CHAPTER 2

Background

In this chapter we introduce the technologies that support short-range wireless communications. We classify the proposed technologies using two criteria. First, we distinguish point-to-point connections utilized to form Wireless Personal Area Networks from multipoint connections used to form Wireless LANs. Second, we classify technologies according to the medium they utilize, radio or infrared optical.

Wireless Personal Area Networks (PANs) allow mobile devices to function together in ad hoc networks within a personal space [62]. Wireless PANs aim to replace wired connectivity between devices such as still and video cameras, laptops and MP3 players. Wireless LANs (WLANs) provide computer connectivity in a small area such as an office complex, a building or a hallway by extending or replacing a wired LAN. The main attraction in wireless LANs is the flexibility and mobility; bandwidth considerations are of secondary importance [88]. Portable terminals forming the WLAN should have access to all services provided for wired terminals. Unlike wired stations, portable terminals suffer from severe limitations in size, weight and power consumption. In addition, WLAN design addresses the special properties of the wireless medium.

Bluetooth [32] and IrDA 1.x [101] protocol stacks support indoor point to point links utilizing the radio and infrared spectrum respectively. HomeRF [70] and HiperLAN [55] support multipoint WLAN connectivity using radio. IEEE 802.11 standard supports multipoint connectivity and offers several choices of physical medium such as spread spectrum radio and infrared [26]. IrDA AIr protocol proposal utilizes the infrared spectrum to implement wireless LANs [73].

The outline of this chapter is as follows. Section 2.1 describes wireless indoor connectivity and section 2.2 presents current standards for wireless PANs and LANs focusing on transmission techniques and medium access procedures. Section 2.3 compares radio and infrared transmission media for indoor wireless connectivity and section 2.4 categorizes indoor infrared communication systems. Infrared radiation exhibits special characteristics when utilized for indoor connectivity. The link layer design challenges arising from these characteristics are discussed in section 2.5. Section

2.6 presents the advantages and disadvantages of computer simulation and mathematical modeling techniques that evaluate the performance of communication systems and section 2.7 presents the performance measures used to evaluate the system performance. Finally, section 2.8 reviews current research related to infrared link layer design challenges.

2.1 Wireless indoor communications

Indoor connectivity is required in the home and office environment to carry telephone conversations, music, television, video (MPEG1, MPEG2 and MPEG4), pictures (JPEG), signals from surveillance cameras and alarm sensors, commands for controlling appliances and multimedia information from the Internet [27]. Portable computers, such as laptops, palmtops and PDAs, also require connections for Internet access, printing and information exchange. Although wired connections can be employed to provide the required information transfer, their use in many cases is impractical or undesirable. For example, it is impractical to install a new wiring system to connect two computers in different rooms at home. Wireless connections provide an attractive alternative, especially when a mobile device is involved and when a low bandwidth is required. At present, the applications utilizing short-range indoor wireless connections fall into two main areas [27]:

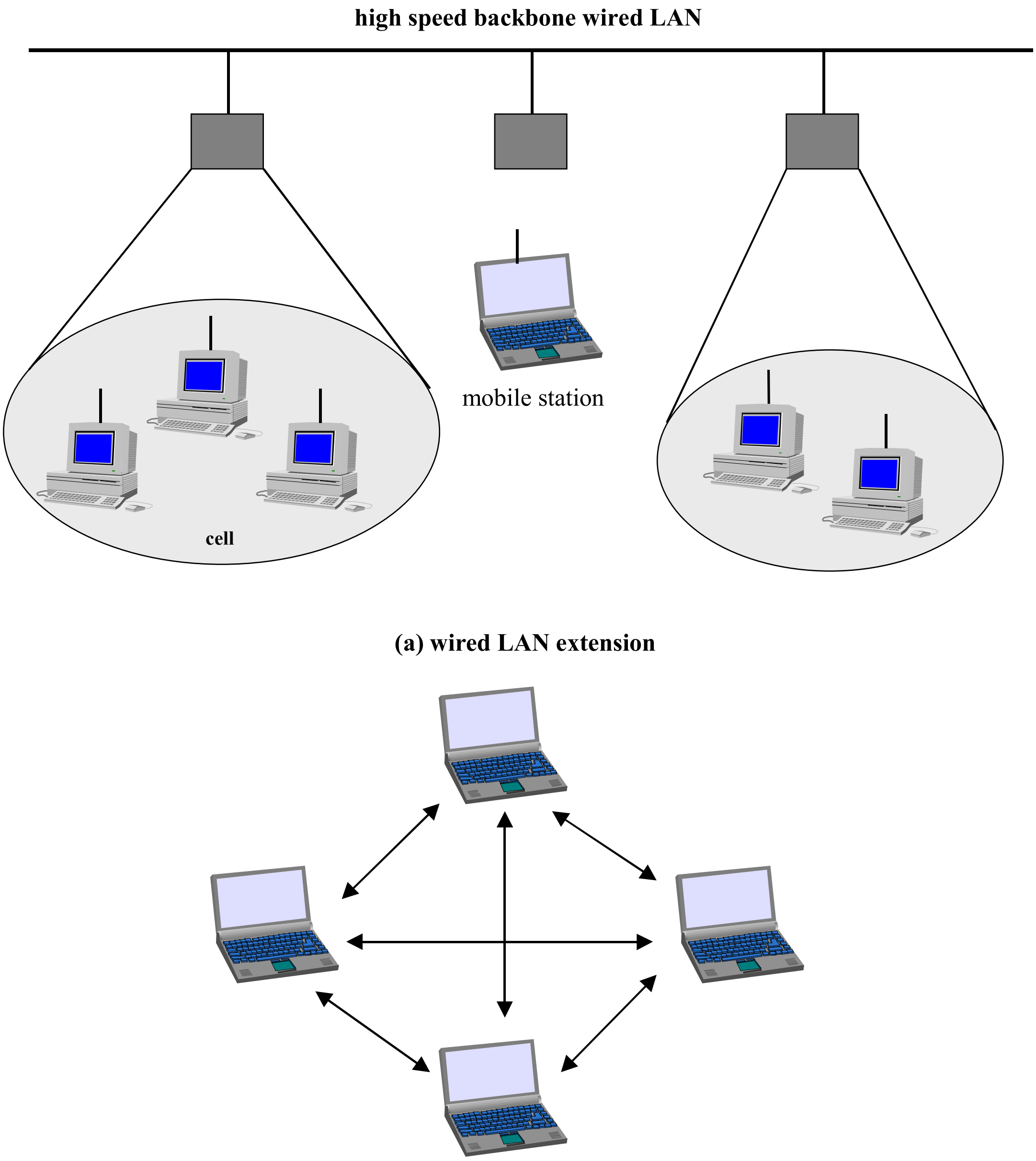
- Controlling items, such as climate control systems, electric appliances (television, video, etc.), lights and surveillance cameras
- Connecting PCs and peripherals for information exchange and entertainment.

Figure 2.1 WPAN applications

This work considers the information exchange between two or more PCs and/or peripherals. Depending on user applications, two categories are defined for wireless information exchange:

a) **Wireless PANs.** A wireless PAN (WPAN) (Fig. 2.1) enables short-range ad hoc connectivity among portable consumer electronics and communications devices, such as laptops, PDAs, MP3 players, still and video cameras, modems, printers, mobile phones and TVs [59]. Wireless PAN technology aims to replace cables between these devices and to provide fast and reliable information transfer abilities to the single user. WPAN technology is often utilized for point-to-point information transfer and implements master/slave communication techniques.

b) **Wireless LANs.** A wireless LAN (WLAN) aims to offer wireless stations the same capabilities that wired LANs provide to stationary stations. WLANs are not widely used due to high prices, low data rates, security issues and license requirements. These drawbacks have been recently addressed and a rapid wireless LAN deployment is expected [86]. Wireless LAN connectivity can be categorized as follows:



(b) Ad hoc wireless LAN

Figure 2.2 Wireless LAN configurations

- LAN extension and nomadic access

  A wireless LAN extension of an existing high-speed backbone wired LAN, (Fig. 2.2a), saves the cost of installing wires and eases the relocation of stationary computers [85]. It also provides easy network access to mobile computers. This scheme is suitable for buildings where wiring is difficult or prohibited (e.g. manufacturing plants, stock exchanges, trading floors and historical buildings). It is also suitable for businesses operating in many buildings and having a large number of employees with laptop computers.

- Ad hoc LAN

  An ad hoc network is a peer-to-peer network with no centralized server (Fig. 2.2b). A wireless ad hoc LANs is suitable for serving an immediate need (e.g. laptop users attending conference meetings or classrooms) and where wiring is impractical (connect two or three computers at home).

Wireless PANs and LANs are divided into two categories according to the transmission technique they implement:

a) **Radio.** Radio transmissions are regulated worldwide and require government licensing. However, the Industrial / Scientific / Medical (ISM) radio bands are an exception to the licensing rule. United States and Canada allocate ISM bands at 902-928 MHz, 2,400–2,484 MHz and 5,725-5,850 MHz [87][2]. They are called the 900 MHz, the 2.4 GHz and the 5 GHz ISM bands respectively. The 2.4 GHz ISM band is allocated worldwide but some countries allocate slightly different 900 MHz and 5 GHz ISM bands [80]. The higher frequency ISM bands require more expensive electronics, are subject to higher interference from microwave ovens and radar installations but can achieve higher data rates. To avoid licensing, wireless radio PANs and LANs utilize the ISM bands.

b) **Infrared (IR).** Infrared waves are suitable for short-range indoor communications. Remote controls for TVs, videos and stereos utilize infrared connections. Infrared components are cheap, easy to build and the infrared radiation is confined to the room of operation. As a result, no licensing is required. However, infrared connections may require a line of sight (LOS) path between the transmitter and the receiver. In fact, as we go from radio to light frequencies, transmissions behave more like rays and less like waves. The infrared spectrum offers virtually unlimited bandwidth capable of accommodating high data rates [57].

2.2 Wireless PAN and LAN standards

The great range of applications requiring wireless information transfers has led to the development of many standards. Devices for wireless PANs and LANs follow specifications developed by independent standard bodies or industry consortia. This section briefly describes current standards for wireless PANs and LANs focusing on physical layer and medium access issues. Table 2.1 gives an overview of the attributes

	applica-tion	Peak data rate (Mbit/s)	cost	range	frequency	modulation	data network support	organization
IrDA 1.x	WPAN	16	Low	<2m LOS	infrared	RZI/ 4PPM/ HHH(1,13)	via PPP	IrDA
Bluetooth	WPAN	1	Medium	10-100m	2.4 GHz	FHSS	via PPP	Bluetooth Special Interest Group
HiperLAN	WLAN	24	High	>30m	5 GHz	OFDM	TCP/IP	ETSI
802.11	WLAN	2	Medium/high	>50m	2.4 GHz/ infrared	FHSS/ DSSS/ 4PPM	TCP/IP	IEEE
802.11a	WLAN	54	High	100m	5 GHz	OFDM	TCP/IP	IEEE
802.11b	WLAN	11	Medium/high	100m	2.4 GHz	DSSS	TCP/IP	IEEE
HomeRF	WLAN	1.6	Medium	50m	2.4 GHz	FHSS	TCP/IP	Home Radio Frequency WG
IrDA AIr	WLAN	4	Medium	<10 LOS	infrared	4PPM	via PPP	IrDA

Table 2.1 WPAN and WLAN technologies

of the proposed technologies. Comparisons should be made bearing in mind that these technologies are more complementary than competitive [2][70].

2.2.1 Wireless PANs

2.2.1.1 IrDA 1.x

IrDA 1.x protocol specification was developed by IBM, Hewlett-Packard and Sharp for short-range, low-cost, half duplex, point-to-point links utilizing the IR spectrum. IrDA 1.x links aim to replace cables between devices such as laptop computers, personal digital assistants (PDAs), digital still and video cameras, mobile phones and printers. Computer manufacturers have widely adopted the IrDA 1.x standard [16] and popular operating systems fully support the IrDA 1.x specification [106]. Almost every portable computer and all Windows CE devices on market today contain an IrDA 1.x infrared port. More than 40 million devices are shipped every year equipped with IrDA 1.x ports and IrDA 1.x technology achieved a widespread deployment in a wide range of devices in a short time [101].

IrDA 1.x supports data rates up to 115,200 bit/s using the standard UART serial hardware and data rates up to 4Mbit/s and 16 Mbit/s using the high speed extension [52]. It utilizes narrow angle IR ports with a viewing of axis angle of between 15 and 30 degrees [67]. The IrDA 1.x link distance is at least 1m. The specified narrow angle and short range allow the operation of multiple independent links in the same room at the same time. IrDA 1.x implements master/slave communication techniques. Any station can claim the master role at the negotiation phase but only one is assigned the master role when the link is established. The remaining (one or more) stations are slaves. The master station coordinates all transmissions and all data flows through the master station; only transmissions between the master and a slave station are permitted.

2.2.1.2 Bluetooth

Bluetooth was originally developed by Ericsson as a cable replacement for laptop to mobile phone connections for Internet access. The Bluetooth Special Interest Group (BSIG) [104] is an industry consortium formed by leading computer and mobile phone manufacturers to develop a standard for wireless connectivity for devices such as cordless and mobile phones, modems, headsets, PDAs, computers, printers, keyboards, MP3 players and projectors. BSIG published Bluetooth ver. 1.0 specification in 1999. Bluetooth is royalty-free and offers a low-cost, low-power, radio based cable replacement [32][33]. It also provides error correction, power management, security, and implements a Code Division Multiple Access (CDMA) transmission scheme.

Bluetooth utilizes the 2.4 GHz ISM radio band to achieve a data rate of 1 Mb/s at a range of 10 or 100 meters, depending on the power of the radio transceiver being used [81]. Devices in range form small networks called piconets. A station in the piconet is assigned the master role. The master implements centralized control; only transmissions between the master and one or more slaves is allowed [32]. A slave can only communicate with the master and only with the granted permission of the master. A piconet can contain up to eight devices (one master and up to seven slaves). Any station can be assigned the master role and master and slave roles are assigned for the piconet time duration. Bluetooth device discovery is a slow procedure but can be accelerated by techniques used in the IrDA specifications [103].

Bluetooth utilizes Frequency Hopping (FH) with carrier spacing of 1MHz. Typically, up to 80 different carrier frequencies can be used in the 2.4 GHz ISM bandwidth of 80 MHz. Devices in a piconet change frequency after every transmission following a well known hopping sequence to minimize radio interference. The master of a piconet provides the piconet identity, the hop sequence and the system clock that coordinates all piconet transmissions.

Many piconets can co-exist in the same area. If it wishes, a device participating in a piconet can also join another piconet that covers its geographical position. This form of overlapping is called scatternet [86]. Piconets in the same space implement different hop sequences. The signal in a piconet is spread over the 80 MHz frequency range but instantaneously only a bandwidth of 1 MHz is occupied. As a result, the 80 MHz bandwidth can support up to 80 simultaneous 1 MHz transmissions, each with a data rate of 1 Mb/s. However, collisions occur when devices in different piconets use the same hop frequency at the same time resulting in performance degradation.

2.2.2 Wireless LANs

2.2.2.1 HomeRF

The Home Radio Frequency Working Group (HRFWG) was launched in 1998 by leading computer companies (most in North America) to develop and promote wireless standards for voice and data communication around the home using radio. The key goal of the group is to enable interoperable wireless voice and data networking around the home at an affordable price. HRFWG proposed the HomeRF standard [105] for connecting PCs, peripherals, cordless phones and other consumer electronic devices using Frequency Hopping Spread Spectrum (FHSS) techniques in the 2.4 GHz ISM band [70][27]. The HomeRF data rate is 1.6 Mb/s and the distance range is 45 meters. HomeRF supports up to 127 data connections (PCs and peripherals) and four high quality voice connections (cordless telephones) [81].

HomeRF MAC layer utilizes contention-free periods and a Time Division Multiple Access (TDMA) scheme for the delay sensitive voice data from cordless phones. It also utilizes contention periods and a CSMA/CA scheme for the delay insensitive data connections [70]. The CSMA/CA scheme is derived from the IEEE 802.11 protocol. HomeRF also provides simultaneous voice and data calls, data security, and power management for both voice and data connections.

2.2.2.2 HiperLAN

The European Telecommunication Standards Institute (ETSI) proposed the High Performance Radio LAN (HiperLAN) protocol. HiperLAN considers a wireless extension of a wired network where Mobile Terminals (MTs), such as laptops and

PDAs, establish wireless connections to Access Points (APs) of a wired network. HiperLAN utilizes the 5 GHz ISM band [81], which provides larger frequency bandwidth than the 2.4 GHz band. By employing an efficient power amplifier and the larger frequency range, a data rate of 24 Mb/s is offered. HiperLAN provides connection-oriented information exchange, power save, quality of service (QoS) support, automatic frequency allocation, security, mobility support and easy integration with a variety of wired networks.

HiperLAN physical layer utilizes Orthogonal Frequency Division Multiplexing (OFDM), which is a special form of multicarrier modulation. OFDM divides data into several interleaved parallel bit steams and every stream modulates a separate sub-carrier. HiperLAN physical layer supports seven data rates ranging from 3 Mb/s to 25 Mb/s and several modulation and coding alternatives. HiperLAN also adapts data rate to current radio link quality. HiperLAN MAC layer utilizes a centralized controller at the AP [63]. It controls medium access using time division duplex (TDD) and dynamic time division multiple access (TDMA) techniques [55].

2.2.2.3 IEEE 802.11

IEEE has proposed the 802.11 standard for wireless LANs. IEEE 802.11 standard proposes three different physical layers utilizing:

a) Frequency Hopping Spread-Spectrum (FHSS) modulation in the 2.4 GHz ISM band
b) Direct Sequence Spread-Spectrum (DSSS) modulation in the 2.4 GHz ISM band
c) Infrared (IR) light using non-directed transmissions and both line-of-sight and reflected reception

All three physical layers support a data rate of 2 Mb/s. Both radio physical layers provide a range of up to 100 m indoors and the IR physical layer provides a range of up to 20 m but it is confined to the room of operation [86]. IEEE 802.11 standard considers interference and reliability, security, power saving, human safety and station mobility [26]. It supports access-point oriented and ad hoc networking topologies [65]. IEEE 802.11 MAC layer supports two medium access methods, the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF). In DCF, all stations utilize CSMA/CA schemes for medium access. DCF is used for relatively insensitive to time delay information exchange, such as electronic mail and file transfers and it is suitable for ad hoc networking topologies. PCF is based on polling that is controlled by a point coordinator, which is called the PCF station. The PCF station coordinates medium access and allows only one station to transmit at any time. PCF is suitable for time-bounded services such as voice and video transmissions [26]. As the PCF station is always an access point, the support of time-bounded services is limited to networks with infrastructure [65].

IEEE recently released the 802.11a and 802.11b standards. IEEE 802.11a utilizes the 5 GHz ISM band and achieves a data rate of 54 Mbps using OFDM. IEEE 802.11b is an extension of the 802.11 DSSS scheme and achieves a data rate of 11Mb/s by utilizing the complex Complementary Code Keying (CCK) modulation scheme [69].

2.2.2.4 IrDA AIr

IrDA proposed the Advanced Infrared (AIr) standard for wireless LANs by extending the IrDA 1.x protocol stack and relaxing the range and viewing angle restrictions posed by the IrDA 1.x physical layer [73][54]. AIr ports have a viewing of axis angle of between 60 and 75 degrees to achieve multipoint connectivity with other devices in range. AIr devices take advantage of line of sight (LOS) propagation paths but they can also communicate relying on infrared signal reflections from the ceiling and walls if the LOS path is obstructed. AIr data rate is 4Mbit/s but lower data rates (up to 256Kbit/s) can be utilized if the link quality is low due to high link distance, intense background light and/or non-LOS path. Adaptive data rate aims to reach all AIr stations operating in the same office or room. AIr transmission range is approximately 5m at 4Mbit/s and 10m at 256 Kbit/s for LOS links [40][41].

AIr standard provides dynamic device discovery procedures, priority delivery service for time sensitive data, power management and co-existence with IrDA 1.x devices [44]. AIr utilizes CSMA/CA techniques for medium access and does not assign master and slave roles to communicating stations.

2.3 Infrared versus radio

Infrared radiation has several advantages over radio for short-range wireless communication [8][57][58]. The infrared spectrum is unregulated worldwide and has a virtually unlimited bandwidth. Infrared detectors and emitters are available at low cost. Infrared is close in wavelength to visible light and exhibits similar behavior. Both are directionally reflected from flat surfaces, diffusely reflected by rough surfaces, absorbed by dark objects and do not penetrate opaque barriers and walls. As a result, infrared transmissions are restricted to the room in which they originate and do not interfere with infrared transmissions in neighboring rooms. The signal room confinement simplifies security issues and offers a high aggregate capacity because the same spectrum can be safely reused in different rooms.

It is very difficult to design a low cost and sensitive infrared detector that collects significant signal power. Receiver sensitivity gets more difficult as we go from radio to infrared spectrum. Thus, the widely ASK and FSK modulation techniques used in radio are less attractive for low cost infrared links. A suitable solution is to implement Intensity Modulation (IM), in which the desired waveform is modulated onto the instantaneous power of the optical carrier [57]. The receiver utilizes a Direct Detection (DD) technique, in which the receiver's output current is proportional to the received instantaneous infrared power. The IM/DD modulation technique simplifies infrared port design and prevents multipath fading [57].

However, indoor infrared communication has several drawbacks. The room confinement is the main infrared disadvantage because it restricts communication range. Communication between different rooms requires the installation of infrared access points interconnected via a wired backbone or radio links. Infrared link quality is affected by infrared noise arising from incandescent and fluorescent lighting, sunlight and other infrared devices such as TV remote controls. Infrared links operate at short distances and although higher transmitter power is needed if the link distance is increased, the transmitter power levels must obey the eye safety regulations. In addition, some form of alignment between infrared ports may be required to achieve a high communication quality. This required alignment between the infrared transmitter and receiver may restrict the desired station mobility.

Infrared links can achieve high data rates; high-speed laboratory systems are presented in [56][57][102]. However, to increase infrared data rate above 10 Mbit/s requires more expensive components [35]. Radio communication can achieve high rates but suffers from interference from other radio transmitters. As radio passes through walls, radio links operating in different rooms of the same building must utilize different frequencies from the limited radio spectrum in order to minimize interference.

	Radio	Infrared	Implication for IR
Bandwidth regulated?	Yes	No	License not required Worldwide compatibility
Passes through walls?	Yes	No	Restricted coverage Simplifies security issues Reuse spectrum in different rooms
Multipath fading?	Yes	No	Simple and cheap link design
Dominant noise	Other users	Background light	Limited range
Range	High	Low	
Security	Low	High	
Pocket receiver	Yes	No	
Electrical interference	Yes	No	

Table 2.2 Infrared versus radio

In addition, the same radio spectrum may be utilized from other applications. For example, Bluetooth WPANs and IEEE 802.11 WLANs operate at the same 2.4 GHz ISM band. When a Bluetooth PAN co-exists in the same room with an IEEE 802.11 WLAN, a serious interference problem arises, which is examined in [22][64][82].

Radio and infrared can be considered as complementary transmission media [2][57]. Radio is preferred when long range transmission or transmission through walls is required [85]. Radio is also preferable when user mobility is of prime importance. Infrared is preferred when the aggregate system capacity must be maximized, when simple and low-cost components must be used and when international compatibility is required [8][57].

2.4 IR wireless communication systems

Depending on the application needs, infrared links can be utilized in different configurations and employ narrow-angle or wide-angle transmitters and receivers. Narrow-angle IR ports have a narrow beam transmission pattern and a narrow reception field of view (FOV). Wide-angle IR ports have a broad beam radiation pattern and a wide FOV.

Infrared links are also classified as line-of-sight (LOS) and non-LOS links. In LOS links, there is always an unobstructed line-of-sight path between the communicating devices. Fig. 2.3 shows the basic configuration of a point-to-point narrow angle LOS link. The transmitter consists of a modulation and encoding circuitry, an amplifier and an infrared LED with a beam-shaping lens. The receiver consists of a photo-detector with a collimating lens, an amplifier and a demodulation and decoding circuitry. Fig. 2.4 presents a narrow-angle LOS infrared communication. Non-LOS links rely on

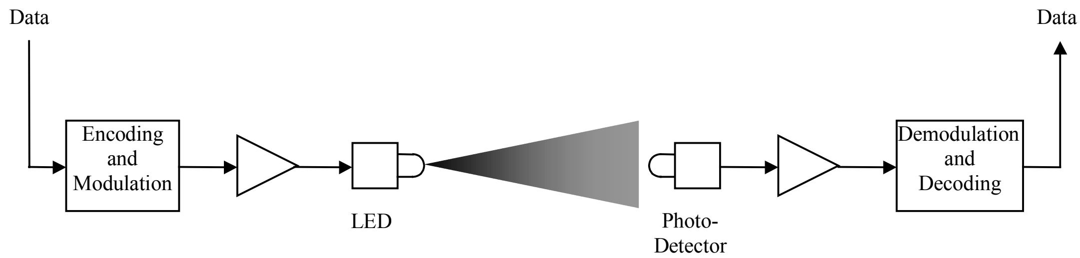


Figure 2.3 Basic line of sight infrared link

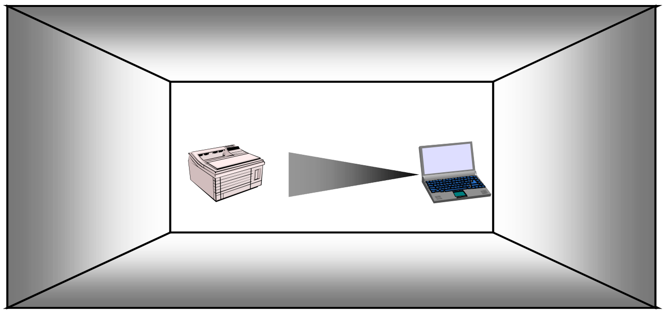


Figure 2.4 Line of sight infrared communication

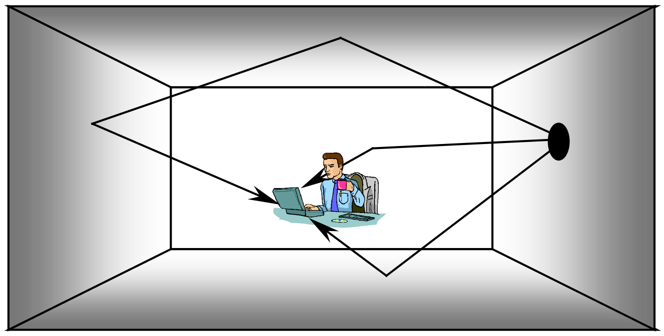


Figure 2.5 Non-line of sight infrared communication

reflections of the infrared radiation from the ceiling or other reflecting surfaces (Fig. 2.5). Non-LOS links are most convenient from the user's perspective, because the user does not have to maintain alignment and a LOS path. As a result, user mobility is increased if a non-LOS link is utilized. LOS links make more efficient use of the optical power and minimize interference because most of the ambient light is rejected by the narrow FOV of the receiver.

The IrDA 1.x standard defines LOS point-to-point infrared links utilizing narrow angle IR ports. The IrDA AIr standard considers LOS and non-LOS multipoint infrared communication employing wide-angle IR ports. Depending on the topology, infrared communications are divided into the following categories:

- **point to point communication** (Fig. 2.6(a)): Two narrow angle infrared devices

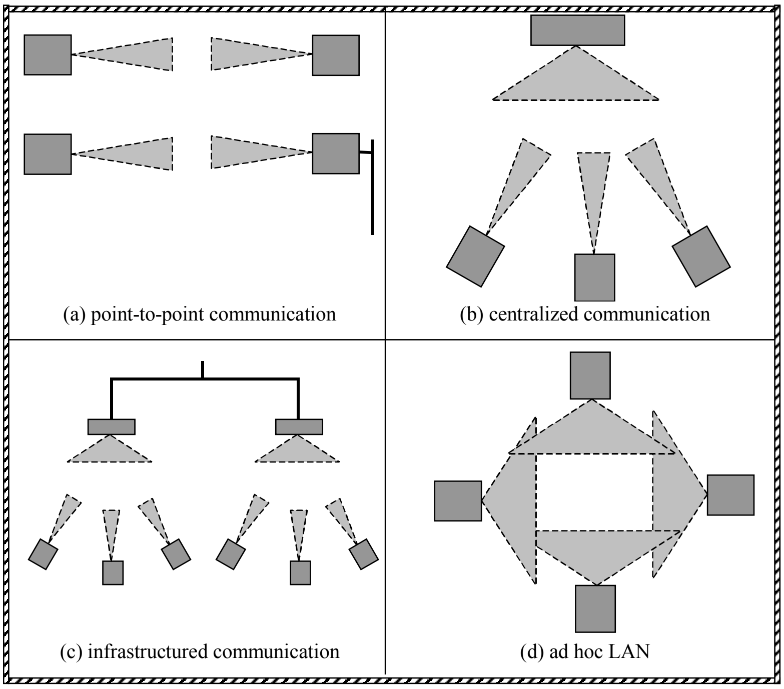


Figure 2.6 Infrared wireless communication systems

exclusively communicate with each other. Typical applications are the information transfer from a portable data-gathering device to a host computer, the printing of pictures from a digital camera and the uploading of music files from a laptop to a portable MP3 player. One of the devices may be fixed and connected to a wired network providing network access to the mobile device.

- **centralised communication** (Fig. 2.6(b)): Multiple narrow angle devices communicate with a wide-angle central node. A laptop computer can be assigned the central node role to form a WPAN. A WLAN is formed if the central node is a hub that echoes the received information to all stations.
- **infrastructured communication** (Fig. 2.6(c)): This is an extension of the centralized communication. In this case, the central hub is connected to a wired backbone providing network access to mobile stations.
- **ad hoc communication** (Fig. 2.6(d)): Multiple wide-angle devices from an ad hoc WLAN. There is no central WLAN coordinator as all stations are allowed to join or leave the network at any time. A typical example is a WLAN formed by laptop computers around a meeting table.

IrDA 1.x connections may be utilized in the first three categories. In the case of centralized and infrastructure IrDA 1.x communications, the central hub must implement a wide-angle instead of a narrow angle IR port. Infrared devices complying with the AIr protocol standard may be utilized for an ad hoc WLAN.

2.5 Challenges in IR link layer design

Many issues in the protocol stack design must be addressed differently if the infrared medium is utilized at the physical layer. Data rate adaptation to channel quality, medium access and retransmission techniques must consider the characteristics of IR transmissions. The IR medium exhibits the following properties:

a) **half duplex operation.** In wireless systems, it is very difficult for a station to receive data when it transmits. The reason is that when a station transmits, a large fraction of the signal leaks into the reception circuit. Usually, the power of the transmitted signal is orders of magnitude higher than the power of the received signal. As a result, the leakage signal has higher power than the received signal, making remote signal detection impossible while transmitting. Half-duplex operation degrades the performance of infrared wireless links.

b) **collision avoidance.** The inability to detect remote transmissions while transmitting results in another implication if many stations compete for medium access; a station can not determine a collision by monitoring channel activity while transmitting, as in Ethernet type protocols. As a result, all stations competing for medium access must implement another collision detection mechanism and employ collision avoidance techniques to minimize the collision probability.

c) **minimum turn around time.** When a station transmits, the leakage signal blinds its own receiver such that it can not receive remote infrared pulses. After the transmission ends, the receiving circuitry needs a minimum Turn Around Time (TAT) to recover. Thus, a transmitting station is able to receive a TAT time period after its transmission ends. As a result, all participating stations must wait a TAT delay after a transmission finishes before initiating a new frame transmission to ensure that all stations (including the station that transmitted the previous frame) will be able to receive the new frame. The TAT delay is high in infrared ports and should be taken into account in the design of medium access and retransmission protocols.

d) **channel errors.** Transmission errors are more likely in wireless IR transmissions. In wired networks, the probability of errors is very small, a small bit error rate (BER)

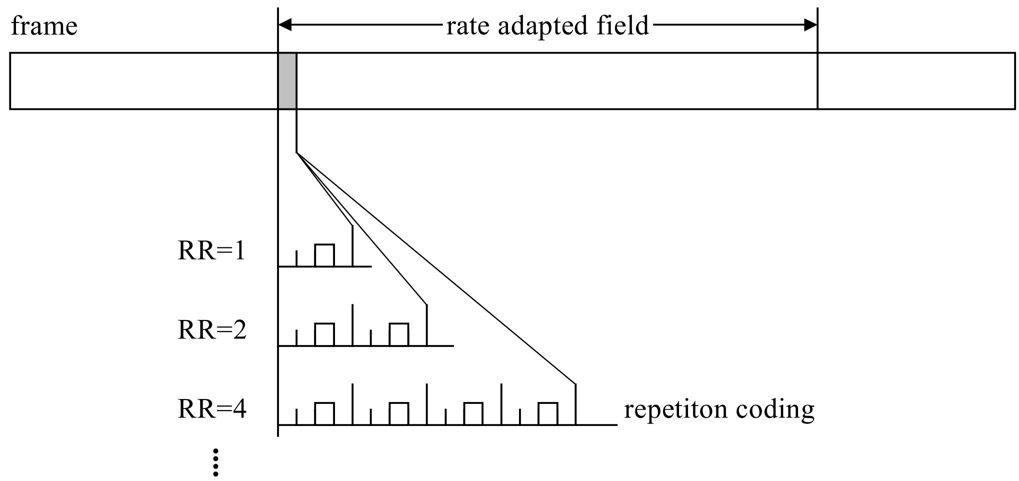


Figure 2.7 RR-coding in 4-PPM transmission

is expected and an immediate frame acknowledgment is meaningless. In contrast, IR wireless channels may have a high BER, resulting in a much higher frame error probability. To cope with frame errors, IR and radio wireless link layer protocols may utilize an immediate acknowledgement (ACK) frame, which follows every data frame transmission. If the ACK frame is not received, the transmitter reschedules the data frame for retransmission. ACK frames may result in significant overhead, especially when followed by considerable TAT delays, as in IR systems.

In order to minimize the ACK frame overhead, infrared wireless link layer protocols may choose to acknowledge a number of data frames using a single ACK frame. They may also employ smaller frame sizes to decrease the frame error probability [31]. Another alternative is the implementation of Forward Error Correcting (FEC) codes or RR coding. Infrared link layer protocols should be efficiently designed to minimize the total delay of data frame retransmissions, ACK frames, frame overheads, TAT delays and FEC or RR coding.

e) **RR-coding.** A power efficient transmission scheme for infrared links is the *L*-slot Pulse Position Modulation (*L*-PPM). A transmitted symbol consists of *L* slots; a pulse is transmitted in one slot and the remaining *L*-1 slots are empty. To cope with transmission errors in communicating with distant stations with low Signal-to-Noise Ratio (SNR), Repetition Rate (RR) coding may be employed. RR coding advises that every transmitted symbol should be repeated RR times in order to increase the symbol capture probability at the receiver (Fig. 2.7). RR coding utilizes the same symbol rate and virtually improves the SNR by employing redundancy [30]. RR

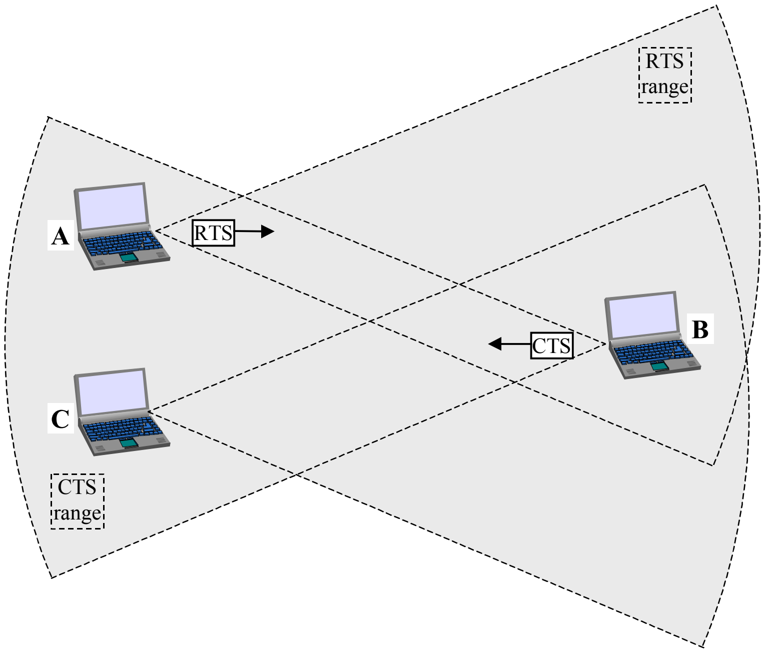


Figure 2.8 The hidden station problem and the RTS/CTS frame exchange

coding results in a better link quality at the expense of a lower link data rate. The receiver may monitor channel quality and advise the transmitter of the suitable RR to be implemented [79][73]. RR coding is a way of adapting the link rate to channel conditions.

RR-coding may be employed on a data frame if the intended receiver has a low SNR. It may also be employed only on the portion of the data frame that contains essential MAC information to ensure that all stations in range will receive this information of the data frame. RR-coding may also be utilized in control frames, such as the RTS and CTS frames. In this way, the reservation information reaches a larger area and the hidden station problem (which is explained next) is minimized.

f) **location dependent carrier sensing (hidden stations).** Infrared signal strength decays with link distance increase. Stations far away from the transmitter may not be able to detect the presence of an infrared transmission. In addition, infrared transmissions are directed; only stations in the reception cone may be able to detect an on-going infrared transmission if adequate reflecting surfaces are not present. The location dependent reception status of an infrared transmission results in the hidden station problem. A hidden station is one that is within the range of the receiver but out of range of the transmitter [34][31][61]. Let's consider the scenario shown in Fig. 2.8. Station A transmits to station B and station C can not hear the on-going transmission because it is out of the reception range of station A. If station C wishes to transmit to station B, it falsely thinks that the channel is idle, it initiates transmission and interferes with the transmission from A to B. In this case, station C is a hidden station to station A.

To minimize collisions from hidden stations, the Request To Send / Clear To Send (RTS/CTS) frame exchange was proposed in the Multiple Access with Collision Avoidance (MACA) protocol [60]. According to MACA, the transmitter first reserves the medium using an RTS frame. The RTS frame contains the reservation time period in a special field. The receiver responds with a CTS frame that echoes the reservation period. Upon receiving the CTS frame, the transmitter proceeds with the data frame transmission. Thus, stations hearing only the RTS or the CTS frame are aware of the medium busy condition and remain silent for the entire data transmission period even if they are not able to hear the data frame [60]. Using the RTS/CTS frame exchange, hidden stations do not result in data frame collisions; collisions can occur only on the short RTS frames if two (or more) stations try to reserve the medium at the same time.

An extension to MACA, MACAW [11], proposed that the reservation time should be extended to include the link layer ACK frame that copes with transmission errors, as discussed in case (d). IEEE 802.11 protocol utilizes the RTS-CTS-DATA-ACK frame exchange and a Stop-and-Wait ARQ scheme.

AIr protocol addresses the hidden station problem by using variable RR coding and the RTS/CTS control frame exchange. Both RTS and CTS frames are transmitted using the maximum Repetition Rate to increase their transmission range and cope with potential hidden nodes. To minimize the RTS/CTS/TAT overhead, every successful medium reservation may include the transmission of a number of data frames. As the data frames may be transmitted using different RR to match varying channel quality, the reservation time duration is not known when the RTS frame is transmitted. As a result, a reservation is terminated using an End Of Burst / End Of Burst Confirm (EOB/EOBC) control frame exchange. AIr utilizes an RTS-CTS-DATA$_0$-DATA$_1$-...-DATA$_n$-EOB-EOBC frame exchange.

2.6 Modeling of communication systems

Many factors affect the performance of wireless IR links. The significance of system parameters to link utilization can be evaluated by studying models of the considered IR scenario. Modeling is very useful in communication systems because it:

- provides a detailed understanding of the system performance in specific load conditions without physically implementing and testing a real system
- analyzes protocol operation and leads to protocol design improvements
- evaluates the effectiveness of all parameter values on system performance
- can by employed to derive optimum parameter values
- evaluates the performance increase of implementing optimum parameter values

There are two types of models that can be used to evaluate the performance of communication systems [36]:

a) **Computer simulation modeling.** Computer simulation involves developing models in software that mimic the operation of an information exchange system. The software model is employed to produce performance results when one or more system parameters are varied. The computer program emulates the behavior of every station independently and produces very accurate results because it replicates the behavior of a real system. Simulation models usually involve a few or no assumptions. The main advantage of simulation models is that they can evaluate the performance of very complex communication systems. The main disadvantage of simulation techniques is that, depending on the system complexity, simulation runs may take a considerable amount of computing time.

b) **mathematical modeling.** A mathematical model provides one or more equations that express system performance as a function of protocol parameters, system load and the number of communicating devices. Probability theory, statistical mathematics, queuing theory and stochastic process modeling are often used to develop an analytical model for an information exchange system. The mathematical model is used to produce computer graphs that show how system performance changes when one or more system parameters are varied. These graphs are very useful for protocol designers and are easily produced once the mathematical model is developed. The disadvantage of analytical modeling is that a number of assumptions are usually necessary to develop an analytical model. As simulation modeling accurately predicts system performance; analytical models are usually validated by comparing analytical with simulation results.

2.7 Performance measures

The measures that are helpful to evaluate the performance of an information exchange system depend on the system in question and on the characteristics of the traffic the system is expected to carry. The traffic presented to the system is usually called the offered load. If the offered load contains time sensitive data, such as human speech and video, the communication system must minimize the delay in delivering the time sensitive data to the destination. More important, significant variations of the delay in delivering various frames with time sensitive data are not acceptable. The reason is that the resulting output will be of low quality or not understandable. In this case, the average and the maximum frame delays are of prime importance. If the offered load contains time insensitive data, such as file transfer, e-mail and web browsing, the communication system must maximize the rate at which data can be sent through the system.

There are two fundamental quantitative measures of an information exchange system:

a) Delay. The delay of a system specifies the time needed for information data to travel from the source to the destination station. Users are particularly interested in the delay in which the system delivers their information data to the destination. Delays are more important on time sensitive data. Types of delays in communication systems are [25]:

i) propagation delay arises from the time needed for the signal to travel between two stations. This work considers short-distance indoor links that have very small propagation delays, which are safely neglected.

ii) switching delay arises from electronic devices in a network, such as hubs and bridges. This work does not analyse links that include such electronic devices and does not consider switching delays.

iii) access delay occurs when several devices access the same shared medium and stands for the time needed until the medium is available to a station. IrDA 1.x WPAN implements centralized control and access delays do not affect the considered link scenario. This work analyses the access delay of the collision avoidance procedures of infrared WLANs in chapter 6.

iv) queuing delay occurs in packet switched WANs. When a packet reaches a packet switching device, it may have to wait on a queue if more packets wait for the intended destination. Queuing delay accounts for the time a packet spends on a queue in a packet switching device. This work does not consider queuing delays.

v) retransmission delay arises when a transmitted frame is not correctly received at the destination due to a transmission error. Transmission errors are more likely when a wireless medium is utilized and may significantly degrade performance. This work considers retransmission delays for point – to-point infrared links in chapters 3 and 4 and for multipoint infrared links in chapter 7.

b) Throughput/utilization

Throughput (D) is the rate at which information data can be sent through the communication system and it is usually specified in bits per second (bit/s). For time insensitive data, network and link designers and implementers aim to increase system throughput in order to achieve a better performance; delays in delivering specific data are of secondary importance. Most technologies deliver the offered load in frames and frame headers do not contribute to throughput. In addition, access and retransmission delays result in throughput degradation.

Throughput usually expresses the performance of a particular information exchange system. Throughput is more useful than the data rate because it specifies the actual performance of the system by evaluating all delays introduced by the communication system. It is usually compared to the link data rate to express the performance degradation introduced by the communication technology, such as frame headers, access delays and transmission errors. This work examines the performance of point-to-point and WLAN communication systems by evaluating the utilization (U) figure, which is defined as

$$U = \frac{D}{C} \tag{2.1}$$

where C is the medium data rate. U expresses the time portion of the total time that the system delivers offered load to destination at the medium data rate. As an example, if U=0.75 for C=4Mbit/s, the system delivers the offered load at 3Mbit/s (D=3Mbit/s) to the destination. It also delivers offered load during the 75% of the time; the remaining

25% is utilized in other communication system tasks, such as medium access delays and transmitting frame headers. Utilization is also referred to as throughput efficiency.

2.8 Research in IR wireless systems

The performance of infrared point-to-point and multipoint connectivity can be measured by the utilization, which can be drawn at the link layer. IrDA 1.x IrLAP is based on the widely used HDLC protocol and utilizes a GBN ARQ scheme. The performance of the GBN ARQ scheme is studied in [9][66]. An analytical model that evaluates HDLC performance using the concept of a frame's virtual transmission time (VTT) is presented in [19][20]. The VTT concept is needed due to the full duplex operation of HDLC. Using the VTT concept, an analytical model for the IrLAP performance is developed in [4][5]. The VTT IrLAP model is employed to study the effect of minimum turn around time as related to link data rate and window size in [6]. An IrLAP simulator using OPNET is developed and used to validate the VTT IrLAP analytical model in [3]. A C++ IrLAP simulator is developed in [84]. This simulator is employed to study the effect of minimum turn around time to link rate increase (up to 4Mbit/s) and to window size increase (up to 7 frames) [84]. The performance improvement of replacing the IrLAP GBN ARQ scheme with a Selective Reject (SREJ) ARQ scheme is presented in [74]. This work concludes that the GBN ARQ scheme is good enough for IrLAP due to the significant turn around delays arising from the IR medium implementation. The effects of extending window size to 127 frames for the 16 Mbit/s data rate is studied in [15] using the VTT IrLAP analytical model. This work questions the effectiveness of increasing window size to 127 frames and advises the implementation of lower or optimum window sizes in high BER links. The derivation of optimum window size values as a function of link BER remained an open challenge. In addition, the VTT model is very complicated and does not give insights (a) for the significance of physical layer parameters to utilization and (b) for the optimum control of the infrared link for maximum utilization. By taking advantage of the IrLAP half-duplex operation, this work develops an analytical model that leads to a simple utilization equation for IrLAP performance. This equation permits a complete analysis to study the significance of the link system parameters on IrLAP utilization performance. By taking the first derivative of the utilization equation, this work derives equations which eventually simplify and allow easy calculation of the optimum values for the IrLAP window size and frame length parameters. Results indicate that significant utilization increase is observed if the optimum values are implemented at high BER links. The achieved practical utilization increase for optimum parameter implementation by the transmitter is also confirmed by means of simulation.

Design challenges in IR WLANs have also drawn the attention of the research community. The effectiveness of implementing RR on L-PPM infrared links is studied in [28][79][83]. Presented results indicate that RR is suitable on L-PPM links as it significantly reduces error rate in hostile medium conditions. Infrared WLANs utilize the RTS/CTS frame exchange to address the hidden station problem. To ensure that the RTS/CTS scheme operates efficiently, it is essential to maintain reciprocity, which means that the SNR should be symmetric in every pair of stations. The effect of non-reciprocity on various station configurations when the Stop-and-Wait ARQ scheme is implemented at the MAC layer is presented in [23][24] using AIr PHY and AIr MAC simulators. Results indicate that non-reciprocity depends on physical location and on ambient light level and may result in significant performance degradation. When hidden stations are present in WLANs, some stations may not get an equal chance to access the infrared medium. This fairness problem for AIr LANs and the suitable improvements for the AIr medium access scheme are presented in [75][78]. The effectiveness of implementing the Stop-and-Wait (SW) ARQ scheme at the AIr MAC layer when two stations are communicating in an AIr LAN is presented in [77][89][90]. These results are not complete, as they consider only two ARQ schemes, and incorporate the fixed and significant collision avoidance delays arising when only one station competes for medium access. AIr MAC and LC performance for LANs with many simultaneously transmitting stations has not been studied yet. In addition, the performance of the AIr MAC collision avoidance procedures and of the AIr MAC Go-Back-N ARQ scheme has not been studied in the literature. This is addressed by research presented in this thesis. This work develops mathematical models that evaluate (a) the collision avoidance delay as a function of the number of stations and (b) the performance of all AIr LC ARQ schemes, assuming LANs that maintain reciprocity, that consist of a fixed number of stations and that have no hidden stations. We also propose protocol modifications that improve AIr performance for the considered scenarios.