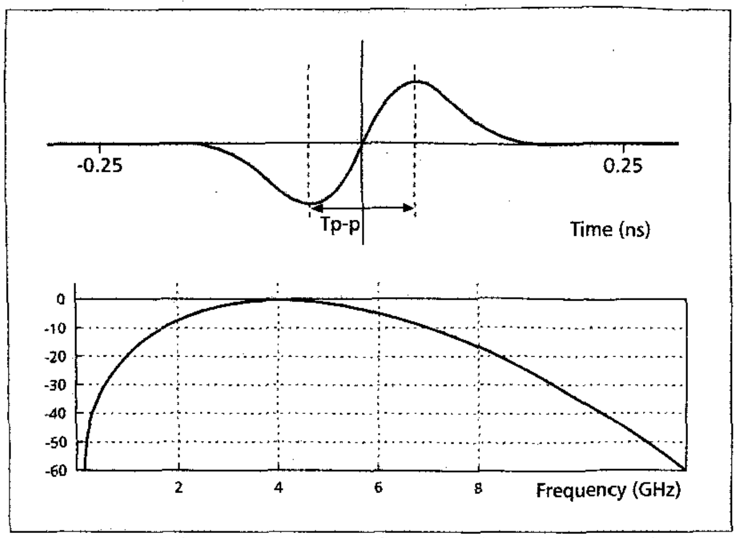
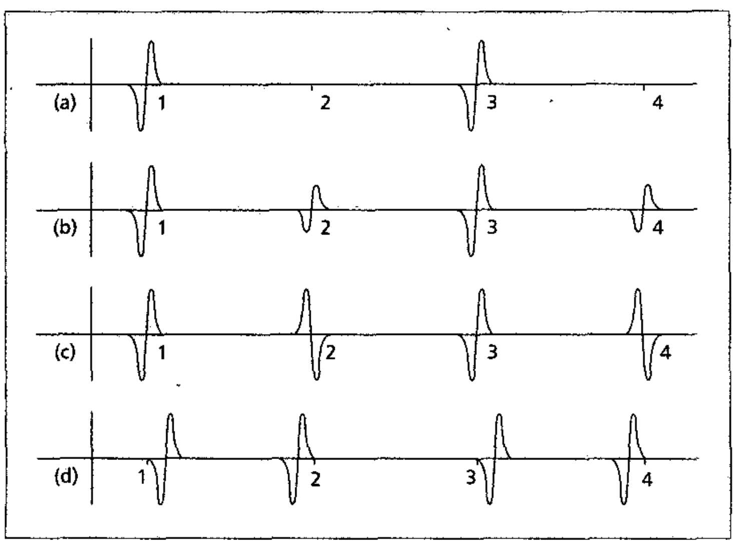


■ **FIGURE 3.** *Time domain response and frequency domain response of a Gaussian UWB monopulse applied to an antenna. Pulses have durations that are fractions of a nanosecond [14].*

need to be overcome before OFDM finds widespread use in modern wireless communication systems. OFDM's drawbacks with respect to single-carrier modulation include:

- OFDM inherently has a relatively large peak-to-average power ratio (PAPR), which tends to reduce the power efficiency of RF amplifiers. Construction of OFDM signals with low crest-factor is particularly critical if the number of subcarriers is large because the peak power of a sum of N sinusoidal signals can be as large as N times the mean power. Furthermore, output peak clipping generates out of band radiation due to intermodulation distortion.
- Multicarrier systems are inherently more susceptible to frequency offset and phase noise. Frequency jitter and Doppler shift between the transmitter and receiver causes intercarrier interference (ICI) which degrades the system performance unless appropriate compensation techniques are implemented.



■ **FIGURE 4.** *Examples of symbols sent using: a) on-off keying; b) pulse amplitude modulation; c) binary phase shift keying; and d) pulse position modulation using UWB technology [20].*

The above problems may limit the usefulness of OFDM for some applications. For instance, the HIPERLAN/1 standard completed by the European Telecommunications Standards Institute (ETSI) in 1996 considered OFDM but rejected it. Since then, much of the research efforts on multicarrier communications at universities and industry laboratories have concentrated on resolving the above two issues. OFDM remains a preferred modulation scheme for future broadband radio area networks due to its inherent flexibility in applying adaptive modulation and power loading across the subcarriers. Significant performance benefits are also expected from the synergistic use of software radio technology and smart antennas with OFDM systems. Several variations of multicarrier communication schemes have been proposed to exploit the benefits of both OFDM and single-carrier systems such as spread spectrum.

ULTRA WIDEBAND (UWB)

Ultra Wideband (UWB) modulation uses baseband pulse shapes that have extremely fast rise and fall times, in the sub-nanosecond range. Such pulses produce a true broadband spectrum, ranging from near-DC to several GHz, without the need for RF upconversion typically required of conventional narrowband modulation. The ideas for UWB are steeped in original 19th century work by Helmholtz, which were viewed as controversial at the time (and are still viewed as such today).

UWB, also known as *Impulse Radio*, allows for extremely low-cost, wideband transmitter devices, since the transmitter pulse shape is applied directly to the antenna, with no upconversion. Spectral shaping is carried out by adjusting the particular shape of the ultra-short duration pulse (called a monopulse), and by adjusting the loading characteristics of the antenna element to the pulse. Figure 3, provided to the authors by XtremeSpectrum, Inc., a pioneer in UWB technology [20], illustrates a typical bimodal Gaussian pulse shape for a UWB transmitter. The peak-to-peak time of the monopulse is typically on the order of tens or hundreds of picoseconds, and is critical to determining the shape of the transmitted spectrum. When applied to a particular antenna element, the radiated spectrum of the UWB transmitter behaves as shown in Fig. 3.

The UWB signals, which may be thinly populated over time as shown in Fig. 4, have extremely low power spectral density, allowing them to be used simultaneously with existing RF devices throughout the spectrum. Because of the extremely wide bandwidths, UWB signals have a myriad of applications besides communications [5]. On February 14, 2002, the FCC in the U.S. authorized the introduction of UWB for radar-ranging, metal detection, and communications applications. The UWB authorization, while not completely final, is likely to limit transmitters according to FCC Part 90 or Part 15 rules. Primary UWB operation is likely to be contained to the 3.1 – 10.6 GHz band, where transmitted power levels will be required to remain below 41 dBm in that band. To provide better protection for GPS applications, as well as aviation and military frequencies, the spectral density is likely to be limited to a much lower level in the 960 MHz to 3.1 GHz band [5].

The ultra-short pulses allow for accurate ranging and radar-type applications within local areas, but it is the enormous bandwidth of UWB that allows for extremely high signaling rates that can be used for next-generation wireless LANs. UWB can be used like other baseband signaling methods, in an on-off keying (OOK), antipodal pulse shift keying, pulse amplitude modulation (PAM), or pulse position modulation (PPM) format (Fig. 4). Furthermore, many monopulses may be transmitted to make up a single signaling bit, thereby providing coding gain and code diversity that may be exploited by a UWB receiver.

Space-Time Processing

Since the allocation of additional protected (e.g., licensed) frequency bands alone will not suffice to meet the exploding demand for wireless data services, and frequency spectrum represents a significant capital investment (as seen from the 3G spectrum auctions in Europe), wireless service providers must optimize the return on their investment by increasing the capacity of cellular systems. Cell-splitting can achieve capacity increases at the expense of additional base stations. However, space-time processing technology and multiple-input-multiple-output (MIMO) antenna architectures, which simultaneously exploit small-scale temporal and spatial diversity using antennas and error-control codes in very close proximities, hold great promise to vastly improve spectrum efficiency for PCS service providers by providing capacity enhancement and range extension at a considerably lower cost than the cell-splitting approach. Moreover, space-time technology is envisioned to be used in both cellular and ad hoc network architectures. For instance, the use of smart antennas in rural areas can be effective in range improvement over a larger geographical area, resulting in lower equipment costs for a cellular system. The use of smart antennas in an ad hoc network could increase network throughput owing to suppression of the co-channel and adjacent-channel interference provided by the directional antenna gain pattern, in addition to supporting LPI/LPD features for military applications. Space-time processing could also enable 3G infrastructure to accommodate location technology in order to meet the requirements for E-911.

Since multipath fading affects the reliability of wireless links, it is one of the issues that contributes to the degradation of the overall Quality of Service. Diversity (signal replicas obtained through the use of temporal, frequency, spatial, and polarization spacings) is an effective technique for mitigating the detrimental effects of deep fades. In the past, most of the diversity implementations have focused on receiver-based diversity solutions, concentrating on the uplink path from the mobile terminal to the base station. Recently, however, more attention has been focused toward practical spatial diversity options for both base stations and mobile terminals [21]. One reason for this is the development of newer systems operating at higher frequency bands. For instance, the spacing requirements between antenna array elements for wireless products at 2.4 GHz and 5 GHz carriers do not significantly increase the size of the mobile terminals. Dual-transmit diversity has been adopted in 3G partnership projects (3GPP and 3GPP2) to boost the data rate on downlink channels because future wireless multimedia services are expected to place higher demands on the downlink rather than the uplink. One particular implementation, known as open-loop transmit diversity or space-time block coding (STBC), is illustrated in Fig. 5.

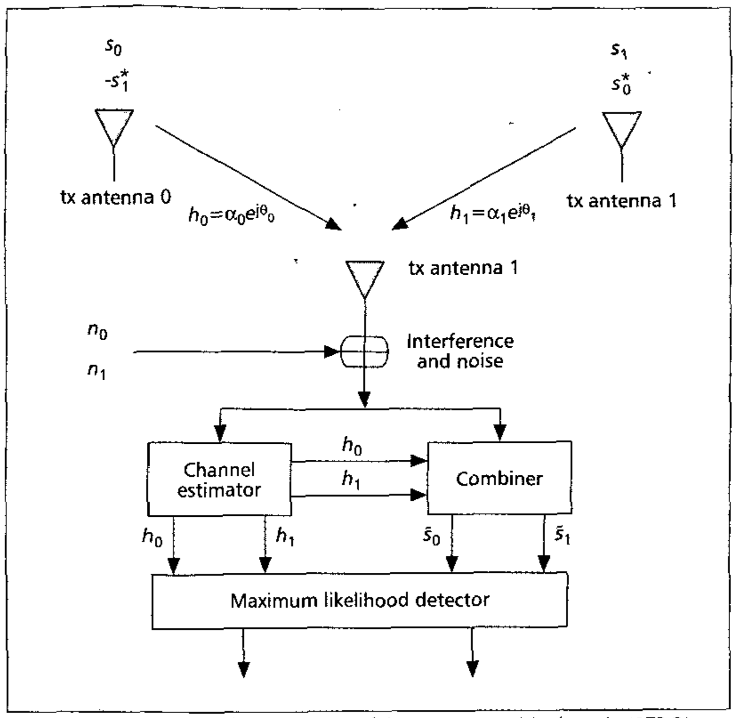


Figure 5. *Functional block diagram of the space-time block code (STBC) [22].*

The "spreading out" of data in time and through proper selection of codes provides temporal diversity, while using multiple antennas at both the transmitter and receiver provides spatial diversity. This implementation increases spectrum efficiency and affords diversity gain and coding gain with minimal complexity (all the transmit coding and receiver processing may be implemented with linear processing). Furthermore, it is shown in Fig. 5 that the resultant signals sent to the maximum likelihood detector are identical to those produced by a single transmit antenna with a two-antenna maximum ratio receiver combiner (MRRC) architecture. Thus, without any performance sacrifice, the burden of diversity has been shifted to the transmitter, resulting in a system and individual receiver that

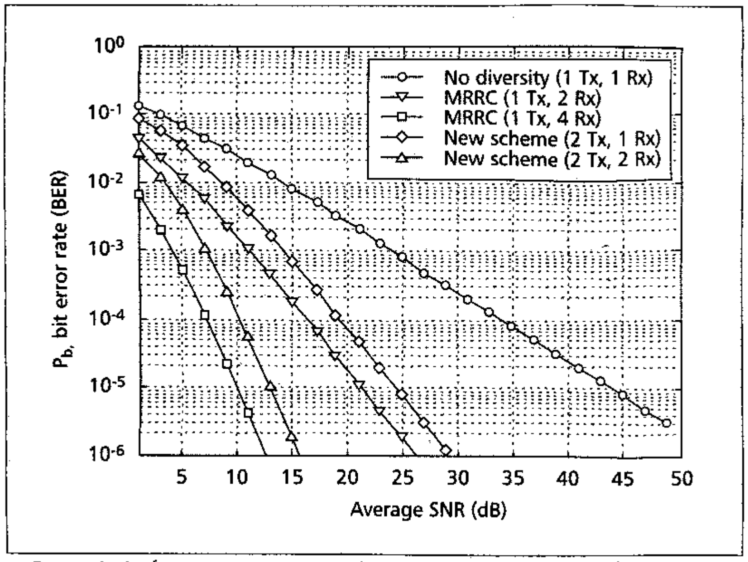


FIGURE 6. *Performance comparison between STBC and MRRC for various antenna configurations [22].*

are more cost effective (Fig. 6). It is possible to further increase the data rate on the downlink by adding one or more antennas at the mobile terminal such as in Qualcomm's High Data Rate (HDR) system specification [23] or in Tantivy's approach.

In a closed-loop transmit diversity implementation scheme, the receiver will provide the transmitter information on the current channel characteristics via a feedback message. It can then select the best signal or pre-distort the signal to compensate for current channel characteristics. Obviously, the performance of a closed-loop transmit diversity scheme will be superior to that of the simple "blind transmit" STBC scheme, shown in Fig. 5. The latter approach would be preferred for small handheld wireless devices since the transmit power and battery life is at a premium. Besides STBC, "blind transmit" diversity may also be implemented using a delay diversity architecture, where the symbols are equally distributed but incrementally delayed among different antennas, emulating a frequency-selective channel. An equalizer at the receiver will utilize training sequences to compensate for the channel distortion, and diversity gain is realized by combining the multiple delayed versions of a symbol. A shortcoming of this approach, however, is that it suffers from intersymbol interference if channel propagation differences are not integer multiples of the symbol periods. In this case, feedback from the receiver may be used to adjust delays.

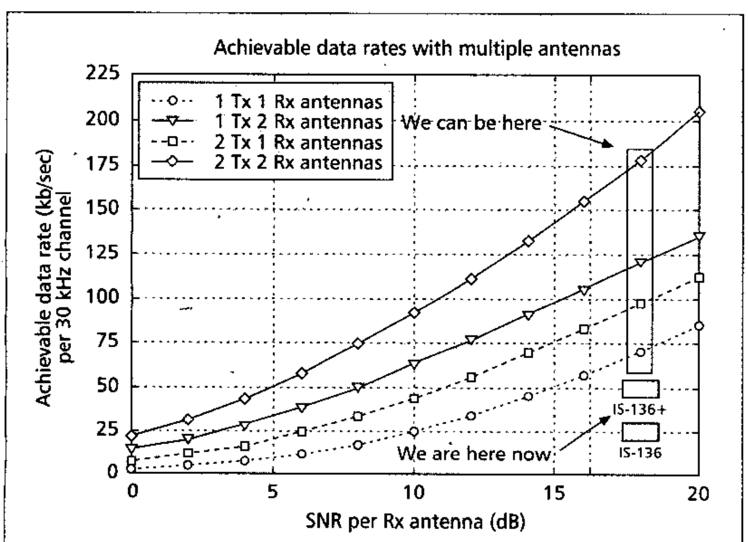


FIGURE 7. *Achievable data rates for several MIMO systems [24].*

MIMO architectures utilizing *multiple* antennas on both transmitter and receiver is one of the important enabling technique for meeting the expected demand for high-speed wireless data services. Figure 7 illustrates the expected capacities for systems exploiting spatial diversity along with capacities of existing wireless standards. Looking at these trends, we may conclude that spatial diversity at both transmitter and receiver will be required for future-generation high capacity wireless communication systems.

The Bell Labs Layered Space-Time (BLAST) approach (also known as Diagonal-BLAST or simply D-BLAST) is an interesting implementation of a MIMO system to facilitate a high-capacity wireless communications system with greater multipath resistance [6]. The architecture could increase the capacity of a wireless system by a factor of m, where m is the minimum number of transmit or receive antennas [7]. Similar to the delay diversity architecture, BLAST does not use channel coding. Instead, it exploits multipath through the use of multiple transmit antennas and utilizes sophisticated processing at the multi-element receiver to recombine the signals that are spread across both in time and space. Figure 8 depicts a functional block diagram of a BLAST transmitter and receiver.

To minimize complexity, the BLAST architecture employs a recursive "divide and conquer" algorithm for each time instant, which is known as a "nulling and cancellation" process. Figure 9 illustrates this process over one complete cycle for one out of m processing channels (four transmit antennas are being received by one of the four receiver channels). In this illustration, the receiver will receive the packet "A" as it sequences through the transmit antennas. At the beginning of a cycle, the signal from a specific transmit antenna is isolated by canceling other signals that have already been received from other transmitters. After the first transmit antenna shift, the known, previously received signals are again subtracted from the composite signal, but now there is a "new" signal that has not been identified and must be removed. The nulling process is performed by exploiting the known channel characteristics (which are determined by the training sequences received from each transmit antenna, typically $2m$ symbols long). By projecting this new received signal vector against the transpose of the channel characteristics from the target antenna, it is effectively removed from the pro-

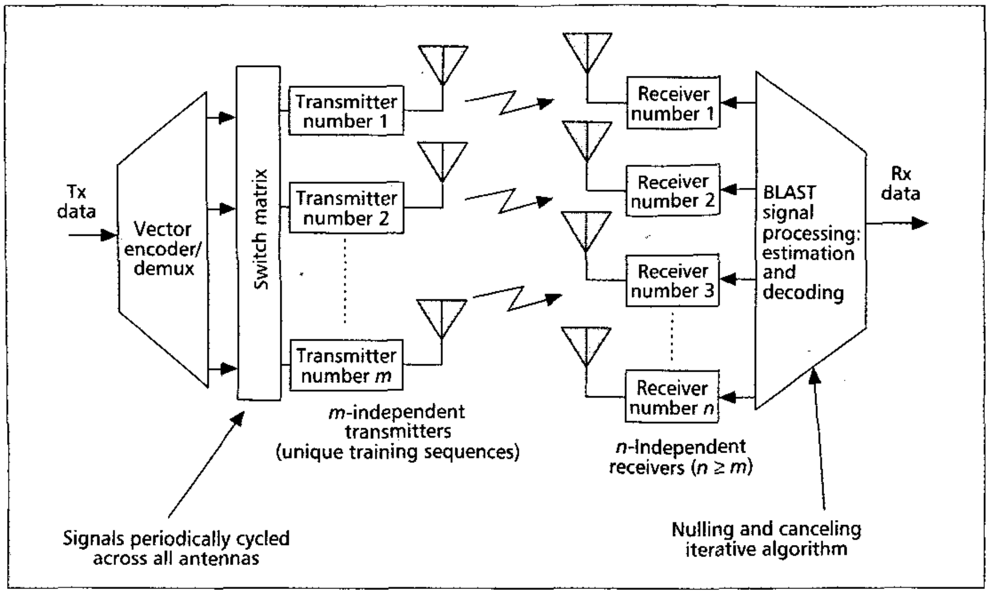


FIGURE 8. *BLAST functional block diagram.*

cessing. At the same time, the known channel characteristics are used to maximize the desired signal. At the next shift of transmit antennas this process continues, with the known signals cancelled and the new signals nulled based on channel characteristics.

With the promise of considerable capacity increase, there has been significant research into BLAST architectures focusing on optimized training sequences, different detection algorithms, and analysis of the benefits of combining the BLAST architecture with coding, among other topics. One of the most prevalent research areas is the development of Vertical BLAST (V-BLAST), a practical BLAST architecture with considerably simpler processing. In V-BLAST, there is no cycling of codes between antennas, and therefore this simplifies the transmitter. At the receiver, the nulling and cancellation process is a recursive algorithm that orders the signals, chooses the optimum SNR at each stage, and linearly weights the received signals. These modifications greatly simplify the receiver processing, making V-BLAST a leading candidate for next-generation indoor and mobile wireless applications.

Several near-future wireless systems already plan to use space-time codes. For instance, the proposed physical layer of the IEEE 802.16.3 broadband fixed wireless access standard is considering using space-time codes as the inner code and a Reed-Solomon outer code. The European WIND-FLEX project is studying the "optimum" number of transmitter and receiver antennas and algorithm complexity for the design of 64 to 100 Mb/s adaptive wireless modems for indoor applications. Also, the fourth generation (4G) cellular standards are expected to support data rates up to 20 Mb/s with bandwidth efficiencies of up to 20 per cell. Space-time coding has been identified as one of the technologies needed to meet this performance requirement.

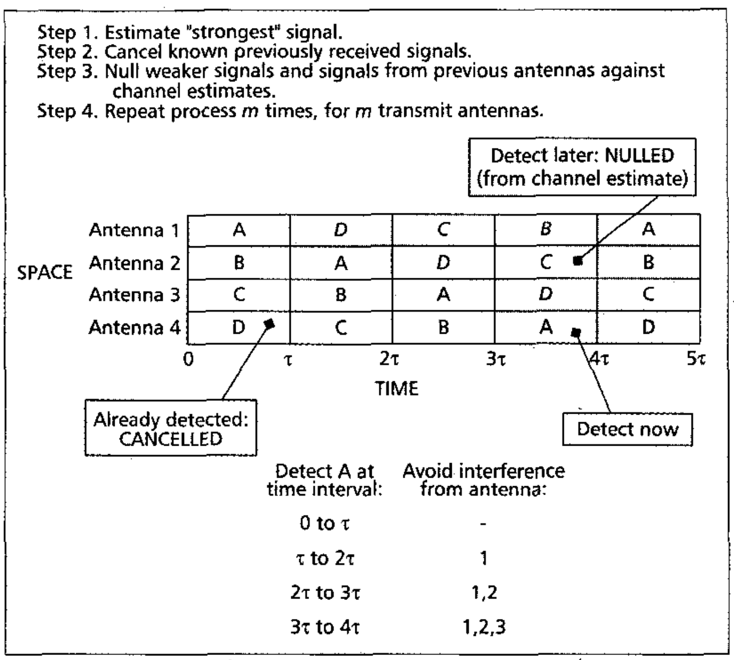
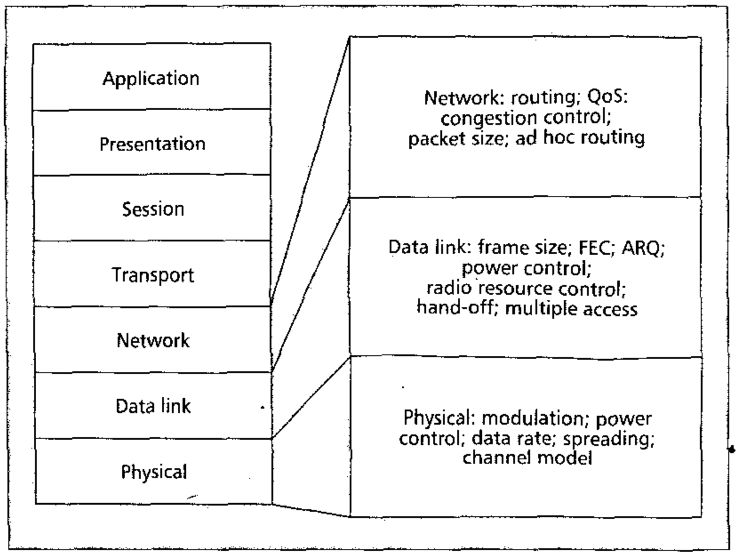


FIGURE 9. *Illustration of one cycle of layered space-time receiver processing for a system with four transmit and receive antennas.*

AD HOC NETWORKING

Clearly, achieving higher data rates at lower cost is a key for wireless ubiquity. The previous section demonstrates that there are several physical-layer technologies that hold promise for achieving higher data rates. However, another key to the future of wireless networks is the ability to adapt and exist without substantial infrastructure. Thus, *ad hoc networks* are a key technology for future systems. An ad hoc network (also known as a packet radio network) is



■ **FIGURE 10.** *Traditional OSI communication network layers [29].*

the cooperative engagement of a collection of mobile nodes that allows the devices to establish ubiquitous communications without the aid of a central infrastructure. The links of the network are dynamic in the sense that they are likely to break and change as the nodes move about the network. The roots of ad hoc networking can be traced back as far as 1968, when the work on the ALOHA network was initiated [25]. The ALOHA protocol supports distributed channel access in a single-hop network (i.e., every node must be within reach of all other participating nodes) although it was originally employed for fixed nodes. Later in 1973, DARPA began the development of a multi-hop packet radio network protocol [26]. The multi-hopping technique increases the network capacity by spatial domain reuse of concurrent but physically separated multihop sessions in a large-scale network (i.e., reduces interference), conserves transmit energy resources, and increases the overall network throughput at the expense of a more complex routing-protocol design.

In the past, ad hoc networking has been primarily considered for communications on battlefields and at the site of a disaster area, where a decentralized network architecture is an operative advantage or even a necessity. For instance, when major catastrophes happen, such as the September 11 attack, the need for a rapidly deployable, seamless communications infrastructure between public service agencies, military entities, and commercial communication systems becomes essential. Now, as novel radio technologies such as Bluetooth[1] materialize, the role of ad hoc networking in the commercial sector is expected to grow through interaction between the applications of various portable devices such as notebooks, cellular phones, PDAs, and MP3 players.

While present day cellular systems still rely heavily on centralized control and management, next-generation mobile wireless systems standardization efforts are moving toward ad hoc operation. For instance, in the direct-mode operation of HIPERLAN/2, adjacent terminals may communicate directly with one another. Fully decentralized radio, access, and routing technologies are enabled by Bluetooth, IEEE 802.11 ad hoc mode, IEEE 802.16 mobile ad hoc networks (MANET), and IEEE 802.15 personal area networks (PAN). Someone on a trip who has access to a Bluetooth PAN could use their GPRS/UMTS mobile phone as a gateway to the Internet or to the corporate IP network [27]. Also, sensor networks enabled by ad hoc multihop networking may be used for environmental monitoring (e.g., to monitor and forecast water pollution, or to provide early warning of an approaching tsunami) [28] and for homeland defense (e.g., to perform remote security surveillance). Therefore, it is not surprising that the trends of future wireless systems, characterized by the convergence of fixed and mobile networks and the realization of seamless and ubiquitous communications, are both attributed to ad hoc networking.

The lack of a predetermined infrastructure for an ad hoc network and the temporal nature of the network links, however, pose several fundamental technical challenges in the design and implementation of packet radio architectures. Some of them include:

- Security and routing functions must be designed and optimized so that they can operate efficiently under distributed scenarios.
- Overhead must be minimized while ensuring connectivity in the dynamic network topology is maintained (approaches are needed to reduce the frequency of routing table information updates).
- Fluctuating link capacity and latency in a multihop network must be kept minimal with appropriate routing protocol design.
- Acceptable tradeoffs are needed between network connectivity (coverage), delay requirements, network capacity, and the power budget.
- Interference from competing technology must be minimized through the use of an appropriate power management scheme and optimized medium access control (MAC) design.

NETWORK OPTIMIZATION: REMOVING BOUNDARIES

NEW NETWORK DESIGN CHALLENGES

While the layered OSI design methodology (Fig. 10) has served communications systems well in the past [29], evolving wireless networks are seriously challenging this design philosophy. Emerging networks must support various and changing traffic types with their associated Quality-of-Service (QoS) requirements as well as networks that may have changing topologies. The problem of various traffic types is typified in newly defined 3G networks. These networks must support multimedia traffic with manifold delay, error-rate, and bandwidth needs [27, 30]. Networks that experience changing topologies include ad hoc networks that lack network infrastructure and have nodes that are continuously entering and leaving the network.

[1] Bluetooth technology was born in 1998 when five companies (Ericsson, Nokia, IBM, Toshiba and Intel) formed a special interest group (SIG) to create an inexpensive and license free technology for universal short-range wireless connectivity that will replace cables between electronic devices. This group expanded in December 1999 with the entry of 3Com, Lucent, Microsoft and Motorola. Bluetooth uses a frequency-hopping scheme in the unlicensed Industrial, Scientific and Medical (ISM) band at 2.4 GHz.

In order to meet the challenges of ubiquitous wireless access, network functions (i.e., the various OSI layers) must be considered together when designing the network. QoS requirements that can and will vary according to application will force the network layer to account for the physical-layer design when optimizing network throughput. Further, different applications are better served by different optimizations. This leads to a design methodology that blurs the lines between layers and attempts to optimize across layer functionality.

As a primitive example, consider two techniques that have been proposed to improve system performance at different layers: 4×1 space-time block codes (STBC) [31] at the physical layer and a "greedy" scheduling algorithm at the MAC layer. By "greedy" scheduling we mean a simplified version[2] of the scheduling algorithm employed in *cdma2000 3G1X-EVDO,* also called HDR [32]. This scheduler is based on feedback from the mobiles, and schedules packet transmissions to the mobile that is currently experiencing the best channel conditions (i.e., highest SINR). STBC is capable of providing significant diversity advantage at the physical layer. An even larger advantage can be provided by "greedy" scheduling provided that the scheduler has 20 users from which to choose. This "multiuser diversity" can provide great advantages (albeit at the sacrifice of delay, which is beyond the scope of this article). However, if we add 4×1 STBC on top of "greedy" scheduling, we obtain virtually no further advantage at a cost of quadrupling the RF cost. It can also be shown that as the number of users increases, STBC can actually degrade the SINR performance. However, in round-robin scheduling or in the case of a small number of data users, STBC helps significantly. Thus, ideally the scheduler and the physical layer should be optimized together to maximize performance. This simple example also shows the importance of the QoS requirements. If an application has very strict delay requirements (e.g., voice), greedy scheduling is not desirable since users experiencing bad channels must wait for service, but STBC would be an acceptable way to achieve diversity advantage. On the other hand, data applications that are delay-insensitive (e.g., Web traffic) would lend themselves well to greedy scheduling rather than STBC, which requires four transmitters and RF chains.

While cross-layer network design is an important step when attempting to optimize new multimedia networks, it is still a step below what will be necessary to truly maximize the performance of future networks. True optimization will not only require cross-layer *design,* but also cross-layer *adaptability*. Traditionally, networks have contained some ability to adapt. For example, many communications systems can adjust to changing channel conditions using signal processing methods, or to changing traffic loads by adjusting routing tables. However, these adjustments have been isolated to a specific layer. Cross-layer adaptability will allow all network functions to pass information between functions and adapt simultaneously [33]. Such adaptability will be required to meet the demand of changing QoS requirements along with changing network loads and channel conditions. While the cross-layer network design requires *static* optimization across network layers, adaptability requires *dynamic* optimization across layers.

Challenges to Cross-Layer Optimization

There are several challenges and research issues associated with the vision of cross-layer optimization. First and most obviously, full network design and optimization is extremely complicated (and nearly intractable). This is particularly true when attempting real-time dynamic optimization. Some attempt must be made to determine design methodologies that encompass the incredible freedom offered to the designer when cross-layer optimization is possible.

A second serious problem involves the metrics to be used in the optimization. Network layers (and, consequently, functionalities) have traditionally had their own isolated optimization criteria. For example, physical-layer design is primarily focused on minimizing the bit error-rate, while the MAC-layer design is concerned with node throughput or channel availability. The network design, on the other hand, typically uses delay or routing efficiency. Thus, we must ask: What metric(s) represent all of these concerns? How do we optimize all concerns together or prioritize them intelligently?

A related issue arises in the context of dynamic optimization. In dynamic optimization, information is passed between the network layers. The system designer must judiciously choose the information to be passed. It must not be overly complicated for risk of creating large delays or computationally expensive optimization routines. However, it cannot be overly simplistic for the risk of communicating too little information.

The design of such systems clearly requires sophisticated modeling (simulation) procedures. Traditional network simulators do not have sufficient granularity at the physical layer to allow physical-layer design. On the other hand, adding network functionality to traditional physical-layer simulators would result in prohibitively long run times. Further, network simulators embrace an event-driven methodology while physical-layer simulators use a time-driven methodology. The typical solution to this problem may be a two-tier simulation approach that uses the output of a physical-layer simulation to stimulate network simulations. However, this does not allow for interaction between the layers and precludes cross-layer optimization. Thus, hybrid approaches are necessary. Some possible options include:

- Combined simulation and semi-analytic approaches that simulate high-level functionality and use semi-analytic simulation approaches to approximate lower-level functionality.
- Combined simulation and hardware approaches that use hardware to perform lower-level functionality.
- Variable-granularity approaches that use a network simulator with coarse granularity (i.e., abstracting lower layers) for a majority of physical-layer links and fine granularity (possibly down to the sample level) for links of specific interest.

In order to meet the challenges of ubiquitous wireless access, network functions (i.e., the various OSI layers) must be considered together when designing the network. QoS requirements that can and will vary according to application will force the network layer to account for the physical-layer design when optimizing network throughput.

[2] *Note that HDR uses proportionally fair scheduling which accounts ensures maximum delay constraints. The simplified version that we are examining here does not account for delay.*

In the 1990s, cellular telephone service and the Internet grew from the incubator stage to global acceptance. In the next 10 years, we suspect the Internet and wireless communications will become intertwined in ways only imagined today.

- Emulation and real-time processing involving all facets, from physical layer to application, simultaneously.

These hybrid approaches have yet to be firmly established and represent significant research areas.

A final research issue in the area of dynamic network optimization concerns network control. When functionality across layers is allowed to adapt, it is important that something has control of the process. Otherwise, the various adaptations can work at cross purposes. Thus, the question becomes, "Who has control?" Arguments can be made for each layer concerning the best place to locate the control, but the fact remains that this is a serious research issue which may indeed have different solutions depending on the end-user application or particular physical environment of operation.

Conclusion

This article has attempted to describe some important new technologies and approaches to the wireless communications field that are likely to evolve in the coming decade. In the 1990s, cellular telephone service and the Internet grew from the incubator stage to global acceptance. In the next 10 years, we suspect the Internet and wireless communications will become intertwined in ways only imagined today.

We noted that the great new frontier for the wireless communications industry is inside buildings, and that the battle for access is emerging between cellular/PCS license holders and ad hoc networks installed by the building owners using license-free WLAN technology.

We illustrated the worldwide acceptance of CDMA as the multiple-access system of choice, and presented some of the challenges CDMA faces as we evolve to fourth-generation wireless networks. Clearly the need for higher data rates will lead to new modulation and coding techniques that can provide high spectral efficiencies. We discussed three candidates for providing improved spectral efficiency at the physical layer: Orthogonal Frequency Division Multiplexing, Ultra-wideband transmission, and space-time modulation/coding. Each of these technologies has the potential to increase the spectral efficiency of the physical layer and will likely find its way into future systems. OFDM was highlighted as an emerging signaling method that holds promise for broadband wireless access. The fundamentals and challenges for OFDM were given, and new applications that use OFDM were presented. Ultra Wideband, recently approved for U.S. deployment by the FCC, was highlighted as an important emerging technology, and some of the fundamentals of this controversial signaling method were given. Space-time coding was also discussed in detail, with several examples given to highlight the tremendous potential of this technique.

While physical-layer advances will be a key to the future, an even more critical area for future networks exists at the higher layers. Ad hoc networks will clearly play a large role in future systems due to the flexibility that will be desired by the consumer. We discussed the key aspects of ad hoc networks and the research issues that must be examined to advance the use of ad hoc networks in future systems. Finally, we discussed the idea of cross-layer optimization. The emergence of wireless applications with diverse delay and fidelity requirements along with constantly changing topologies and requirements for future networks will require a new design methodology. Specifically, future network designs will need to consider the interaction of network layers. We examined a simple example as well as the key challenges associated with such a design approach.

While predicting the future is a tricky business, it is clear that wireless will be a key technology in the future of communications. We have attempted to present several of the technologies that will advance wireless communications, and the challenges that must be met to make ubiquitous communications a reality.

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While physical-layer advances will be a key to the future, an even more critical area for future networks exists at the higher layers. Ad hoc networks will clearly play a large role in future systems due to the flexibility that will be desired by the consumer.