100

Chapter 3: Physical Layer

The *Physical Layer* is the first layer of the OSI reference model and the hybrid reference model. The transmission media and all devices that are directly connected to the transmission media, including antennas, connectors, and repeaters, are part of the Physical Layer. Another task of this layer is the definition of the line codes, which specify how the data (bit sequences) is sent via the transmission media.

3.1 Networking Technologies

This section covers the wired networking technologies Ethernet and Token Ring and the wireless network technologies Bluetooth and WLAN, while the focus is on Ethernet and WLAN (WiFi).

3.1.1 Ethernet

Ethernet (IEEE 802.3) was developed in the 1970s, and it is the most widely used LAN technology since the 1990s. Because of Ethernet, other standards such as Token Ring became obsolete or turned into niche products for special applications like FDDI.

Numerous Ethernet standards differ in the data rate and the transmission medium.

Table 3.1: Data rates and Ethernet standards

Standard	Mbps	Transmission medium
10BASE2/5	10	Coaxial cables (50 Ohm impedance)
10BROAD36	10	Coaxial cables (75 Ohm impedance)
10BASE-F	10	Fiber-optic cables
10BASE-T	10	Twisted pair cables (Cat-3)
100BASE-FX	100	Fiber-optic cables
100BASE-T4	100	Twisted pair cables (Cat-3)
100BASE-TX	100	Twisted pair cables (Cat-5)
1000BASE-LX	1,000	Fiber-optic cables
1000BASE-SX	1,000	Fiber-optic cables (Multi-mode fiber)
1000BASE-ZX	1,000	Fiber-optic cables (Single-mode fiber)
1000BASE-T	1,000	Twisted pair cables (Cat-5)
1000BASE-TX	1,000	Twisted pair cables (Cat-6)
2.5GBASE-T	2,500	Twisted pair cables (Cat-5e)
5GBASE-T	5,000	Twisted pair cables (Cat-6)
10GBASE-SR	10,000	Fiber-optic cables (Multi-mode fiber)
10GBASE-LR	10,000	Fiber-optic cables (Single-mode fiber)
10GBASE-T	10,000	Twisted pair cables (Cat-6A)
40GBASE-T	40,000	Twisted pair cables (Cat-8.1)

Looking at Table 3.1, the naming scheme of the Ethernet standards becomes obvious. Each name consists of three parts. Part 1 indicates the data rate, part 2 the transmission method (baseband or broadband) and part 3 the hundredfold factor of the maximum segment length or the transmission medium. For example, the name 10BASE5 indicates:

- Data rate: 10 Mbps
- Transmission method: Baseband
- Maximum segment length:

$5 \times 100m = 500m$

Transmission Methods of Ethernet

With one exception, all Ethernet standards operate according to the *baseband* transmission method (BASE). Baseband systems have no carrier frequencies. This means that data is transmitted directly (in the baseband) on the transmission medium. Digital signals are injected directly as impulses into the copper cable or fiber-optic and occupy the entire bandwidth of the cable or a part of it. The unused part of the bandwidth cannot be used for other services. Therefore, baseband systems offer just a single channel.

In the *broadband* transmission method (BROAD), the data is modulated onto a carrier frequency. This allows several signals to be transmitted simultaneously in different frequency ranges (bands).

3.1.2 Token ring

Token Ring (IEEE 802.5) is a standard for LANs, in which the terminal devices are logically connected as a ring. A *token* travels in the ring and is passed from one node to the next. The *connection type* to the transmission medium is *active*. This means that the network devices continuously participate actively in the token passing. Token Ring with a data rate of 4 Mbps was introduced in 1985 for the IBM PC. The standard with a data rate of 16 Mbps was introduced in 1989. Since 1998, there is also a standard for 100 Mbit/s. Token Ring has been IBM's preferred networking technology until the mid-1990s but is rarely used today since IBM abandoned this technology in 2004.

A token ring is a data link for a local area network (LAN) in which all devices are connected in a ring or star topology and pass one or more tokens from host to host. A token is a frame of data transmitted between network points. Only a host that holds a token can send data, and tokens are released when receipt of the data is confirmed.

3.1.3 Wireless Local Area Network (WLAN)

WLAN (WiFi) is the most popular technology for setting up wireless computer networks. **Some unique characteristics of the transmission medium cause the following challenges**, which need to be considered when setting up and working with wireless networks:

- ***Interference with other sources***. Examples include other WLANs and Bluetooth. Both network technologies operate on the same frequency band and can interfere with each other. Electromagnetic noise from motors or microwave ovens can also cause interferences.
- ***Multipath propagation***. This effect occurs when parts of the electromagnetic waves are reflected and therefore travel paths of different lengths from the sender to the receiver. As a result, a difficult to interpret signal arrives at the receiver, because the reflections influence subsequent transmissions.
- ***Hidden Terminal*** (invisible or hidden terminal devices).
- ***Fading*** (decreasing signal strength).

WLAN is based on the IEEE 802.11 family of standards. **Communication** between wireless terminal devices can take place directly in ***Ad-hoc mode*** or ***Infrastructure mode*** via an access point.

In Ad-hoc mode, the terminal devices form a meshed network. So they communicate directly with each other. Each terminal device can have multiple connections to other devices. To set up an Ad-hoc mode network, the same network name – Service Set Identifier (SSID) and the same encryption parameters must be set for all terminal devices.

In Infrastructure mode, each terminal device registers with its MAC address at the access point. The access point sends small *Beacon Frames* to all terminal devices in range at adjustable intervals (e.g., ten times per second). The Beacons contain the network name (SSID), the list of supported data rates and the encryption type.

Data Rate of WLAN

The various WLAN standards offer different data rates. The transmission rates of WLAN are shown in Table 3.2.

Table 3.2: Data Rates of the IEEE Standards for WLAN

IEEE standard	Maximum (gross) data rate	Realistic (net) data rate
802.11	2 Mbps	1 Mbps
802.11a	54 Mbps[a]	20-22 Mbps
802.11b	11 Mbps[b]	5-6 Mbps
802.11g	54 Mbps	20-22 Mbps
802.11h	54 Mbps[a]	20-22 Mbps
802.11n	600 Mbps[c]	200-250 Mbps
802.11ac	1733 Mbps[d]	800-850 Mbps

[a] Some manufacturers added proprietary extensions to their products, enabling them to support 108 Mbps at 40 MHz channel width

[b] Some manufacturers added proprietary extensions to their products, enabling them to support 22 Mbps at 40 MHz channel width

[c] When using 4x4 MIMO and 40 MHz channel width

[d] When using 4x4 MIMO and 80 MHz channel width

Frequencies of WLAN

Most WLAN standards use the frequency blocks 2.4000–2.4835 GHz and 5.150–5.725 GHz in the microwave range. The standards differ – among other things – in the data rates (see Table 3.2), frequency blocks used (see Table 3.3), and modulation methods, as well as the resulting channel width (see Table 3.5).

Table 3.3: IEEE Standards for WLAN

IEEE standard	Standard since	Frequencies 2.4 GHz	5 GHz
802.11	1997	X	
802.11a	1999		X
802.11b	1999	X	
802.11g	2003	X	
802.11h	2003		X
802.11n	2009	X	X
802.11ac	2013		X

The frequency block 2,4000 – 2,4835 GHz, for example, is divided into 13 channels with a bandwidth of 5MHz each. In Japan, an additional channel 14 is available, which is restricted for use only with the modulation method DSSS, and it is located 12MHz above channel 13 (see Table 3.4).

Table 3.4: Permitted use of the WLAN Frequencies in the 2.4 GHz Range

Channel	Frequency (GHz)	EU	USA	Japan
1	2.412	X	X	X
2	2.417	X	X	X
3	2.422	X	X	X
4	2.427	X	X	X
5	2.432	X	X	X
6	2.437	X	X	X
7	2.442	X	X	X
8	2.447	X	X	X
9	2.452	X	X	X
10	2.457	X	X	X
11	2.462	X	X	X
12	2.467	X	X	X
13	2.472	X	X	X
14	2.484			X

The various WLAN standards use different modulation methods (see Table 3.5).

Table 3.5: Modulation Methods and Channel Widths of the IEEE Standards for WLAN

IEEE standard	Modulation method	Channel width
802.11	FHSS[a] or DSSS[b]	22 MHz
802.11a	OFDM[c]	20 MHz
802.11b	DSSS[b]	22 MHz
802.11g	OFDM[c]	20 MHz
802.11h	OFDM[c]	20 MHz
802.11n	OFDM[c]	20 or 40 MHz
802.11ac	OFDM[c]	20, 40, 80 or 160 MHz

[a] Frequency Hopping Spread Spectrum
[b] Direct Sequence Spread Spectrum
[c] Orthogonal Frequency Division Multiplexing

Multiple Input Multiple Output (MIMO)

The maximum gross data rate at IEEE 802.11n is 150, 300, 450 or 600 Mbit/s, depending on the number of antennas in the stations. The fact that 802.11n uses *MIMO* causes this performance increase in comparison to IEEE 802.11a/b/g/h. In addition to expanding the channels to 40 MHz, 802.11n uses up to four antennas for simultaneous working in the frequency ranges 2.4 GHz and 5 GHz. With each parallel data stream (antenna), a maximum data rate (gross) of 150 Mbps can be achieved. Up to four data streams can be bundled. The corresponding number of antennas (up to four) is required on both sides.

Also, the standard IEEE 802.11ac uses MIMO. This standard even allows a maximum of eight antennas to be used in parallel. In practice, access points usually do not have more than three or four antennas. For 3x3 MIMO with 80MHz channel width, the maximum (gross) data rate is 1.3 Gbps.

Additional Extensions of the WLAN Standard

Additional WLAN standard extensions exist. Some of them may only be used in specific regions. One example is the standard IEEE 802.11j, which was released in 2004 for Japan and uses the frequency block 4.9–5 GHz.

Another example is IEEE 802.11y. This standard was released in 2008 and may only be used in the United States because it uses the frequency block 3.65–3.7 GHz. Due to increased transmission power, ranges of up to 5000m (outdoor) are possible. The standard is suitable for public WLAN networks.

WLAN Security

WLAN according to IEEE 802.11 implements the security standard *Wired Equivalent Privacy* (WEP), which is based on the RC4 algorithm. The use of tool like **Aircrack** allow to break the algorithm in few second, this made WEP vulnerable to attacks.

Better security is provided by the standard ***Wi-Fi Protected Access*** (WPA). This is also based on the RC4 algorithm but contains additional protection through dynamic keys. These are based on the Temporal Key Integrity Protocol (TKIP), which encrypts each data packet with a different key. WPA can also be cracked with brute force methods or with dictionary attacks on the password used.

The best current security standard is *Wi-Fi Protected Access 2* (WPA2). It is based on the Advanced Encryption Standard (AES) and in addition to TKIP contains the Counter-Mode/CBC-Mac Protocol (CCMP) encryption protocol, which offers higher security than TKIP. A WLAN protected with a sufficiently long password and WPA2 encryption is currently considered secure. WPA and WPA2 both are defined in the IEEE 802.11i standard, which extends IEEE 802.11.

3.1.4 Bluetooth

Bluetooth is a wireless network system for data transmission over short distances. The Swedish company Ericsson initiated its development in 1994. Further development is carried out by the Bluetooth Special Interest Group (BSIG).

Bluetooth devices may be operated worldwide without approval and use the frequency block 2.402–2.480 GHz. To avoid interferences, Bluetooth uses a frequency hopping method in which the frequency band is divided into 79 frequency stages at intervals of 1 MHz.

Bluetooth defines three performance classes. Class 1 devices operate with a maximum transmission power of 100mW. Class 2 devices use a maximum transmission power of 2,5mW. Class 3 devices use a maximum transmission power of 1mW.

Network Topologies of Bluetooth

Via Bluetooth, connectionless and connection oriented transmissions from point-to-point networks or as ad-hoc networks (so-called piconets) are possible.

Bluetooth devices are organized in *Piconets* (see Figure 3.1). A piconet consists of a maximum of 255 participants, of which a maximum of eight may be active. One active node is the *master*, and the remaining seven active nodes are *slaves*. The remaining 247 participants are passive and can be activated by the master at any time. The master assigns the transmission medium to the nodes by providing transmission slots to the slaves. This procedure is called Time Division Multiplexing. Thus, the master coordinates the media access.

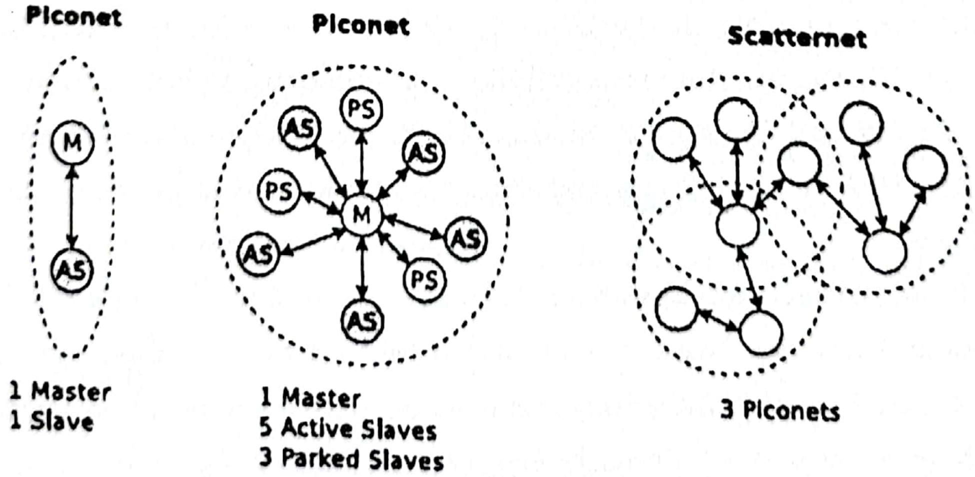

Figure 3.1: Bluetooth Topologies

Chapter 3: Physical Layer

A Bluetooth device can be registered in several piconets. However, it can only be the master of a single network. If a station is in range of two piconets, it can connect them to a *scatternet*.

Versions of the Bluetooth Standards

There are several versions of the Bluetooth standard.

While **Bluetooth up to revision 1.2** offered a maximum data rate of **1 Mbps** (of which 721 kbit is payload), the data rate was increased **to 3 Mbps** (of which 2.1 Mbps is payload) with **Bluetooth revision 2.0.**

Bluetooth 3.0 + HS (High Speed) increases the maximum data transfer rate by using WLAN. The standard uses a 3 Mbps connection to transmit control data and session keys. If two devices want to exchange large amounts of data, they switch into the high-speed mode and establish an ad-hoc connection via WLAN 802.11g with a 54 Mbps data rate. Then the achievable (net) data rate is about 24 Mbps. Hence, Bluetooth 3.0 + HS is a combination of Bluetooth and WLAN.

Bluetooth 4 offers – among other things – a reduced power consumption. **Bluetooth 5** raises the maximum range and improves the data rate.

3.2 Transmission Media

Various cable-based transmission media for computer networks exist. Copper cables are *electrical conductors* on which data is transmitted via twisted pair cables or coaxial cables in the form of electrical impulses, and there are *fiber optic cables* on which data is transmitted as light impulses. Moreover, *wireless transmission* can be used.

3.2.1 Coaxial Cables

Coaxial cables are bipolar cables with a concentric (coaxial) structure. The inner conductor carries the signals and the outer conductor is on ground potential, surrounding the inner conductor (see Figure 3.2). The shielding of the signal-carrying conductor by the outer conductor that is kept at ground potential reduces electromagnetic interference.

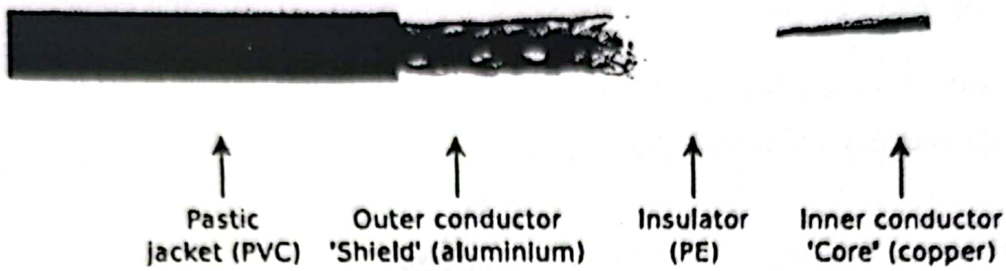

Figure 3.2: Structure of a Coaxial Cable

The Ethernet standards Thick Ethernet and Thin Ethernet both use coaxial cables as the transmission medium.

3.2.2 Twisted Pair Cables

Twisted pair cabling is a type of wiring in which two conductors of a single circuit are twisted together for the purposes of improving electromagnetic compatibility. Twisted wire pairs offer better protection against alternating magnetic fields and electrostatic influences from the outside than parallel signal wires.

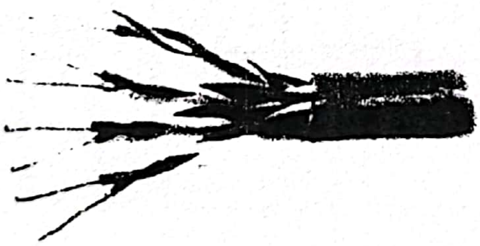

Figure 3.3: Twisted pair cable

There are different performance levels (categories) of twisted pair cables (see Table 3.6). The component of the lowest category determines the performance of a network connection. For example, if Cat 6-capable network devices are connected via a Cat 5 cable, the performance of the connection is reduced to Cat 5.

Table 3.6: Categories of Twisted Pair Cables

Category	Max. frequency	Compatible with...
Cat-1	100 kHz	Modem
Cat-2	1 oder 1.5 MHz	ISDN
Cat-3	16 MHz	10BASE-T (10 Mbps, 2 wire pairs, 100 m)
		100BASE-T4 (100 Mbps, 4 wire pairs, 100 m)
Cat-4	20 MHz	Token Ring (16 Mbps, 2 wire pairs)
Cat-5	100 MHz	100BASE-TX (100 Mbps, 2 wire pairs, 100 m)
		1000BASE-T (1 Gbps, 4 wire pairs, 100 m)
Cat-5e	100 MHz	2.5GBASE-T (2.5 Gbps, 4 wire pairs, 100 m)
Cat-6	250 MHz	5GBASE-T (5 Gbps, 4 wire pairs, 100 m)
		10GBASE-T (10 Gbps, 4 wire pairs, 55 m)
Cat-6A	500 MHz	10GBASE-T (10 Gbps, 4 wire pairs, 100 m)
Cat-7	600 MHz	10GBASE-T (10 Gbps, 4 wire pairs, 100 m)
Cat-7A	1000 MHz	10GBASE-T (10 Gbps, 4 wire pairs, 100 m)
Cat-8.1	2000 MHz	40GBASE-T (40 Gbps, 4 wire pairs, 30 m)

3.2.3 Fiber-optic Cables

An optical fiber consists (from inside to outside) of a light-transmitting *core*, which is made of quartz glass. The core is surrounded by a *cladding*, which has a refractive index lower than that of the core and causes the beams to be guided by total reflection at the boundary layer with the core. The cladding is enclosed by a protective *coating* that is also called *buffer* (see Figure 3.4). The final layer is the outer protective cover (*jacket*).

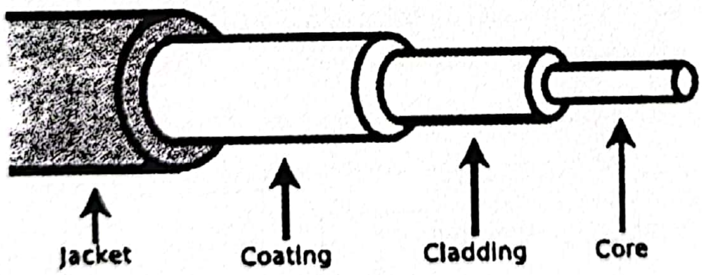

Figure 3.4: Structure of a Fiber-Optic Cable

The structure, dimensions and refractive index of the core and cladding determine the number of *propagation modes*, by which light can propagate along the optical fiber. Each mode corresponds to a path in the optical fiber. *Multi-mode fibers* have up to several thousand propagation modes. *Mono-mode (single-mode) fibers* have only a single propagation mode. For shorter distances of up to approximately 500 m, multi-mode fibers are used, and mono-mode fibers are used for longer distances of up to approximately 70 km without repeater.

3.3 Devices of the Physical Layer

Repeater, Hub and Modem are equipment's of physical Layer.

Since the problem of ***attenuation*** (signal weakening) exists for all transmission media, the maximum range of a network is limited. ***Repeaters* extend the range of a LAN** by cleaning received electrical or optical signals from noise and jitter (deviation of the transmission timing) and by amplifying them. A Repeater interprets the signal levels it receives, re-encodes and retransmits the data. It only forwards signals but does not analyze their meaning or examines their correctness. **A Repeater has only two interfaces (*ports*).**

Repeaters with more than two interfaces are called *multiport Repeater* or *Hub*. Hubs implement the physical star network topology and logical bus network topology. Equal to a long cable that connects all network devices, a Hub forwards incoming signals to all other ports. Therefore, each terminal device, which is connected to a Hub, can receive and analyze the entire traffic that passes through the Hub. Hubs, too, cannot analyze the signals they transmit, but can only clean and amplify them.

Just like a physical bus topology, all network devices connected to a Hub are inside a *Collision Domain.* A Collision domain refers to any part of network in which packet collision could occur (Figure 3.5).

Modems operate on the Physical Layer. These devices make it possible to transport signals over long distances by modulating them onto a carrier frequency in the high-frequency range.

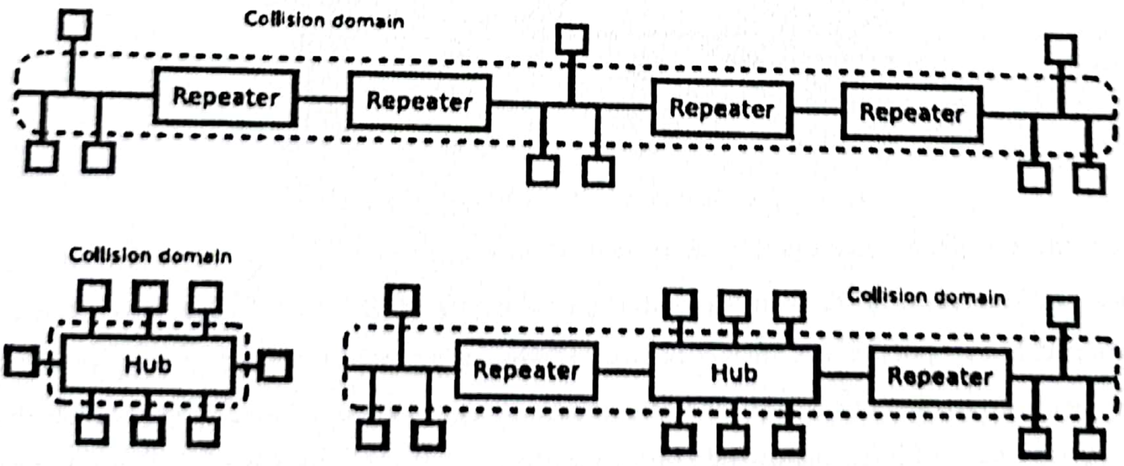

Figure 3.5: Collision Domains of Repeaters and Hubs

3.4 Encoding Data with Line Codes

In computers network, encoding is the process of putting a sequence of characters (letters, numbers, punctuation, and certain symbols) into a specialized format for efficient transmission or storage.

The encoding is called *line code* in this context and specifies how signals are transmitted on the used transmission medium of a computer network. Specific signal level sequences are assigned to bit sequences in the data stream. Computer networks must implement these operations:

- Conversion (*encoding*) of binary data to signals.
- Transmission of the signals via the transmission to the receiver.
- Reconversion (*decoding*) of the signals to binary data.

3.4.1 Non-Return to Zero (NRZ)

NRZ line code is a binary code in which ones are represented by one significant condition, usually a positive voltage, while zeros are represented by some other significant condition, usually a negative voltage, with no other neutral or rest condition.

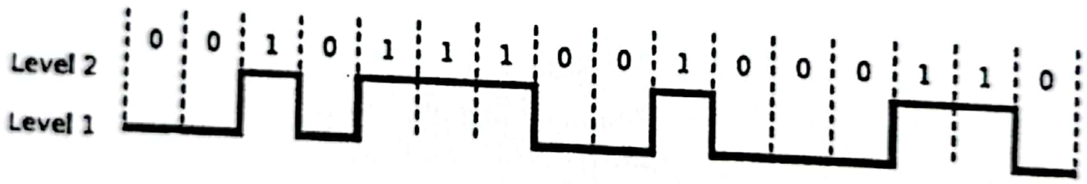

Figure 3.6: NRZ

3.4.2 Non-Return to Zero Invert (NRZI)

NRZI is a variant of NRZ. To send a one-bit, a signal level change occurs at the beginning of the clock. To send a one-bit, the signal level remains unchanged for a whole clock (see Figure 3.7).

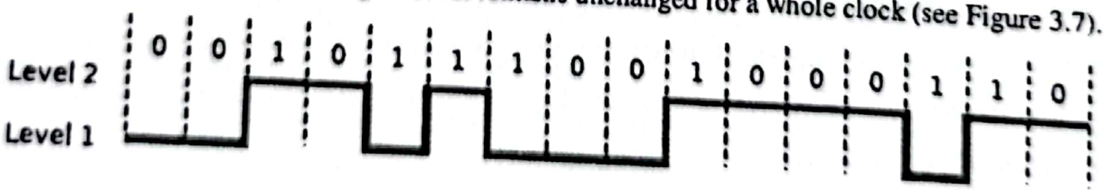

Figure 3.7: NRZI

This line code is used, among others, by FDDI and Ethernet 100BASE-FX.

3.4.3 Multilevel Transmission Encoding - 3 Levels (MLT-3)

This line code uses three signal levels (+, 0 and -). If a zero-bit is transmitted, no signal level change takes place. A one-bit value is encoded alternately according to the sequence [+, 0, -,0] (see Figure 3.8).

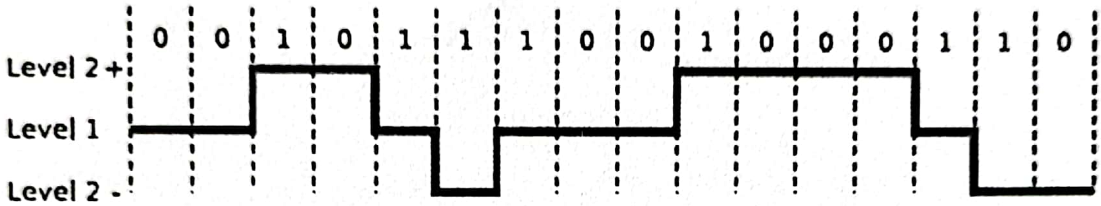

Figure 3.8: MLT-3

This line code is used, among others, by Ethernet 100BASE-TX.

3.4.4 Return-to-Zero (RZ)

RZ also uses three signal levels. To send a one bit, the positive signal level is transmitted for half a clock cycle, and then the signal level returns to the average signal level. To send a zero-bit, the negative signal level is transmitted for half a clock cycle, and then the signal level returns to the average signal level (see Figure 5.23).

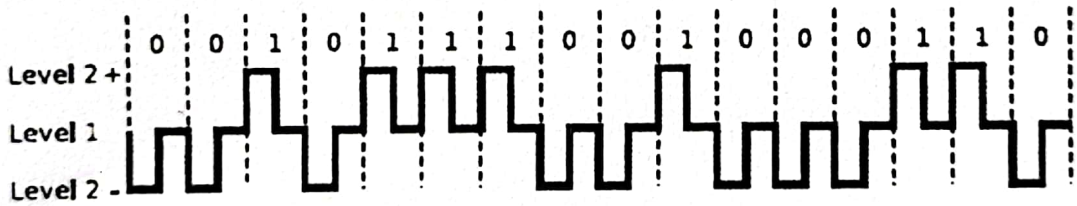

Figure 3.8: Return-to-Zero

3.4.5 Unipolar RZ

This line code, which is among others used for wireless optical data transmission via IrDA (Infrared Data Association) in the SIR (Serial Infrared data transmission) transmission mode, is a particular form of the RZ line code because it uses only two signal levels. For sending a one-bit, the signal level returns to the low signal level after half the clock cycle. Sending a zero-bit does not cause a signal level change (see Figure 3.9).

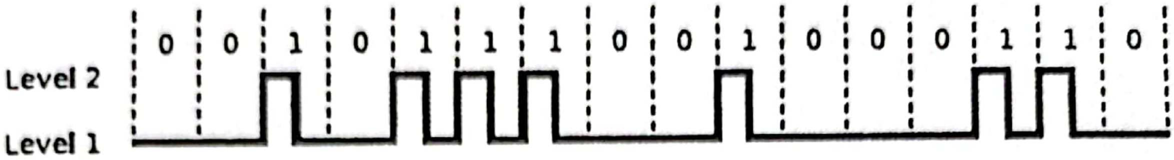

Figure 3.9: Unipolar Return-to-Zero

3.4.6 Alternate Mark Inversion (AMI)

AMI, which is also called *bipolar encoding*, uses three signal levels. A zero-bit is transmitted as average signal level (0). One-bits are transmitted alternately as a positive (+) or negative signal level (-).

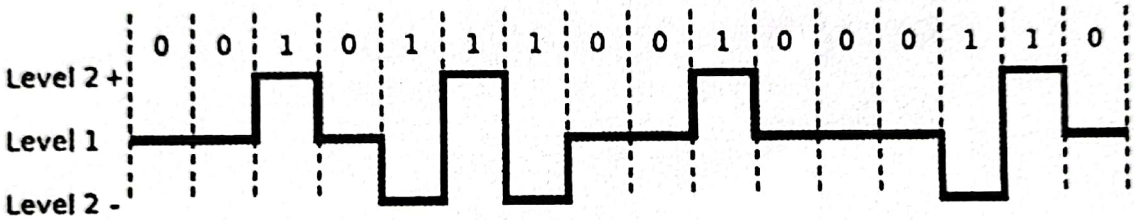

Figure 3.10: Alternate Mark Inversion

The ISDN S_0 bus uses a modified version of this line code. A one-bit is transmitted as average signal level, and zero-bits are transmitted alternately as a positive or negative signal level.

3.4.7 Manchester

The Manchester line code uses two signal levels and is self-synchronizing because of the signal level changes in each bit cell. A logical one-bit is encoded with a change from signal level 1 to signal level 2 (rising edge), and a zero-bit is encoded with a change from signal level 2 to signal level 1 (falling edge). If two identical bits follow each other, at the end of the bit cell, the signal level changes to the initial level (see Figure 3.11). Ethernet uses this line code with 10 Mbps (for example 10BASE2 and 10BASE-T).

Figure 3.11: Manchester

3.4.8 Manchester II

This line code is the opposite of the Manchester encoding. In Manchester II, a one-bit is encoded with a falling edge, and a zero-bit is encoded with a rising edge (see Figure 3.12).

Figure 3.12: Manchester II

3.4.9 Differential Manchester Encoding

This variant of the Manchester encoding is also called *Conditional DePhase Encoding* (CDP). Here, too, a signal level change inside each bit cell occurs for clock recovery.

If the next data to be encoded is a one-bit, the signal level does not change at the beginning of the bit cell, but only in the middle. If the next data to be encoded is a zero-bit, a signal level change also takes place at the beginning of the bit cell. Depending on the initial level, two signal sequences are possible, which are inverse to each other (see Figure 3.13). This line code is used by Token Ring (IEEE 802.5).

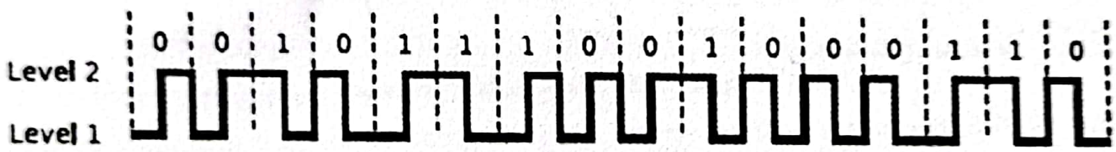

Figure 3.13: Differential Manchester Encoding