2

Physical Layer

r The first layer in the OSI reference model is the physical layer, as shown in Fig. 2.1. The physical layer specifies the communication media, the type of energy used for communication, and the mapping of information bits to energy. A transmitter can send a signal through a variety of physical media, including wires, air, and water. Several communication technologies that use different energy types for encoding information also exist, such as radio frequency waves, microwave, infrared, ultra wide band radio, and acoustics. In this chapter, we briefly explore the communication media and technology possibilities for ad hoc and sensor networks.

The chapter is structured as follows. Section 2.1 surveys the types of communication media. Section 2.2 discusses the communication technology alternative for ad hoc and sensor networks.
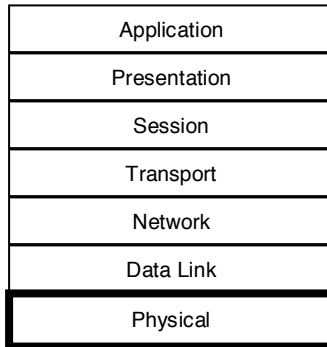
Application
Presentation
Session
Transport
Network
Data Link
Physical

Fig. 2.1. The physical layer in the OSI reference model

2.1 Communication Media

The communication medium specifies the physical channel over which signals are transmitted. Communication media fall into 2 broad categories: wired communications and wireless communications. The remainder of this section explores each category in more detail.

2.1.1 Wired Communication

Wired communications involve signal transmission over a wire or cable. Transmitting signals over wires provides a high degree of control over the signal path, so the quality of signals in wired communications is more stable and relatively higher than the signal quality of comparable wireless communications.

A common type of wire used for both telephone communication and wired local area networks is the copper twisted pair. Twisted pair cables consist of two conducting wires wound around each other in order to reduce electromagnetic interference, referred to as crosstalk, and a plastic enclosure. There are several categories of twisted pair cables that provide different degrees of signal quality depending on the number of twists per meter and the shielding type. For example, category 3 twisted pair cables typically support lower bit rate voice communication on telephone networks, in the range of Kbits per second. Category 5 cables support higher speed data transfer for local area networks, up to 100 Mbits per second. Shielded versions of category 5 and the higher grade category 6 cables can support even higher bit transfer rates, making them suitable for Gigabit ethernet networks.

Another type of wire that also supports local area networks is the coaxial cable, which is used as a transmission line to carry a high-frequency or broadband signal. Coaxial cables consist of a round conducting wire, surrounded by an insulating spacer, surrounded by a cylindrical conducting sheath, usually surrounded by a final insulating layer. The magnetic field created between the conducting sheath and conducting wire is used for transmitting broadband signals, including cable television signals. Coaxial cable is attractive for its relative immunity to outside interference sources, yielding a high signal quality.

The final type of wired communication media we consider is the fibre optic cable. These cables promise extremely high bit transfer rates because of the huge available bandwidth. Fiber optic cables typically serve as long haul communication lines for transcontinental communications as well as shorter range high speed communications.

Wired communication media can serve certain applications of ad hoc and sensor networks. For example, a set of laptops can use category 5 cables to autonomously form an ad hoc network. Similarly, a network of sensors connected by wires on the ceiling of a factory can keep track of merchandize movements. However, wired communication media are not generally suitable

for ad hoc and sensor networks. Despite the higher degree of control and the higher signal quality for wired communications, this communication medium lacks the flexibility required by mobile and transient applications that characterize ad hoc and sensor networks. In many cases, the mere reliance on wired communications implies the need for installation and deployment of some form of infrastructure, violating the basic premise of ad hoc and sensor networks. Furthermore, the use of wires severely limits the mobility of a system by the length of wires. Finally, many ad hoc and sensor network applications require deployment in situations where wire installation is not practical, such as disaster relief or environmental monitoring.

The above discussion has shown that wired communications could be useful for particular ad hoc and sensor applications, but it is not suitable for the general application space of these networks. The next section focuses on wireless communications, which overcome many of the drawbacks of wired communications for ad hoc and sensor networks.

2.1.2 Wireless Communication

Wireless communications rely on signal transmission over a medium without the presence of wires or cables between the sender and receiver. Possible communication media for wireless communication include air, water, or vacuum. Wireless communications can support a high degree of mobility and deployment flexibility, so they are the main communication medium of choice for ad hoc and sensor networks.

The attractive feature of wireless communications, the absence of wires, also presents drawbacks. The absence of a physical wire connecting the sender and receiver render the transmitted signal much more vulnerable to interferences and background noise while traversing the wireless medium. As a result, the expected signal quality of a wireless communication link is relatively lower, less stable, and less predictable than a comparable wired link. The higher vulnerability to interferences requires higher quality margins and smarter control of wireless links to maintain communication. Wireless communications are also inherently less secure than wired communications. An eavesdropper simply needs to capture the wireless signal through an available receiver, whereas listening in to wired communications requires physically tapping into the communication line. The use of wireless communications also complicates higher layer network functionality, such as the hidden terminal problem at the MAC layer, which is discussed further in Ch. 3. Wireless communications require more sophisticated and adaptive mechanisms at several layers of the network stack.

The flexibility, practicality, and support for mobility of wireless communications overweigh the drawbacks discussed above. The wide scope of potential applications for wireless communications, especially in the context of ad hoc and sensor networks, warrants the added development and operating cost for advanced network management mechanisms.

This section has covered the potential communication media for ad hoc and sensor networks. The next section explores the communication technologies that utilize the medium.

2.2 Communication Technologies

A system's communication technology specifies the energy type for encoding information bits, as well as the methods for encoding information bits into energy and decoding them. Examples of communication technologies include radio frequency, infrared, microwave, laser, ultra wide band radio, and acoustics. The adoption of different communication technologies stems from the diverse needs of communication applications. For example, microwave and infrared technologies provide point-to-point links between a sender and receiver, yielding better communication efficiency and signal quality. However, ad hoc and sensor network applications may benefit more from broadcast communication technologies, such as radio frequency and ultra wide band radio. In this section, we survey the potential communication technologies and their suitability for ad hoc and sensor networks. Section 2.2.1 discusses the technologies that typically use point-to-point communication, while Section 2.2.2 focuses on broadcast communication technologies.

2.2.1 Point-to-Point Communication Technologies

Point-to-point communication technologies have their roots in many wired communication applications, such as telephone networks or long-distance data transmission lines. The main purpose of point-to-point communication technologies is to establish a one-to-one communication link between a sender and the intended receiver. Achieving this property through wires is relatively simple, since wires can physically guide the signal along its designated path.

Point-to-point communication through wireless technologies is a more challenging task. The wireless medium is inherently a broadcast medium in which the signal of a wireless transmitter spreads in all outbound directions. Due to the inherent broadcast nature of many wireless communication technologies, directional antennas are used to guide the transmitter's signal energy towards the receiver. Directional antennas provide a higher signal quality at the receiver by channeling most of the energy in the direction of the receiver. The drawback of directional antennas is the higher cost and hardware complexity. Even with the use of directional antennas, most wireless point-to-point communication technologies also require an unobstructed line-of-sight (LOS) between the sender and receiver.

Network applications have used certain communication technologies, such as infrared and microwave signals, for point-to-point wireless communications. Infrared technology encodes information through signals with a wavelength between 750nm and 1mm, the so-called infrared spectrum. For example, many

laptops are equipped with built-in infrared ports for interfacing with cell phones and other laptops. When a laptop comes into the vicinity of another device equipped with infrared communication capability, the two devices can establish a communication link. The infrared port of the two devices must be closely aligned without any physical obstacles between them to ensure a LOS. Another common example of one-way infrared wireless communications is television remote controls. The disadvantage of using infrared technology for ad hoc and sensor networks, in addition to the LOS requirement, is its susceptibility to interference from light sources, such as neon lights or sunlight. Furthermore, available infrared transceivers have limited communication ranges within the order of tens of meters, which constrains network range.

Microwave technology uses high frequency radio signals, with wavelengths ranging between 1mm to 30cm. Microwave technology can be either a point-to-point or a broadcast technology. A common application of point-to-point microwave technology is the provision of television signals to subscribers through small dishes for signal transmission and reception. Point-to-point microwave applications are highly directive, requiring a careful alignment and maintenance of orientation between the sender and receiver. In urban areas, microwave transceivers are generally installed on roofs in order to ensure a LOS from an antenna tower, because an obstruction in the LOS severely affects the communication.

In general, point-to-point wireless communication technologies require precise positioning and orientation of the transceiver to maintain acceptable communication links. This property renders point-to-point technologies suitable for a small and specific subset of ad hoc and sensor network applications, namely scenarios with limited mobility and highly predictable topologies. The next section discusses the class of communication technologies that is more suitable for ad hoc and sensor networks: broadcast technologies.

2.2.2 Broadcast Communication Technologies

Broadcast communication technologies support the concurrent reception of a transmitted signal by multiple receivers. In contrast to point-to-point technologies that require careful positioning and alignment of the transceivers, broadcast communications can use lower complexity omnidirectional antennas that require much less maintenance, so they provide better support for ad hoc deployments and mobile networks. The above properties of broadcast technologies have made them the top choice for ad hoc and sensor networks.

A related technology is satellite communications through which a network of artificial satellites orbiting the earth relays earth-based signals. Satellite communications currently support telephone, television, radio, scientific, and military applications. Satellites inherently represent infrastructure networks, since satellite deployment involves extensive planning and high deployment cost for putting the nodes into orbit. In the context of ad hoc and sensor networks, satellites can serve as the supporting infrastructure for the network.

For example, many ad hoc and sensor network design approaches consider that each network node possesses location information through the satellite-based Global Positioning System (GPS) [4].

One of the more established broadcast communication technologies is through radio frequency (RF) waves. Sending radio frequency waves entails feeding alternative current to an antenna to produce electromagnetic waves. The RF spectrum includes frequencies from a few hertz to several hundred gigahertz. Applications that use RF technology include radio, television, cellular telephones, and radar. A large portion of the current standards that are applicable for wireless networks, and especially ad hoc and sensor networks, uses RF waves. The popular IEEE 802.11 standard [5], which supports both centralized and ad hoc modes for wireless local area networks, relies on RF waves in both the 2.4 Ghz and the 5 Ghz bands. Similarly, the recent Bluetooth standard [6] for wireless personal area networks (WPAN) also uses RF waves in the 2.4 Ghz band.

Many sensor network manufacturers have also adopted RF communication technology. For example, the widely used Crossbow mica motes [7] have adopted RF communication in the 400Mhz, 900Mhz, and 2.4Ghz bands. The latter band satisfies the recent Zigbee [8] standard for sensor networks. Radio frequency identification (RFID) [9], an emerging technology for replacing bar codes through tiny radio frequency tags, represents another application for RF communication. Chapter 10 covers a case study of an RF sensor network.

Another emerging RF technology is ultra wide band (UWB) radio, a spread-spectrum technique based on the modulation of short nanosecond low power pulses [10]. This technology has been used for radar applications for over half a century. In recent years, UWB has received increasing recognition for its applicability to short range communication networks because of desirable features such as high data rates, low power consumption, precise ranging capability, resistance to multipath fading, and penetration of dense objects. All of the above properties make UWB a strong candidate technology for ad hoc and sensor networks. For example, emergency workers using an UWB ad hoc network for earthquake recovery could place nodes equipped with sensors in the rubble to detect signs of living survivors. Because of UWB's ground penetrating capability, the nodes in the rubble can effectively communicate with surface nodes. Chapter 11 presents an example scenario of UWB ad hoc networks.

Acoustic communication is yet another broadcast technology that has recently received increasing attention. Acoustic communication relies on the modulation of acoustic waves with digital data. While acoustics has been the technology of choice for underwater communications for over half a century [11], several projects have demonstrated the usefulness and applicability of acoustics for affordable and easily deployable mobile applications within the area of ubiquitous computing [13–16]. For instance, many mobile devices can exploit on-board speakers and microphones to communicate acoustically. Acoustic waves typically have a short communication range, and they do not

penetrate walls, which adds security to the communication. On the downside, the supportable information transfer rate of acoustics is limited by the narrow acoustic bandwidth. Chapter 12 provides an example of how ad hoc and sensor networks can exploit the low bit rate and short communication range capabilities of acoustic communications to form multihop networks.

Broadcast communication has commonly been associated with wireless media, but there are also networks that employ broadcast communications over wired media. For example, Ethernet networks that work over category 5 cables broadcast signals over wires and through hubs. The broadcast nature of Ethernet necessitates mechanisms at higher layers to avoid collisions.

2.3 Physical Layer Optimization Parameters

This section identifies the relevant parameters at the physical layer, which can be incorporated into cross-layer design strategies.

2.3.1 Transmission Power

In wireless communications, the transmitter emits signals at a certain power level, which is referred to as the transmission power. The signal loses energy as it propagates from sender to receiver. The so-called signal path loss varies proportionally with d^α, where d is the distance between sender and receiver, and α is the path loss coefficient ranging between 2 and 4. The transmission power must be high enough to achieve an acceptable signal quality at the receiver. However, the transmission power is also upper bounded by regulatory limits and by interference considerations at neighboring transceivers. Transmitters must use a power level within these constraints i.e. a power level that is both sufficient to communicate effectively with the receiver and that adheres to regulatory emission limits. Because the medium conditions in ad hoc and sensor networks are highly dynamic, nodes should ideally adapt their transmission power continuously to the current conditions. Cross-layer design can enable interaction between the physical layer and higher layers for better transmission power adaptation.

2.3.2 Processing Power

Many of the traditional network protocols do not consider processing power in determining network behavior. However, processing power can play a significant role for ad hoc and sensor network protocols. Most ad hoc networks employ a multihop communication strategy with a short distance per link. For networks with short range wireless links, the processing power becomes non-negligible relative to the transmission power. While it is difficult to enforce strict processing power control at run-time, consideration of processing

power in determining network behavior can improve performance. For example, some sensor networks support in-network processing. A load balancing strategy for these sensor networks must consider processing power at each node to determine how to distribute the network load evenly. Because load balancing typically occurs at higher layers, a cross-layer design strategy is required to expose the processing power information to higher layers.

2.3.3 Sensing Power

In sensor networks, the sampling of physical indicators also consumes power, referred to as the sensing power. As for the case of processing, sensing power becomes appreciable relative to transmission power for shorter wireless links. For instance, consider a seismic monitoring sensor network in which nodes periodically sample their sensors to determine if the seismic activity is above a certain threshold level. If so, then the nodes communicate the sensed data towards the user. Otherwise, the node continues the periodic sampling of their sensors until an event occurs. If a long time passes before the occurrence of a seismic event, the network nodes do not consume power due to transmissions during that time. However, the nodes do consume sensing power for periodic sampling of the sensors.

2.3.4 Signal-to-Noise Ratio

The signal-to-noise ratio (SNR) is a quality indicator for communication links. The SNR provides a figure of merit through the comparison of the received signal strength with noise level at the receiver. Thus, the SNR is proportional to the received power and inversely proportional to the sum of the background noise and interference at the receiver. Stated differently, improving the signal quality at a receiver can be achieved either by increasing the transmission power (which causes an increase in the received power) or by reducing background noise and interference. Typically, wireless applications set minimum requirements for SNR on a network-wide or a per-link basis. In cross-layer design, the individual link SNR can serve as an input to a comprehensive optimization of node behavior that satisfies the physical layer quality requirements.

2.3.5 Transmission Rate

The transmission rate indicates the current transfer rate of a communication link. Transmission rates are closely related to the transmission power. Consider an active communication link that satisfies the SNR quality requirements. Increasing the link's rate while maintaining the SNR unchanged requires an increase in the transmission power. Network mechanisms can exploit this relationship to trade off lower rates for a reduced transmission power for rate-elastic traffic. Similarly, nodes can achieve higher transmission rates through an increase in transmission power.

2.3.6 Modulation Code and Rate

Modulation is the process of varying a carrier signal in order to use that signal to convey information. Three basic features of the signal can be varied to carry information: amplitude, frequency, or phase. In addition, modulation techniques can use a combination of these features. For example, Pulse Position Modulation (PPM) is a common modulation technique for time-hopping UWB networks. UWB relies on the regular transmission of nanosecond signals, called monocycles. To encode information, PPM shifts monocycles in time. For example, sending the monocycle 1 ns earlier indicates a zero bit, and delaying the monocycle by 1 ns indicates a one bit. M-ary PPM can also encode several bits per monocycle, by defining 2^M shift positions of the monocycle. The number of bits encoded in each PPM symbol is referred to as the modulation rate. Increasing the modulation rate yields increases in the transmission rate, but it also lowers the signal quality since it makes it more difficult for the receiver to decode the signal.

Adaptive cross-layer mechanisms can vary the modulation rate according to dynamic medium conditions. For example, if a node observes a rise in the interference level, it can lower its modulation in order to ensure that the receiver can still decode the signal.

A common feature of spread-spectrum technologies, such as UWB or Code Division Multiple Access (CDMA) [17], is the use of codes to provide signal robustness and security. Spread-spectrum technologies enable concurrent transmission through the use of codes that are orthogonal or quasi-orthogonal. In a network with ongoing links, selecting an appropriate code for a new link can maximize the rate for the new link and minimize the impact on the perceived interference of neighboring nodes.