Table 15.3: ▶
Comparison of WMAN Standards [15.23]
From R.L. Ashok, and D.P. Agrawal, “Next Generation Wearable Networks,” *IEEE Computer*, November 2003, Vol. 36, No. 11, pp. 31–39.

Technology	**Wireless MAN**	
	IEEE 802.16	**Ricochet**
Operational spectrum	10–66 GHz, LOS required, 20/25/28 MHz channels	900 MHz
Physical layer	TDMA-based uplink, QPSK, 16-QAM, 64-QAM	FHSS
Channel access	TDD and FDD variants	CSMA
Nominal data rate possible	120/134.4 Mbps for 25/28 MHz channel	176 kbps
Coverage	Typically a large city	As of September, 2002 only Denver, CO
Power level issues	Complicated power control algorithms for different burst profiles	Low-power modem compatible with laptops and hand-helds
Interference	Present but limited	Present
Price complexity	Not available	Medium
Security	High. Defines an extra privacy sublayer for authentication	High (patented security system)

of “hops” an RF packet might take to reach the Metricom backbone network. A comparison between WMAN standards as given in Table 15.3.

15.6 Wireless Personal Area Networks (WPANs)

15.6.1 Introduction

Bluetooth is the only WPAN technology to be commercially available that was initially conceived to replace RS232 cables. Even though it was developed in the mid-1990s, it is only since 2002 that its presence has become visible in a gamut of devices ranging from laptops to wireless mouse to cameras to headsets to printers and cell phones. The IEEE has now taken a significant interest in WPANs and has initiated the development of the IEEE 802.15.x protocols to address the needs of WPANs with varied data rates. Bluetooth has been adopted as the IEEE 802.15.1 (medium rate), and the IEEE 802.15.3 (high rate) and 802.15.4 (low rate) are also available.

The IEEE 802.15 working group is formed by four task groups (TGs)[15.28]:

- **The IEEE 802.15 WPAN/Bluetooth TG1**: The TG1 has been established to support applications that require medium-rate WPANs (such as Bluetooth). These WPANs will handle a variety of tasks ranging from cell phones to PDA communications and will have a QoS suitable for voice applications.
- **The IEEE 802.15 Coexistence TG2**: Several wireless standards, such as Bluetooth and the IEEE 802.11b, and appliances, such as microwaves, operate in the unlicensed 2.4 GHz ISM frequency band. TG2 (the IEEE 802.15.2) is developing recommended practices to facilitate coexistence of WPANs (the IEEE 802.15) and WLANs (the IEEE 802.11).
- **The IEEE 802.15 WPAN/High Rate TG3**: The TG3 for WPANs is chartered to draft a new standard for high-rate (20 Mbps or greater) WPANs. Besides a high data rate, the new standard provides low-power and low-cost solutions, addressing the needs of portable consumer digital imaging and multimedia applications.
- **The IEEE 802.15 WPAN/Low Rate TG4**: The goal of the TG4 is to provide a standard for ultra-low complexity, cost, and power for low-data-rate (200 kbps or less) wireless connectivity among inexpensive fixed, portable, and moving devices. Location awareness is being considered as a unique capability of the standard. The scope of the TG4 is to define the physical and medium access control layer specifications. Potential applications are sensors, interactive toys, smart badges, remote controls, and home automation.

One key issue in WPANs is the interworking of wireless technologies to create heterogeneous wireless networks. For instance, WPANs and WLANs will enable an extension of devices without direct cellular access to 3G cellular systems (i.e., UMTS, W-CDMA, and CDMA2000). Moreover, devices interconnected in a WPAN should be able to utilize a combination of both 3G access and WLAN by selecting the access mechanism that is best suited at a given time. In such networks, 3G, WLAN, and WPAN technologies do not compete against each other but enable users to select the best connectivity for their intended purposes.

15.6.2 IEEE 802.15.1 (Bluetooth)

Bluetooth [15.29] is named after the King of Denmark who unified different factions in Christianity throughout Denmark. If you are in a building not wired, and suddenly an email is sent to your notebook and your cellular phone is in your briefcase, you will be unable to respond to the email. If Bluetooth is present with your cellular phone (basically, Bluetooth is a wireless wire), as illustrated in Figure 15.11, you can easily reply.

Bluetooth has been designed to allow low-bandwidth wireless connections to become so simple to use that they seamlessly integrate into your daily life [15.30]. Ericsson, Intel, IBM, Nokia, and Toshiba started this in 1998 by establishing a Bluetooth special-interest group. In December 1999, many companies, including 3COM, Lucent, Motorola, and Microsoft, joined in an attempt to evolve a reliable

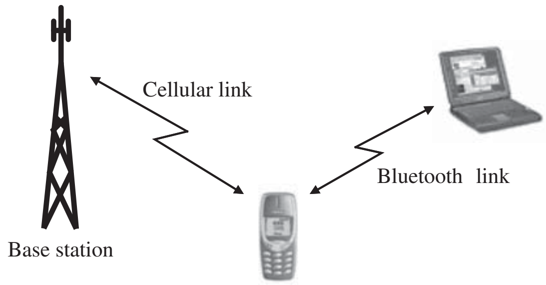

Figure 15.11
Use of Bluetooth to connect notebook.

universal link for short-range RF communication. It is widely recognized that as time progresses, the number of short wires connecting computer peripherals has been increasing day by day. Low-cost, low-power, radio-based wireless links eliminate the need for short cables. An infrared link can easily provide speeds up to 10 Mbps at very low cost and ease of installation, but it requires line of sight and offers only a point-to-point link. Hence, the concept of Bluetooth evolved to provide a universal standard for short-range RF communication of both voice and data.

Bluetooth [15.31] offers many options to the user by replacing the cable used to connect a laptop to a cellular phone, printers, desktops, fax machines, keyboards, joysticks, and virtually any other digital device can be networked by the Bluetooth system (Figure 15.12). Bluetooth also provides a universal bridge to existing data networks (Figure 15.13) and a mechanism to form small private MANETs (Figure 15.14).

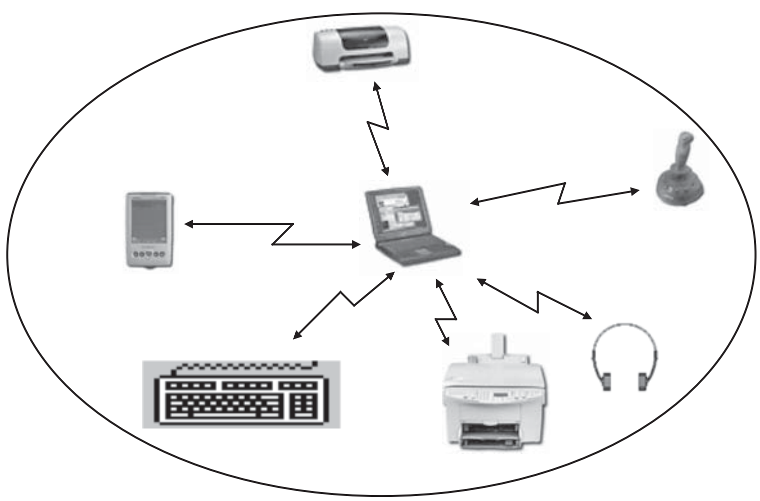

Figure 15.12
Bluetooth connecting printers, PDAs, desktops, fax machines, keyboards, joysticks, and virtually any other digital device.

A simple example of a Bluetooth application is updating the phone directory of your PC from a mobile telephone. With Bluetooth, entering numbers of all your contacts between your phone and your PC could happen automatically and without

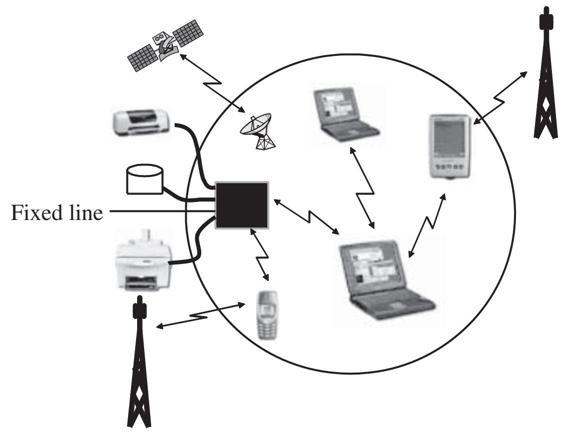

Figure 15.13
Bluetooth providing a universal bridge to existing data networks.

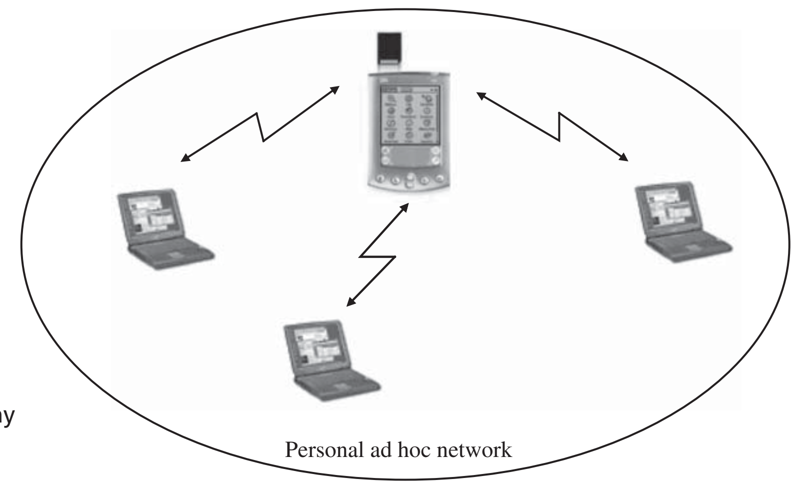

Figure 15.14
Bluetooth: A mechanism to form ad hoc networks of connected devices away from fixed network infrastructures.

any user involvement. Of course, you can easily include your calendar, to-do list, memos, email, and so on. It is reasonable to assume that it would be feasible to find the price of all sale items automatically on your cell phone or PDA.

The ultimate goal is to make computers (PCs/laptops) have only one wire attached to them, which is the power cord, and make a portable computer truly portable. In the case of a PDA, the power cord is also eliminated. Communication protocols between two computers in a conference room environment do exist for Bluetooth. However, the demands placed on the network by the voice and data traffic are different; multimedia traffic is likely to use most of the asynchronous real-time interactive data. These packets consume nearly one-third of bandwidth in traditional peer-to-peer networks and much more in connections involving peripherals. Any of the existing transport protocols cannot be used in this scenario and efficient protocols to handle this general situation need to be developed.

Bluetooth utilizes the unlicensed ISM band at 2.4 GHz. A typical Bluetooth device has a range of about 10 meters. The communication channel supports data (asynchronous) and voice (synchronous) with a total bandwidth of 1 Mbps. The synchronous voice channels are provided using circuit switching (slot reservation at fixed intervals). The asynchronous data channels are provided using packet switching utilizing a polling access scheme. A combined data-voice packet is also defined to provide 64 kbps voice and 64 kbps data in each direction. The time slots can be reserved for synchronous packets with a frequency hop for each transmitted packet. A packet usually covers a single time slot but can be extended to cover up to five slots. The Bluetooth specification defines two power levels: a low-power level that covers a small personal area within a room and a high-power level that can cover a medium range, such as an area within a home. Software controls and identity coding built into each microchip ensure that only those units preset by their owners can communicate with the following characteristics:

- Fast frequency hopping to minimize interference
- Adaptive output power to minimize interference
- Short data packets to maximize capacity
- Fast acknowledgments allowing low coding overhead for links
- CVSD (continuous variable slope delta) modulation voice coding, which can withstand high bit-error rates
- Flexible packet types that support a wide application range
- Transmission and reception interface tailored to minimize power consumption

Architecture of the Bluetooth System

Bluetooth devices can interact with other Bluetooth devices in several ways (Figure 15.15). In the simplest scheme, one of the devices acts as the master and (up to) seven others as slaves and it is known as a piconet. A single channel (and

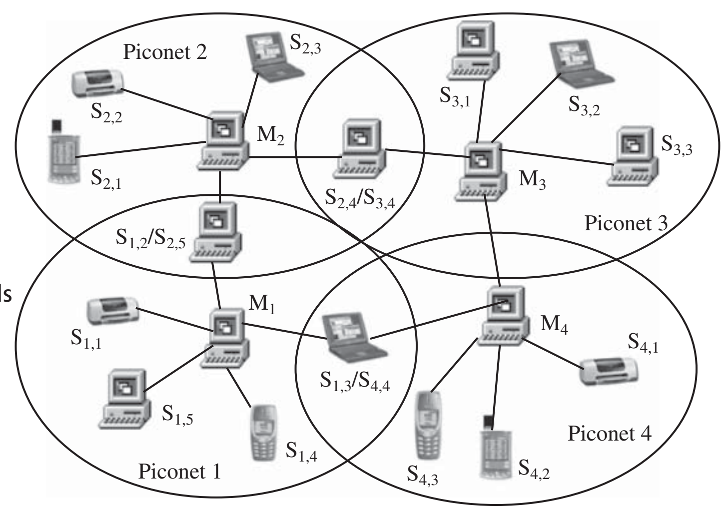

Figure 15.15 Architecture of Bluetooth system and scatternet [15.32]. From Carlos de Morais Cordeiro, "Medium Access Control Protocols and Routing Strategies for Wireless Local and Personal Area Networks," Ph.D. Dissertation, University of Cincinnati, December 2, 2003.

bandwidth) is shared among all devices in the piconet. Each of the active slaves has an assigned 3-bit active member address. Many other slaves can remain synchronized to the master though remaining inactive slaves, referred to as parked nodes. The master regulates channel access for all active nodes and parked nodes. If two piconets are close to each other, they have overlapping coverage areas. This scenario, in which nodes of two piconets intermingle, is called a scatternet. Slaves in one piconet can participate in another piconet as either a master or slave through time division multiplexing. In a scatternet, the two (or more) piconets are not synchronized in either time or frequency. Each of the piconets operates in its own frequency hopping channel, and any devices in multiple piconets participate at the appropriate time via time division multiplexing. Before any connections in a piconet are created, all devices are in STANDBY mode, where unconnected units periodically "listen" for messages every 1.28 seconds. Each time a device wakes up, it tunes on the set of 32 hop frequencies defined for that unit.

Piconet supports both point-to-point and point-to-multipoint connections; details of Bluetooth technological characteristics are shown in Table 15.4.

Table 15.4: ▶
Bluetooth Technological Characteristics

Frequency band	2.4 GHz (unlicensed ISM band)
Technology	Spread spectrum
Transmission method	Hybrid direct sequence and frequency hopping
Transmission power	1 milliwatt (0 dBm)
Range	10 meters (40 feet)
Number of devices	8 per piconet, 10 piconets per coverage area
Data speed	Asymmetric link: 721 + 57.6 kbps Symmetric link: 432.6 kbps
Maximum voice channels	3 per piconet
Maximum data channels	7 per piconet
Security	Link layer with fast frequency hopping (1600 hops/s)
Power consumption	30 μA sleep, 60 μA hold, 300 μA standby, 800 μA max transmit
Module size	3 square cm (0.5 square inches)
Price	Expected to fall to $5 in the next few years
C/I cochannel	11 dB (0.1% BER)
C/I 1 MHz	−8 dB (0.1% BER)
C/I 2 MHz	−40 dB (0.1% BER)
Channel switching time	220 μs

The connection procedure for a piconet is initiated by any of the devices, which then becomes master of the created piconet. A connection is made by sending a PAGE message if the address is already known, or by an INQUIRY message followed by a subsequent PAGE message if the address is unknown. In the PAGE state, the master unit sends a train of 16 identical messages using 16 different hop frequencies defined for the device to be paged (slave unit). If it does not get any response, the master transmits a train on the remaining 16 hop frequencies. The maximum delay before the master reaches the slave is twice the wake-up period (0.64 seconds). A power-saving mode can be used for units in a piconet if there are no data to be transmitted. The master unit can put slave units into HOLD mode, where only an internal timer is running. Slave units can also demand to be put into HOLD mode. Data transfer restarts instantly when units move out of HOLD mode. The HOLD is used when connecting several piconets or managing a low-power device such as a temperature sensor. In the SNIFF mode, a slave device listens to the piconet at a reduced rate, reducing its duty cycle. The SNIFF interval is programmable and depends on the application. In the PARK mode, a device is still synchronized to the piconet but does not participate in the traffic.

The Bluetooth core protocols are shown in Figure 15.16; the rest of the protocols are used only as needed. Service discovery protocol (SDP) provides a means for applications to discover which services are provided by or are available through a Bluetooth device. Logical link control and adaptation layer protocol (L2CAP) supports higher-level protocol multiplexing, packet segmentation, and reassembly, and the conveying of quality of service information. Link manager protocol (LMP) is used by the link managers (on either side) for link setup and control. The baseband and link control layer enables the physical RF link between Bluetooth units forming a piconet. It provides two different kinds of physical links with their corresponding baseband packets, SCO and ACL, which can be transmitted in a multiplexing manner on the same RF link.

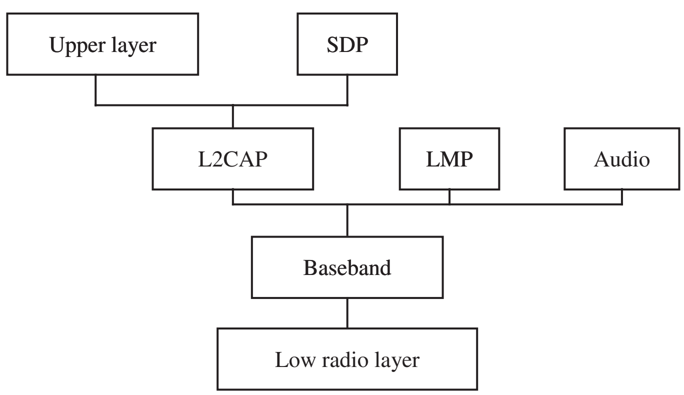

Figure 15.16 Bluetooth core protocols.

Each link type supports up to 16 different packet types. Four of these are control packets which are common for both SCO and ACL links. Both link types use a TDD scheme for full-duplex transmissions. The SCO link is symmetric and typically supports time-bounded voice traffic. SCO packets are transmitted over reserved intervals. Once the connection is established, both master and slave units may send

SCO packet types and allow both voice and data transmissions—with only the data portion being retransmitted when corrupted.

The ACL link is packet oriented and supports both symmetric and asymmetric traffic. The master unit controls the link bandwidth and decides how much piconet bandwidth is given to each slave and the symmetry of the traffic. Slaves must be polled before they can transmit data. The ACL link also supports broadcast messages from the master to all slaves in the piconet. There are three error-correction schemes defined for Bluetooth baseband controllers:

- 1/3 rate FEC
- 2/3 rate FEC
- ARQ scheme for data

There are three- and five-slot packets as depicted in Figure 15.17. A TDD scheme divides the channel into 625 μs slots at a 1 Mb/s symbol rate. As a result, at most 625 bits can be transmitted in a single slot. However, to change the Bluetooth device from transmit state to receive state and tune to the next frequency hop, a 259 μs turn around time is kept at the end of the last slot. This results in reduction of effective bandwidth available for data transfer. Table 15.5 summarizes the available packet types and their characteristics [15.4]. Bluetooth employs HVx (high-quality voice) packets for SCO transmissions and DMx (data medium-rate) or DHx (data high-rate) packets for ACL data transmissions, where $x = 1, 3$, or 5. In the case of DMx and DHx, x represents the number of slots a packet occupies as shown in Figure 15.17, while in the case of HVx, it represents the level of forward error correction (FEC). The purpose of the FEC scheme on the data payload is to reduce the number of retransmissions. In the ARQ scheme, data transmitted in one slot are directly acknowledged by the recipient in the next slot, performing both the header error check and the cyclic redundancy check.

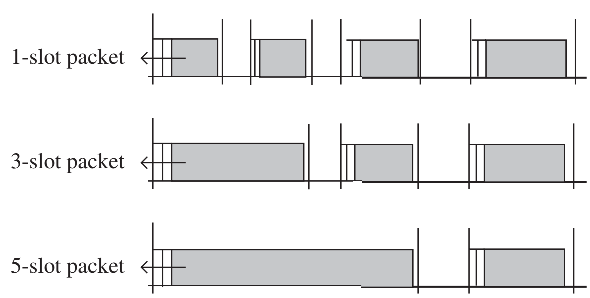

Figure 15.17 Packet transmission in Bluetooth.

15.6.3 IEEE 802.15.3

The IEEE 802.15.3 Group is developing an ad hoc MAC layer suitable for multimedia WPAN applications and a PHY capable of data rates in excess of 20 Mbps. The current draft of the IEEE 802.15.3 standard (being dubbed WiMedia) specifies data rates of up to 55 Mbps in the 2.4 GHz unlicensed band. The technology employs an