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Electronics, Photonics, Microsystems

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OPTICAL FIBER NETWORKS

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1 Introduction to networking

1.1 Basic idea and networking media

Comparing bandwidth of different networking media, one may note that optical fiber offers the lowest attenuation and the highest bandwidth.

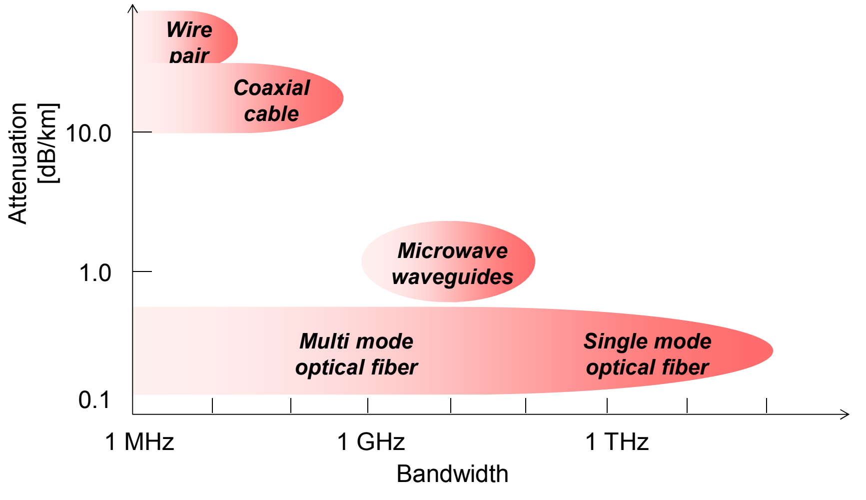

Fig. 1.1 Bandwidth comparison of networking media.

Networks may be classified according to several criteria, the most popular is classification according to the area covered:

1. Local Area Network - LANs connect computers and peripheral devices in a limited physical area, such as a business office, laboratory, or college campus, by means of permanent links (wires, cables, fiber optics) that transmit data rapidly
2. Metropolitan Area Network – MAN size falls intermediate between LANs and WANs. A MAN typically covers an area of between 5 and 50 km diameter. Many MANs cover an area the size of a city, although in some cases MANs may be as small as a group of buildings or as large as a country region.
3. Wide Area Networks (long haul networks) - Wide-area networks connect computers and smaller networks to larger networks over greater geographic areas, including different continents. They link the computers by means of cables, optical fibers, or satellites.

Contemporary LAN technologies allow different topologies, protocol and media. Each of them, however, includes optical fiber as a possible transmission medium.

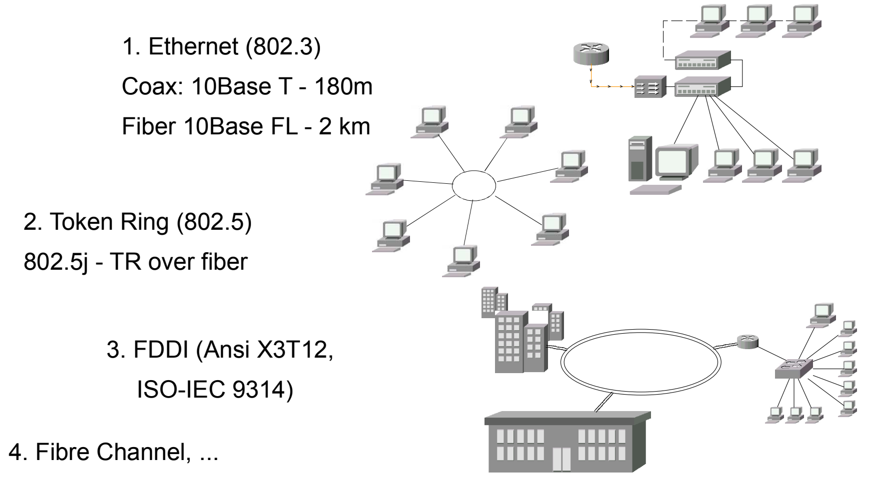

Fig. 1.2 Examples of contemporary LAN technologies.

Definition of a computer network: in plain English it is a system of several computers which are connected to one another by cables.

Another, more general definition: a network of data processing nodes that are interconnected for the purpose of data communication.

The “network” name is not reserved for the computer systems, there are other, non-computer-based, examples. E.g. communications network - with roads, bus stations, buses, containers and actual load.

1.2 Principles of operation and fundamental terms

- Fundamental terms: **layer** and **protocol**
- Other terms: frame, access method, coding
- **Protocol**: set of rules describing how to prepare data for sending, establish communication, control data transfer etc. Protocols are standardized.

Protocol description according to OSI (Open System Interconnection), model have layered structure. For computers connected by the network layers of given level communicate between themselves, transferring data only to the layer immediately above and beneath them.

	Device 1			Device 2	
7	Application	<--->	7	Application	program
6	Presentation	<--->	6	Presentation	
5	Session	<--->	5	Session	
4	Transport	<--->	4	Transport	
3	Network	<--->	3	Network	
2	Data Link	<--->	2	Data Link	hardware
1	Physical layer	<--->	1	Physical layer	

Fig. 1.3 The OSI -ISO Network Model (Open Systems Interconnection).

The three bottom layers are related to hardware (the layers are usually listed from bottom to top):

- Layer 3 - (Network) Flow control to avoid congestion and also customer use and accounting. Link Layer Control (LLC). Internet Protocol (IP), routing protocols.
- Layer 2 - (Data Link) Presentation of error-free transmission to the network layer. Creates data frames and receives acknowledge frames. Media Access Control (MAC)
- Layer 1 - (Physical) Physical Layer Protocol (PHY) specifies coding (e.g. 4B/5B), clock synchronization. Physical Medium Dependent (PMD) sublayer provides digital communications between nodes. This layer specifies fiber-optic drivers, receivers, mechanical, cables, connectors, optical signal requirements including power levels, jitter and BER

The four upper layers are software or protocol related:

- Layer 7 - (Application): Common protocols such as network virtual terminal, file transfer protocol (FTP), electronic mail, and directory lookup
- Layer 6 - (Presentation)- Encoding/decoding including compression and cryptography, terminal emulation.
- Layer 5 - (Session)- Communication between processes including data exchange, remote Procedure Call (RPC), synchronization, and activity management
- Layer 4 - (Transport)- Lowest level at which messages are handled. Segmentation and reassembly of data to and from session layer. Transmission Control Protocol (TCP), User Datagram Protocol (UDP)

In plain words, a protocol is a standard way of dealing with data transfer

More formal definition: Protocol is a formal set of conventions governing the format and control of interactions among communicating functional units. Protocols may govern portions of a network, types of service, or administrative procedures.

Examples of protocols: CSMA/CD - carrier sense multiple access / collision detection, CSMA/CA- carrier sense multiple access / collision avoidance, IP, …

1.3 Signal Encoding

Signal encoding is used to increase system robustness against noise. Examples: FDDI uses 4b/5b NRZI (Non-Return to Zero Invert on ones) with 125 Mb/s baud rate to achieve 100 Mb/s data rate: Ethernet uses Manchester encoding with 20 Mb/s baud rate (20 MBd) to achieve 10 Mb/s data rate.

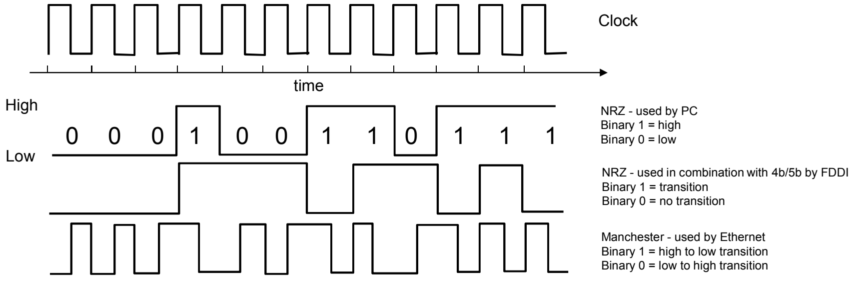

Fig. 1.4 Examples of signal encoding. One may note, how encoding scheme influences required bandwidth.

1.4 Advantages of fiber over copper

We have already shown, that fiber offers longer transmission distances and higher bandwidth. There are several other advantages, in fact the list may be quite long. Let us divide the list according to the different classes of recipients [Fiber Optics LAN Section of the Telecommunications Industry Association, Fiber in the Horizontal: The better way to carry information. 2000,retrived from http://www.fols.org].

Fiber advantages for network designers:

- Error-free transmission over longer distances. More flexibility in planning networks, possibility of taking advantage of new architectures.
- Ability to support higher data rates.
- Ease of handling, installing, and testing. Fiber can now be installed and tested in the same or less time than copper networks.
- Long term economic benefits over copper (over the lifetime of the network),
  - superior reliability reduces operating costs by minimizing network outages
  - higher bandwidth can produce considerable savings by eliminating the need to pull new cable when the network is upgraded to support higher bandwidth
  - long distance capability allow all hub electronics to be centrally located. Centralization reduces the cost of cabling and electronics, and reduces administration and maintenance efforts.

Fiber advantages for network technicians:

- Fiber is immune to EMI/RFI signals.
- Fiber is immune to crosstalk.
- Fiber systems are easier to test. (For copper cabling, there are now more than 20 specified parameters for Gigabit Ethernet as opposed to two for optical fiber - attenuation and bandwidth).
- Fiber provides greater reliability and equipment safety.

2 Optical Ethernet – 10M and 100M

2.1 Basic network types

Considering network spread, area covered by network, computer networks are classified as:

- Local Area Network - LANs connect computers and peripheral devices in a limited physical area, such as a business office, laboratory, or college campus, by means of permanent links (wires, cables, fiber optics) that transmit data rapidly
- Metropolitan Area Network – MAN size falls intermediate between LANs and WANs. A MAN typically covers an area of between 5 and 50 km diameter. Many MANs cover an area the size of a city, although in some cases MANs may be as small as a group of buildings or as large as a country region.
- Wide Area Networks (long haul networks) - Wide-area networks connect computers and smaller networks to larger networks over greater geographic areas, including different continents. They link the computers by means of cables, optical fibers, or satellites.

2.2 Contemporary LAN technologies – examples

Figure Fig. 2.1 gives several examples of commonly used network technologies that employ different telecommunication standards:

1. Ethernet (802.3)

2. Token Ring (802.5)
3. FDDI (Ansi X3T12, ISO-IEC 9314)

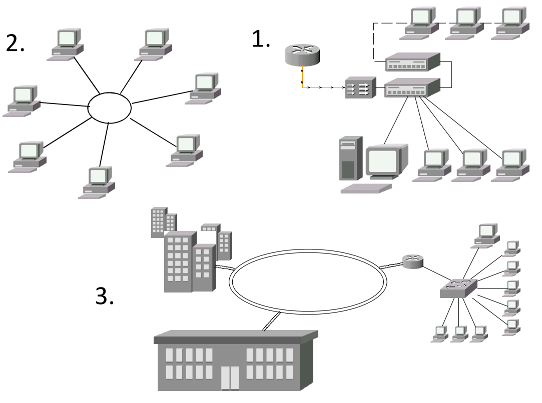

Fig. 2.1 Contemporary LAN technologies.

2.3 Computer network - a definition

Before we go on to individual network technologies, let us first give some basic definitions of ideas we will encounter in further parts of the lecture. What is then a computer network?

In plain English: system of several computers which are connected to one another by cables.

A more formal definition states: A network of data processing nodes that are interconnected for the purpose of data communication.

Of course the term network is not only associated with telecommunications. Out of many “non-computer” networks let us mention here e.g. the transportation networks, i.e. roads, bus stations, buses, containers.

2.4 Optical Fibers in Computer Networks

The earliest implementations of computer networks were based on copper cable employed as transmission medium. Optical fiber utilization was a step in network technology evolution and a response to an ever increasing demand for faster telecommunication links (higher transmission capacities). Optical fiber-based computer networks can be classified as follows:

1. Ethernet (802.3)
   - Ethernet (10Base-F)
   - Fast Ethernet (100Base-TX, 100Base-FX)
   - Gigabit Ethernet (1000Base-SX, 1000Base-LX)
   - 10 Gigabit Ethernet
2. Token Ring (802.5)
3. FDDI
4. Fiber Channel

2.5 Advantages of fiber optical networks

Actually, contemporary copper cable-based networks achieve high transmission speeds and installation costs of such networks are significantly lower than that involved in the installation of optical fiber networks. Despite these positive features of copper cable-based network technologies, optical fiber telecommunications are widely used due to their unique advantages ("Fiber in the Horizontal: The better way to carry information," 2000):

- Error-free transmission over longer distances. More flexibility in planning networks, possibility to take advantage of new architectures.
- Ability to support higher data rates.
- Ease of handling, installing, and testing. Fiber can now be installed and tested in the same or less time than copper networks.
- Long term economic benefits over copper (over the lifetime of the network),
  - superior reliability reduces operating costs by minimizing network outages
  - higher bandwidth can produce considerable savings by eliminating the need to pull new cable when the network is upgraded to support higher bandwidth
  - long distance capability allow all hub electronics to be centrally located. Centralization reduces the cost of cabling and electronics, and reduces administration and maintenance efforts .
- Fiber is immune to EMI/RFI signals. Optical fiber carries light rather than electricity, so it is not affected by electromagnetic interference from power, radio, or microwave sources. Further, radiated emissions and susceptibility to external interference are almost entirely eliminated simply by the inherent design of optical cables.
- Fiber is immune to crosstalk. Crosstalk occurs when unwanted signals are coupled between copper conductors. Signals cannot couple between fibers in a cable, thus eliminating crosstalk.
- Fiber systems are easier to test. (For copper cabling, there are now more than 20 specified parameters for Gigabit Ethernet as opposed to two for optical fiber - attenuation and bandwidth).
- Fiber provides greater reliability and equipment safety. Unlike copper facilities, all-dielectric fiber cabling systems do not conduct lightning strikes or electrical currents that can damage sensitive electronic transmission equipment.

2.6 The OSI -ISO Network Model (Open Systems Interconnection)

Device 1			Device 2		
7	Application	<--->	7	Application	program
6	Presentation	<--->	6	Presentation	
5	Session	<--->	5	Session	
4	Transport	<--->	4	Transport	
3	Network	<--->	3	Network	
2	Data Link	<--->	2	Data Link	hardware
1	Physical layer	<--->	1	Physical layer	

Fig. 2.2 Block diagram of the OSI-ISO model.

The Open System Interconnection (OSI) model is a standard defined by the International Organization of Standardization (ISO) and the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T). The OSI model describes the structure of network communication. The standard was developed in the 1980s (ratified in Poland in 1995) and its goal was the creation of guidelines for network equipment manufacturers to ensure compatibility between all the newly developed equipment solutions. The ISO model divides each networking system into 7 layers (see figure Fig. 2.2) and strictly defines ways in which individual layers cooperate:

- Layer 7 - (Application): Common protocols such as network virtual terminal, file transfer protocol (FTP), electronic mail, and directory lookup
- Layer 6 - (Presentation)- Encoding/decoding including compression and cryptography, terminal emulation.
- Layer 5 - (Session)- Communication between processes including data exchange, remote Procedure Call (RPC), synchronization, and activity management
- Layer 4 - (Transport)- Lowest level at which messages are handled. Segmentation and reassembly of data to and from session layer. Transmission Control Protocol (TCP), User Datagram Protocol (UDP)
- Layer 3 - (Network) Flow control to avoid congestion and also customer use and accounting. Link Layer Control (LLC). Internet Protocol (IP), routing protocols.
- Layer 2 - (Data Link) Presentation of error-free transmission to the network layer. Creates data frames and receives acknowledge frames. Media Access Control (MAC)
- Layer 1 - (Physical) Physical Layer Protocol (PHY) specifies coding (e.g. 4B/5B), clock synchronization. Physical Medium Dependent (PMD) sublayer provides digital communications between nodes. This layer specifies fiber-optic drivers, receivers, mechanical, cables, connectors, optical signal requirements including power levels, jitter and BER

2.7 OSI model - an example

Figure Fig. 2.3 presents some further details of the OSI model, particularly the tasks assigned to each of the 7 network layers defined by the model.

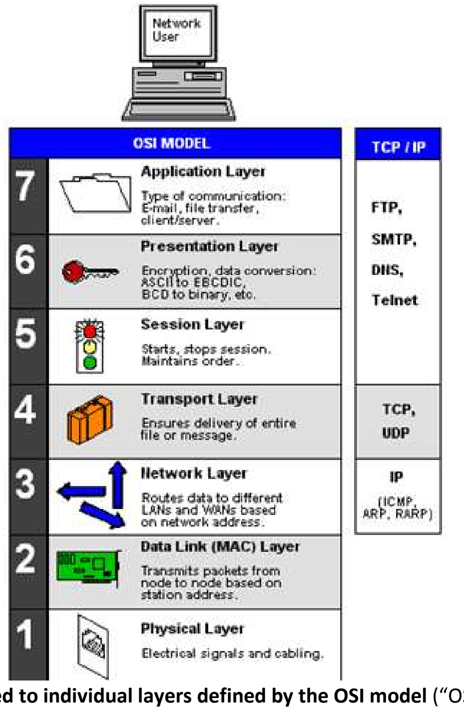

Fig. 2.3 Tasks assigned to individual layers defined by the OSI model ("OSI Model Example," 1998)

2.8 Ethernet

In figure Fig. 2.4 there is shown a historical schematic of the Ethernet network as it was presented in the National Computer Conference in June 1976 by on of Ethernet inventors, Dr. Robert M. Metcalf. He discussed an idea of nodes that send / receive information to / from a common transmission medium.

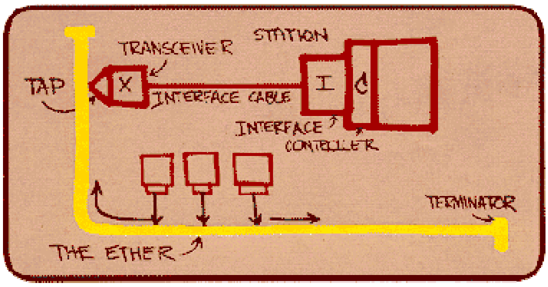

Fig. 2.4 Historical schematic of the Ethernet network (Metcalf, 1976)**.**

2.9 Protocol

Basic concepts required for the description of communication within a single network and between different networks, are: protocol and layer. Other concepts include: frame, access method, coding.

A protocol is a set of rules defining how data need to be prepared for sending (transmitting), how communication is initiated, how to control paths (routes) data travel in the network, etc. Protocols are subject to standardization.

Definition of a protocol is:

A formal set of conventions governing the format and control of interactions among communicating functional units. Protocols may govern portions of a network, types of service, or administrative procedures.

2.10 CSMA/CD and CSMA/CA

Ethernet network access is based on medium access competition. This means that each of the network devices competes for access to the medium. Medium access competition results in the creation of the so called collision domains as at a given moment of time, only one transmission may be realized. The Ethernet does not feature any central control mechanism. Each individual device is supposed to monitor the medium busy states and assure the transmission opportunity for itself. Two alternative methods of such a multi access to the network link are provided:

- Carrier Sense Multiple Access with Collision Detection (CSMA/CD) – utilized in Ethernet-type LAN networks
- Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) – utilized in local wireless networks

2.11 What is CSMA/CD?

How can we then define the CSMA/CD protocol? (“What is CSMA/CD?,” 2010)

Defining CSMA/CD - CSMA/CD is Carrier Sense Multiple Access with Collision Detection. This rule, which applies to all Ethernet networks, means that computers listen to the network before sending data. (Kind of a listen before talking rule).

Defining Contention - When working with CSMA/CD you'll encounter the term contention. In plain English contention means a dispute in the form of a heated debate : “lively contention among the candidates”. Contention is the process a computer takes to speak on the network.

The network has to be clear before a computer can transmit - it is in contention to speak on the network. Only one computer can speak on the network at once.

Defining CSMA/CD Limits - CSMA/CD limits the network to 2,500 meters (7950 feet) in length. Beyond this length the node at one of the cable can't detect that another node at the other end of the network is also starting to send data on the network.

Why Use CSMA/CD? CSMA/CD is used to ensure that only one computer sends data at a time so every computer on the network may accept packets. When data is sent from computer to computer, the data is actually sent to every computer on the network. When the network card of each machine receives the packets of data it examines who the data is intended for. If the packet is intended for this computer then the packet is accepted, if not, it's discarded.

2.12 Signal encoding

Signal encoding is used to increase system robustness against noise.

Examples:

- FDDI uses 4b/5b NRZI (Non-Return to Zero Invert on ones) with 125 Mb/s baud rate to achieve 100 Mb/s data rate.
- Early Ethernet uses Manchester encoding with 20 Mb/s baud rate (20 MBd) to achieve 10 Mb/s data rate.

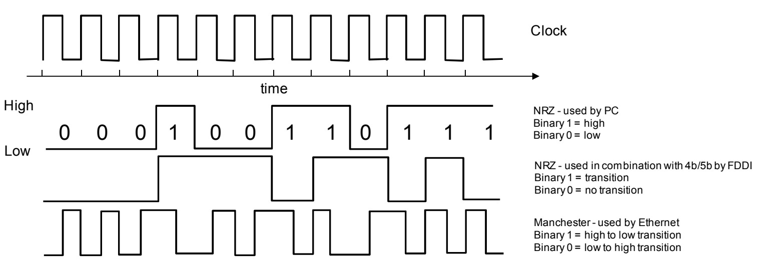

Fig. 2.5 Manchester encoding.

Baud rate - refers to the modulation rate (the shortest modulation unit interval). Manchester encoding was present in the earlier Ethernet implementations and it ultimately enabled a 10 Mb/s transmission speed with frequency bandwidth being two times wider. State of the medium is always changed in the middle of data bit (thus creating a possibility of modulator-demodulator synchronization): transition from high state to low state – "0", transition from low state to high state – "1". Thanks to eliminating the DC component of the modulated signal, Manchester encoding allow the use of electronic elements that do not transfer the DC component, e.g. transmission-line transformers.

2.13 Ethernet Frame

Ethernet traffic is transported in units of a frame, where each frame has a definite beginning and end. The form of the frame is in Fig. 2.6.

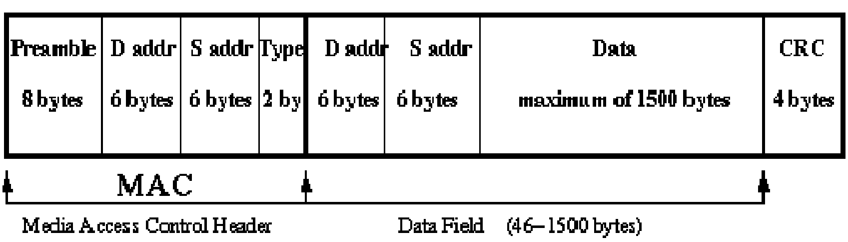

Fig. 2.6 Ethernet frame schematic.

A typical Ethernet frame contains:

- preamble – a train of alternating “1” and “0” pulses which notificate the receiving stations of a frame that is about to arrive; preamble is synchronization – 64 bits
- destination address – address of the station to which the frame is addressed – 48 bits
- source address – address of the source station – 48 bits
- type – denotes the packet type (i.e. of what kind of data is being transmitted) – 16 bits.
- data field containing the source and the destination station address – 46 – 1500 bytes
- cyclical redundancy check (CRC) value – used for error detection; it allows the identification of corrupted (distorted) messages – 32 bits

2.14 MAC

Ethernet Frame transmission and reception must be controlled – via the Media Access Control (MAC) layer. MAC is a sublayer of the OSI-defined Data Link Layer and it is characterized by the following features:

- operates in half or full duplex dependent on support from the physical layer
- handles: data encapsulation from upper layers, frame transmission, frame reception, data decapsulation and pass to upper layers
- does not care about the type of physical layer in use - need to know speed of physical layer

2.15 Elements of Ethernet system

The Ethernet system consists of three basic elements:

1. The physical medium used to carry Ethernet signals between computers
2. A set of medium access control rules embedded in each Ethernet interface that allow multiple computers to negotiate access to the shared Ethernet channel
3. An Ethernet frame that consists of a standardized set of bits used to carry data over the system

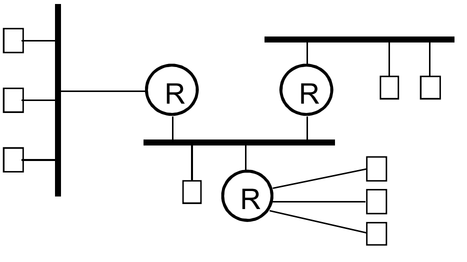

Fig. 2.7 Ethernet network topology.

2.16 Ethernet – early implementations (10 Mbit/s and 1 Mbit/s)

One of the earliest Ethernet implementation is the 10BASE5 being based on a thick coaxial cable. 10BASE5 is thus commonly known as the “thick Ethernet”. It allowed at most 100 computers to be networked and put a limitation of 500 m on the maximum network segment length.

A subsequent implementation, the 10BASE2, relied on the transmission medium realized in form of a thin coaxial cable. Due to the medium type, 10BASE2 is also called the “thin

Ethernet". This implementation featured a maximum number of networked stations equal 30 and a maximum network segment length of 185 m.

A significant improvement in the Ethernet technology was the 10BASE-T implementation in which twisted-pair cables play the role of transmission medium. Introduction of the CAT3 and CAT5 cables increased the maximum segment length up to 500 m.

The first optical fiber-based Ethernet implementation is the 10BASE-F. It employs multimode fibers 62.5/125 and allows network segments 2 km long.

Name	Standard	Description
10BASE5	802.3 (8)	Single coaxial cable (yellow), **Thick-Ethernet**, 10 Mbit/s, max cable length 500m, max number of nodes 100, min intervals 2.5m
10BASE2	802.3 (10)	Single coaxial cable (RG58A/U), **Thin-Ethernet**, 10 Mbit/s, max cable length 185m, max number of nodes 30, min intervals 0.5m
10BROAD36	802.3 (11)	coaxial cable (RG59/U CATV), broad bandwidth, max cable length 3600m, 10 Mbit/s
1BASE5	802.3 (12)	twisted pair telephone wires, max cable length 500m, 1 Mbit/s
10BASE-T	802.3 (14)	4 wires (2 twisted pairs) on a CAT3 or CAT5 cable, max cable length 500m, 10 Mbit/s
10BASE-F	802.3 (15)	Optical Fibers (including passive networks), 10 Mbit/s

Based on ("IEEE Std 802.3," 2008)

2.17 10M Optical Ethernet

In fact, 10BASE-F comprises an entire family of Ethernet standards: -FL, -FB, -FP. Considering its area of applications, the fiber optic 10BASE-F standard can be characterized as shown below.

Name	Standard	Description
10BASE-F	802.3 (15)	
10BASE-FL	802.3 (15&18)	Fiber-optic asynchronous link
10BASE-FB	802.3 (15&17)	Intended for backbones connecting a number of hubs or switches – synchronous link
10BASE-FP	802.3 (15&16)	Passive star Network

Based on ("IEEE Std 802.3," 2008)

Out of the above, only the 10BASE-FL gained popularity. The 10BASE-FP, in turn, has never been implemented.

2.18 10BASE-FL fiber optic Ethernet

In figure Fig. 2.8 a way is shown in which computer can be connected to a 10BASE-FL network segment. The computer is equipped with an Ethernet interface that has a 15-pin AUI connector. This connector allows a connection to an outboard fiber optic MAU (FOMAU), using a standard AUI cable. The FO-MAU, in turn, is connected to the repeater hub with two strands of fiber optic cable.

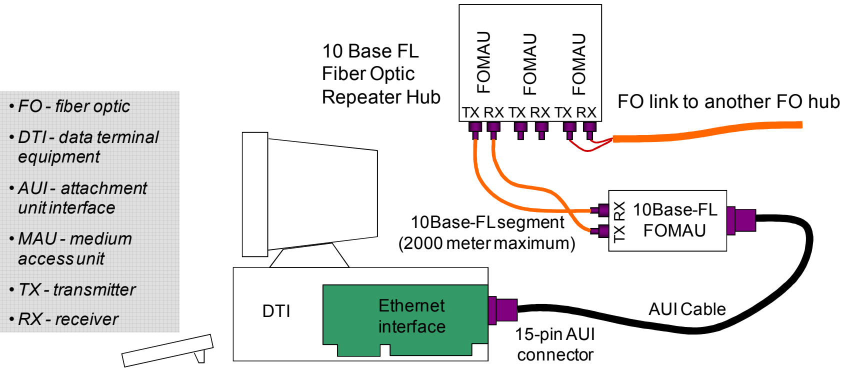

Fig. 2.8 Example of optical Ethernet realization based on the 10BASE-FL standard – connecting a computer (Spurgeon, 1995)**.**

2.19 10Base-FL Network medium

In the 10 BASE-FL, the physical layer has properties that are listed below.

- Transmission medium - multimode fiber cable (MMF) with a 62.5 micron fiber optic core and 125 micron outer cladding (62.5/125). Each link segment requires two strands of fiber, one to transmit data, and the other one to receive data.
- The fiber connectors used on link segments are "ST" connectors
- The wavelength of light used on a fiber link segment is 850 nm.
- The optical loss budget for a fiber link segment must be no greater than 12.5 dB. The loss budget refers to the amount of optical power lost through the attenuation of the fiber optic cable, connector and splices

2.20 Fast Ethernet (100 Mbit/s)

In the early 1990s, a new Ethernet standard was developed. It attained the transmission speed of 100 Mb/s and it is known as the Fast Ethernet. A lot of similarity to the fiber optic standard discussed before, can be found in the Fast Ethernet Data Link Layer behavior at high transmission speeds. The Physical Layer, however, required modifications in order to be capable of supporting the 100 Mb/s data rates. Fast Ethernet standards together with their respective transmission medium types are given below.

Name	Standard	Description
100BASE-T	802.3 (21)	100 Mbit/s Ethernet over twisted pair cable, star topology.
100BASE-TX	802.3 (24)	CAT5 copper cabling with two twisted pairs, 100 Mbit/s
100BASE-T4	802.3 (23)	CAT3 copper cabling (as used for 10BASE-T), 4 twisted pairs (uses all four pairs in the cable), Limited to half-duplex, 100 Mbit/s
100BASE-T2	802.3 (32)	CAT3 copper cabling with 2 twisted pairs, star topology, supports full-duplex, 100 Mbit/s
100BASE-FX	802.3 (24)	two strands of multi-mode optical fiber, Max length 400 m for half-duplex connections (to ensure collisions are detected) or 2 km for full-duplex, 100 Mbit/s

100BASE-SX	TIA	100 Mbit/s Ethernet over multi-mode fiber, Max length 300 m, short wavelength 850 nm (sharable with 10BASE-FL)
100BASE-BX10	Proprietary	100 Mbit/s Ethernet bidirectionally over a single strand of single-mode optical fiber, multiplexer splits transmit and receive signals into different wavelengths allowing them to share the same fiber, max cable length 10 km.
100BASE-LX10	Proprietary	100 Mbit/s Ethernet up to 10 km over a pair of Single Mode Fibers.

Based on (“IEEE Std 802.3,” 2008)

2.21 100Base-FX 100Mb/s Ethernet over the fiber

Figure Fig. 2.9 presents how a connection is realized between computer and a Fast Ethernet 100BASE-FX network segment. In this case, optical fibers are used to directly connect the computer to a repeater. The Ethernet computer interface is furnished with SC, ST or M optical connectors.

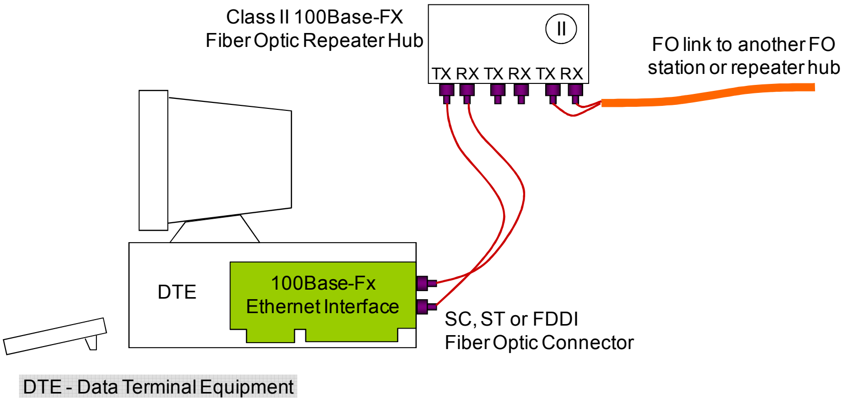

Fig. 2.9 Example of a 100BASE-FX optical Ethernet realization – connecting a computer.

2.22 100Base-FX Network medium

Features of a 100BASE-FX compatible Physical Layer are:

- Multi-mode fiber cable (MMF) with a 62.5 micron fiber optic core and 125 micron outer cladding (62.5/125).
- Maximum cable length is: Half Duplex - 412 m and Full Duplex – 2 km (round trip timing)
- The fiber connectors used on link segments are SC, M or ST connectors
- The wavelength of light used on a fiber link segment is 1350 nm.
- The optical loss budget for a fiber link segment must be no greater than 11 dB. The loss budget refers to the amount of optical power lost through the attenuation of the fiber optic cable, connector and splices

2.23 10M and 100M Ethernet – comparison

Below, a comparison is given between transmission speeds and maximum segment length for the Ethernet and Fast Ethernet network technologies. Several different transmission media are considered: twisted-pair cable, coaxial cable, multimode fiber, and single-mode fiber.

	Ethernet	Fast Ethernet
Transmission Speed	10 Mbit/s	100 Mbit/s
CAT5 UTP	100 m	100 m
STP/Coax	500 m	100 m
Multi Mode Fiber	2 km	412 m (half duplex) 2 km (full duplex)
Single Mode Fiber	25 km	20 km

3 Optical Ethernet – 1G

3.1 Standard IEEE 802.3 History

Although the beginning of the Ethernet dates back to the 1970s, the first Ethernet standard was developed in 1985 by the IEEE 802.3 group and it concerned the 10BASE5 and 10BASE2 technologies enabling a maximum transmission speed of 10 Mb/s. Already three years after the ratification of the first standard, the IEEE 802.3d standard emerged. It concerned the FOIRL (Fiber-Optic Inter-Repeater Link) technology, which enabled network concentrators to be interconnected with optical fibers. The 1990s are a period of intensified efforts aiming at making the Ethernet faster. Numerous new standards were developed including even that of the Gigabit Ethernet technology (Kaplan & Noseworthy, 2001).

- 1985 – IEEE 802.3 – 10Base-5 & 10Base-2
- 1987 – IEEE 802.3d – FOIRL
- 1990 – IEEE 802.3i – 10Base-T
- 1993 – IEEE 802.3j – 10Base-F
- 1995 – IEEE 802.3u – 100Base-T4 / TX / FX
- 1997 – IEEE 802.3y – 100Base-T2
- 1998 – IEEE 802.3z – 1000Base-SX / LX / CX
- 1999 – IEEE 802.3ab – 1000Base-T

3.2 Optical Ethernet Evolution

History of optical Ethernet (i.e. the one employing optical fibers as transmission medium) is described in some more detail below (Kaplan & Noseworthy, 2001).

- 1987 – Fiber Optic Inter-Repeater Link (FOIRL):
  - This technology only dealt with interconnecting the network concentrators by means of multimode fibers.
  - Only allowed a maximum segment size of 2 km.
  - It was historically the first Ethernet standard that described fiber optic telecommunications.
- 1993 – 10Base-F:
  - A family of Ethernet standards of which were all based on multimode fibers.
  - Maximum segment size – 2 km.
- 1995 – 100Base-FX:
  - This standard had adopted solutions originating from the FDDI technology.

        - Fast Ethernet (100 Mb/s) employing fiber optic cables.
    - 1998 – 1000Base-SX / LX:
        - Application of solutions originating from the Fiber Channel technology.
        - Historically, the first Gigabit Ethernet.
        - Transmission speed of 1 Gb/s.
        - Utilization of multimode as well as single-mode fibers.

3.3 Gigabit Ethernet design

The IEEE 802.3z group defined specific guidelines concerning the Gigabit Ethernet network design. The guidelines are (Norris, 2003):

- The network should offer transmission bandwidth 10 times wider than Fast Ethernet does – 1000 Mb/s
- Frame format specified for the IEEE 802.3 standard should be used.
- The MAC layer should use the same scheme of half- and full-duplex operation as it was the case in previous versions of Ethernet.
- Compatibility with technologies earlier applied in the 10 Mb/s and 100 Mb/s Ethernet, should be maintained.
- All network protocols used in Ethernet technologies should be supported.

3.4 Architectural Model of IEEE 802.3z Gigabit Ethernet

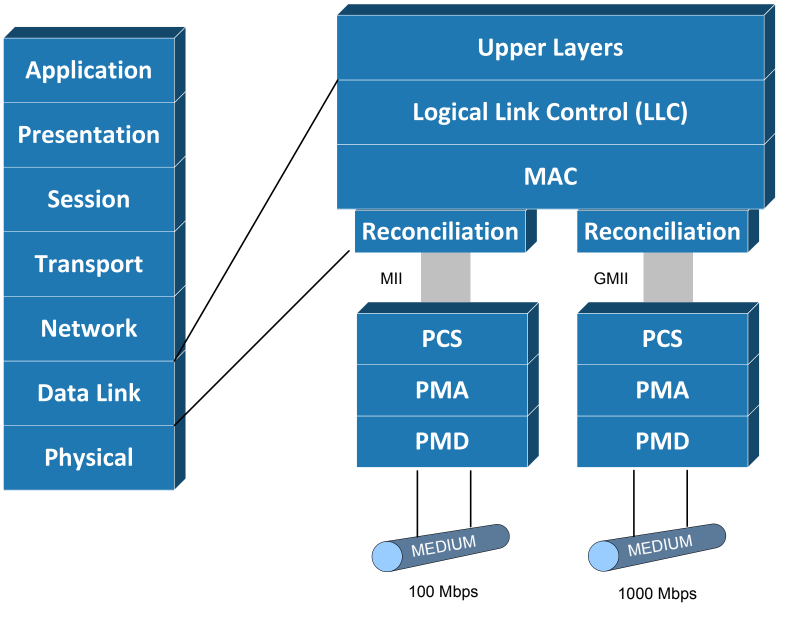

Fig. 3.1 Gigabit Ethernet architecture (based on ("Introduction to Gigabit Ethernet," 2000)**).**

In figure Fig. 3.1 there is shown the architecture defined by the IEEE 802.3z standard for Gigabit Ethernet. The Data Link layer contains a Logical Link Control (LLC) sublayer, which, as long as transmission is considered, is responsible for demultiplexing of data transmitted by the MAC layer. In the case of reception, LCC is responsible for multiplexing of data. It can also control the data flow, detect and resend missing data packets. LCC is identical for all different Physical layers.

The MAC layer is coupled with the Physical layer by means of the GMII (Gigabit Media Independent Interface) interface, which is an extension of the MII interface used in the Fast Ethernet technology. GMII features two separate 8-bit data paths, which enable it to operate in both half- and full-duplex modes. Moreover, it supports transmission speeds of 10 Mb/s, 100 Mb/s, and 1000 Mb/s thus meeting the requirement for backward compatibility of Gigabit Ethernet with its predecessors.

The Physical layer is divided into three sublayers: PCS, PMA, and PMD. The first one, the PCS (Physical Coding Sublayer), is connected with the Reconciliation sublayer. Here, the 8B/10B encoding (identical as in Fiber Channel technology) and PAM5 encoding (Pulse Amplitude Modulation) are used in the case of optical fiber and twisted-pair cables, respectively. PCS sublayer's responsibility is the encoding / decoding of data flowing to / from the MAC layer. The PMA (Physical Medium Attachment) sublayer transforms signals into bit trains suitable for transmission over the transmission medium. The PMD (Physical Medium Dependent) sublayer is responsible for signal transmission.

3.5 Gigabit Ethernet PHY

In figure Fig. 3.2 there is shown a comparison between Physical layers of Ethernet technologies is shown defined by the IEEE 802.3z and IEEE 802.3ab standards. In the 1000BASE-X standard, the 8B/10B encoding followed by the NRZ line encoding, is employed. In 8B/10B a train of 8 bits is converted into a 10 bit train. Similarly to the 4B/5B encoding, there is a 20% data redundancy, which is used for control characters (start of packet, end of packet, idle) as well as for cyclic redundancy codes (CRC). The NRZ line encoding (i.e. encoding that produces digital signal suitable for transmission without a need of any further encoding) relies on detecting signal pulse levels rather than signal pulse edges as it is the case in other line encodings. In other words, determining a signal pulse to be the logical "1" or "0" is performed based on pulse level instead of pulse level transition (edge). The encoded signal is coupled into optical fiber by means of a LED or LD. In the case of the 1000BASE-SX technology, LEDs or LDs emitting at 850 nm are employed. In the 1000BASE-LX standard, only laser sources (LDs) emitting at 1300 nm are used.

The 802.3ab standard concerns the 1000BASE-T technology, which is based on unshielded twisted-pair cables as transmission medium. Cables CAT5 or better are allowed. In the PCS sublayer, the 4D-PAM5 (4 Dimensional Pulse Amplitude Modulation with 5 levels) line encoding is performed.

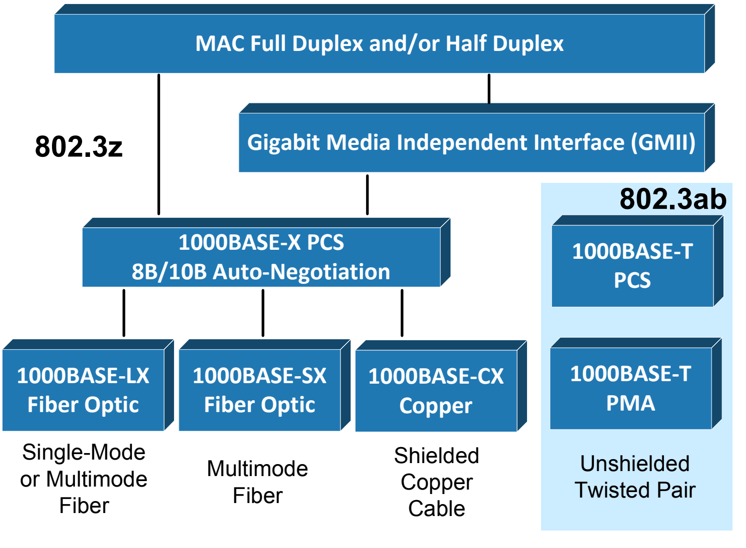

Fig. 3.2 Physical layers of the 802.3z and 802.3ab standards (based on ("Introduction to Gigabit Ethernet," 2000)**).**

3.6 PHY Standards for GigE

Below, a summary is presented of Physical layer configurations that are characteristic of several basic Gigabit Ethernet technologies. Also maximum segment length values are given. The highest segment length is attainable with the 1000BASE-LX technology by using a single-mode fiber as transmission medium and a laser emitting at the wavelength of 1300 nm.

	1000BASE-SX	1000BASE-LX	1000BASE-CX	1000BASE-T
Medium	Optical fiber Multimode Two strands	Optical fiber Singlemode Multimode Two strands	Shielded copper cable	Twisted pair category 5 UTP
Max. Segment Length	550 m	5 km	25 m	100 m
Topology	Star	Star	Star	Star

3.7 Distances for the media (IEEE 802.3z and 802.3ab)

Figure Fig. 3.3 shows a summary of available Physical layer configurations in the 802.3z and 802.3ab standards. Also maximum segment length values are given. There are mentioned different kinds of multimode and single-mode fibers mentioned for the 1000BASE-X family of optical technologies, 4-pair CAT5 unshielded twisted pair cables for the 1000BASE-T technology, and balanced (containing 2 conductors) copper shielded cables for 1000BASE-CX.

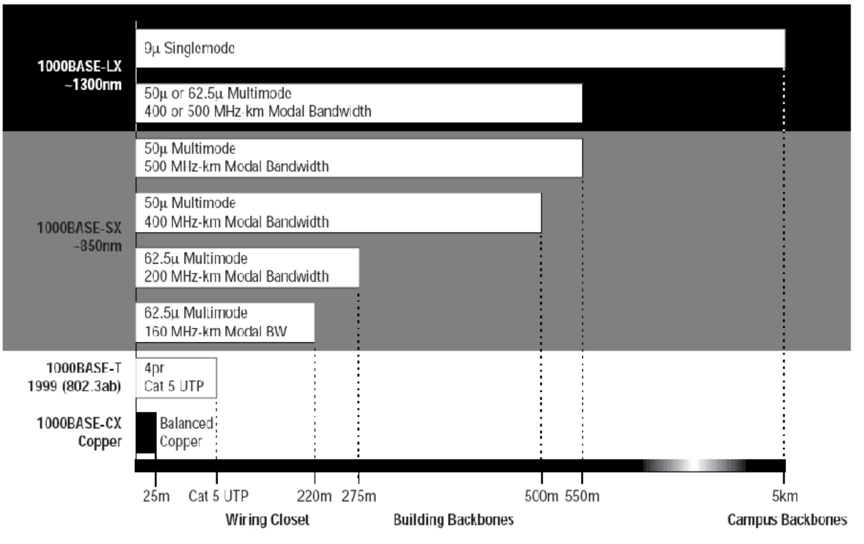

Fig. 3.3 Maximum segment lengths allowed in the 802.3z and 802.3ab standards ("Introduction to Gigabit Ethernet," 2000)

3.8 GBIC

Gigabit Ethernet Interface Converter (GBIC) is a standard designed for transceivers (transmitting / receiving devices) and frequently employed by the Gigabit Ethernet technology. GBIC offers an easy way of realizing a coupling between optical and electrical transmission media. GBIC devices ensure a high degree of flexibility, which is a significant advantage over fixed configurations of physical interfaces. The following GBIC types exist:

- SX – multimode fiber, maximum cable distance of 500 m

- LX – single-mode fiber, maximum cable distance of 10 km
- LH – single-mode fiber, maximum cable distance of 70 km

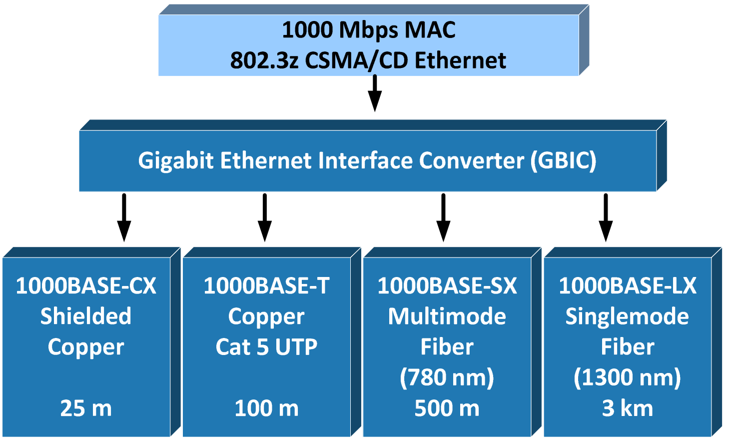

Fig. 3.4 Areas of GBIC application (based on (“Introduction to Gigabit Ethernet,” 2000)**).**

3.9 Evolution of existing FO networks towards 1G Ethernet – photonic hardware issues

Designers of new network standards usually adjust network structure do already existing cabling standards. It is because they aim at building networks that can be characterized as “plug-and-play”. Sometimes, however, discrepancies can occur:

- Application of 850 nm laser diodes for multimode fibers in 1000BASE-SX requires the maximum cable length to be limited down to 200 m (instead of 300 m).
- Application of 1300 nm laser diodes in 1000BASE-LX requires the use of mode conditioning patch cords.

As a conclusion: Gigabit Ethernet networks (and other advanced network solutions) will not be “plug-and-play” with the TIA-568 cabling.

The EIA/TIA 568A standard (Building Telecommunications Wiring Standards) concerns telecommunication cabling for large office buildings. The TSB-72 (Centralized Optical Fiber Cabling Guidelines) is a telecommunications bulletin supplementing the EIA/TIA 568A standard. It introduces a centralized optical fiber cabling. Comparisons between the TIA standard for optical cables and the Gigabit Ethernet requirements is given below.

Optical Fiber	Interbuilding	Intrabuilding TSB-72	TSB-72
62.5/125 µm	max 2000 m	max 500 m	max 300 m
Singlemode	max 3000 m	max 3000 m	

Gigabit Ethernet distances

Gigabit Ethernet	Wavelength (nm)	Fiber Type	Modal BW (MHz*km)	Minimum Range (m)
1000BASE-SX	850	62.5/125 µm	160	2 – 220
1000BASE-LX	1300	62.5/125 µm	500	2 – 550

Multimode waveguide TIA 62.5/125 has been adapted from FDDI networks, which for backbone guaranteed a range of 2000 m. TIA 62.5/125 fiber bandwidth has been determined for overfilled launch (OFL) with a LED light source. In the course of work on 1 Gigabit Ethernet it turned out, that LD bandwidth can be lower than original LED bandwidth. Because of limited capabilities of LED modulation, only LD light sources are used in Gigabit Ethernet.

The highest networking bandwidth obtained with LED is ATM 622 Mb/s fiber optic link.

3.10 LD and LED – Light Sources Comparison

Figure Fig. 3.5 illustrates how light coming from a LED diode covers (fills) the entire core of a multimode fiber. In turn, a narrower beam emitted by a laser diode covers only the central part of the multimode fiber core. Optical fiber defects arising during fiber manufacture, may result in much more severe consequences when a narrow laser beam interacts with a fiber core than it is the case when LED diode beam is considered. In fiber manufacturing process, especially in case of gradient-index fibers, some unintended inhomogeneities in fiber material arise. These defects will affect light propagation more severely when light source beam diameter is low (see figure Fig. 3.6). To avoid difficulties introduced by the mechanism described above, the so called mode conditioning patch cords can be applied (see figure Fig. 3.8).

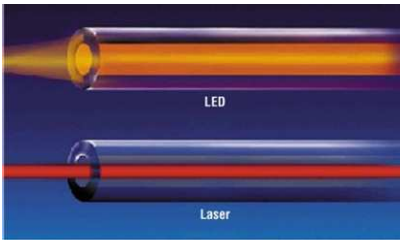

Fig. 3.5 Light beam emitted by a LED diode fills the volume of a multimode fiber core (top). A narrow beam emitted by a laser diode mostly propagates near the central part of the core (bottom) (DiMinico, 2001)**.**

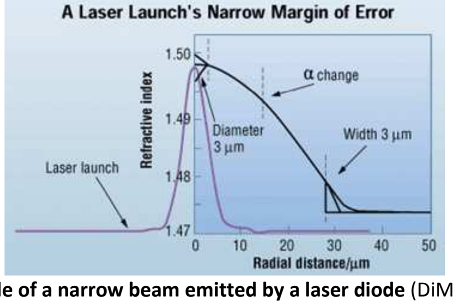

Fig. 3.6 Profile of a narrow beam emitted by a laser diode (DiMinico, 2001)**.**

3.11 Modal Dispersion Issue

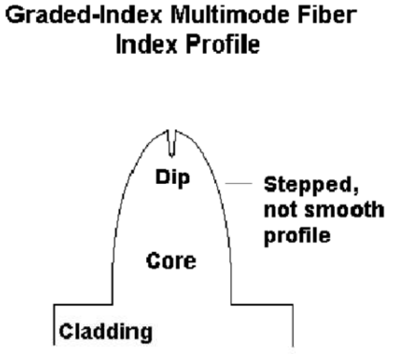

Fig. 3.7 Deviation in the center of the core in graded-index multimode fiber (Kaplan & Noseworthy, 2001)

A significant fraction of already installed gradient-index multimode fibers shows some deviations from an ideal refractive index profile. Especially, a dip may be observed (see figure Fig. 3.7) in the center of a parabolic profile. Deviations of this kind increase the fiber mode dispersion (DMD, differential modal delay). This, in turn, results in a decrease of maximum attainable fiber length in Gigabit Ethernet installations (Kaplan & Noseworthy, 2001).

3.12 Launch Condition

Elimination of DMD is realized by means of mode conditioning patch cords (MCP). The MCP technology relies on connecting (splicing), in a single patch cord, a single-mode fiber to a multimode fiber with a precisely controlled amount of lateral shift between cores of the fibers. If the shift is adjusted properly, light emerging from the single-mode fiber excites a large number of multimode fiber's modes thus realizing the mode conditioning idea. By eliminating the DMD it is possible to extend transmission distances attainable in Gigabit Ethernet networks.

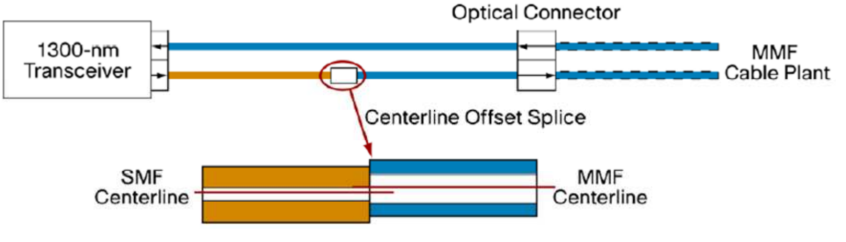

Fig. 3.8 Mode-conditioning patch cord ("Fiber Types in Gigabit Optical Communications," 2008)

3.13 Gigabit Ethernet Standards – Overview.

3.13.1 1000BaseT

- Transmission Rate:1 Gb/s (2 Gb/s in Full-Duplex mode
- Medium: 4-pairs of Cat 5 or better (100Ω impedance)
- Maximum Distance: 100 m
- Connectors 8-Pin RJ-45
- Signal Encoding: PAM5

3.13.2 1000BASE-LX Overview

- Transmission Rate: 1 Gb/s (2 Gb/s in Full-Duplex mode)
- Medium:
    - Two 62.5/125 or 50/125 MMFs
    - Two 10 μm SMFs
- Maximum Distance:
    - Half-Duplex MMF & SMF: 316 m
    - Full-Duplex MMF: 550 m
    - Full-Duplex SMF: 5000 m
- Connectors : Duplex SC
- Signal Encoding: 8B/10B

3.13.3 1000BASE-SX Overview

- Transmission Rate:1 Gb/s (2 Gb/s in Full-Duplex mode)
- Medium:
    - Two 62.5/125 or 50/125 MMFs, 770 to 860 nm
- Maximum Distance:
    - Half-Duplex 62.5/125: 275 m
    - Half-Duplex 50/125: 316 m
    - Full-Duplex 62.5/125: 275 m
    - Full-Duplex 50/125: 550 m
- Signal Encoding: 8B/10B

3.14 Non-Standard Interfaces

There also exist some Gigabit Ethernet versions that are still not included in any widely accepted standard. Such unstandardized versions are listed below.

- 1000Base-LH
    - 10km distances over SMF
    - Cooperation with LX for 5 km (same wavelength, higher transmit power and lower receive sensitivity)
- 1000base-XD
    - 50km distances over SMF
    - Does not interoperate with any other interface type
- 1000Base-ZX
    - 70km distances over SMF (100km on dispersion shifted fiber)
    - Does not interoperate with any other interface type

4 Optical Ethernet, beyond 10G

4.1 10 Gigabit Ethernet - 802.3ae

In 2002 the first version of the IEEE 802.3ae standard was published. The standard defined the 10 Gb/s Ethernet technology employing optical fibers as transmission medium. Later versions of this standard, the IEEE 802.3ak and IEEE 802.3an, assumed copper cables as transmission medium (4-pair unshielded twisted-pair cables like in Gigabit Ethernet). As all new Ethernet technologies maintain backward compatibility, also the standards mentioned above used data frame of length and structure identical to earlier members of the Ethernet technology family.

There are three main differences between the optical version of 10 Gb/s Ethernet and its predecessors. Before all, the optical 10 Gb/s Ethernet only supports full-duplex operations. This modification enabled the elimination of the CSMA multiple access protocol. Secondly, maximum segment lengths of 40 km became common due to single-mode fibers that began to be frequently used in the Physical layer. Significant increase in segment length encouraged the adaptation of Ethernet technology to MAN or even WAN networks (earlier, Ethernet application was only rational in LANs). Thirdly, besides the Physical layer's interface that supported LAN, another interface, WAN PHY, was developed. Thanks to WAN PHY, 10 GbE (10 Gigabit Ethernet) is compatible with networks based on the OC-192 SONET technology.

To summarize, optical 10 Gigabit Ethernet defined by the IEEE 802.3ae standard, can be characterized by the following features:

- Supports full-duplex operation only.
- Provides Physical layer specifications which support link distances of:
    - At least 300 m over installed MMF
    - At least 65 m over MMF
    - At least 2 km over SMF
    - At least 10 km over SMF
    - At least 40 km over SMF
- Defines two families of PHYs:
    - a LAN PHY, operating at a data rate of 10.000 Gb/s
    - a WAN PHY, operating at a data rate compatible with the payload rate of OC-192c/SDH VC-4-64c

4.2 Architectural positioning of 10GbE

The 10 Gigabit Ethernet architecture displayed in figure Fig. 4.1 shows details of the two lowest OSI-model layers (the Physical and the Data Link layers). Similarly to earlier Ethernet versions, in the Data Link layer, there are LLC and MAC sublayers that ensure logical connection between MAC layer clients and the Physical layer. The 10 GbE MAC layer is also similar to its predecessors. It uses identical addresses, frame size and frame format only operations performed by 10 GbE MAC are more complicated.

As mentioned earlier, 10 Gigabit Ethernet (only) supports full-duplex transmissions. Thanks to this feature, neither competition for medium access nor collisions occur. Network operations are performed faster, and transmission bandwidth of each network node has been doubled. Moreover, besides being faster, the full-duplex mode operation is generally simpler.

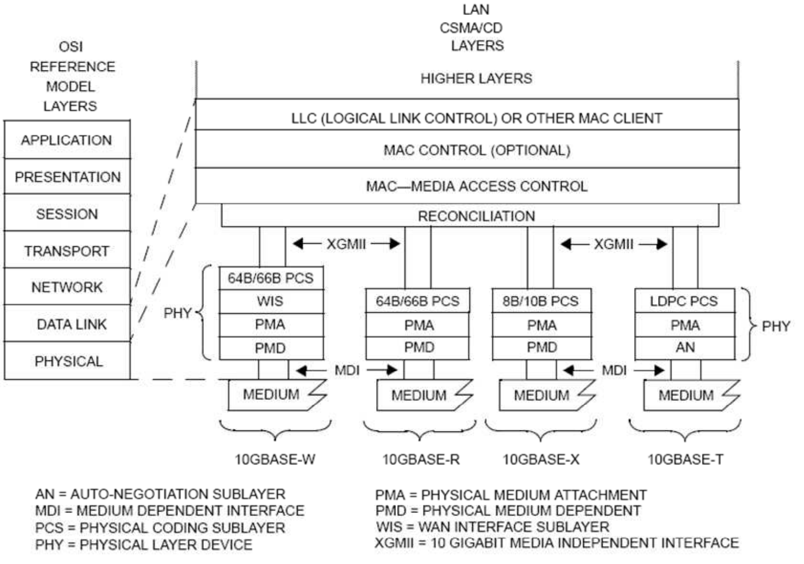

Fig. 4.1 10 Gigabit Ethernet architecture – a detailed view of the two lowest OSI-model layers ("IEEE Std 802.3," 2008)**.**

4.3 XGMII

Connection between the Physical and Data Link layers is carried out by an independent XGMII (10 Gigabit Media Independent Interface) interface that is an extension of earlier interfaces: GMII and MII. XGMII's task is to provide a fast, low-price, and easily implementable connection between the MAC and Physical layers. According to the 10 Gigabit Ethernet guidelines, the XGMII interface only supports operations at 10 Gb/s (at slower speeds, GMII or MII need to be employed) and only works in full-duplex mode. Like its predecessor, XGMII is independent of transmission medium type being used.

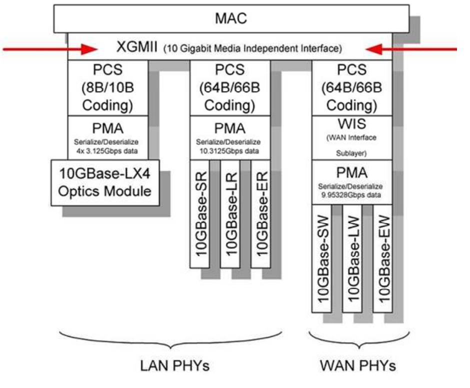

Fig. 4.2 XGMII interface supporting different types of 10 GbE Physical layers (Kaplan & Noseworthy, 2001)**.**

XGMII ensures a 32-bit data path divided into four 8-bit lines. Additionally, there exist a 4-bit path for control signals. Finally, taking into consideration also the full-duplex operation and some additional control signals, the XGMII connector needs 74 pins (Kaplan & Noseworthy, 2001).

4.4 PHY Sublayers

The 10 GbE Physical layer can be divided into, known from earlier Ethernet versions, three sublayers:

- physical coding sublayer (PCS)
- physical medium attachment (PMA)
- physical medium dependent (PMD)

Additionally, in order to match the transmission speeds of long-reach Ethernet systems to speeds present in SONET/SDH networks, additional sublayer is needed:

- WAN Interface Sublayer (WIS)

10 Gigabit Ethernet features two Physical layer specifications:
Both LAN PHY and WAN PHY support the same PMD sublayers thus allowable maximum segment lengths are identical.

- LAN PHY
  - works as a local area fiber network
  - compatible with earlier Ethernet versions
  - asynchronous network
- WAN PHY
  - interconnects Ethernet and SONET/SDH networks
  - compatible with OC-192c/SDH VC-4-64c
  - asynchronous network
  - additional sublayer is employed (WIS)

Both LAN PHY and WAN PHY support the same PMD sublayers thus allowable maximum segment lengths are identical.

4.5 Physical Coding Sublayer

Similarly to earlier Ethernet versions, the PCS sublayer is responsible for encoding / decoding of data flowing form / to MAC layer. The IEEE 802.3ae standard allowed two different encoding types. The 10GBASE-LX4 technology, which assumed multiplexing of four parallel data streams, employed the 8B/10B encoding (known from Gigabit Ethernet). The 8B/10B encoding increased the transmission bandwidth demand by 20% per channel. Transmission bandwidth required by each of the four channels, changed from 2.5 Gb/s to 3.125 Gb/s thus summing up to a value of 12.5 Gb/s.

To summarize, employing the 8B/10B encoding in a four-channel transmission increases the transmission bandwidth demand by 25% to support the 10 Gb/s transmission.

For serial transmission, a new encoding scheme was developed, 64B/66B, that relies on converting 64-bit trains into 66-bit trains. In this way, transmission bandwidth demand is only increased by 3.125%. This, in turn, translates into 10.3125 Gb/s when 10 Gb/s transmissions are considered.

Taking the PCS sublayer configuration as a classification criterion, the family of 10 Gigabit Ethernet technologies is classified in the following way:

- 10GBASE-R – Serially encoded (64B/66B); 10.3125 Gb/s rate not SONET compatible (LAN PHY)
- 10GBASE-X – Serially encoded (8B/10B); used for wavelength division multiplexing (WDM) transmissions (LAN PHY)
- 10GBASE-W – Serially encoded (64B/66B); compatible with SONET standards for a 10 Gb/s WAN (WAN PHY)

4.6 Physical medium dependent

The PMD sublayer is again responsible for data transmission. In the 10 Gigabit Ethernet technology, utilization of three telecommunication windows is allowed: 850 nm, 1310 nm, and 1550 nm. Single-mode as well as multimode fibers play the role of transmission medium.

Let us now look at requirements imposed on 10 Gigabit Ethernet networks in terms of achievable distances, costs, utilization of already existing infrastructure, and compatibility. We will identify four PMD sublayer configurations that best match different needs. And so, if achieving the longest segment distance is crucial, a network of choice is the one that operates in the third telecommunication window and employs serial transmission. With serial transmission-based networks operating in the second telecommunication window, slightly shorter segment distances are possible. Such networks, however, offer compatibility with already existing transponders and require lower costs. In cases when costs of building a 10 GbE network are the decisive factor, the optimal solution from economic standpoint is operating in the first telecommunication window for which the most cost-effective light sources are available. Finally, in order to maximally adapt already existing optical fiber cabling (both single-mode and multimode), employing the WWDM technology operating in the second telecommunication window is recommended.

The analysis of requirements and optimal solutions is repeated in a concise form below.

Application	Optimal Solution
Longest Distance (40+ km)	1550 Serial
Med. reach, lower cost, transponder compat.	1310 Serial
Max reuse of installed MM/SM (Building LAN)	1310 WWDM
Low cost on MM (Equipment Room)	850 Serial

Based on (Kaplan & Noseworthy, 2001)

4.7 PMD Names

Each Physical layer configuration is identified by its unique name. Below, there are general rules listed of how such names are created (Kaplan & Noseworthy, 2001).

- Wavelength: S=850nm L=1310nm E=1550nm
- PMD Type:
  - X=WDM LAN(Wave Division Multiplexing – 4 wavelengths on 1 fiber)
  - R=Serial LAN using 64B/66B coding (LAN Application)
  - W=Serial WAN – SONET OC-192c compatible speed/framing

There are thus seven basic versions of 10 Gigabit Ethernet:

- 10GBASE-LX4
- 10GBASE-SR / -LR / -ER
- 10GBASE-SW / -LW / -EW

4.8 Types of 10 Gigabit Ethernet

Below, possible Physical layer configurations in 10 GbE are listed.

Interfaces	Type	Encoding	Wavelength	Fiber Type	Distance
10GBASE-LX4	WWDM	8B/10B	1310 nm	MMF or SMF	300 m or 10 km
10GBASE-SR	Serial	64B/66B	850 nm	MMF	65 m
10GBASE-LR	Serial	64B/66B	1310 nm	SMF	10 km

10GBASE-ER	Serial	64B/66B	1550 nm	SMF	40 km
10GBASE-SW	Serial	64B/66B, SONET	850 nm	MMF	65 m
10GBASE-LW	Serial	64B/66B, SONET	1310 nm	SMF	10 km
10GBASE-EW	Serial	64B/66B, SONET	1550 nm	SMF	40 km

Based on (Kaplan & Noseworthy, 2001)

4.9 WAN Interface Sublayer (WIS)

WAN Interface Sublayer (WIS) is the optional sublayer of the Physical layer. WIS is located between the data encoding sublayer (PCS, see 4.3 and 4.4) and a sublayer responsible for transmitting into medium (PMA). WIS ensures the possibility of interconnecting the Ethernet technology-based networks with SONET/SDH networks (WIS realizes transmission management, error detection, and other tasks). SONET data packets (16-bit words) differ from data packets used in 10 Gigabit Ethernet (66-bit words). This is the WIS sublayer that converts packets between the two systems. It also appropriately converts transmission speeds between the SONET's 9.95328 Gb/s and Ethernet's 10 Gb/s.

WIS only appears in the WAN PHY configuration. Thanks to this sublayer, connecting network stations over distances as long as tens of kilometers, is possible.

4.10 10 Gigabit Ethernet in LAN

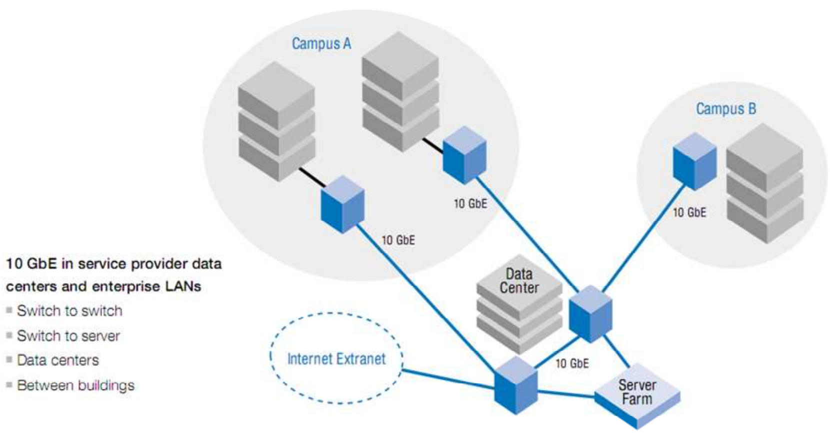

Fig. 4.3 Example of a LAN network realized in the 10 Gigabit Ethernet technology ("10 Gigabit Ethernet Technology Overview," 2003)**.**

Ethernet technologies, which are currently the most popular standards in LAN network realizations, are being continuously extended and enhanced. This enables the Ethernet-based networks to meet more and more stringent requirements put on telecommunication networks. The increasing number of applications require wider transmission bandwidths and longer transmission distances achievable with a given type of network. LAN networks realized in the 10 GbE technology, allow enterprises that posses vast network infrastructures, to effectively locate data centers and server farms. Locations can be chosen without practically any limitation if we consider that single LAN segment can reach as far as 40 km. Even within data centers themselves, network backbones can be created that will rely on efficient, cost-effective solutions employing single-mode or multimode optical fibers. Such backbones realize either switch-to-switch or switch-to-server connections. Furthermore, 10 GbE-based backbones can easily realize connections between workstations and computers without creating excessive load in the network. Thus, bandwidth demanding applications can be supported (e.g. video streaming, medical imaging, centralized applications, or high-end graphics) ("10 Gigabit Ethernet Technology Overview," 2003).

Transmission bandwidth offered by 10 GbE-based network backbones enables the use of modern network applications in the following areas:

- telemedicine
- telecommuting
- e-learning
- videoconferences
- HDTV
- video-on-demand
- internet gaming

4.11 10 Gigabit Ethernet in MAN

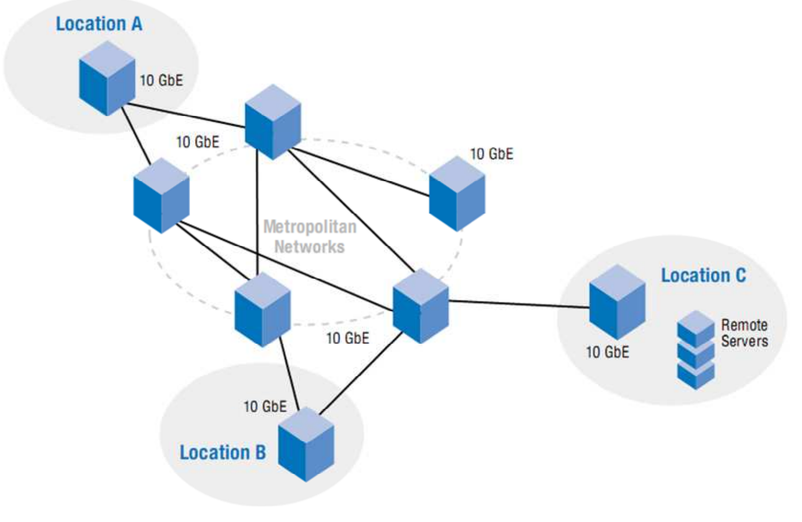

Fig. 4.4 Example of a MAN network realized in the 10 Gigabit Ethernet technology ("10 Gigabit Ethernet Technology Overview," 2003)**.**

10 Gigabit Ethernet technology also proves useful in metropolitan networks thanks to adapting already existing backbone networks based on the Gigabit Ethernet technology.

By appropriately configuring the 10 GbE interface and by employing optical transmitters and single-mode fibers, it is possible to build 40 km long network segments that encompass metropolitan areas. This way, network access for entire city can be offered.

Building the infrastructures for SAN (Storage Area Network) and NAS (Network Attached Storage) networks is currently mostly carried out with Fiber Channel, ATM, or HIPPI (High-Performance Parallel Interface) networks. The 10 GbE standard can, however, also be used successfully in these types of applications as it offers fast connections and is economically reasonable. There are multiple applications that use (can use) the 10 Gigabit Ethernet technology, e.g. ("10 Gigabit Ethernet Technology Overview," 2003):

- business continuance / disaster recovery
- remote back-up
- storage on demand
- streaming media

4.12 40 and 100 Gigabit Ethernet

In June 2010, a new standard, IEEE 802.3ba, was ratified. It defines requirements that must be met by the 40 Gigabit Ethernet and 100 Gigabit Ethernet technologies. It is the first IEEE standard, that allows two transmission speeds. As earlier Ethernet version, also the new standard is compatible with already existing LAN networks and it supports identical frame format. Achieving such high data rates is realized by means of multiplexing four data lines each one transmitting at 10 Gb/s or 25 Gb/s. It should be noted that the new solutions will not be compatible with the already existing 40 Gigabit DWDM.

To summarize, assumptions made for 40 and 100 Gigabit Ethernet are ("IEEE Std 802.3ba," 2010):

- Ethernet standards developed by IEEE 802.3ba Ethernet Task Force
- Ratified in June 2010
- Support sending Ethernet frames at 40 and 100 gigabits per second over multiple 10 Gb/s or 25 Gb/s lanes
- NOT compatible with 40 Gigabit transport solutions DWDM (four 10 Gigabit signals in one optical medium)

4.13 IEEE 802.3ba Objectives

Requirements defined for 40 GbE and 100 GbE and ratified by the IEEE 802.3ba working group are cites below (D'Ambrosia, Law, & Nowell, 2008).

- Support full-duplex operation only
- Preserve the 802.3 / Ethernet frame format utilizing the 802.3 MAC
- Preserve minimum and maximum FrameSize of current 802.3 standard
- Support a BER better than or equal to 10^{-12} at the MAC/PLS service interface
- Provide appropriate support for OTN
- Support a MAC data rate of 40 Gb/s
- Provide Physical Layer specifications which support 40 Gb/s operation over:
    - at least 10km on SMF
    - at least 100m on OM3 MMF
    - at least 7m over a copper cable assembly
    - at least 1m over a backplane
- Support a MAC data rate of 100 Gb/s
- Provide Physical Layer specifications which support 100 Gb/s operation over:
    - at least 40km on SMF
    - at least 10km on SMF
    - at least 100m on OM3 MMF
    - at least 7m over a copper cable assembly

Like previously in 10 GbE, only full-duplex operations are supported and frame format and frame length remain identical as they are in the entire 802.3 family of standards. Compatibility with OTN and SONET/SDH networks should also be mentioned.

4.14 PHY Specifications for IEEE P802.3ba

Physical layer specification in the IEEE 802.3ba standard has been divided into two parts in respect to data transmission speeds being available. The PHY for 40 Gigabit Ethernet technology aims at the following application areas (Hankins, 2010):

- Servers
- Data Center
- Campus
- Metro
- Backbone

Before all, single-mode and multimode fibers are planned as transmission medium. Nevertheless, two versions of the standard still consider copper cables in the role of transmission medium. Such copper cabling-based solutions are only intended to be employed at very short distances like e.g. within server racks and entire server rooms. Thus, building efficient networks of closely spaced devices is possible at relatively low costs. Solutions based on multimode fibers are limited to maximum segment lengths of 100 m in the case of MMF OM3 and 125 m in the case of MMF OM4. The most expensive implementation is the one based on the 40GBASE-LR4 standard. However, thanks to single-mode fibers, segments 10 km long are possible in this implementation.

Below, Physical layer specifications for 40 GbE are listed together with their expected availability dates and rough cost estimates (Hankins, 2010).

<table>
<tr><th>Physical Layer Reach</th><th>1 m backplane</th><th>7 m copper cable</th><th>100 m OM3, 125 m OM4, MMF</th><th>10 km SMF</th><th>40 km SMF</th></tr>
<tr><td>Name</td><td>40GBASE-KR4</td><td>40GBASE-CR4</td><td>40GBASE-SR4</td><td>40GBASE-LR4</td><td></td></tr>
<tr><td>Signaling</td><td>4 x 10 Gb/s</td><td>4 x 10 Gb/s</td><td>4 x 10 Gb/s</td><td>4 x 10 Gb/s</td><td></td></tr>
<tr><td>Media</td><td rowspan="2">Copper Backplane</td><td>Twinax Cable</td><td>MPO MMF</td><td>Duplex SMF</td><td></td></tr>
<tr><td>Module/ Connector</td><td>QSFP Module, CX4 Interface</td><td>QSFP Module</td><td>QSFP Module, CFP Module</td><td></td></tr>
<tr><td>Availability</td><td>No Known Development</td><td>2010</td><td>2010</td><td>CFP 2010
QSFP 2011-2012</td><td></td></tr>
<tr><td>Price</td><td>$$</td><td>$$</td><td>$$</td><td>$$$$</td><td></td></tr>
</table>

The PHY for 100 Gigabit Ethernet technology aims at the following application areas (Hankins, 2010):

- Data Center
- Campus
- Metro
- Backbone
- WAN

As compared to 40 GbE, the Physical layer will no longer support the backplane 1 m connections. In order to meet requirements present in WAN networks, it will be possible to achieve transmission speeds of 100 Gb/s at distances of 40 km. Single-mode fiber will be required in that case. Implementation of this version of the standard is expected for years 2011-2012 and will definitely be the most expensive one. Also costs of building the networks based on other Physical layer configurations, will become higher. This is due to the need for a higher number of optical fibers as well as more complicated network modules and connectors.

Below, Physical layer specifications for 100 GbE are listed together with their expected availability dates and rough cost estimates (Hankins, 2010).

Physical Layer Reach	1 m backplane	7 m copper cable	100 m OM3, 125 m OM4, MMF	10 km SMF	40 km SMF
Name		1000GBASE-CR10	100GBASE-SR10	100GBASE-LR4	100GBASE-ER4
Signaling		10 x 10 Gb/s	10 x 10 Gb/s	4 x 25 Gb/s	4 x 25 Gb/s
Media		Twinax Cable	MPO MMF	Duplex SMF	Duplex SMF
Module / Connector		CXP Module	CXP Module, CFP Module	CFP Module	CFP Module
Availability		2010	2010	2010	2011-2012
Price		$$$	$$$	$$$$$	$$$$$$

4.15 Bandwidth Growth

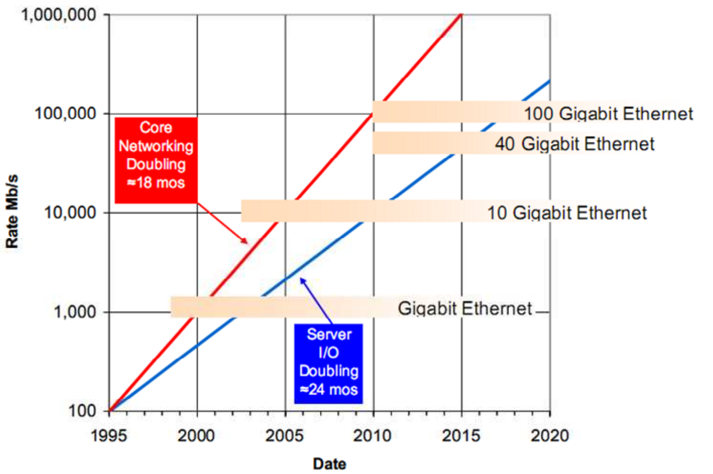

Fig. 4.5 Ethernet yesterday, today and tomorrow – transmission bandwidth evolution ("40 Gigabit Ethernet and 100 Gigabit Ethernet FAQ," 2010)**.**

Figure Fig. 4.5 shows how transmission bandwidth demand increased over the years. Two main application areas of the Ethernet technology are considered: computing and network aggregation spaces. As can be seen from the plot, rates of bandwidth demand increase are different depending on application. Whereas in the computing application area, bandwidth demand doubles every 24 months, in applications related to network aggregation, only 18 months pass before bandwidth demand becomes two times higher. Let us remind here, that all previous versions of the Ethernet technology were characterized by a ten-fold increase in transmission bandwidth regardless of present demands in individual application areas. In the new standard, the IEEE P802.3ba working group decided to allow two different transmission speeds, 40 Gb/s and 100 Gb/s, because of the different demand increase rates discussed above.

5 Design and measurements procedures of optical networks.

5.1 Introduction, general considerations and short look at standards

Design procedures are governed by standards. One can distinguish two groups of standards: networking standards describing transmission protocols and cabling standards that are, in principle, independent of the protocols.

The group of cabling standards defining the main rules of cabling and network design include:

- TIA/EIA-568 Structured Cabling Standard
- Standard is now composed of the following three discrete Standards:
- TIA/EIA-568B.1,Commercial Building Telecommunications Cabling Standard -Part 1:General Requirements,
- TIA/EIA-568B.2, Commercial Building Telecommunications Cabling Standard -Part 2: Balanced Twisted Pair Cabling Components,
- TIA/EIA-568B.3, Optical Fiber Cabling Components Standard.

Here, B is revision numbers and number indicates part of the standard.

Network design task, as any other project, starts with assessment of needs of the future network user.The assessment can be performed by the so called 5W approach, that is answering the following questions: Who? What? Why? Where? When?

5.2 Methodology of fiber optic network design

Network design process is can take on one of two forms:

- Technical approach – applicable for well-defined tasks based on standard solutions
- Systematic, open-ended approach, for general consideration of future systems or new generations on such systems[Andy Devine and Ron Deppen, Fiber Optic Cable and Connector Selection, *Connector Specifier* November, 2000].

Below is given a simple list of steps, illustrating the technical approach:

1. Define Environmental Requirements, e.g. office LAN vs. under-see system
2. Select Transmission Standard, e.g. Ethernet, FDDI
3. Select System Architecture (topology, fiber length, number of connectors, splices, fiber length)
4. Select Type of Fiber (MM, SM, POF, verify fiber attenuation and bandwidth)
5. Select Optoelectronic Packages (for standard or harsh environment, standard interfaces of pigtailed elements)
6. Select Type of Connector
7. Select the Cable Configuration/Type
8. Select Backshell for Multichannel (Multifiber) Connectors
9. Select Cable Clamping Method
10. Select Tools for Inspection, Cleaning and Testing
11. System Qualification (according to the proper standard)

5.3 Fundamental design consideration for network cabling

[The following part of the lecture is based on Corning Cable Systems LANscape® Solutions Fiber Optic Design Guide, 2002].

The task of design and building efficient communication network is a complicated one, involving collection and processing of plenty of information. The information can by effectively organized and processed by creation of an organized checklists. In the following text, the checklist is composed to collect the basic information necessary to begin optical-fiber network design and specify fiber optic products.

Preliminary design consideration include selection of:

- Networking standard (Ethernet, Token Ring, FDDI...)
- Type of service (Data, voice, video, telemetry, sensors)
- Area covered (Campus, building, horizontal)

To make an informed decision, the above considerations are put into a checklist, or a decision table. Below, one can find a set of tables that organize requirements for communication requirements versus applications, services and area covered by the fiber optical networks.

Table5. 1 Communication requirements – networking standards

	Campus Backbone	Building Backbone	Horizontal Cabling
Ethernet	☐	☐	☐
Token Ring	☐	☐	☐
Fast Ethernet	☐	☐	☐
FDDI	☐	☐	☐
Fibre Channel	☐	☐	☐
Gigabit Ethernet	☐	☐	☐
10 Gigabit Ethernet	☐	☐	☐
Wireless	☐	☐	☐
FS0	☐	☐	☐

„Corning Cable Systems LANscape® Solutions Fiber Optic Design Guide", 2002

Table 5.2 Communication requirements – voice transmission

	Campus Backbone	Building Backbone	Horizontal Cabling
T1	☐	☐	
T3	☐	☐	
TDM	☐	☐	
VOIP	☐	☐	
_____	☐	☐	

„Corning Cable Systems LANscape® Solutions Fiber Optic Design Guide", 2002

Table 5.3 Communication requirements – data transmission: video

	Campus Backbone	Building Backbone	Horizontal Cabling
Video Conference	☐	☐	☐
Security	☐	☐	☐
Broadcast	☐	☐	
__________	☐	☐	

„Corning Cable Systems LANscape® Solutions Fiber Optic Design Guide”, 2002

Table 5.4 Communication requirements – telemetry and sensor systems

	Campus Backbone	Building Backbone	Horizontal Cabling
Environmental	☐	☐	
Process	☐	☐	
Card Readers	☐	☐	☐
____________	☐	☐	

„Corning Cable Systems LANscape® Solutions Fiber Optic Design Guide”, 2002

Once we are finished with preliminary factors above, we can consider network design and installation issues. In tables below the checklists for networking topology, fiber selection and cable structure are presented.

Table 5.5 Network design and installation –selection of networking topology

	Campus Backbone	Building Backbone	Horizontal Cabling	Equipment room
Star				☐
One-level hierar. star	☐	☐		
Two-level hierar. star	☐	☐		
Backbone ring	☐			
Centralized cabling		☐	☐	
Zone cabling			☐	
Single-user outlet			☐	
Multi-user outlet			☐	

„Corning Cable Systems LANscape® Solutions Fiber Optic Design Guide”, 2002

Table 5.6 Selection of the type of fiber

	Campus Backbone	Building Backbone	Horizontal Cabling	Other system
Standard 50 μm		☐	☐	☐
Laser optimized 50 μm	☐	☐		☐
Single mode	☐			☐
Other	☐	☐	☐	☐

„Corning Cable Systems LANscape® Solutions Fiber Optic Design Guide”, 2002

Tabele 5.7 Listing of parameters of optical fibers

	Multimode 50 µm	Multimode 62,5 µm	Single mode	Units
Attenuation@850 nm				dB/km
Attenuat. @1300 nm				dB/km
Disp. @ 850 nm OFB				MHz.km
Disp. @ 1300 nm OFB				MHz.km
Disp. SM @ 1300 nm				dB/km.nm
Disp. SM @ 1550 nm				dB/km.nm

„Corning Cable Systems LANscape® Solutions Fiber Optic Design Guide", 2002

Parameters of optical fiber depends on the method of coupling of light. Accordingly, the following bandwidth parameters are available:

- OFB – over filled bandwidth,
- RML BW – reduced mode set laser bandwidth,
- EMB – effective mode set bandwidth (calculated from RML BW).

Optical cables utilized in optical networks, offer unique possibility of adding extra fibers, that are not planned for use at the time of installation – They are called dark fibers. Additional fibers are needed:

- To future-proof the network
- To provide redundancy to the system

In addition to increasing the number of fibers of the same type, the use of both single-mode and multimode (hybrid cable) should be considered. Mixing different fibers of the same type should be avoided.

Table 5.8 A check-list for the number of fibers in optical cable (fiber count)

	Campus Backbone	Building Backbone		Horizontal Cabling			Equipment room – demarcation point
Standard 50 µm	☐	☐	☐	☐	☐	☐	☐
Single mode	☐						☐

Sometimes, a check-list can be made as a simple list, instead of a multi-column table, e.g. The check-list for cables for a campus or building backbone.

Cable types – Campus Backbone:

☐ Loose-Tube All-Dielectric Cable (Outdoor)
☐ Loose-Tube Armored Cable (Outdoor)
☐ Loose-Tube Low-Smoke/Zero-Halogen LSZH™ Cable
☐ Indoor/Outdoor Cable (stranded loose tube)
☐ Indoor/Outdoor Cable (ribbon)

Cable types – Building Backbone
☐ Tight-buffered Cable
☐ Indoor/Outdoor Cable (stranded loose tube)
☐ Indoor/Outdoor Cable (ribbon)
☐ Tight-buffered Interlocking Armored Cable
☐ Ribbon Riser Cable

In some, rare, cases the check-list is reduced to a simple verification, like e.g. choise of fiber for a horizontal cabling system:

☐ Tight-buffered Cable

Other issues, that should be analyzed in the way described above, include:
1. Splicing methods
2. Connectors and termination methods
3. Connecting hardware and outlets
4. Testing
5. Documentation

One issue that should not be overlooked, is safety of working with fibers. The following rules should be applied [1. The FOA Reference For Fiber Optics, Internet, retrieved 2010 Nov 24, http://www.thefoa.org/tech/ref/safety/safe.html]:

1. Keep all food and beverages out of the work area. If fiber particles are ingested they can cause internal hemorrhaging
2. Wear disposable aprons to minimize fiber particles on your clothing. Fiber particles on your clothing can later get into food, drinks, and/or be ingested by other means.
3. Always wear safety glasses with side shields. Treat fiber optic splinters the same as you would glass splinters.
4. Never look directly into the end of fiber cables until you are positive that there is no light source at the other end. Use a fiber optic power meter to make certain the fiber is dark. When using an optical tracer or continuity checker, look at the fiber from an angle at least 15 cm away from your eye to determine if the visible light is present.
5. Work only in well ventilated areas.
6. Contact wearers must not handle their lenses until they have thoroughly washed their hands.
7. Do not touch your eyes while working with fiber optic systems until they have been thoroughly washed.
8. Keep all combustible materials safely away from the curing ovens.
9. Put all cut-off fiber pieces in a safe place.
10. Thoroughly clean your work area when you are done.
11. Do not smoke while working with fiber optic systems.

6 WDM networks and all-optical network of the future

Optical fibers allow many different wavelengths (colors) of laser light to be transmitted down the same optical fiber simultaneously (see figure Fig. 6.1). In the wavelength-division multiplexing (WDM) telecommunication systems, this property of optical fibers is employed in order to increase the amount of information that can be transferred. In other words, adding more wavelengths (WDM channels) increases the total transmission capacity of an optical data link, but it leaves the transmission speeds (data rates) of individual channels unchanged.

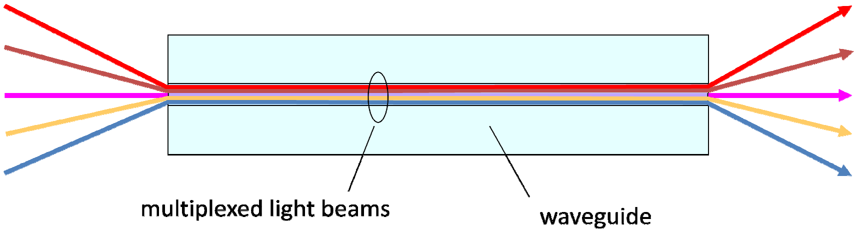

Fig. 6.1 Idea of wavelength-division multiplexing (WDM).

6.1 The shipwreck story

The story. After a shipwreck two groups of people are stranded on two separated islands. They want to communicate, so they found some lamps and flash information at each other. That's (almost) exactly like the f-o (fiber optic) system works. They started with two lamps, one for each island. With time the need for communication (bandwidth) increased (see figure Fig. 6.2).

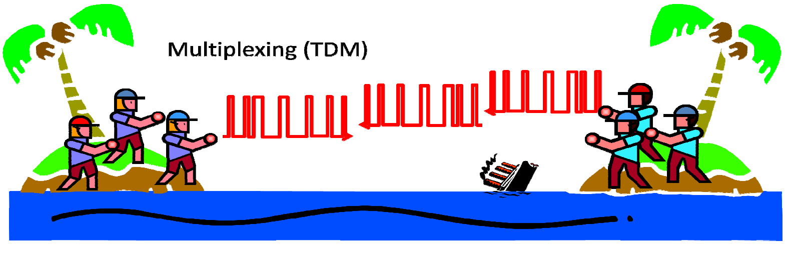

Fig. 6.2 Time Division Multiplexing – each data channel in the communication link (data link) is transmitted in a dedicated time slot.

Using laps of three different colors, they could communicate three times more effectively without the need to increase the transmission speed (see figure Fig. 6.3). Using multiple colors of light for transferring information in a single communication link is the idea of the WDM systems.

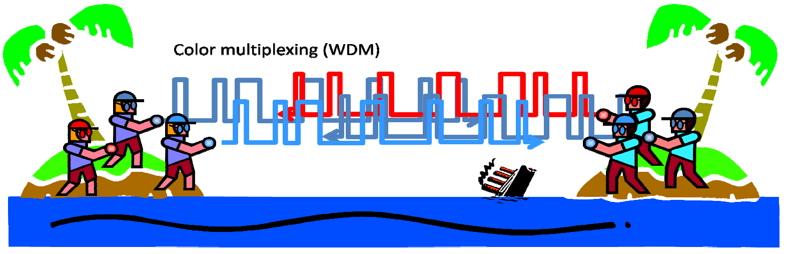

Fig. 6.3 Wavelength Division Multiplexing – many signals in a single communication link (data link).

6.2 Why WDM? Increasing bandwidth transmissions demand

In the WDM systems, the total transmission capacity is increased by means of the frequency-division multiplexing. This enables high transmission data-rates directly to a given network node (host), which is not possible in the typical, traditional systems that are based on the time-division multiplexing (TDM). In the TDM systems, the transmission capacity must be divided among the number of devices accessing the system. In figure Fig. 6.4 there are shown transport solutions (horizontal axis) as well as services being supplied in the function of the transmission bandwidth demand.

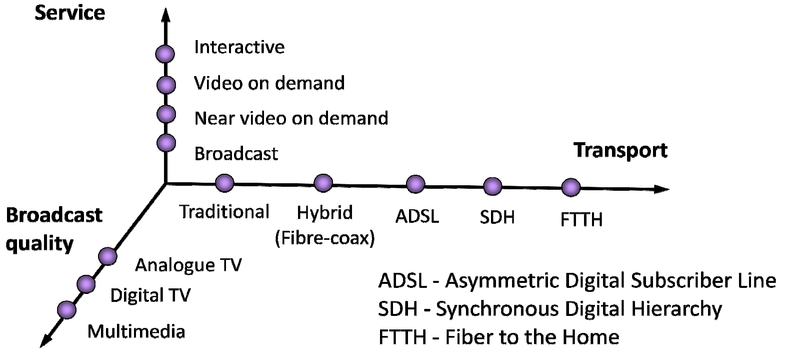

Fig. 6.4 Bandwidth transmissions demand.

The transmission bandwidth demand does not increase linearly with one factor only (e.g. quality) but rather as a simultaneous request for service, quality and transport improvement.

The transmission bandwidth of a network system can be extended in several ways:

- Increase the modulation speed (new equipment, new systems)
- Increase the number of installed fibers (new cabling)
- Introduce new transmission channels (WDM) (new input-output modules)

The WDM systems offer economic advantages because their introduction does not require an installation of new fiber optic cables. Only multiplexing and demultiplexing modules dedicated for WDM need to be installed. Figure Fig. 6.5 presents an idea of a simple wavelength-division multiplexing system. Four data channels are coupled into a single telecommunication link by means of a WDM multiplexer. All the channels, without interacting with each other, are then transmitted over the telecommunication link to a receiver. In the receiver, by means of a WDM demultiplexer, the entire transmission is separated back into individual data channels.

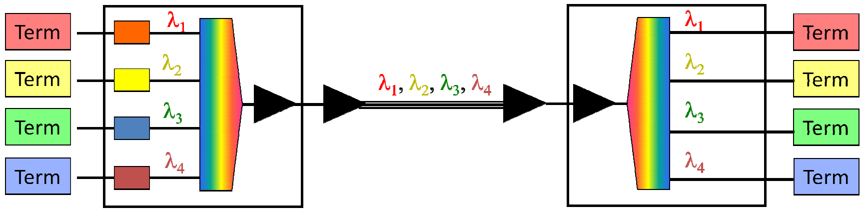

Fig. 6.5 Simple 4-channel WDM transmission system.

Let us assume, we deal with a SONET-type telecommunication system featuring the OC-48 transmission speed, i.e. about 2.5 Gb/s (OC stands for Optical Channel and OC-1 corresponds to a transmission speed of 51 Mb/s; subsequent editions are the multiplicities of the OC-1 transmission speed). We want to make a four-fold improvement in system's bit rate, i.e. we want reach the OC-192 (10 Gb/s). In order to do this, we could install new fibers (new cabling) (1) thus increasing the number of physical channels up to four, or we could introduce a four-channel WDM system (2). Alternatively, we could also install a four times faster electronic equipment (3). If we analyze the economic aspects of the individual solutions (e.g. prices of the equipment required) and if we assume in the analysis that each of the transmission channels is not longer than 50 km, we arrive at a conclusion that installing new fibers is the cheapest option. Under the circumstances we have assumed, installing a faster electronic equipment is by far the most expensive solution. The situation changes, however, when individual transmission channels are longer than 50 km. Under such circumstances, introduction of a WDM system becomes the cheapest possibility. At the same time, installing new fibers turns out to be the most expensive option. The analysis described above is also schematically depicted in figure Fig. 6.6.

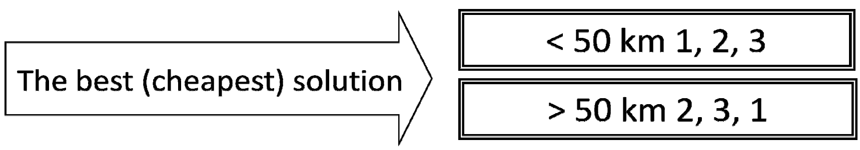

Fig. 6.6 Comparison of economical aspects of three different solutions to the transmission capacity enhancement of a network system. Digits visible in the figure correspond to the solutions under consideration: 1 – new cabling, 2 – WDM system, 3 – new electronic equipment.

In figure Fig. 6.7, a typical telecommunication system is presented. For clarity, optical and electrical signal paths are marked with different colors. The most important transmission speed limiting factor is the electronic equipment where signal modulation is performed The optical part of the system only plays a role of a transport medium. Attempts at increasing the transmission capacity by means of upgrading the electronic equipment, are thus expensive and limited by the capabilities of technologies currently available. Introducing a WDM system into a transmission link allows to increase the total transmission capacity of the system without the need for increasing the signal modulation frequency.

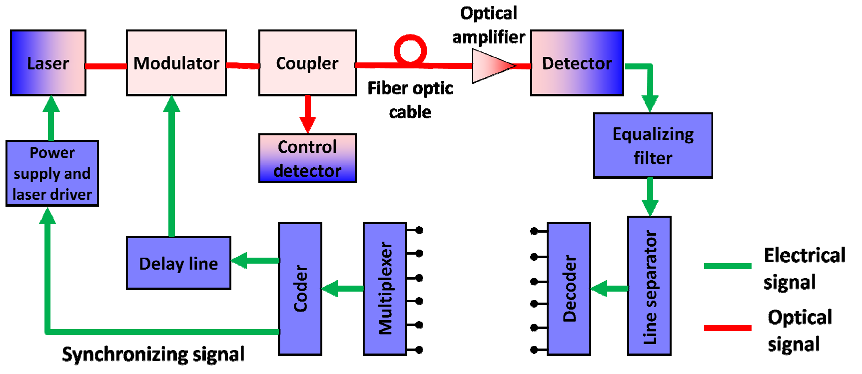

Fig. 6.7 Contemporary (classical) telecommunications link.

In traditional digital telecommunication systems, usually the light amplitude modulation circuits are employed together with light sources emitting at 1.31 μm or 1.55 μm. Common types of light sources are the FP-LD/DFB-LD or VCSEL lasers (laser semiconductor diodes). In systems solely based on the time-division multiplexing (TDM), transmission capacities reaching 2.4 Gb/s are possible. Such systems require signal regenerators to be placed every 40 km in an optical link. In systems that have higher transmission capacities (10 Gb/s), costs of TDM electronic system equipment increase significantly, possibly beyond economic viability.

6.3 Limitations of time division multiplexing (TDM)

Different channels can be carried in a single fiber by time switching. A schematic of time-division multiplexing of two channels into one train of pulses is shown in figure Fig. 6.8. Each pulse represents the bit value '1', and lack of pulse represents the bit value '0'.

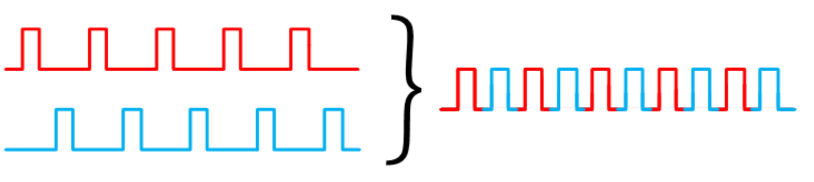

Fig. 6.8 Time division multiplexing of two channels into one train of pulses.

A typical contemporary transmission line: TDM on one light wavelength (see figure Fig. 6.9 on the right). Frequencies of individual (time) channels sum up at optical input/output ports. Speed increase in individual channels requires optical modules of very high frequency. Whereas a TDM system of a total transmission capacity of 1 Gb/s is feasible, electronic circuits realizing a 1 Tb/s modulation are hardly imaginable. However, such a high modulation frequency would be required in a system consisting of a thousand transmitters/receivers and featuring a 1 Gb/s transmission bandwidth guaranteed for each user (subscriber) (see figure Fig. 6.9 on the left).

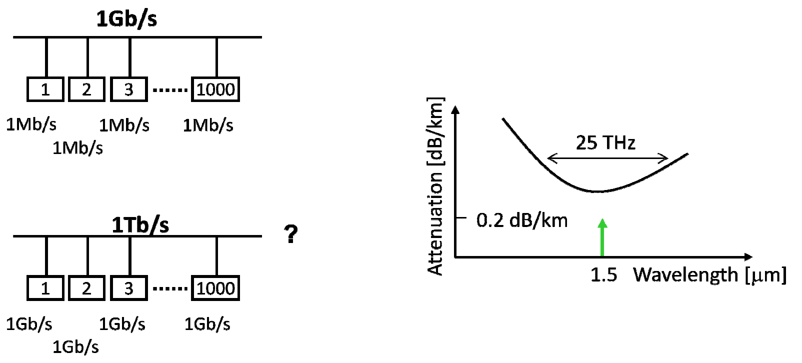

Fig. 6.9 One-wavelength time division multiplexing – a 1000 of 1 Mb/s channels require a data link of 1 Gb/s total transmission capacity, where 1000 of 1Gb/s channels 1 Tb/s.

6.4 WDM - solution for TDM limitations

A WDM-based solution considered below allows building a transmission link that will guarantee a 1 Gb/s transmission speed for each subscriber. Moreover, the maximum modulation speed of electronic equipment does not exceed the single user's bit rate (i.e. 1 Gb/s). By using 1000 different wavelengths of light for individual data channels (WDM channels), data can be transmitted simultaneously over a single physical channel (i.e. an optical fiber). Of course, thanks to the physical properties of light, data in individual channels will not distort each other. Figure Fig. 6.10 presents an idea of positioning the optical frequencies (light wavelengths) of multiple WDM channels within the 25 THz wide frequency band which are available in the third telecommunication window.

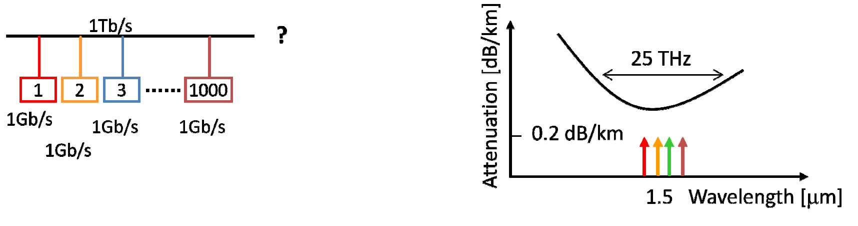

Fig. 6.10 Wavelength division multiplexing – a 1000 of 1 Gb/s channels require a data link of 1 Gb/s total transmission capacity not 1Tb/a as in TDM systems.

In systems like the one described above, one can avoid the limitations resulting from electronic circuits speed being low as compared to the huge transmission bandwidth offered by optical fiber. In other words, WDM transmission systems are able to use more of the optical-fiber bandwidth than it is possible with TDM systems. Maximal electronics speed remains unchanged (speed of individual WDM channels). Multiplexing and demultiplexing is performed with optical – usually passive – elements. Figure Fig. 6.11 shows fiber attenuation in the function of light wavelength. Spectral positions of several light wavelengths assigned to WDM channels, are marked with colorful arrows. (Note that the colors used in the diagram are for illustration only as the third telecommunication window is located in the infrared (IR), thus invisible, part of the electromagnetic spectrum).

From the side of shorter wavelengths, spectral width of the third telecommunication window is limited by a peak of light absorption on –OH ions. Although in trace amounts only, the –OH ions are present in fiber material (silica glass). However, if an appropriate technological process is used for fiber perform fabrication, the –OH absorption peak can be reduced and the window frequency bandwidth be extended.

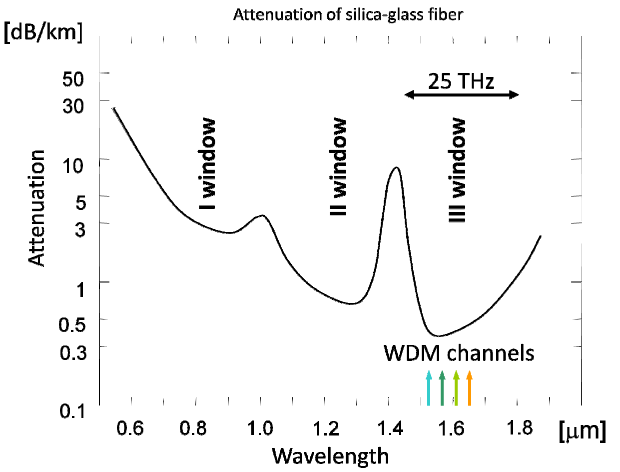

Fig. 6.11 Optical waveguide transmission - attenuation and available wavelengths.

6.5 Frequency vs. wavelength

In DWDM (Dense Wavelength Division Multiplexing) systems channel separation is very narrow. For this reason it is useful to characterize light waves by frequency rather than wavelength.

Starting off with the formula connecting the lightwave length and frequency with the speed of light

$$c = f * \lambda \tag{6.1}$$

we calculate a difference between two lightwave frequencies

$$\Delta f = f_2 - f_1 = \frac{c}{\lambda_2} - \frac{c}{\lambda_1} = \frac{c * (\lambda_1 - \lambda_2)}{\lambda_1 * \lambda_2} \tag{6.2}$$

Then, assuming that the difference between frequencies of two neighboring (adjacent) WDM channels is small (as compared to the frequencies themselves), we can write

$$\lambda_1 \approx \lambda_2 \Rightarrow \lambda_1 * \lambda_2 = \lambda^2 \tag{6.3}$$

As a result we get

$$\Delta f \approx c \frac{\Delta\lambda}{\lambda^2} \tag{6.4}$$

$$\Delta\lambda \approx \Delta f \frac{\lambda^2}{c} \tag{6.5}$$

6.6 Light wavelengths for DWDM systems

The ITU-T G.694.1 (2002) recommendation defines the light wavelength values that are to be used in DWDM systems operating within the third telecommunication window (i.e. around

1550 nm) (see table Tab. 6.1). All the wavelengths are defined in relation to the emission line of krypton at 1552.52 nm (193.1THz).

Tab. 6.1 European Telecommunications Standards Institute (ETSI) suggestions for WDM-channel wavelengths (ITU-grid).

Frequency (THz)	Wavelength (nm)
193.7	1547.72
193.5	1549.32
193.3	1550.92
193.1	1552.52
192.9	1554.13
192.7	1555.75
192.5	1557.36
192.3	1558.98

Contemporary commercial WDM i DWDM systems:

- inter-channel space 200GHz (1.6nm); 8 channels
- inter-channel space 100GHz (0.8nm); 16 channels
- inter-channel space 50GHz (0.4nm); 32 channels

6.7 Modern WDM telecommunications system

Structure of a typical WDM system is shown in figure Fig. 6.12. The system consists of: XMTR – light transmitters, OMUX – optical multiplexer, OA – optical amplifiers, ODMUX – optical demultiplexer, and DET – (photo)detectors.

LED diodes or laser diodes, both accompanied by specialized electronic circuits, play a role of light transmitters in real-world WDM systems. The optical multiplexer collects the individual WDM channels (from different fibers) and couples them into a single optical fiber (optical link). Along the optical link, optical amplifiers, also called the repeaters, can be located to boost the optical power. Optical demultiplexer, as opposed to the previously mentioned optical multiplexer, then separates the individual WDM channels and couples them into separate fibers. Finally, optical detectors (photodetectors) transform the optical signal into electrical signal.

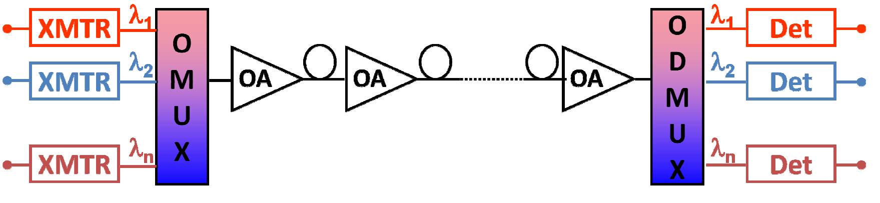

Fig. 6.12 Modern WDM telecommunications system.

Advantages of the WDM approach

- Transparent for different frequencies and coding systems
- One (optical) amplifier for many channels
- Large repeater spacing 80-140km

Disadvantages of the WDM approach

- Accumulation of signal distortion (dispersion) and noise

Optical channel multiplexing increases link capacity.

In modern WDM systems, additional elements like add/drop filters are utilized. The add/drop filters (add/drop optical multiplexers, OADMs) enable light of a desired, precisely defined wavelength, i.e. a single WDM channel, to be extracted out of the rest of WDM channels that are simultaneously transmitted down the fiber. Besides the extraction, an add/drop filters also provide the possibility of an opposite operation – a WDM channel can be included back into the total WDM transmission. In this way, certain network functionalities can be realized. This is e.g. channel routing among subscribers as well as more advanced signal processing tasks.

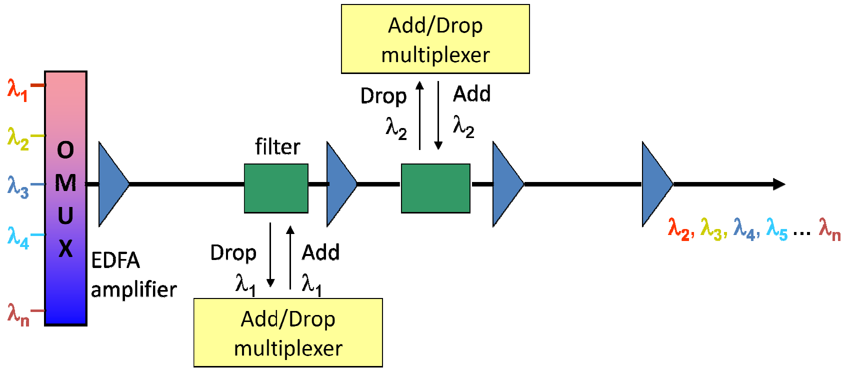

Fig. 6.13 Fiber optic (WDM) transmission system of the future with add/drop filtr.

6.8 Limiting factors in DWDM systems

The mayor physical phenomena that put limitations on WDM systems:

- attenuation – gradual decrease in optical power along fiber length
- dispersion – temporal pulse broadening caused by different propagation speeds of lightwaves propagating as different fiber modes; dispersion affects transmission bandwidth, i.e. the maximum achievable transmission speeds (bit rates)
- nonlinear effects – multiple optical signals inside one optical link (fiber), can increase the optical power density in fiber core to a level at which optical nonlinear phenomena can no longer be neglected; again, transmission bandwidth is affected

In order to minimize the negative effects of the limitations listed above, fiber optic cables of special design are used in dense WDM (DWDM) systems:

- Corning LEAF(R) fiber, single-mode non-zero dispersion-shifted fiber (NZ-DSF) with large effective area. Effective mode area typically 32% larger than in conventional NZ-DSF
- TrueWave (R) (Fitel Lucent) high performance NZ-DSF

In WDM systems, transmission bandwidth limitations resulting from chromatic dispersion are of mayor significance. This is why appropriate dispersion-compensating devices need to be allowed for already during system design. Such devices are then placed at certain intervals along the optical link. Among the most common solutions, are:

- dispersion compensating fibers (negative or reversed dispersion) – disadvantages: large size, designed for the specific length of the f-o link, not applicable for all-optical networks
- fiber Bragg gratings – disadvantages: separate grating for every WDM channel; circulator required

- Fabry-Perot (F-P) etalon compensators – single compensator can be designed for a range of wavelengths; in F-P etalon-based compensators, however, light of different wavelengths remain trapped within the etalon (cavity) for different periods of time

6.9 Integrated optoelectronics - advanced photonics circuits for WDM systems

In figure Fig. 6.14 there is shown an example of an InP-based optoelectronic modulator enabling a 10 Gb/s modulation of optical signal. Within a single casing, a Mach-Zehnder (M-Z) type modulator is combined with a semiconductor multi-quantum well (MQW) DFB laser. The entire device (module) is designed to work with DWDM systems. It is manufactured by Bookham Technology. The device is compatible with non dispersion-shifted fibers (NDSF). Transmission speed of 10 Gb/s over 80 km long fibers is possible without any additional dispersion-compensating devices. It is achieved by controlling the laser chirp by means of an appropriate DC polarization of the M-Z modulator. In cases when dispersion-shifted fibers (DSF) are employed, transmission over distances up to 480 km is possible. The module features a wavelength stabilization circuit capable of maintaining the wavelength stability on the level of +/- 20 pm (picometers). Wavelength stability is not affected by an optical power control circuit also present in the device.

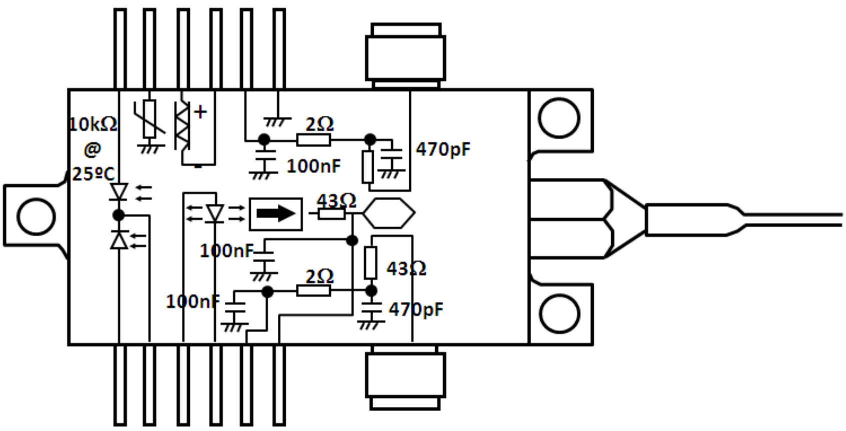

Fig. 6.14 InP-based Mach-Zender type modulator capable of achieving a modulation speed of 10 Gb/s. The modulator is connected to light source, a MQW DFB laser diode, of precisely controlled emission wavelength and power. The device is manufactured by Bookham Technology ("Oclaro Datasheets," 2010)**.**

7 RAINBOW – an example of all optical network

The following lecture is based on (Jue, Borella, & Mukherjee, 1996).

One of all-optical telecommunication networks is a network known under the name of RAINBOW. Considering the network spread, RAINBOW belongs to a class of metropolitan-area networks (MANs). RAINBOW employs WDM systems to realize broadcasting. Figure Fig. 7.1 shows an example of a RAINBOW-type network. It contains four hosts, each one being assigned a unique wavelength at which it transmits. Optical signals in the WDM system are coupled into one optical channel and are delivered to each subscriber. In the so called optical network attachments (ONAs), optical signal reaching each host is optically filtered (a proper wavelength is extracted) and transformed into electrical signal. Then, using the high-performance parallel interface (HIPPI), electrical signal is delivered to subscriber.

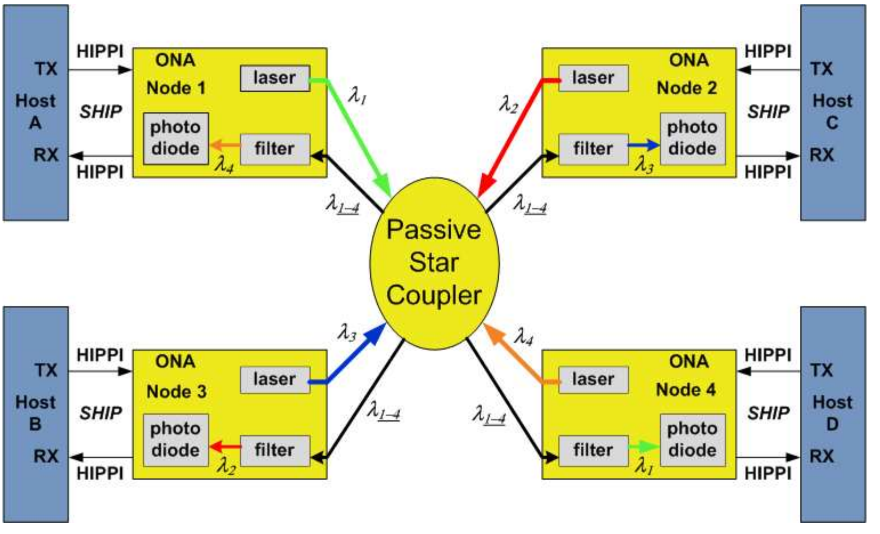

Fig. 7.1 RAINBOW – an example of all optical network.

7.1 RAINBOW network – characterization

RAINBOW I

- 32 nodes (IBM PS/2 stations)
- Network span - 25 km
- Number of WDM channels = number of stations
- Transmission speed per WDM channel 300 Mb/s
- Node type FT-TR
- Detector tuning time 25 ms (Fabry-Perot resonator)
- Application: circuit switched network

RAINBOW II

- Transmission speed per WDM channel 1 Gb/s

RAINBOW III (planned)

- Transmission speed per WDM channel 1 Gb/s
- Detector tuning time 1 μs
- Application: packet switched network

7.2 RAINBOW network topology - passive star

Topology of RAINBOW-type networks is organized as a passive star coupler (PSC). Each network node transmits at its individual light wavelength. All wavelengths are combined into a common optical transmission that is delivered to all network nodes. The PSC topology is shown in figure Fig. 7.2.

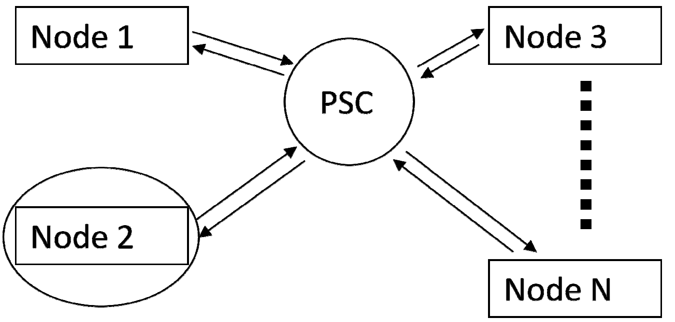

Fig. 7.2 RAINBOW network topology with N nodes.

In figure Fig. 7.3, some details of a single RAINBOW network node are shown. The node contains a network interface unit (NIU) that is terminated, on one side, with an electrical interface (E) and, on the other side, with an optical interface (O). Whereas NIU's transmitter is fixed at a given light wavelength, NIU's receiver is tunable. The receiver contains a photodetector, and the tuning is accomplished by means of an optical filter.

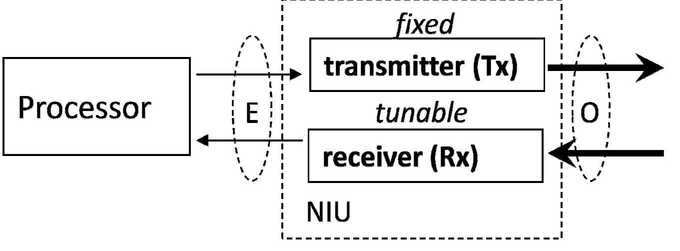

Fig. 7.3 Details of Node 2.

7.3 Description of the RAINBOW protocol

Each individual nodes works at a dedicated (constant) light wavelength.

Data from station A are supposed to be delivered (relayed) to station B

- Computer A first tunes its detector to a channel (wavelength) λ_B and then, still being tuned to this channel, it waits until contact with B is confirmed (acknowledged).
- Station A begins to continuously transmit a hand-shake signal in channel λ_A. The hand-shake signal contains addresses of both the transmitter and the receiver.
- Once B receives the hand-shake signal in channel λ_A, it sends an acknowledgement in channel λ_B.
- From this moment on, station A (already aware of the B's readiness) begins transmitting the data signal.

The connection just established is full duplex

In the protocol a problem of the so called deadlock can occur. Deadlock is a situation in which two stations simultaneously send hand-shake signals to each other. Deadlocks are resolved by introducing time-out mechanisms. In case establishing a connection fails after a prescribed amount of time, transmission of the hand-shake signals is finished and both stations return to the listening mode.

7.4 RAINBOW system model

7.4.1 Model goal

The model is created (used) in order to determine the relations between sender and receiver, in a possibly simple way.

7.4.2 Assumptions

- Total number of stations – N.
- There is no buffering. Buffer of a single station only processes a current message (portion of received data). The message is removed from the buffer right after the processing completes.
- The sender station tunes its receiver to the receiver station channel and then it begins to transmit the hand-shake signal.
- Each station monitors all channels on a cyclic basis in the following order: 1, 2, ..., N, 1, 2, ... (the round-robin order).
- Time is divided into time slots of 1 μs duration (time slot is a fundamental unit of time in the model). Short time slot duration ensures a low granularity of the model.
- Tuning to any given channels lasts for a time τ (expressed in time slots).
- Probability of receiving a message by any given station, within a single time slot, is σ. More precisely: messages reach the station according to the binomial distribution (Bernoulli distribution) with the parameter σ. This means, in any time slot, a station currently having an empty slot, will receive a message with probability σ.
- Message lengths obey the geometric distribution. The mean message length is $1/\rho$ (in the unit of time slots).
- Transmission delay between computers equals R (time slots). For example, assuming the signal delay due to propagation in fiber is 5 μs/km, then for a station-star coupler distance of 10 km, we get R = 50 (for a 1 μs time slot duration).
- The expiry time Φ (timeout duration).
- Times of hand-shake and acknowledgement transmissions are negligibly short.

7.4.3 State diagram

Figure Fig. 7.4 shows a block diagram of states (situations) which any of the N stations can enter. If given station is in the transmission (TR) state, it can remain in this state for a time determined by the geometrical distribution. Otherwise, i.e. if a station is in any other state, it can remain in this state for a finite period of time (one time slot). For a given time slot, station will leave the TR state with probability ρ or it will remain in this state with probability $1-\rho$. In table 7.1, descriptions of symbols visible in the state diagram (figure Fig. 7.4) are given.

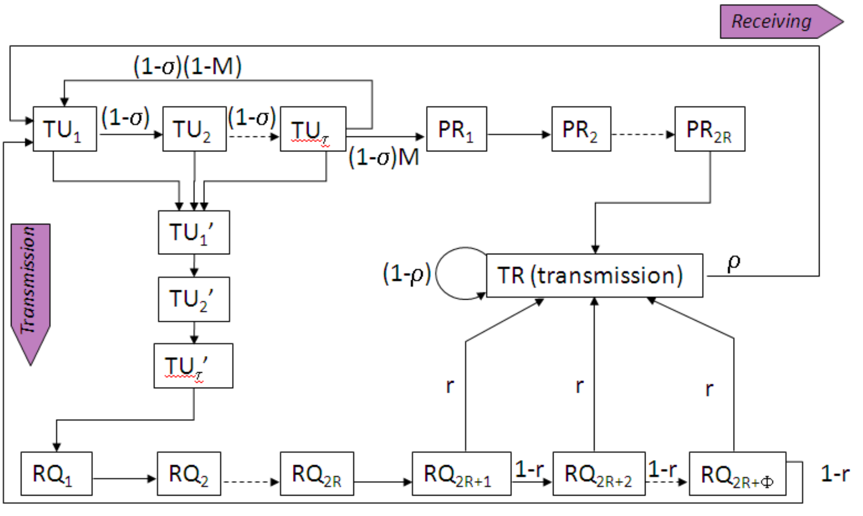

Fig. 7.4 State diagram of RAINBOW network.

Tab. 7.1 Symbols and descriptions of states in which any given RAINBOW network station can be.

Symbol	Meaning
σ	probability of a message being ready to be sent in an empty time slot
τ	time needed for a receiver to tune to any channel
M	probability that station finds a message addressed to itself while channel scan is being performed by the station
ρ	probability that station leaves the TR (transmission) state at the and of current time slot ($1/\rho$ – average message length)
r	probability that station receives acknowledgment (from the target station) of the target station being ready to receive transmission
R	delay, propagation time over the station-concentrator distance
Φ	expiry time (timeout duration)
TU_i	scanning in search for hand-shake signal
TU_i'	receiver tuning prior to sending a message, after tuning a request is sent
RQ_i	after the request is sent, station waits for acknowledgement (time from 2R to 2R+Φ)
PR_i	waiting for message, sending acknowledgement
TR	transmitting or receiving a message

7.4.4 TU_i – scanning for requests

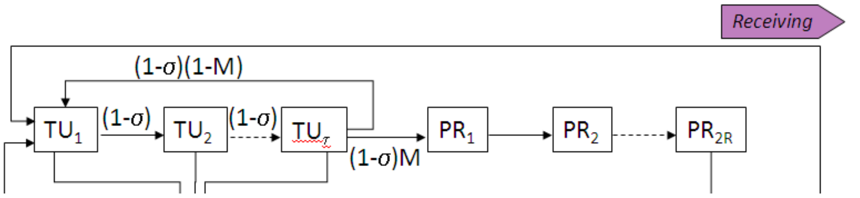

Fig. 7.5 TU_i – scanning for request; part of state diagram.

TU_1, TU_2, ..., TU_τ: in this state, receiver scans channels in search of hand-shake signal or message. Time needed for scanning of a single channel equals τ, and probability of any message ready to be sent equals σ. In the state TU_τ, hand-shake signal (and thus the request for acknowledgement) is possible with probability M. Otherwise, the receiver proceeds to scan the of a next channel.

7.4.5 TU'_i – tuning

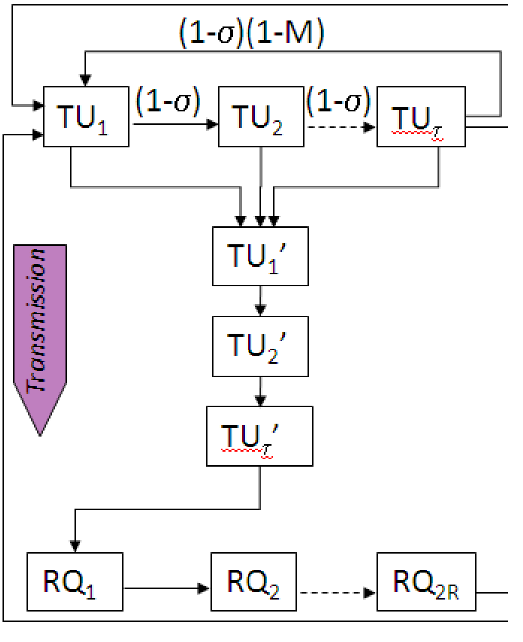

Fig. 7.6 TU'_i – tuning; part of state diagram.

TU'_1, TU'_2, ..., TU'_τ : In this state, receiving station immediately begins tuning the receiver to an appropriate channel. Time needed for tuning equals τ. After this time, the station proceeds to send the request.

7.4.6 RQ_i – waiting for the request acknowledgement

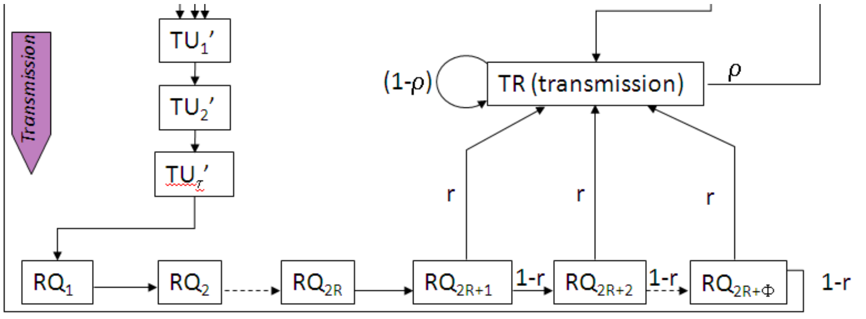

Fig. 7.7 RQ_i – waiting for the request acknowledgement; part of state diagram.

RQ_1, RQ_2, ..., $RQ_{2R+\Phi}$: After sending the request, a time delay of *R* time slots takes place. This delay is needed for the signal to reach the second station (also compare figure Fig. 7.10). The acknowledgement can reach the transmitting station after a time of 2*R* time slots. It can also happen, however, that after the time *R*, the station keeps on sending the acknowledgement request for the time Φ, the so called timeout. If the acknowledgement does not arrive within the time $2R+\Phi$, the current operation is terminated (due to timeout) and the station returns to the scanning mode. Probability of receiving an acknowledgement equals *r* and it is identical in all the states: RQ_{2R+1} to $RQ_{2R+\Phi}$. In case an acknowledgement is received, the station enters the message transmission state TR.

7.4.7 PR_i – waiting for the message

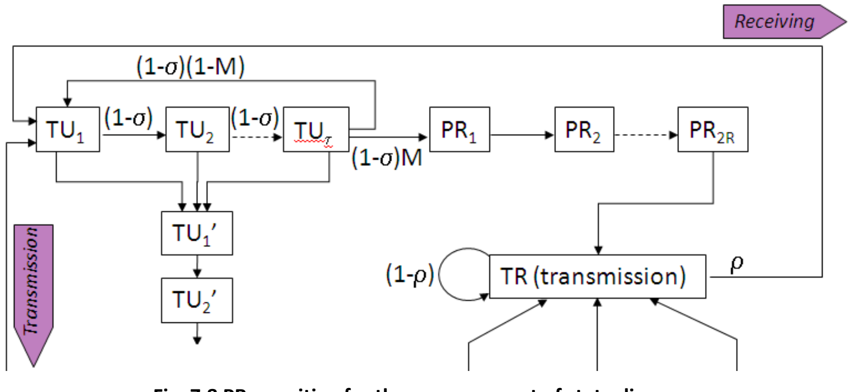

Fig. 7.8 PR_i – waiting for the message; part of state diagram.

PR_1, PR_2, ..., PR_{2R}: Station enters this state in case hand-shake request arrives while scanning (TU_τ) is in progress. In other words, this means that a message addressed to a given station is present in network. After identifying the request, station sends a reception acknowledgement. Then, after an *R* time slot long delay, the reception acknowledgment is received by the requesting station. The delay results from signal propagation time i.e. time needed for the signal to reach the requesting station. After the next delay *R* time slots long, the transmitted signal is received by the destination station which now enters the transmission state TR.

7.4.8 TR – transmission

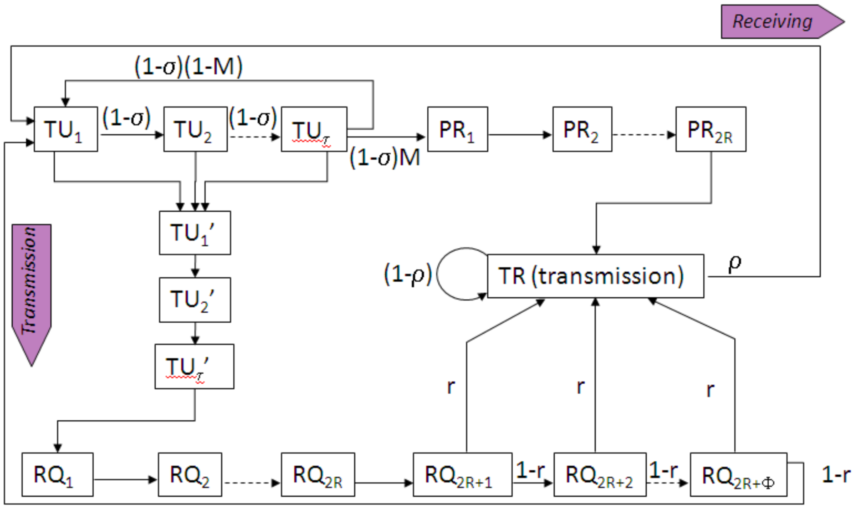

Fig. 7.9 TR – transmission; part of state diagram.

TR (transmission): in this state, the station can transmit as well as receive a signal. Both the transmission and reception can last longer than a single time slot and the probability that transmission / reception finishes equals ρ. After finishing, station returns to channel scanning.

7.4.9 Timing for connection setup

Figure Fig. 7.10 presents a time diagram of connection request (hand-shake signal) and connection acknowledgement between stations A and B. During the first phase, station A awaits the acknowledgement which can arrive within the time period between 2R and 2R+Φ. The connection request is being sent until acknowledgement arrives or until the maximum time 2R+Φ is elapsed.

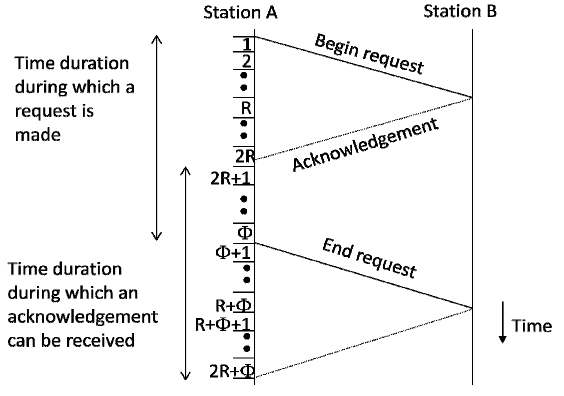

Fig. 7.10 Time diagram representing the request-acknowledgement procedure.

7.5 Equilibrium Point Analysis EPA

System can be modeled with the Markov chain (a stochastic process that varies in time). System state is described by a state vector (a vector in system's state space):

N = {N_{TU1}, N_{TU2}, …, N_{TUt}, $N_{TU1'}$, $N_{TU2'}$, …., $N_{TUt'}$,
N_{RQ1}, N_{RQ1}, N_{RQ2}, …, N_{RQ2R+F}, N_{PR1}, N_{PR2}, …, N_{PR2R}, N_{TR}},

where N (N_{XX}) denotes the number of stations currently being in state XX:

TU_i -> N_{TUi} TU'_i -> $N_{TU'i}$ RQ_i -> N_{RQi} PR_i -> N_{PRi} TR -> N_{TR}

Since a complete analysis of such a multidimensional space is difficult, an equilibrium point analysis (EPA) is usually applied. In EPA, we assume that system under consideration currently works at an equilibrium point. This means that the change of the number of stations being in any given state, equals zero. In other words, in any time slot, the number of stations entering any given state equals the number of stations leaving this state. In the discussed analysis method, K continuity equations (flow equations) involving K unknowns are created, where K is the number of states. All the flow equations can be expressed as a function of the number of computers being in state TU_1 = N $_{TU1}$. In the EPA analysis, values of N are assumed to be equal to the corresponding average values. In the Markov chain-based analysis, values of N were assumed to be random.

By solving the set following of equations

$$N_{TU_i} = (1-\sigma)^{i-1} N_{TU_1} dla\ i = 2,3,\dots,\tau \tag{7.1}$$

$$N_{PR_1} = N_{PR_2} = \cdots = N_{PR_{2R}} = (1-\sigma)^{\tau} M \times N_{TU_1} \tag{7.2}$$

$$\begin{aligned} N_{TU'_1} = N_{TU'_2} = \cdots = N_{TU'_r} = N_{RQ_1} = N_{RQ_2} = \cdots = N_{RQ_{2R}} \\ = [1-(1-\sigma)^{\tau}] N_{TU_1} \end{aligned} \tag{7.3}$$

$$N_{RQ_{2R+j}} = (1-r)^{j-1}[1-(1-\sigma)^{\tau}] N_{TU_1} dla\ j = 1,2,\dots,\Phi \tag{7.4}$$

$$\begin{aligned} \rho \times N_{TR} &= N_{PR_{2R}} + \sum_{j=1}^{\Phi} r \times N_{RQ_{2R+j}} \\ &= [(1-\sigma)^{\tau} M + \{1-(1-r)^{\Phi}\} \times \{1-(1-\sigma)^{\tau}\}] \times N_{TU_1} \end{aligned} \tag{7.5}$$

we find the unknown N_{TU1}, ρ i M.

M is the probability that, during the channel scan, station finds a message addressed to itself. M equals the probability that another station is in one of the states RQ_{R+1} do $RQ_{R+\Phi}$:

$$M = \frac{1}{N-1} \times \frac{1}{N} \left(\sum_{i=R+1}^{R+\Phi} N_{RQ_i} \right) \tag{7.6}$$

Using (7.3) and (7.4), N_{RQi} can be calculated. Then, after substituting into (7.6), the final expression for M can be found

$$M = \frac{1}{N-1} \times \frac{1}{N} [1-(1-\sigma)^{\tau}] \times \left\{ R + \frac{1}{r}[1-(1-r)^{\Phi-R}] \right\} N_{TU_1} \tag{7.7}$$

The above reasoning results from the fact, that any station can be in the transmission state only while some other station is in the reception state at the same time. The number of transitions from the request state to an active state must equal the number of transitions from an active state to the PR_{2R} state

$$N_{PR_{2R}} = \sum_{i=1}^{\Phi} r \times N_{RQ_{2R+i}} \tag{7.8}$$

On substituting (7.2) (7.4) into (7.8), we get

$$(1-\sigma)^{\tau} M = [1-(1-\sigma)^{\tau}][1-(1-r)^{\Phi}] \tag{7.9}$$

In the steady state, the total number of stations being at any given state equals the total number of stations present in the system

$$N = \sum_{i=1}^{\tau} N_{TU_i} + \sum_{i=1}^{\tau} N_{TU_i'} + \sum_{i=1}^{2R+\Phi} N_{RQ_i} + \sum_{i=1}^{2R} N_{PR_i} + N_{TR} \tag{7.10}$$

Or, after substitution

$$\begin{aligned} N = [1-(1-\sigma)^{\tau}] \times \left\{\frac{1}{\sigma} + \tau + 2R + \left(\frac{1}{r} + \frac{1}{\rho}\right)[1-(1-r)^{\Phi}]\right\} N_{TU_1} \\ + \left[\left(2R + \frac{1}{\rho}\right)(1-\sigma)^{\tau} M\right] N_{TU_1} \end{aligned} \tag{7.11}$$

The obtained equations (7.7), (7.9) and (7.11) can be solved simultaneously for r, M, TU_1.

7.6 Definitions of network parameters

Basic parameters that characterize network effectiveness are:

- Throughput
- Delay
- Timeout probability

Normalized throughput – is defined as an expected fraction of stations which are currently in an active state

$$S = \frac{N_{TR}}{N} \tag{7.12}$$

Delay – time between the moment a message (that is ready for transmission) occurs and the moment the transmission of this message is completed. The considered delay contains: tuning duration, acknowledgement signal propagation delay, time needed for the acknowledgement to be received, and transmission duration

$$D = \tau + 2R + \sum_{k=1}^{\Phi} k \times (1-r)^{k-1} \times r + \frac{1}{\rho} \tag{7.13}$$

Timeout probability - probability that station will time out after entering the request mode

$$p_{TO} = (1-r)^{\Phi} \quad (7.14)$$

7.7 Example parameters

Parameter values used in an example analysis:

- N = 32 stations
- slot length = 1 μs
- R = 50, corresponding to a 10 km distance between a station and a star coupler
- τ = 1000, for a tuning time of 1 ms
- $\rho = 10^{-5}$, for an average message length of 100 ms
- $\sigma = 10^{-4}$, for a message arrival rate of 100 msg/s
- $\Phi = 10^{4}$, a timeout of 10 ms

7.7.1 Throughput (S) vs. arrival rate (σ)

Figure Fig. 7.11 presents the normalized throughput in the function of message arrival rate. The calculations shown were conducted for two different timeout values. In the first phase of the dependence visible in the figure, i.e. when the message arrival rate increases, also the system throughput becomes higher. However, at a certain point, saturation occurs. The saturation results from the number of connection requests being too high as compared to the number of unoccupied stations currently present in the system.

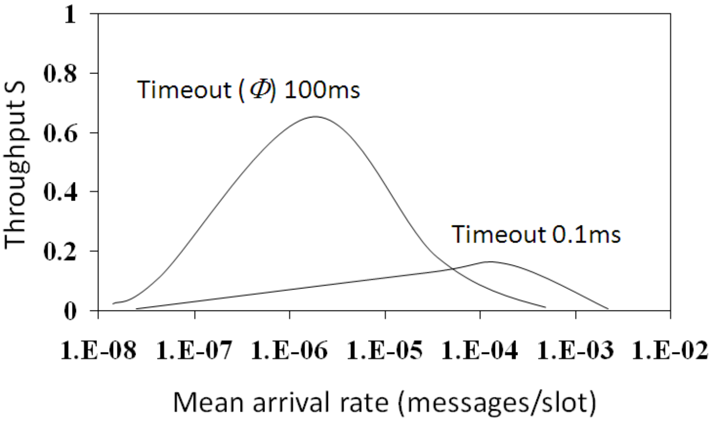

Fig. 7.11 Throughput versus mean arrival rate for an ex ample RAINBOW system.

7.7.2 Throughput (S) vs. Message size (1/ρ)

Figure Fig. 7.12 shows the normalized throughput in the function of a mean (average) message length ($1/\rho$). The system throughput asymptotically reaches its maximum value (i.e. 1) for long messages. This means that the probability ρ of station leaving the TR state (transmission, reception), is low.

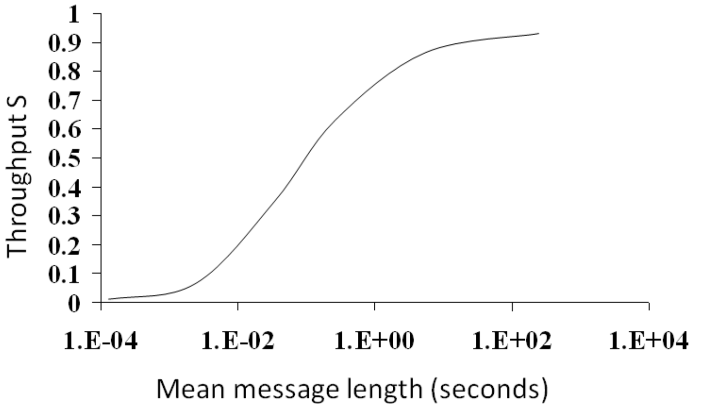

Fig. 7.12 Throughput versus mean message length for an example RAINBOW system.

7.7.3 Throughput (S) vs. timeout duration

Figure Fig. 7.13 shows how the timeout duration influences the normalized throughput of the system. For short timeouts, stations give up the connection requests too quickly as compared to an average time required for a connection to be established. This makes the system throughput low.

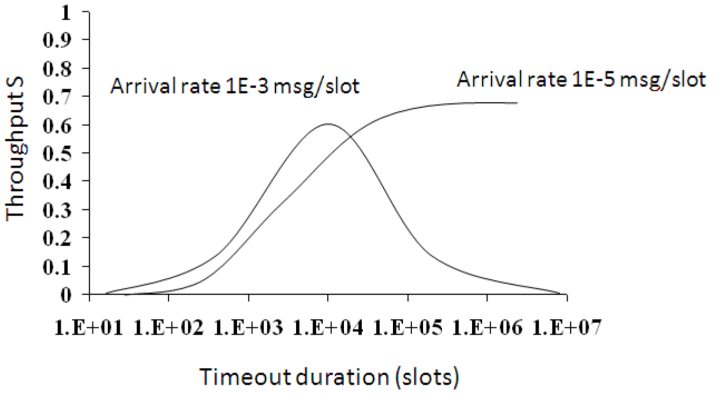

Fig. 7.13 Throughput versus timeout duration for an example RAINBOW system.

By increasing the timeout duration, the system throughput can be enhanced to some extent. Further enhancement, however, is prevented by the fact that, for a certain timeout duration, most of the stations, instead of being unoccupied, will be in the state of waiting for requests.

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