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DEMYSTIFYING WIRELESS TECHNOLOGIES: NAVIGATING THROUGH THE WIRELESS TECHNOLOGY MAZE

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ABSTRACT

A significant part of the growth in consumer-to-business electronic commerce is likely to originate from the increasing numbers of mobile computing devices and smart telephone devices. Most of the data from mobile computers will be carried over by emerging wireless networks. Many wireless technologies and standards are now available. As a result, it is becoming increasingly difficult for non-domain experts like managers, to sort through the maze of wireless technologies and standards to make business decisions involving these technologies. This article surveys existing and emerging wireless technologies and uses the Open System Interconnect (OSI) framework to organize the wireless landscape. The survey provides a quick reference to the entire spectrum of wireless technologies in use today.

Keywords: wireless networks, data communications, 3G

I. INTRODUCTION

Wireless data communications services advanced considerably since the introduction of mobile telephony in the United States by AT&T in 1948 [Garg and Wilkes 1996]. Early systems used a single transceiver to provide mobile telephony within a 50-mile radius. Although the early mobile telephony systems were technologically sophisticated for their time, they used 120 kHz of spectrum to transfer a 3 kHz filtered voice stream. Since the available spectrum was being used extremely inefficiently, the increase in the usage of mobile telephony led to blocking probabilities that were 65% or higher, with as many as 50 – 100 subscribers for every available radio channel. In contrast, existing 2G technologies use radio channels with a bandwidth of only 25-30 kHz, where each channel supports multiple calls through time division multiplexing. Wireless technologies and services, which form the transport infrastructure of mobile computing and communications, evolved significantly over the last few years.

As mobile computing devices and software platforms evolve to support commercial applications, wireless networks are likely to create many of the avenues for growth in electronic commerce [Varshney and Vetter 2000a]. Based on the exponential growth in mobile computing devices, the Gartner Group expects that by 2004, more than 25% of consumer-oriented eCommerce will originate from smart mobile phones. To support future mobile applications, the underlying wireless technologies that provide the transport infrastructure, are beginning to offer higher data rates, quality of service guarantees, security, and location management [Varshney et al. 2000b].

Although the capabilities of existing wireless technologies are spurring the development of new mobile applications, the wireless industry does not yet generate a large market for data services, although the future looks bright. For example only an estimated 3% of the total traffic on cellular networks is data, with the rest being voice [Garg 2001]. Close to a billion people subscribe to cellular services worldwide, and as technologies improve and wireless services begin to provide higher data rates, wireless services are likely to be one of the major service offerings in the data communications industry. It is expected that data services will account for 25% of the total traffic on cellular networks by 2005 [Pahlavan and Krishnamurthy 2002].

Wireless technologies can be associated with four broad categories of wireless networks- personal area network, local area network, metropolitan area network and wide area network. These networks cover different ranges of mobility from a few feet to thousand of miles. Each of these categories of wireless networks has seen tremendous enhancements and the evolution of many new standards in the last few years, thereby making it difficult to navigate through the maze of these technologies while deciding on a wireless solution for a given application.

In this paper, we provide a comprehensive survey of wireless technologies. This survey is expected to help readers understand the wireless landscape. In this regard, we use the Open System Interconnect (OSI) framework [Stallings 2001] to view wireless technologies. This paper is organized as follows. Section II contains an overview of wireless networks. The various generations of cellular technologies are also described in this section. In Section III, wireless technologies are examined using the OSI framework. The conclusions of this paper are presented in Section IV.

II. CATEGORIES OF WIRELESS NETWORKS

Numerous wireless technologies were created to meet specific user needs. These technologies are embedded in the four categories of wireless networks:

- personal area networks (PAN),
- local area networks (LAN),
- metropolitan area network (MAN) and
- wide area networks (WAN).

PANs provide a range between 1/3 and 10 meters. They provide inexpensive and portable wireless connectivity between mobile computing devices and access points.

LANs are designed to serve as alternatives as well as adjuncts to traditional departmental or campus wired LANs. LANs are setup by installing access points 30-100 meters apart.

MANs are designed to provide broadband wireless access to business and end-users within line-of-sight range.

WANs are nationwide networks that enable users to exchange data from virtually any business location in the nation. In this section, we provide an overview of the four network categories.

PERSONAL AREA NETWORKS (PAN)

Wireless personal area networks interconnect multiple mobile personal computing devices within users' vicinity. They are extremely portable and use ad hoc network connections that are temporary in nature, and require extremely low power.

Over the last few years, improvements in technology made electronic devices smaller and reduced their power requirements. The significant reductions in costs that accompanied these developments led to the proliferation of powerful electronic devices such as cell phones, pagers, personal digital assistants (PDAs) and digital cameras. Unfortunately, it is not easy for these devices to exchange data. For example, the simplest way to exchange contact information between a PDA and a cell-phone is to integrate the two devices together. If a simple and universal communication protocol could facilitate exchange of information between the two devices, then contact information in a PDA could automatically update the phonebook on the cell phone. PANs aim to achieve this goal and could facilitate the creation of many interesting new services.

Notable features of PANs include the ability of various devices on PANs to locate each other, support for high data rates, and in some cases, support for quality of service (QoS). The first PAN was the BodyLAN, a small, lightweight network to connect personal devices within a 5 feet radius that was announced as an offshoot of a defense project in the mid 1990s. Around this time, a consortium of firms led by Ericsson developed the Bluetooth standard for PANs, which then evolved into the IEEE 802.15 standard for 1 Mbps PANs in 1999 [Haartsen 2000]. Another popular PAN standard based on Infrared links was published in 1994 by the Infrared data association (IrDA) to support high-speed point-to-point communications [Williams 2000]. Infrared technology is extremely useful in exchanging data and applications between handheld devices.

Bluetooth provides both point-to-point and point-to-multipoint connections. Piconets are created when two or more units share the same channel. Each Piconet contains a master unit and up to seven slave units, where slaves can participate in different piconets using time-division multiplexing. Multiple piconets with overlapping coverage areas create a scatternet.

An application of PANs is a wireless network for homes. It is the focus of Zigbee alliance that includes companies such as Philips and Motorola. This alliance is developing a standard for low powered wireless communications between devices for the home environment. The lower layers are being standardized as IEEE 802.15.4. Zigbee devices will have a range of upto 30 meters (compared to 10 meters in Bluetooth) and will sleep when not in use to conserve battery power.

Three basic application scenarios are considered candidates for wireless PANs [Pahlavan et al. 2002].

1. The popular wire replacement for peripheral devices around computers.
2. Ad hoc networking between devices owned by different users as they walk-up to each other in confined spaces such as conference rooms.
3. Use of PANs as access points to corporate voice and data networks. In particular, the integrated QoS support in Bluetooth allows seamless connection between voice and data services.

LOCAL AREA NETWORKS (LAN)

Wireless LANs typically connect computers within a single building. They allow users to stay connected to their network while users roam around a building with a wireless-capable computer, without being constrained by the limitations of a cable connection. Wireless LANs are becoming increasingly common on college campuses, office buildings, and other high-traffic areas. In recent years they also became popular in homes because they allow multiple users to share printers and high-speed Internet connections easily. Although convenient to use, Wireless LANs do not offer data rates comparable to wired Ethernets. For many institutions however, they provide a quick and inexpensive way to set up a computer network because expensive cabling is not needed. Therefore, facilities with no existing LANs are strong candidates for setting up Wireless LANs.

Wireless LANs are typically administered by user organizations. Of late significant activity is taking place in creating business models to exploit the potential of license-free wireless connections. For example, IBM, AT&T, Intel and other companies founded Cometa networks to establish and manage wireless LANs at client sites such as airports, malls, and business parks.

Wireless LAN access points cover a radius of 50-100 meters. Several access points can be used to provide the necessary coverage over a campus. A key difference between wireless LANs and wireless PANs is that the access points in wireless PANs are designed to be mobile whereas the access points in wireless LANs are fixed.

The concept of wireless LANs originated in the late 1970s to replace expensive wiring at manufacturing facilities. However, early attempts were unsuccessful due to the lack of technology and the non-availability of frequency bands for wireless LANs. In 1985, FCC released unlicensed bands for Industrial, scientific and medical use (ISM). These bands are located at 902-928 MHz, 2.4-2.4835 GHz and 5.725-5.875 GHz. The ISM bands were the first unlicensed bands available for the development of consumer products and they significantly facilitated the development of wireless applications. The availability of unlicensed bands allows individuals and organizations to set up private networks without waiting or paying for wireless spectrum.

The only limitation for devices operating in unlicensed bands is that their transmission power must be limited to 1 watt, and modems radiating more than 1milliwatt are required to use spread spectrum technology. Since spread spectrum technologies can mutually coexist in the same geographical area with minimal interference [Smith and Collins 2002], several wireless applications can operate in the limited ISM bands. In practice, some ISM bands are prone to interference, such as from microwave ovens that radiate energy in the 2 GHz band, thereby limiting their utility as a communications medium.

Following the availability of ISM bands and the introduction of wireless LAN products, IEEE initiated standardization efforts resulting in the creation of 802.11 standards in 1997. Initial wireless LAN products were shoebox-sized, and were designed as LAN extensions for organizations to connect networks in adjacent buildings. However, improvements in technology reduced the size of wireless LAN hardware to a PCMCIA card, and facilitated wireless connectivity to laptops. Notable applications of wireless LANs are temporary networking situations such as conferences where the costs of wiring a fixed LAN are prohibitive, or historical monuments such as the Breakwater Prison which houses the University of Cape Town's Graduate School of Business, where wiring is not favored [Shapshak 2001]. The most popular application however is the connectivity of laptops to home or office networks. Wireless LANs are becoming popular in Japan in particular, where small office spaces promote the use of laptops that are naturally suited for connection to networks exclusively over wireless links.

The most common wireless LAN technology today is 802.11b that uses the 2.4 GHz band to provide connectivity at upto 11 Mbps. For higher speeds, the 802.11a standard (using the 5 GHz band) and the 802.11g (using the 2.4 GHz band) were defined. The 802.11h standard is being developed to address regulatory concerns regarding the use of 802.11a in Europe. The 802.11i is a specification in the MAC (data-link) layer to improve security in wireless LANs.

To create wireless LANs, administrators install base stations that are connected to the wired network. Mobile computers within the operating range of base stations can connect to the wired network through the base station. Based on current technologies, data rates of up to 54 Mbps can be obtained using wireless LANs.

A considerable amount of research is underway to develop ultra wide-band wireless technologies that can offer data rates in the Gbps range using signal pulses instead of sine waves. These signals occupy bandwidths greater than 1.5 GHz (compared to bandwidths of about 1 MHz in the 2.4 GHz band). The underlying basis for these technologies is Shannon’s theorem [Shannon 1948; Shannon and Weaver 1949] that suggests that channel capacity increases more by increasing bandwidth rather than by increasing transmission power. Using signal pulses causes signals to occupy large bandwidths and deliver high data rates. The pulses also keep signal power down, thereby eliminating the interference between these signals and existing wireless systems.

METROPOLITAN AREA NETWORKS (MAN)

Large businesses typically use high capacity access links such as those based on fiber optic and copper cables to meet data communication needs. In contrast, small businesses and residential customers typically use cable modem networks and DSL for high-speed (broadband) data connections. Since cable systems are based on the residential cable-TV infrastructure, they are often not available to serve business customers. DSL uses the existing phone network and therefore can potentially serve all small-business customers. Unfortunately, the use of DSL technology is limited because the allowable distance from the central telephone office limits the availability of the DSL service to many small businesses. Both DSL and cable systems require low upstream bandwidth.

In the late 1990s, major telephone companies invested tens of billions of dollars to wire the nation with high-speed fiber-optic trunks. However, only a small fraction of commercial structures were directly connected to these fiber networks. Extending cable networks to wire these buildings is costly, time consuming and a risky business proposition [IEEE 2001]. Wireless local loops (WLL), which are wireless MANs, provide an alternative to wired access lines.

IEEE 802.16 standards that are available for WLL, are designed to offer differentiated broadband services at minimal cost. Wireless MANs enable thousands of users in a metropolitan area within the line-of-sight of an antenna to share high-speed data capacity for data, voice, and video. They can be effective in providing the "last-mile" broadband connections to backbone fiber-optic networks. Since cabling is not needed, wireless MANs can be created in just weeks by deploying a small number of base stations on buildings or poles to create high-capacity wireless access systems [IEEE 2001][1].

WIDE AREA NETWORKS (WAN)

Unlike LANs and PANs, wireless WANs are nationwide networks that traditionally provided text messaging services at low data rates of approximately 10 kbps. The three major components of WANs are

- the mobile station,
- the base station and
- the network system.

Some WAN services such as Mobitex provide their own network infrastructure. Other WAN data services such as Cellular Data Packet Service (CDPD) leverage the network infrastructure and frequency spectra of existing cellular voice networks. Cellular networks are rolling out nationwide coverage at data rates up to 144 kbps with the goal of eventually reaching speeds up to 2 Mbps.

In light of the huge demand for services and the constraints on the availability of wireless spectrum, it is necessary to develop technologies that use the available bandwidth and provide services to as many users as possible. Cellular networks that were developed in the 1970s are unique in that they use the concept of frequency reuse to provide services to a large number of users. In frequency reuse, the same set of frequencies is used to serve customers who are located at some distance from each other. Reuse is possible because the strength of wireless signals falls rapidly with distance and does not interfere with users operating on the same frequencies at a reasonable distance. Cellular networks therefore use a large number of low-powered base stations, each of which provides coverage over a limited area. Various generations of cellular technologies evolved over a period of time. They are described next.

CELLULAR DATA NETWORK GENERATIONS

Cellular phone networks were originally developed to support voice communications and were based on circuit switching. Over a period of time, new generations of technology emerged to handle data and multimedia. Figure 1 traces the evolution of the various generations of cellular technologies and provides a global view of wireless.

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[1] Obtaining right-of-way is one of the biggest legal hurdles in deploying networks. Many companies such as Sprint and Williams Communications decided to enter the telecommunications business because they realized that their right-of-way acquired for other businesses (railway lines and gas pipelines respectively) were invaluable for telecommunications networks.

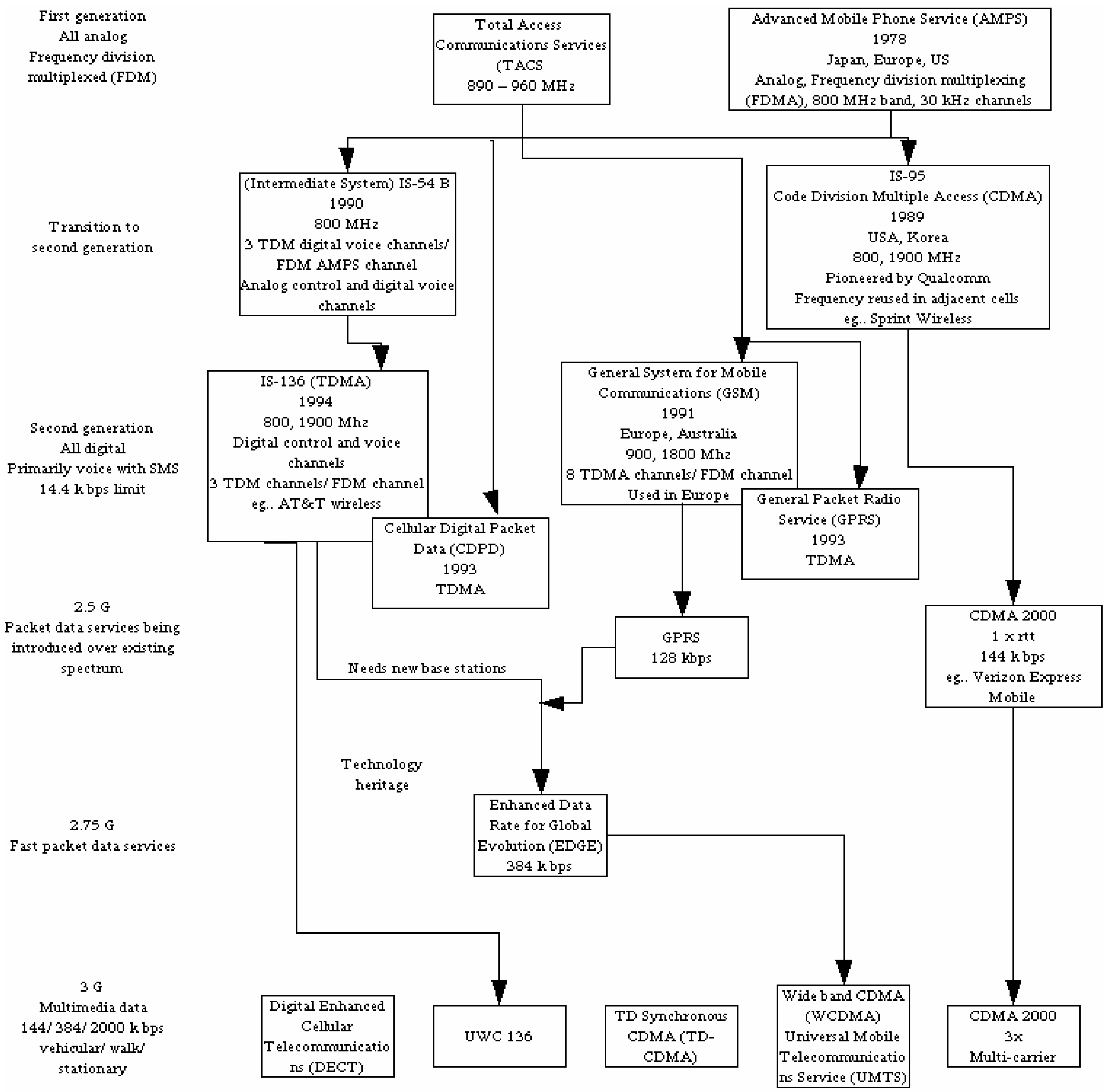

Figure 1. Evolution of Cellular Networks.

The first generation (1G) of cellular networks was introduced in 1978 and was called Advanced Mobile Phone Systems (AMPS). 1G networks were analog networks that used frequency division multiplexing (FDM)[2] to multiplex users onto the available bandwidth. Although these networks were extremely useful, the limitations of analog communications were soon apparent. The limitations included the inefficient use of limited wireless spectrum, limited or no encryption, and the lack of support for advanced services. To overcome these problems, network operators introduced digital networks in the early 1990s.

The digital networks of the 1990s are referred to as the second-generation (2G) networks. Technology platforms began to diverge in 2G when two competing technologies were developed to digitize voice traffic on the existing bands. These technologies were time division multiplexing

[2] Transmitting signals from several channels on a single link is known as multiplexing.

(TDM) and direct sequence spread spectrum (DSSS). In the former case, each FDM band in the AMPS system was split into a fixed number of time slots, each of which could be allocated to an end-user. Two systems based on the TDM technology emerged.

- The TDM technology, Intermediate System (IS)-136 became popular in the US. This system uses three TDM slots/ FDM AMPS channel.
- The Global System for Mobile communications (GSM) technology involved splitting an FDM channel into eight TDM channels became popular in Europe.

The second major competing technology in the second generation was based on DSSS, and was introduced by Qualcomm in 1989. DSSS-based technology involves multiplexing many spread spectrum (DSSS) channels using a process known as code division multiple access (CDMA). In DSSS, all end-stations spread their signals over the entire channel based on a code sequence. CDMA is used to assign DSSS codes such that signals interfere minimally with each other.

2G networks were primarily designed for voice communications. However, with the popularity of data services, network operators started overlaying data traffic on these networks by allowing the use of voice channels to send circuit-switched data. However, each user could only access one channel at a time for data transmission; the data rate in 2G networks adapted for data transmission was limited to 14.4 kbps. To enable networking applications on 2G networks, a simplified protocol called the wireless application protocol (WAP) was also developed.

In the mid 1990s, the International Telecommunications Union (ITU) released specifications for the next generation of cellular services called International Mobile Telecommunications-2000 (IMT-2000). IMT-2000 specifications are popularly known as 3G and are designed to support true packet-switched data services on cellular networks. The advantages of packet-switched data services over circuit switching include the always “on” state of packet-switched networks and the absence of the call-establishment phase associated with phone modems. Because user data can be statistically multiplexed over the same channels, it is possible to bill users based on the amount of data sent instead of the length of time connected to the system.

The principal recommendation of IMT-2000 was that 3G technologies should provide packet switched data rates of 144 kbps to vehicular users, 384 kbps to pedestrian users, and 2Mbps to stationary users. Technologies for air-interfaces were not specified. After evaluating a number of technologies, five technologies were selected in 1999 to provide 3G services. These are shown in Figure 1. Of these, two are likely to be popular,

1. W-CDMA (Wideband CDMA), also called the Universal Mobile Telecommunications Service (UMTS) and
2. CDMA2000 based on the 2G CDMA technologies.

UMTS defines four service classes:

- *Conversational*. This service class supports low delay, jitter and error tolerance. Voice and video conferencing are notable examples. Data rates are approximately equal in both directions.
- *Interactive*. This class involves low error tolerance but allows larger delay and jitter tolerance than conversational service. Interactive service provides request-response transactions, and its data rate is usually significant in one direction. A notable example application is e-mail retrieval.
- *Streaming*. This service class supports one way streaming audio and video. It error tolerance is low but buffering raises delay and jitter tolerance.
- *Background*. This service has no delay constraint and no error tolerance. An example application for this service is mail-delivery between servers.

3G technologies are standardized using CDMA as the underlying carrier technology of choice instead of TDMA. The principal advantage of CDMA over TDMA is that it can transport almost eight-to-ten times the amount of data/voice in a given bandwidth than TDMA. One of the reasons for this increased capacity is that, unlike TDMA, CDMA systems can reuse the same set of frequencies in all the cells because end users calls can be distinguished and separated from one another based on orthogonal code sequences. Another advantage of CDMA is that it does not require synchronization pulses for time synchronization and therefore does not interfere with hearing aids and aircraft navigation systems.

3G networks are expected to provide high-quality Quality of Service (QoS)-enabled data services to users. However, they face hurdles in their deployment. The introduction of new wireless services requires new frequency bands, which involve significant upfront expenses in buying spectrum at spectrum auctions. In many cases, these networks must be deployed over frequency bands that are not yet cleared of existing users, thereby further delaying deployment. Finally, the bulk of traffic on cellular networks continues to be voice traffic and the demand for high-speed data services is uncertain. Network operators therefore chose to ease the route towards 3G deployments by deploying technologies that provide reasonably high-speed data services (in the range of 144 kbps) on frequency bands that are already available. These transitional technologies are called 2.5G networks and include CDMA 2000 1x, the precursor to CDMA 2000 3x; General Packet Radio Service (GPRS), the precursor to W-CDMA. Typically, the technologies enable higher speeds than 2G networks by allowing users to send data on more than one voice channel at a time. As shown in the Figure 1, the migration path from 2G to 3G depends as much upon the existing infrastructure as the eventual 3G platforms. Another service being developed by networks that currently use TDM is the enhanced data rate for global evolution (EDGE). This technology provides about 384 kbps and is sometimes called 2.75 G.

Table 1 summarizes key developments associated with the generations of cellular technologies. In 1G, limited mobility was achieved. This mobility was then extended to roaming in 2G. Quality of service, and packet data transfer are key features associated with the current 2.5G networks. 3G networks are expected to realize high date rates to support multimedia traffic.

Table 1. Key Developments in Cellular Wireless Technologies

AMPS (Mobility)	TDMA, GSM (Roaming)	IS-95A (Quality, data)	CDMA2000 (high-data rate)
1G	2G	2.5G	3G

III.OSI FRAMEWORK FOR COMPARING WIRELESS TECHNOLOGIES

The protocols for wireless data communications are layered. The bulk of these protocols are at the physical and the data link layer of the OSI model [Stallings 2001]. The physical layer performs encoding and signal transmission while the data link layer provides media access, error control and data security (in some cases), taking into account the inherently noisy wireless links. In this section, we provide a bottoms-up comparison of various wireless technologies examined along the dimensions appropriate for each layer using the OSI model as the underlying framework. For each layer, we list the available protocols and their principal characteristics.

PHYSICAL LAYER

The physical layer in wireless networks is responsible for functions such as the specification of the wireless medium, modulation techniques, and supported data rates. Unlike wired media where capacity between any two points can be virtually made infinite by simply adding more cables to the network, wireless networks must operate within the available bandwidth. Therefore, the goal of physical layer technologies is to use the limited bandwidth available in wireless channels efficiently to multiplex the data transmissions from multiple users. Older wireless systems such as radio and broadcast television that use simple frequency division multiplexing are inefficient in bandwidth use. The extremely inefficient bandwidth use by broadcast television is one of the primary drivers behind the United States' government's push for universal HDTV transmission in the U.S. by 2006 [Murray 2002]. In contrast, the physical layers in data communication technologies use very sophisticated modulation techniques such as code division multiple access (CDMA), frequency hopping spread spectrum (FHSS) and Gaussian minimum shift keying (GMSK) that significantly reduce the bandwidth requirements for individual data channels.

Table 2 provides a comparison of the various physical layer wireless technologies. These technologies are arranged in the increasing order of range, and within each range, in the increasing order of data rates. It can be seen from Table 2 that IrDA is the shortest range of all technologies. In the case of wide area wireless networks, 3G cellular systems such as WCDMA and CDMA 2000 3x allow the highest data rates, while for local area networks, IEEE 802.11a and

Table 2. Physical Layer Protocols

Technology	**Data rate**	**Modulation**	**Frequency Band**	**Logical Topology**	**Compatibility with Previous Generation**
Infrared (IrDA compliant)	9600 to 115,200 bits/s (Serial IR), 115 kbits/s, 4/16 Mbits/s (Fast Infrared)	Return-to-Zero (RZ) Pulse-width modulation (PWM) Pulse-position modulation (PPM) for FIR	850 nm (10^{20} Hz)	Point-to-point Master/ slave	NA
Blue Tooth (IEEE 802.15)	Upto 1 Mbps	FHSS/ TDD	2.4 – 2.48 GHz ISM	Master/ slave piconet (logical star)	NA
Wireless LAN (IEEE 802.11b)	5.5, 11 Mbps	Direct sequence spread spectrum	2.4 GHz ISM	Star (Point-coordination framework) Multicast (Distributed coordination framework)	NA
Wireless LAN (IEEE 802.11a)	6-54 Mbps	Orthogonal FDM	5 GHz ISM	Star (Point-coordination framework) Multicast (Distributed coordination framework)	No (with IEEE 802.11b)
Wireless LAN (IEEE 802.11g)	54 Mbps	Orthogonal FDM	2.4 GHz ISM	Star (Point-coordination framework) Multicast (Distributed coordination framework)	Yes (with IEEE 802.11b)
Wireless Local Loop (WLL) (IEEE 802.16)	Local multipoint distribution: < 1 Mbps upstream, 36 Mbps downstream Multichannel multipoint	QPSK	LMDS: 8 bands from 24-24.25 GHz MMDS: 7 bands from 2.15 to 2.68	Fixed Star (Not mobile). Sometimes also called point-to-multipoint (downstream) and multipoint-to-point	Yes, with phone system

	distribution: 300 kbps – 3 Mbps		GHz	(upstream)	
Mobitex [Khan and Kilpatrick 1995]	8 kbps, (used in Palm VII networks)	Gaussian minimum shift keying (GMSK)	12.5 KHz channels in 400 MHz band. Channels also available in 800/ 900 MHz bands	point-to-multipoint (downstream), multipoint-to-point (upstream)	n/a
Cellular digital packet data (CDPD)	19.2 kbps (user data rate of 10-15 kbps) over bidirectional 30KHz channels. ≤ 3 time slots/ frame	Gaussian minimum shift keying (GMSK)	824-894/ 1900 MHz	Like WLL, point-to-multipoint (downstream) and multipoint-to-point (upstream)	Yes, with AMPS (but which is not a data service).
General packet radio service (GPRS)	9.6 kbps from 8 time slots/ 200 KHz channel	Gaussian minimum shift keying (GMSK)	900/1800/ 1900 MHz	Point-to-multipoint (downstream), multipoint-to-point (upstream)	n/a
Code division multiple access (CDMA) (IS-95)	9.6 kbps	Direct Sequence Spread Spectrum (DSSS). Q-PSK for modulation	800/ 1900 MHz	Point-to-multipoint (downstream), multipoint-to-point (upstream)	n/a
CDMA 2000 1x (2.5 G)	144 kbps	Direct Sequence Spread Spectrum (DSSS)	Frequencies can be reused in adjacent cells in CDMA.	Point-to-multipoint (downstream), multipoint-to-point (upstream)	Yes, with IS-95
Enhanced data rates for GSM evolution (EDGE) (2.5 G)	144 kbps outdoor low speed 384 kbps outdoor high speed	8-PSK over Gaussian minimum shift keying (GMSK)	900/1800/ 1900 MHz	Point-to-multipoint (downstream), multipoint-to-point (upstream)	Yes, with GPRS
Wireless CDMA	144/284/2000 kbps Rates higher than 480 kbps obtained by multiplexing data transmission on multiple channels in 1900 MHz band	Direct Sequence Spread Spectrum (DSSS) signals at 3.84 Mega chips/ sec. (Mcps) modulated using QPSK	5 MHz of spectrum needed/ channel	Point-to-multipoint (downstream), multipoint-to-point (upstream)	Probably, with dual-mode phones.
CDMA 2000 3x [Telecommunication Industry Association 2002]	144/284/2000 kbps	Direct Sequence Spread Spectrum (DSSS) with Q-PSK	5 MHz of spectrum needed/ channel	Point-to-multipoint (downstream), multipoint-to-point (upstream)	Yes, with IS-95

IEEE 802.11g provide the highest data rates. As may be seen from this table, PAN and LAN technologies operate exclusively over the ISM bands whereas WANs operate exclusively over licensed bands.

One of the significant advances that have enabled the deployment of new wireless technologies is in modulation techniques. For example, spread spectrum technology improves communication between devices sharing the same band, while Gaussian mean shift keying improves the efficiency of utilization of wireless bandwidth. The modulation techniques used in each technology are also indicated in Table 2 where applicable, we indicate the technologies that are backward-compatible to a given technology. Compatibility is not relevant for the first generations of services.

DATA LINK LAYER

The data link layer performs important functions such as media access control and creating reliable links between devices with possible support for security through encryption. One of the unique features of wireless networks is the inherent broadcast nature of signals unlike wired networks, where signals are confined to the medium in which they propagate. This characteristic makes wireless signals easy to eavesdrop and therefore poses a potential security threat. As a result, where appropriate, data link layers in wireless networks contain mechanisms for securing data from eavesdroppers.

Wired networks generally do not face bandwidth constraints the way wireless networks do. Therefore, QoS support in wired networks can be obtained by simply making huge bandwidths available, whereas wireless networks need to make explicit provisions for supporting quality of service that may be needed for services such as voice. For example, Table 3 indicates that Bluetooth, which supports QoS, provides reserved time-slots for voice. Table 3 also indicates whether or not, a technology provides error correction, security, and QoS support. Where applicable, the mechanisms for providing such support are described. Because of the constraints arising from the limitations in bandwidth, wireless technologies can only support a limited number of users within a geographical area as shown in Table 3. The access method column shows the technique used to share the available spectrum among users.

UPPER LAYERS

The protocols above the data link layer are responsible for providing end-to-end data transfer between senders and receivers. The most common protocol suite used in the upper layers is TCP/ IP. Some technologies like Mobitex provide a dedicated protocol stack whereas others such as WAP and TCP/IP can work with many different data-link layer technologies.

WAP is an interesting model in wireless WANs. The WAP architecture specification only provides a framework for a variety of protocols, features, and services. By itself, WAP does not mandate any specific implementation. The separation of service interfaces from the protocols that provide those services, facilitate the evolution of the specifications and selection of the most appropriate protocol for a given context. Many of the services in the stack may be provided by more than one protocol.

Most of the standard components defined by WAP to enable communication between mobile terminals and network servers are derived from the web programming model including:

- standard WWW URLs to identify WAP content on origin servers;
- content typing to help WAP user agents to process the content correctly based on its type;
- content formats based on WWW technology such as display markup, calendar information, electronic business card objects, images, and scripting language.

WAP can also use many communication protocols for communicating browser requests from the mobile terminal to the network web server.

Table 3. Data Link Layer Protocols

Protocol	**Security**	**# of users**	**Error correction**	**QoS support**	**Access method**	**Addressing**	**Connection**
MASC (Mobitex Asynchronous Communication)	Application level using SSL with 128-bit RSA.	400/ channel. 1000s nation wide	16 bit CRC and Hamming code for error-correction	No	Reservation-slotted ALOHA	24-bit MOBITEX access number	Connection oriented
SNDCP) with mobile data link protocol (MDLP) and MAC (used in CDPD)	Above network layers. Security management protocol (SMP) for encryption. Mobile network registration protocol (MNRP) for authentication	1000s nation wide	Forward error correction	No	Digital sense multiple access/ CD(DSMA/CD). Forward transmissions from base station indicates if data received correctly.	48 bit equipment address and dynamically assigned identifier	Connection-oriented
SNDCP(Subnetwork Dependent Convergence Protocol with LLC, RLC (Radio Link Control) and MAC (used in GPRS)	Encryption supported at LLC layer using symmetric key encryption and A5 algorithm. Authentication uses A3 algorithm. Both are possibly secret and were not subject to review during development	1000s	Forward error correction at physical layer. Also 3-bit CRC for error-detection	Yes, 3 classes of priority	TDMA/FDMA using off-line control channels. Mobile uses random access channel to request access and is assigned a channel using access grant channel. Base station (BSC) may allot multiple time slots dynamically to accommodate traffic. In downlink packets, BSC uses uplink state flag (USF) field in header to indicate which MS can use the channel in uplink.	Static or dynamic packet data protocol (PDP) address. Can be an IP address	Connection-oriented
Link Access Control (LAC) with Radio Link protocol (RLP) (used in IS-95)		1000s		No	CDMA		
LAC and RLP with QoS module (used in CDMA2000 1x)	AKA and cellular message encryption algorithm (CMEA) protocol at LAC sublayer and upper layer to encrypt signaling information. Optional symmetric encryption for data.	1000s	Forward error correction at physical layer. 8-bit CRC for error detection	No	CDMA	8-bit MAC identifier	Connection-oriented with sequence numbers
SNDCP, LLC, RLC (with link quality control) and MAC (used in EDGE)	Like GPRS	1000s	Like GPRS	Yes	TDMA over FDM	Static or dynamic packet data protocol (PDP) address. Can be an IP address	

PDPC with RLC and MAC (used in W-CDMA)	Encryption, integrity check and challenge-response authentication. Unpublished algorithm	1000s	FEC for error correction and CRC for error detection	Yes, 4 classes of service	CDMA		Transparent mode, Acknowledge mode, Unacknowledged mode
MAC/ LLC (used in 802.11(a)/(b)/(g))	40-128 bit shared key based wired equivalent privacy. No specification of procedure to share key.	~200	Only 32 bit CRC for error detection	No	CSMA/ CA (collision avoidance instead of collision detection)	47 bit MAC address	Connection-mode Unacknowledged connectionless Acknowledged connectionless
Link manager protocol (LMP) and LLC and adaptation protocol (L2CAP) (used in 802.15)	128 bit Authentication and 8-128 bit encryption	7 simultaneous links, upto 200 users/ piconet and 10 piconets	16 bit CRC	Yes, Can reserve time slot on link for voice communication.	Duplex TDMA/ TDD with frequency hopping	48 bit fixed device address	Asynchronous connectionless for data Synchronous connection-oriented for voice
Service-specific convergence sublayer (SSCS) with common part sublayer (CPS) and MAC (used in 802.16)	None	100s	32 bit CRC	MMDS: no LMDS: Yes	Demand assignment multiple access TDMA (DAMA-TDMA, basically statistical TDMA)	16 bit connection identifier	Connection oriented
Infrared link management protocol (IrLMP) and link access protocol (IrLAP) (used in Infrared)	None. Implicit from point-to-point connection and short range	2	(CRC-16 for speeds up to 1.152Mb/s and CRC-32 at > 4 Mb/s).	No	CSMA with no multiplexing	7 bit dynamically assigned connection address 32 bit random self-generated device address	Connection-oriented

To optimize and enhance the connection between the wireless domain and the WWW, WAP defines the use of proxies. WAP proxies may provide a variety of functions, including caching, user profile management, protocol gateway and content encoding and decoding. The WAP Architecture also includes supporting servers that provide services to devices, proxies, and applications as needed. These supporting servers include the PKI portal to create new public key certificates and the provisioning server to provide provisioning information.

Cellular wireless technologies popular in Japan include i-mode and personal digital cellular (PDC). Since Japan took an early lead in implementing cellular services, i-mode installed base of over 30 million paying subscribers is huge. However, unlike the layered model of protocols that is presented in this paper, i-mode is a complete service specification covering everything from the physical signals to the application development framework. i-mode uses a packet-switched network laid over the underlying circuit-switched voice network. Introduced in 1994, PDC is a popular 2G network in Japan. In the coming years, PDC networks are expected to be replaced with CDMA networks. i-mode services are available over both PDC and CDMA networks.

Tables 4 to 6 present the upper layer protocols considered in this paper and the lower layer protocols they work with.

Table 4. Network Layer Protocols

Protocol	Data link Technologies Supported
Mobitex Packet protocol (MPAK)	MASC
Internet protocol (IP)	802.11, GPRS, CDPD, EDGE, WCDMA, Bluetooth, WLL
Wireless datagram protocol (WDP) (used in WAP)	GPRS, CDMA, CDMA2000, WCDMA, Bluetooth

Table 5. Transport Layer Protocols

Protocols	Network Protocols Supported	Flow control
Mobitex transport protocol (MTP)	MPAK	No
TCP	IP	Yes
Wireless transport layer security (WTLS) (used in WAP)	IP, WDP	Yes

Table 6. Application Layer Protocols

Protocol	Transport Protocols
HTTP	TCP
Wireless application environment (WAE) (used in WAP)	WTLS

Upper Layer Security Support

Table 3 indicates that many data link protocols provide native support for security through encryption. However, many wireless encryption solutions are known to be weak and inadequate for industrial use. In these cases, and in cases when the lower layers do not provide encryption support, security and encryption is typically implemented at the upper layers. Two commonly used protocols supporting encryption at higher layers are Secure Sockets Layer (SSL) and Wireless Transport Layer Security (WTLS). SSL, which is also called Transport Layer Security (TLS), is documented in RFC 2246 [Dierks and Allen 1999], and provides end-to-end security between the source and destination. SSL runs on top of the TCP/IP protocol and is called by many protocols such as HTTP, and HTTPS. SSL, like most modern security mechanisms, uses public key encryption to exchange private keys.

WTLS provides security services between the wireless device and the WAP gateway on the network. To provide end-to-end security, the WAP gateway uses SSL to communicate with the destination. As the name suggests, WTLS is based on SSL but uses fewer messages to make it more efficient on narrowband and error-prone wireless links. WTLS provides data integrity, privacy, authentication, and protection against denial-of-service attacks.

IV. CONCLUSION

As mobile computing devices become ubiquitous, they are expected to drive much of the growth in business to consumer electronic commerce. To facilitate mobility, any implementation of a mobile computing application is required to have a robust wireless communications infrastructure. With the introduction of a wide variety of wireless technologies in the recent past, organizations need to navigate through the available choices to identify the technology that best meets their needs. To help in this task, we presented a survey of the wireless technology landscape using the OSI framework. Managers and software developers can use this survey to plan their wireless applications. We also used the information presented in this paper to create a simple expert system [Chari et al. 2003] for generating protocol stacks for wireless applications based on application needs.

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REFERENCES

EDITOR'S NOTE: The following reference list contains hyperlinks to World Wide Web pages. Readers who have the ability to access the Web directly from their word processor or are reading the paper on the Web, can gain direct access to these linked references. Readers are warned, however, that

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LIST OF ACRONYMS

1G, 2G, 3G	1st, 2nd, and 3rd generation cellular wireless technologies
802.11a, 802.11b, 802.11g	Specifications for wireless local network technologies
802.11i	Specifications for wireless security
802.15	Specifications for Bluetooth wireless technology
802.15.4	Specifications of Zigbee (a variant of Bluetooth to standardize domestic remote control devices)
AMPS	Advanced Mobile Phone Systems
AT&T	American Telephone and Telegraph Company
bps	Bits per second
CDMA	Code division multiple access
CDPD	Cellular digital packet data
DSL	Digital subscriber line
DSSS	Direct sequence spread spectrum
EDGE	Enhanced data rate for global evolution
FCC	Federal Communications Commission
FDM	Frequency division multiplexing
FHSS	Frequency hopping spread spectrum
GMSK	Gaussian minimum shift keying
GPRS	General Packet Radio Service
GSM	Global system for mobile communications (European cell phone technology)
HDTV	High-definition TV
HTTP/HTTPS	Hypertext transport protocol/ Secure HTTP
Hz, kHz, MHz, GHz	Hertz (a unit of frequency), Kilo Hertz (1000 Hertz), Mega (10^6 Hertz), Giga Hertz (10^9 Hertz)
IBM	International Business Machines
IEEE	Institute of Electrical and Electronics Engineers
IMT-2000	International Mobile Telecommunications-2000 (also known as 3G)
IrDA	Infra-red data association
IS	Intermediate system
ISM	Industrial, Scientific and Medical band (for unlicensed wireless access)
ITU	International Telecommunications Union
LAN	Local area networks

MAN	Metropolitan area network
OSI	Open Systems Interconnect
PAN	Personal area networks
PCMCIA	Personal Computer Memory Card International Association
PDA	Personal digital assistant
PDC	Personal digital cellular
QoS	Quality of service
RFC	Request for comment
SSL	Secure sockets layer
TCP/IP	Transport control protocol/ Internet protocol
TDM	Time division multiplexing
TLS, WTLS	Transport layer security, wireless transport layer security
UMTS	Universal Mobile Telecommunications Service
WAN	Wide area networks
WAP	Wireless application protocol
W-CDMA	Wideband CDMA
WLL, 802.16	Wireless in local loop

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