request that the buffered frames be sent by sending a polling message to the AP. With an inter-beacon time of 100 msec, a wakeup time of 250 microseconds, and a similarly small time to receive a beacon frame and check to ensure that there are no buffered frames, a node that has no frames to send or receive can be asleep 99% of the time, resulting in a significant energy savings.

6.3.6 Personal Area Networks: Bluetooth and Zigbee

As illustrated in Figure 6.2, the IEEE 802.11 WiFi standard is aimed at communication among devices separated by up to 100 meters (except when 802.11 is used in a point-to-point configuration with a directional antenna). Two other IEEE 802 protocols—Bluetooth and Zigbee (defined in the IEEE 802.15.1 and IEEE 802.15.4 standards [IEEE 802.15 2012]) and WiMAX (defined in the IEEE 802.16 standard [IEEE 802.16d 2004; IEEE 802.16e 2005])—are standards for communicating over shorter and longer distances, respectively. We will touch on WiMAX briefly when we discuss cellular data networks in Section 6.4, and so here, we will focus on networks for shorter distances.

Bluetooth

An IEEE 802.15.1 network operates over a short range, at low power, and at low cost. It is essentially a low-power, short-range, low-rate "cable replacement" technology for interconnecting notebooks, peripheral devices, cellular phones, and smartphones, whereas 802.11 is a higher-power, medium-range, higher-rate "access" technology. For this reason, 802.15.1 networks are sometimes referred to as wireless personal area networks (WPANs). The link and physical layers of 802.15.1 are based on the earlier **Bluetooth** specification for personal area networks [Held 2001, Bisdikian 2001]. 802.15.1 networks operate in the 2.4 GHz unlicensed radio band in a TDM manner, with time slots of 625 microseconds. During each time slot, a sender transmits on one of 79 channels, with the channel changing in a known but pseudo-random manner from slot to slot. This form of channel hopping, known as **frequency-hopping spread spectrum (FHSS),** spreads transmissions in time over the frequency spectrum. 802.15.1 can provide data rates up to 4 Mbps.

802.15.1 networks are ad hoc networks: No network infrastructure (e.g., an access point) is needed to interconnect 802.15.1 devices. Thus, 802.15.1 devices must organize themselves. 802.15.1 devices are first organized into a **piconet** of up to eight active devices, as shown in Figure 6.16. One of these devices is designated as the master, with the remaining devices acting as slaves. The master node truly rules the piconet—its clock determines time in the piconet, it can transmit in each odd-numbered slot, and a slave can transmit only after the master has communicated with it in the previous slot and even then the slave can only transmit to the master. In addition to the slave devices, there can also be up to 255 parked devices in the

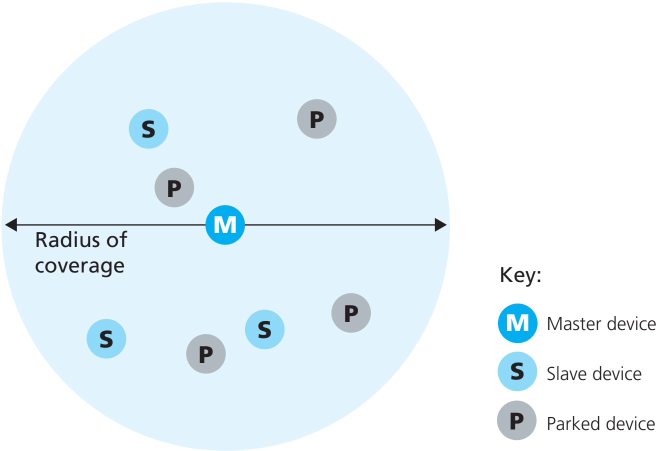

Figure 6.16 ♦ A Bluetooth piconet

network. These devices cannot communicate until their status has been changed from parked to active by the master node.

For more information about 802.15.1 WPANs, the interested reader should consult the Bluetooth references [Held 2001, Bisdikian 2001] or the official IEEE 802.15 Web site [IEEE 802.15 2012].

Zigbee

A second personal area network standardized by the IEEE is the 802.14.5 standard [IEEE 802.15 2012] known as Zigbee. While Bluetooth networks provide a "cable replacement" data rate of over a Megabit per second, Zigbee is targeted at lower-powered, lower-data-rate, lower-duty-cycle applications than Bluetooth. While we may tend to think that "bigger and faster is better," not all network applications need high bandwidth and the consequent higher costs (both economic and power costs). For example, home temperature and light sensors, security devices, and wall-mounted switches are all very simple, low-power, low-duty-cycle, low-cost devices. Zigbee is thus well-suited for these devices. Zigbee defines channel rates of 20, 40, 100, and 250 Kbps, depending on the channel frequency.

Nodes in a Zigbee network come in two flavors. So-called "reduced-function devices" operate as slave devices under the control of a single "full-function device," much as Bluetooth slave devices. A full-function device can operate as a master device as in Bluetooth by controlling multiple slave devices, and multiple full-function devices can additionally be configured into a mesh network in which full-function devices route frames amongst themselves. Zigbee shares

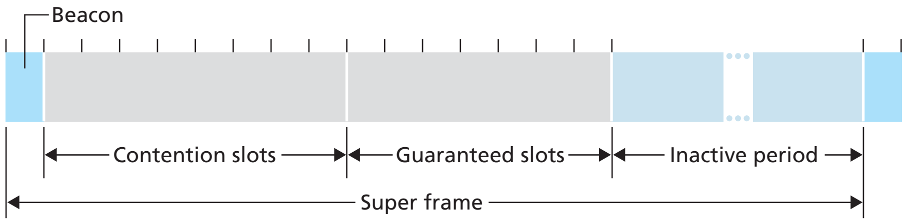

Figure 6.17 ♦ Zigbee 802.14.4 super-frame structure

many protocol mechanisms that we've already encountered in other link-layer protocols: beacon frames and link-layer acknowledgments (similar to 802.11), carrier-sense random access protocols with binary exponential backoff (similar to 802.11 and Ethernet), and fixed, guaranteed allocation of time slots (similar to DOCSIS).

Zigbee networks can be configured in many different ways. Let's consider the simple case of a single full-function device controlling multiple reduced-function devices in a time-slotted manner using beacon frames. Figure 6.17 shows the case where the Zigbee network divides time into recurring super frames, each of which begins with a beacon frame. Each beacon frame divides the super frame into an active period (during which devices may transmit) and an inactive period (during which all devices, including the controller, can sleep and thus conserve power). The active period consists of 16 time slots, some of which are used by devices in a CSMA/CA random access manner, and some of which are allocated by the controller to specific devices, thus providing guaranteed channel access for those devices. More details about Zigbee networks can be found at [Baronti 2007, IEEE 802.15.4 2012].

6.4 Cellular Internet Access

In the previous section we examined how an Internet host can access the Internet when inside a WiFi hotspot—that is, when it is within the vicinity of an 802.11 access point. But most WiFi hotspots have a small coverage area of between 10 and 100 meters in diameter. What do we do then when we have a desperate need for wireless Internet access and we cannot access a WiFi hotspot?

Given that cellular telephony is now ubiquitous in many areas throughout the world, a natural strategy is to extend cellular networks so that they support not only voice telephony but wireless Internet access as well. Ideally, this Internet access would be at a reasonably high speed and would provide for seamless