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Multimode Passive Optical Network for LAN Application

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1. Introduction

PON's (*Passive Optical Networks*) have gained a lot of interest in recent years. They minimize the number of required optical transceivers, reduce the fiber optic infrastructure and the need to power the intermediate network nodes. Single-mode PON structures are commercially available and presently they are used in LAN's (*Local Area Networks*). Usually these structures are point-multipoint networks which do not require any active components between the signal's source and the destination point. In other words, there's no need to supply electrical power to components such as fibers or optical splitters/combiners etc. Unfortunately, single-mode structures are not cheap, they're not easy to install nor are they customer-friendly.

Point-to-point multimode fiber optic structures have marked their presence in literature. Positive results obtained for different multimode optical fibers have been shown in the past (Gilmore M.C., 2006). The bandwidths and maximum transmission distance have been determined for three types of multimode fibers. Another paper includes a theoretical description connected with multimode transmission line (Pepeljugowski P., 2003). The same work presents an investigation of multimode coupler cascades' transmission bands supported by experimental results (Stepniak G., 2009).

This chapter describes several commercial applications for multimode passive network structures designed and constructed to include N-equivalent nodes. Such networks should be cheaper and more flexible than single-mode structures (part 2). Medium Access Method in PON's is presented in part 3. Some basic communication parameters like bandwidth or bit error have been tested in multimode networks and presented in part 4.

Some new solutions that came through for multimode fiber optic structures are presented here as well.

Measurements taken let us estimate the distance and possibility to obtain desired speed transmission in designed structures (part 5). There are many methods of designing a passive-optical-structure LAN. Each of the methods entail features that need to be considered carefully before designing a network. Two important features are structure of the network and medium access network. They are covered in detail in next two paragraphs.

Finally, possibilities of applying the CWDM method in multimode structures are examined in part 6.

2. Passive LANs network structures

There are two known types of passive optical structures – symmetrical and asymmetrical. The former includes reflective star, directivity star and transmissive star; The latter includes a typical tree structure. Each of them can be built using 3dB 50/50 multimode optical couplers. Examples of different topologies are presented further down in this chapter (Beres-Pawlik E., 2007).

It is assumed that the structures presented below will be built using 1×2(Y) and 2×2(X) couplers based on multimode (graded GI - and step-index SI) fibres. Silica fibre-based couplers or plastic-based couplers may be used. In some of the proposed structures it would be more advantageous to use asymmetric couplers but, to the best of our knowledge, no such elements are commercially available (Pawlik E., 1993).

2.1 Tree structure

In a tree structure, the transmission is of broadcast downward type (from operator to subscriber) and there is a point-to-point link upward (from subscriber to operator). This requires a power thirsty optical transmitter in the tree trunk and sensitive detectors in the receiving devices in the nodes. An exemplary structure with 4 rows and 8 access nodes is shown in the Fig.1.

Y couplers are usually used to construct tree structures but some structures are built using only X couplers. The coupler's extra branch can be used for monitoring a given tree branch.

This type of access service structure is collisionless since the network nodes can transmit only and exclusively in fixed time slots using TDMA (*Time Division Multiple Access*).
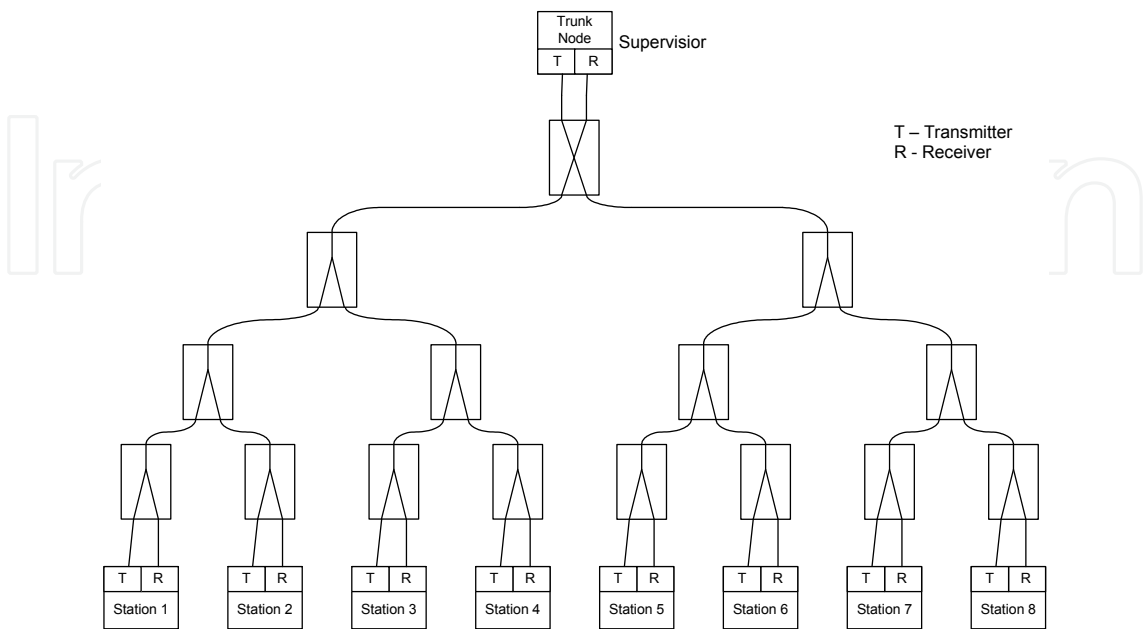

Fig. 1. Tree structure of order 4.

2.2 Transmissive star

A transmissive star is a structure in which a signal fed to one of the inputs on one side will be distributed equally among all the outputs on the other side. Since the structure is symmetric, the signal fed into one of the inputs will obviously be uniformly distributed among all the outputs on the opposite side. The structure requires, however, quite a large number of couplers. The number of nodes in a transmissive star is the power of 2.
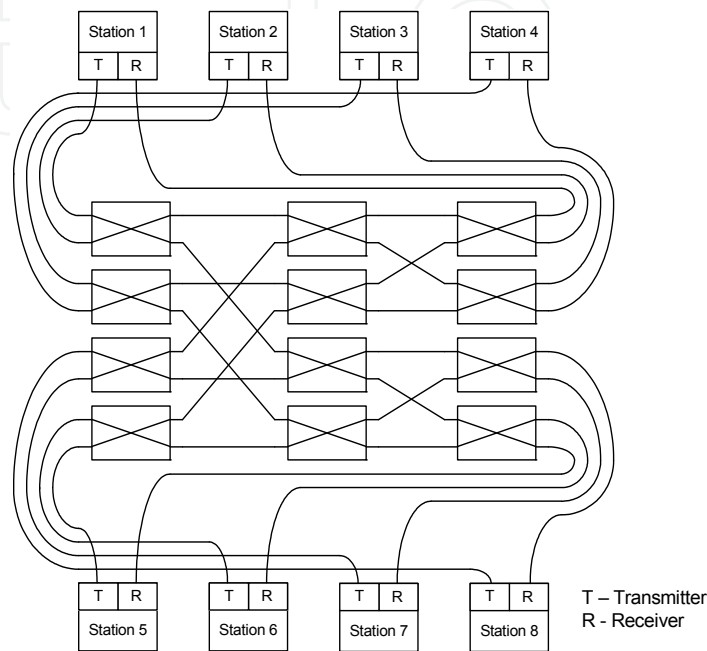

Fig. 2. Transmissive star with 8 nodes.

2.3 Reflective star

A reflective star is designed as a structure in which a signal fed to any of the inputs is uniformly distributed among all inputs/outputs. A drawback of this solution is that the light emitted by a given transmitter returns to it, and this adversely affects the operation of the laser transmitter. Because the transceiver notifies itself, the use of effective collision detection methods is impossible.

Y couplers can be used to build such a reflective star. It is a kind of tree structure where the trunk node is looped. An exemplary reflective star structure is shown in the Fig. 3.

2.4 Directional star

A directional star is a structure in which a signal sent from the transceiver of a selected network node reaches all the other transceivers without notifying itself. This is achieved by appropriately connecting directional couplers. The directionality of the couplers is an important parameter of the star's components. For multimode couplers it is usually at the level of 35 dB. This parameter determines the structure's dynamics and its size if one assumes that the transceiver cannot notify itself. Assuming a coupler loss of 4 dB and a directionality of 35 dB, a directional star structure with 12 nodes can be designed (fig.4). Attenuators were employed to level the attenuation of the optical paths between any two nodes.
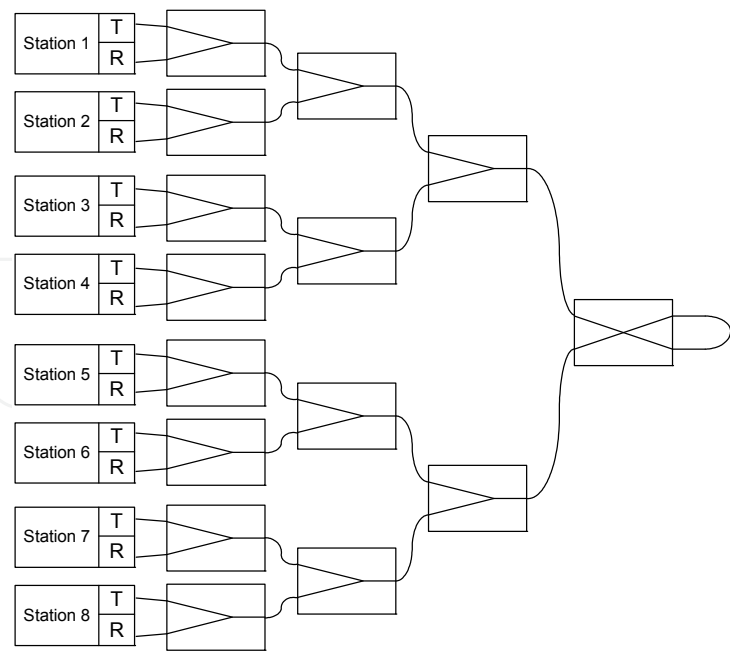
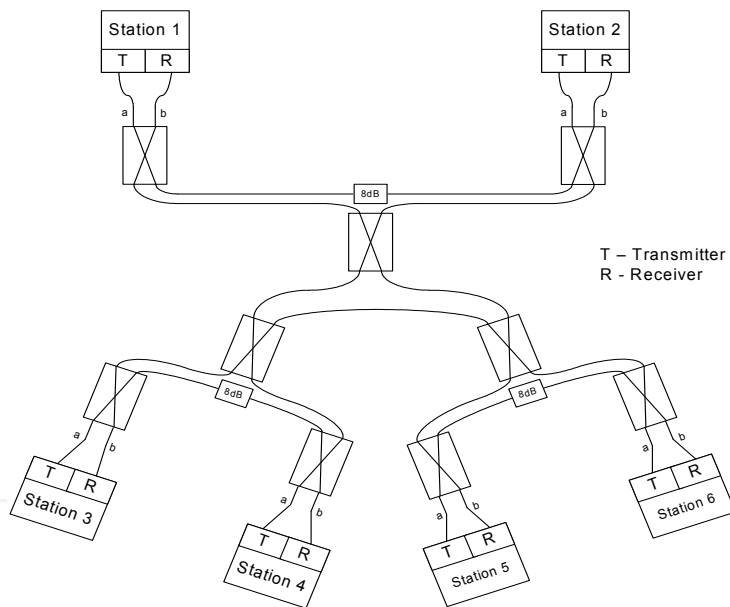Fig. 3. Reflective star with 8 nodes.

Fig. 4. Directional star with 6 nodes.

The structure can be expanded using asymmetric couplers whereby one can increase the number of network nodes and eliminate the necessity of using attenuators to level the attenuation of all the paths.

2.5 Optical elements in PONs

Each of the structures presented above requires different number of couplers in the network C and different number of couplers in the path between nodes S. The values for the described network types were given in the figures 5 and 6. The largest number of couplers in the network C is required for the Transmissive Star structure. On one hand it increases
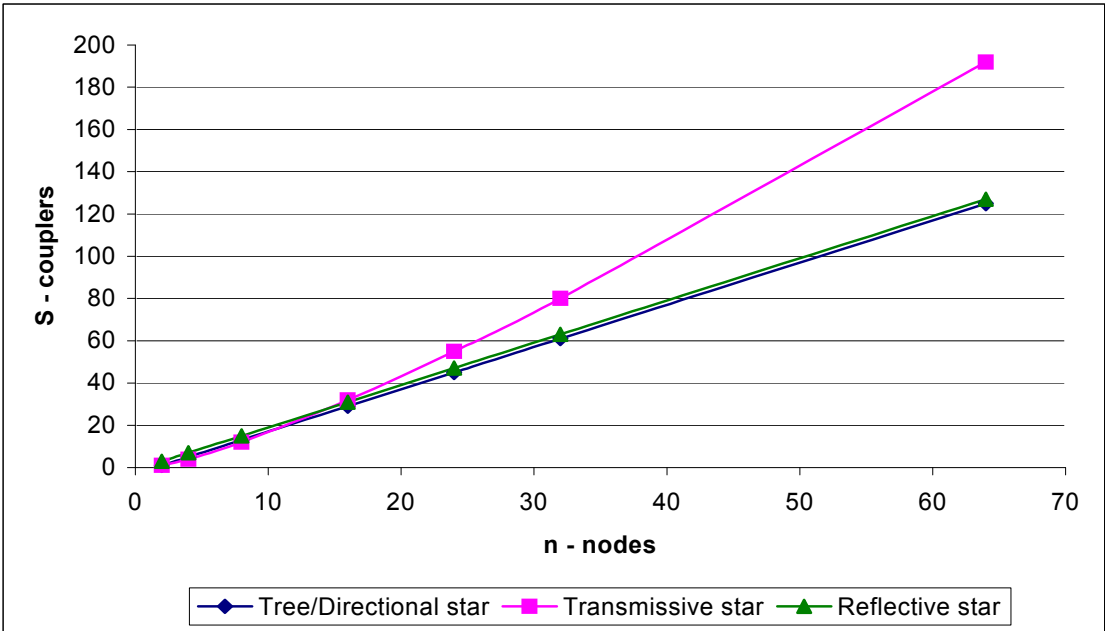
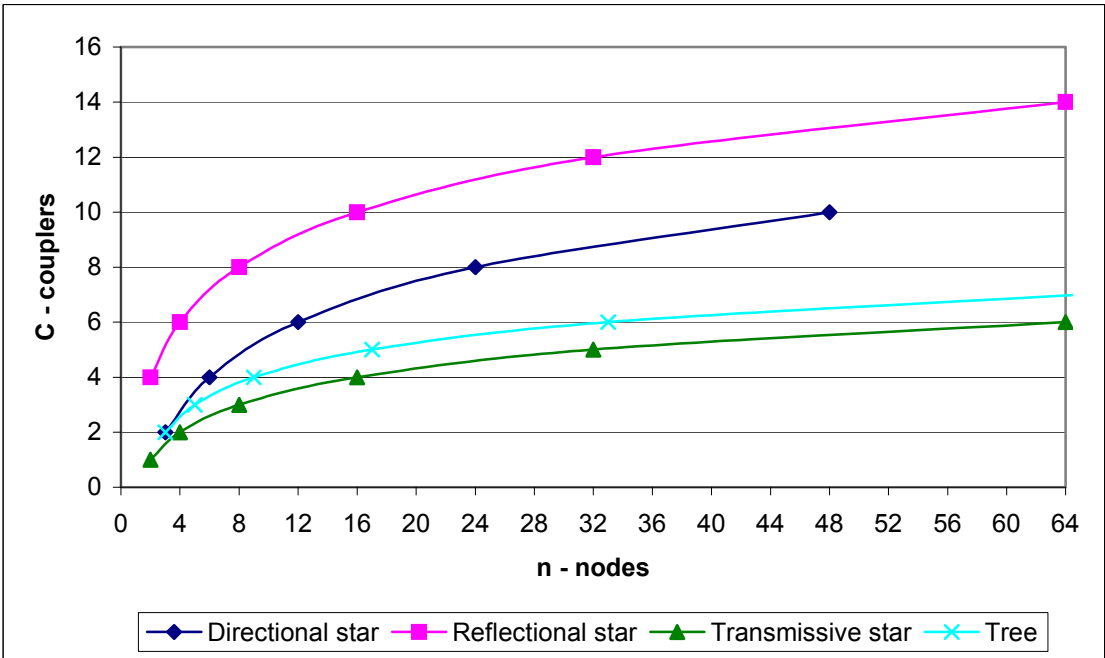Fig. 5. Number of couplers in the network C

Fig. 6. Number of couplers in the optical path S

the total cost of the network. On the other hand in this structure there is the lowest number of couplers in the optical path S, which makes it possible to improve the signal quality between nodes and to increase the overall network size.

Apart from the number of network nodes, parameters limiting a network size are the dynamic range of the transceivers and the length of the used patchcords. It seems that the number of couplers used has little influence on transmission speed but GI couplers bring losses around 3,5 dB (splitting 50% = 3dB and their intrinsic losses of about 0.5 dB). It can be

assumed that losses introduced by inserting less than 7 couplers do not depend on the signal frequency. However, fiber losses depend on the signal frequency. Probably connector losses increase with frequency but that fact is yet to be investigated. It can be proven that the optical power budget changes with the frequency.

3. Medium access methods in PONs

3.1 Introduction

Ethernet networks based on the CSMA/CD (*Carrier Sense Multiple Access with Collision Detection*) protocol have gained widespread popularity thanks to their easy expandability and the simplicity of their node arrangements. Unfortunately, the introduction of the CSMA/CD method into optical networks is complicated because of the peculiar nature of optical signals. Collision detection in conventional copper cabling networks takes place in the electric domain: the voltage level elevated above a certain threshold is measured. Collision detection in the case of optical signals carried in networks is much more difficult. Since fibre optic circuits have different signal attenuation coefficients, bouncing occurs at circuit junctions whereby the power of the carried signals changes. As a result, such simple collision detection methods as the ones used for electric circuits cannot be employed here.

Below, the collision detection methods used in the passive optical networks, their advantages and limitations and the potential for implementing them in proposed specific passive structures are discussed. We show several possible uses for different medium access mechanisms: CSMA/CD, CSMA/CA (*Carrier Sense Multiple Access with Collision Avoidance*), TDMA *(Time Division Multiple Access)* and WDMA (*Wavelength Division Multiple Access*).

3.2 Methods of detecting collisions in CSMA/CD networks

We assume that the network structure is based exclusively on optical fibre circuits and optical fibre couplers (Reedy J.W., 1985). The collision detection methods can be classified as:

- operating exclusively in the optical domain – the solutions presented in sections 3.2.1 and 3.2.2,
- ones in which collision detection is performed after the optical signal has been converted into an electric signal in a network node – the solutions presented in sections 3.2.3 and 3.2.4.

3.2.1 Measurement of average optical power

In the average optical power measurement method a collision occurs when the optical power received in a receiver is higher than the power transmitted by a single network node. The threshold power above which a collision is detectable is higher than the power required to receive data in normal transmission conditions. In order to increase the method's effectiveness the optical transmitter must be switched off when no transmission occurs. This increases the transmitting system's complexity and has an adverse effect on the laser sources. The time needed for switching on the laser reduces the effective speed of transmission in the network. In order to minimize this drawback, one can use power supply systems with two working points. In the idle state the laser current is low but sufficient for

lasing to occur. A working point for collision detection requires a much higher laser feed current to emit the higher optical power needed for the proper transmission of data in a network. One should also take into account the laser sources' power level tolerance, the effectiveness of the laser source/optical fibre coupling and the quality of the fibre optic connections. Hence one must determine the allowable optical power level in the network for both transmission and no transmission (Fig. 7).
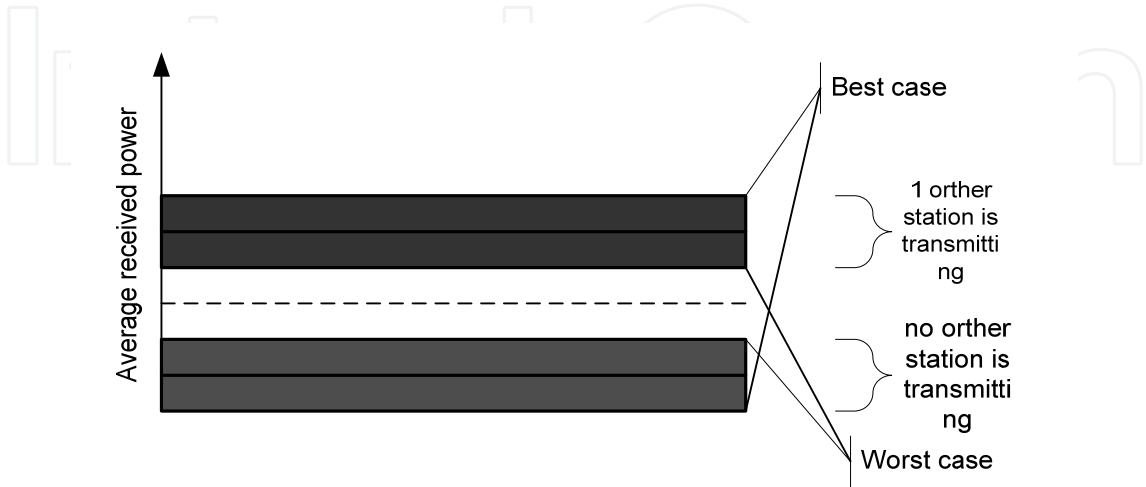

Fig. 7. Power levels at transmission and at no transmission.

3.2.2 Directional coupling

This method makes use of special optical fibre coupling techniques whereby one can create such a system in which a given station can hear all the stations, but not itself. Collisions in this case are detected directly: if a given station transmitting data detects a signal in its receiver, this means that a collision has occurred.

How can such a directional system of connections be built to meet the requirements? An example here is the construction of a duplex bus based on two optical fibres, as shown in Fig.8. In such a system each node transmits data through the lower fibre to the neighbouring nodes on its left and via the upper fibre to its neighbours on the right. As a result, all the stations, except for the transmitting station, receive the data signal.

Since this bus topology is now outdated, efforts are made to build more effective networks using the star topology. A directional star coupler in which optical power from each of the
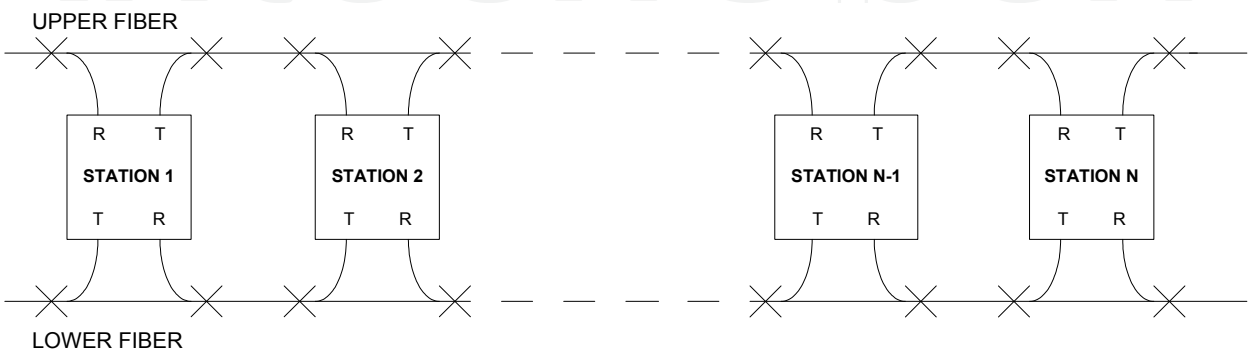

Fig. 8. Duplex fibre optic bus.

inputs is equally distributed among all the outputs except for one is used for this purpose. Such a network can be constructed by connecting 2×2(X) and 2×1(Y) couplers. An M×M star coupler can be obtained by connecting 2*M couplers with M – 1 inputs/outputs. The function of the inputs/outputs is to split or combine optical powers. An exemplary four-port star with sending-receiving systems is shown in Fig. 9.
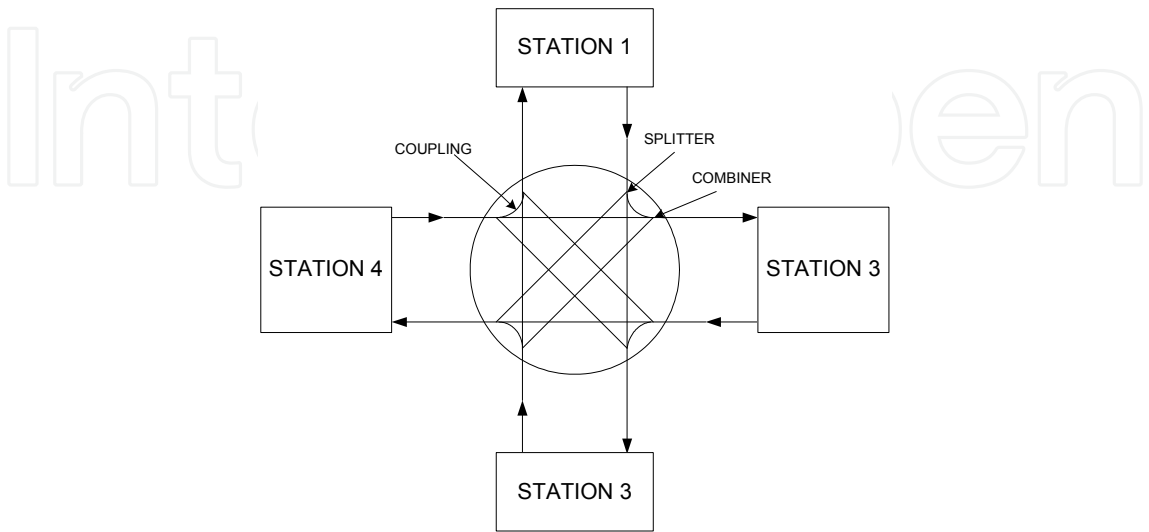

Fig. 9. Directional four-port star.

3.2.3 Pulse width disturbance

The pulse width disturbance measurement method exploits the fact that in the primary Ethernet system a data stream is encoded using the Manchester code so that the information bit is always encoded as transition "01" or "10". Consequently, one can exactly define the data stream pulse width free of any collisions. Modulation at a rate of 20 Mbaud was employed in a system with a throughput of 10 Mbps whereby a single pulse should be nominally below 100 ns. The collision detection system's function is to detect signals exceeding the nominal pulse width (Fig. 10).
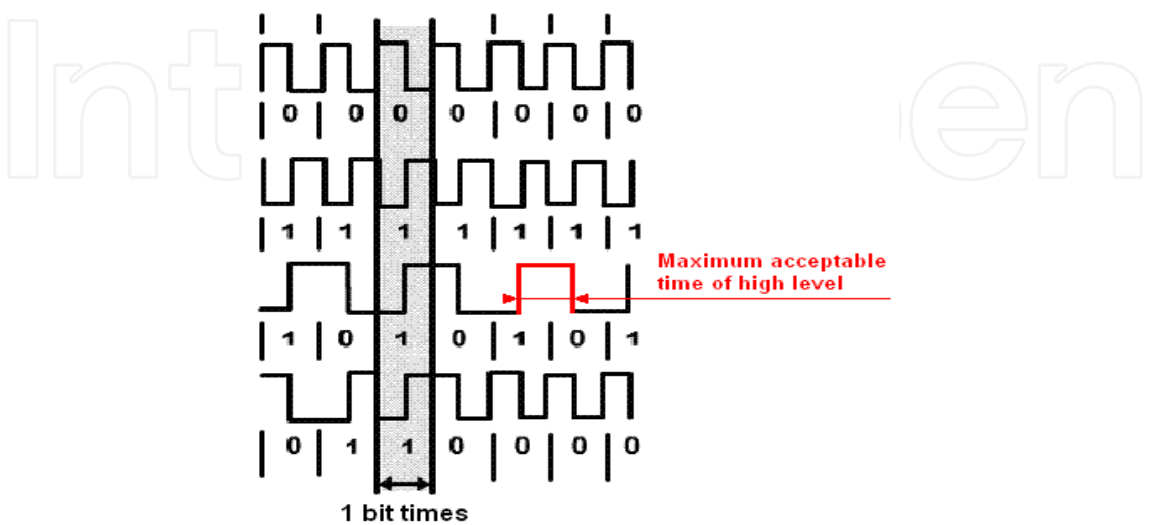

Fig. 10. Manchester coding scheme.

Similarly to other amplitude measurement techniques, this method is limited by situations in which a weaker signal is masked by another stronger signal. Hence, it is essential to build junctions between network nodes having the same attenuation for each optical circuit. Optical attenuators or asymmetric couplers are used for this purpose. Another way of solving this problem is to employ a centralized collision detection unit. If a collision is detected by the central mechanism, the latter sends a strong jam signal to all the sending-receiving devices in the network whereby a change in the pulse width is easily detectable. This represents, however, a departure from the fully passive network concept. The jam signal can be used to amplify collisions in systems with collision detection, in which at least one station informs another transmitting station in the network that a collision has occurred. The method's drawback is the necessity of using Manchester encoding, i.e. modulation twice as fast as the transmission speed. For this reason, the above method is limited to speeds below 10 Mbps, becoming highly ineffective at higher speeds.

3.2.4 Direct comparison of streams

This method consists in comparing the sent binary stream with the received stream in the electrical signal domain within a given sending-receiving device. If the received bit stream does not tally with the sent one (allowing for propagation delay), the system determines that a collision has occurred. This complicates a little the system since it is necessary to install memories buffering the card's outgoing traffic. One should also include a system analysing incoming signal delays relative to the sent signal. The system ought to be able to negotiate the connection parameters by sending test packets when a new card is installed in the system. Obviously, one should also specify the attachment of a sending-receiving device to the network in such a way that the detector of one device could receive the signal from its own transmitter (Fig. 11).
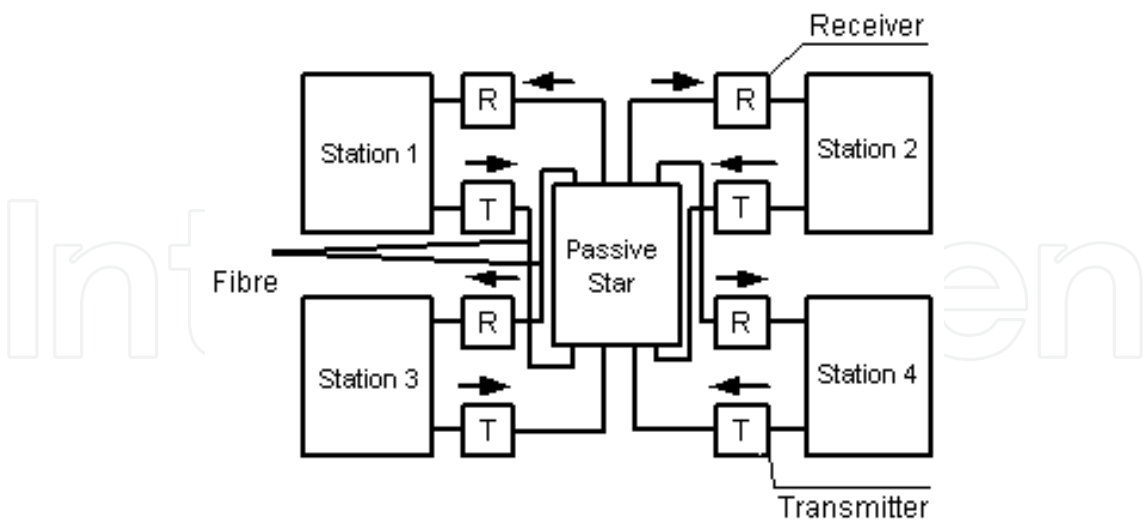

Fig. 11. Device-to-passive-star attachment diagram.

The method's apparent advantage is the system's transparency with regard to coding since the detection of collisions takes place at the level of analysis of individual binary pulses. Moreover, the method does not introduce significant transmission rate limitations and is suitable for transmission rates of 100 Mbps.

3.3 Medium access in CSMA/CA networks

A need of all-optical networks has prompted the design of protocols that could detect the presence or absence of optical signal on a specific channel without regard to the high-bit rate data being transmitted. One of these kinds of protocols is protocol CSMA/CA, whereby nodes using optical carrier-sense capability prevent transmitting a packet at times when it would collide with other packets which are already in transit. Unlike the CSMA/ protocol where collisions are tolerated and the retransmission is required, here the collisions cannot happen.

Below there is a presented exemplary scheme of arbitrary node in a ring network that enables collision detection. Each node receives packets on a single unique wavelength but can transmit packets on any wavelength (Wong E., 2004).
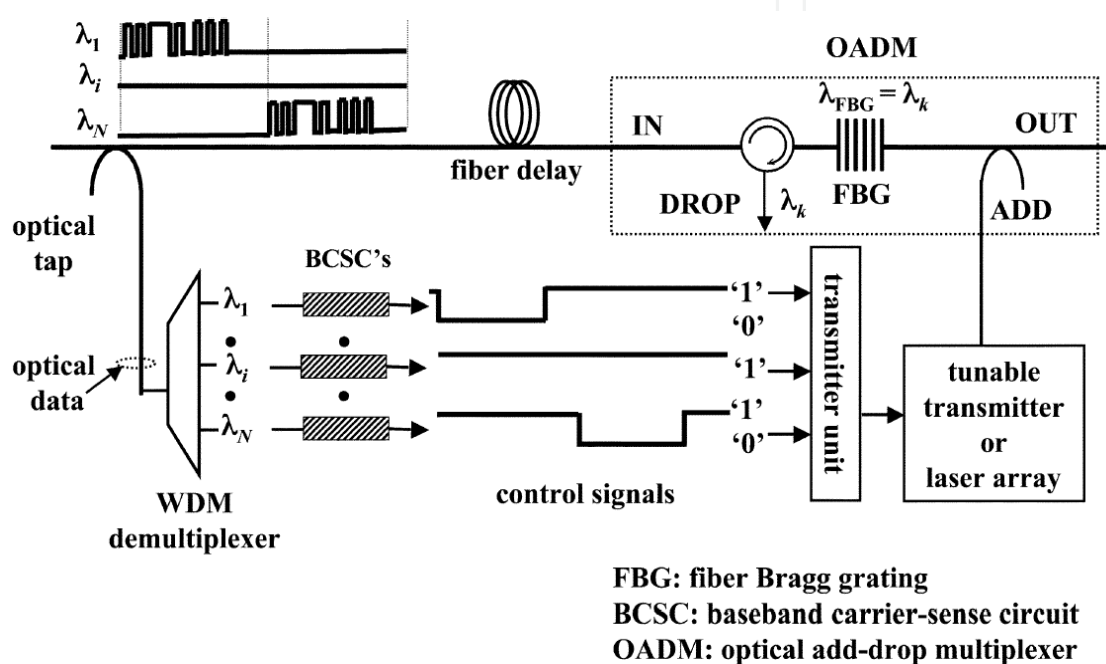
Fig. 12. Architecture of an arbitrary node in a CSMA/CA network.

To prevent collisions at the out ports between the transmitted packets and those that are already in transit, a part of the optical power of all packets arriving at the node is tapped.

The tapped signals are demultiplexed into individual wavelengths, which are then detected by BCSCs (*Baseband Carrier-Sense Circuits*) that perform packet detection. Each BCSC generates a control signal that informs if the channel is occupied or not. Based on this, the transmitter unit evaluates the duration of the transmission gap between adjacent arriving packets and if it is suitably long to send its own packet.

Presented scheme concerns the module based on the single-mode optical fibres. According to our knowledge there are no presented similar solutions for multimode optical fibres so far, but we predict it is potentially possible.

The proposed protocol requires complicated and expensive electronic processing so it can not be used in the planned commercial applications.

The main advantage is a simple management layer (L2) and the main disadvantage is a complicated physical layer (L1).

3.4 Medium access in TDMA networks

TDM *(Time Division Multiplexing)* is a technology that is used mainly in access networks, but it may also be useful in local networks. This technique relies on the assignment of suitable time cells for the input streams. TDMA technique is usually used in tree type structures (Pesavento G., 2003).
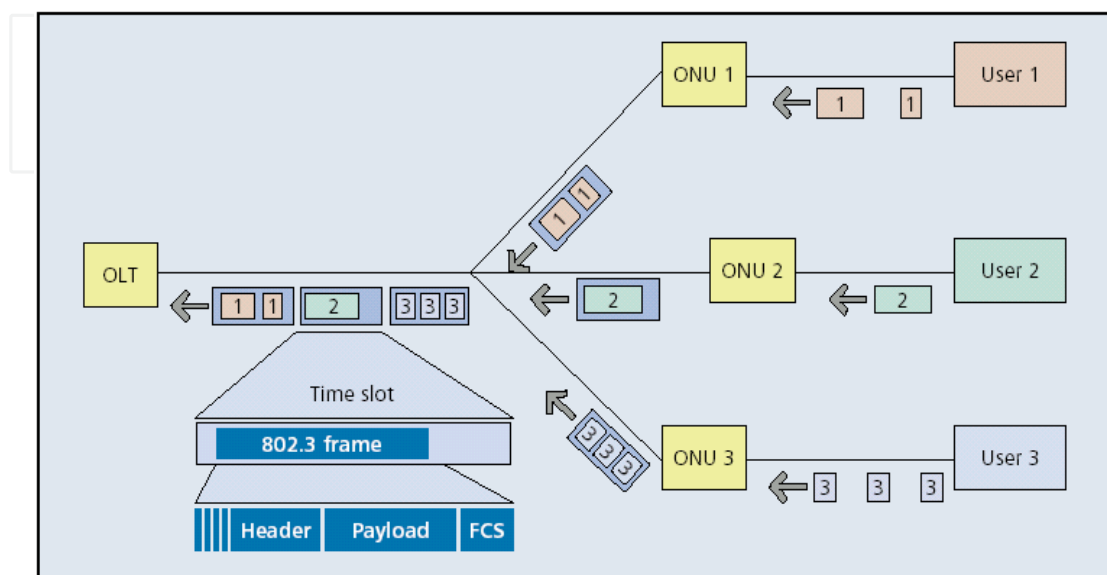

Fig. 13. Architecture of TDMA network.

The main advantages of TDMA protocol are:

a.   possible larger network span at higher efficiency than in CSMA/CD
b.   management algorithms adaptable from EPON (*Ethernet Passive Optical Network*) networks
c.   centralised management
d.   very easy to prioritise traffic
e.   QoS support

The main disadvantages of TDMA protocol are:

a.   required complicated algorithms for traffic management
b.   efficiency dependent on network size and network load
c.   central node much more complicated than other ones

3.5 Medium access in WDMA networks

Although PON's provide higher bandwidth than traditional cooper-based access networks, there exists the need for further increasing the band of the PON's by employing WDM (*Wavelength Division Multiplexing*) so that multiple wavelengths may be supported in either or both upstream and downstream directions. Such a PON is known as a WDM-PON. Fiber optical networks, working on the basis of WDMA technique, are natural evolution of optical fiber links working in point-to-point topology using WDM. WDMA network development can also be considered as abilities to increase the effect of one wavelength-based passive optical networks (Banarjee A., 2005).

The ability of data sharing between users, when a common transmission medium is being used, is an important feature of these kinds of networks.

Data streams are transmitted, using different wavelength multiplied optical transmitters, to all network nodes. When the detector receives information, it selects a desirable signal from all transmitted signals in one fiber using selective optical filter. In order to meet the above-mentioned requirements co-shared medium currently requires the star topology network architecture.

Standard PON operates in the "single wavelength mode" where one wavelength is used for upstream transmission and a separate one is used for downstream transmission.

Different sets of wavelength may be used to support different independent PON subnetworks, all operating over the same fiber infrastructure.

Even though they provide the highest capacity, optical WDMA networks are usually too expensive. Also, their reliability is usually low due to the use of active systems (e.g. multiplexers or switches). Access networks still require inexpensive solutions in which the costs of the network will be shared between all users.

In the world literature there are no interesting solutions concerning the use of WDM technique in multimode networks based on wavelengths 850 or 1300 nm. We propose installation of several sources with various wavelengths (1310, 1330, 1350, 1370 nm) and passive filters in nodes, which would increase the transmission speed but decrease the number of users. We must use supplementary couplers for connecting several sources and detectors with CWDM (Coarse *Wavelength Division Multiplexing*) multimode couplers.

As far as we know, an interesting solution can be achieved for wavelengths 1300 –1550nm in multimode optical fiber (there can be used the fiber elements which are commercially available).

Based on the preliminary measurement of the passive structures, one can assess parameters of the network built presented above and working with 1Gbps transmission speed. Parameters presented in Table 1 were determined for optical path with 100m fiber optical patchcords connecting nodes with the structure. In the table, based on the date from our measurement, we present projects of structures and parameters possible to achieve. There are also proposals of suitable protocols for the chosen structures.

The number of nodes in the networks depends significantly on the dynamics of available electro-optical converters. For the 850nm bandwidth the normal off-the-shelf transceivers usually offer dynamics only slightly better than 15dB, while in 1300nm windows the dynamics can reach beyond 25dB.

The main advantages of WDMA protocol are:

- possibility of building a few "logical networks" on top of only one physical structure
- "logical networks" can be invisible to each other (depends on the central node)
- efficiency depends on the access mechanism used in "logical networks" (usually TDMA)
- more wavelengths = better utilised fibre
- ease of adding a special channel for network management

- most elastic with tunable receivers and transmitters

The main disadvantages of WDMA protocol are:

- complicated and expensive in most configurations
- efficiency depends on the access mechanism used in "logical networks" (usually TDMA)
- most flexible with tunable receivers and transmitters

4. Measurements of base transmission parameters

4.1 BER measurement

Special systems were designed in order to measure BER (*Bit Error Rate*) in multimode passive optical networks based on a FPGA programmable logic combined with electro-optical transceivers for 850nm and 1300nm wavelengths. The transmitters used in the 850nm transceivers were VCSEL lasers whereas in the 1300nm transceivers there were DFB lasers. The spectra of both are presented in Fig.14. The dynamic of the AFBR-53D5Z was 13dB and HCDTR-24 was 22dB. The built system allows for the selection of a number of transmitted bits in the range between $10^6 - 10^{12}$ as well as the transmission speed. Communications with the FPGA setup was carried out using standard LVPECL differential signals. The measurements were performed in two speed ranges: 100Mbps and 1Gbps.
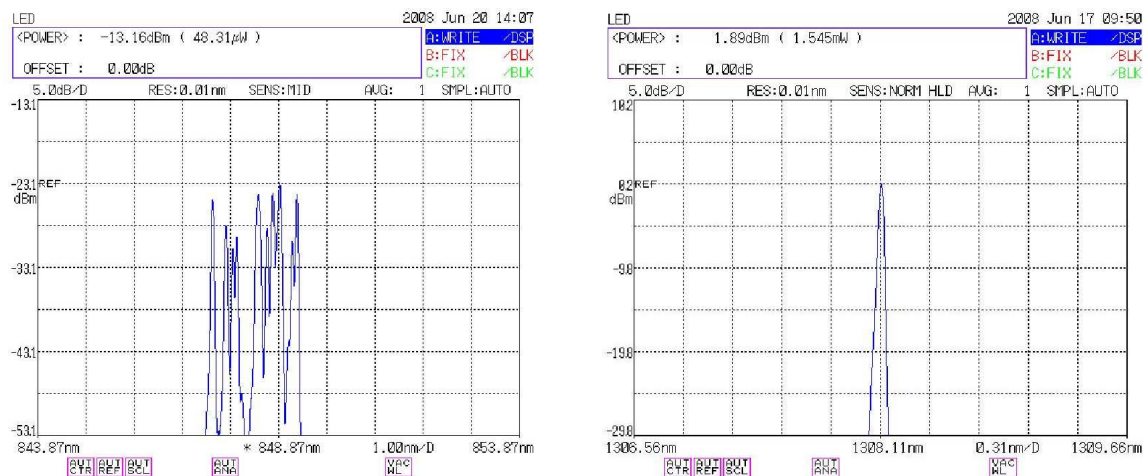

Fig. 14. Spectra of used VCSEL (850 nm) and DFB (1300 nm) lasers.

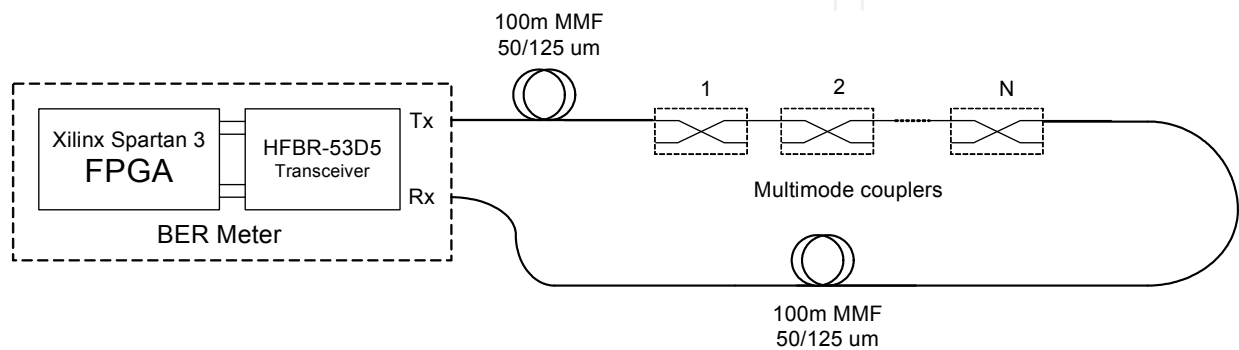The network configuration the measurements were carried out in are presented in Fig. 15.

Fig. 15. The tested optical path.

The tested optical path included a cascade of GI optical couplers and two 100m GI patch-cords at the start and the end of the cascade of couplers. The obtained measurement results for two different wavelength BER in 100Mbps range are presented in Fig.16.
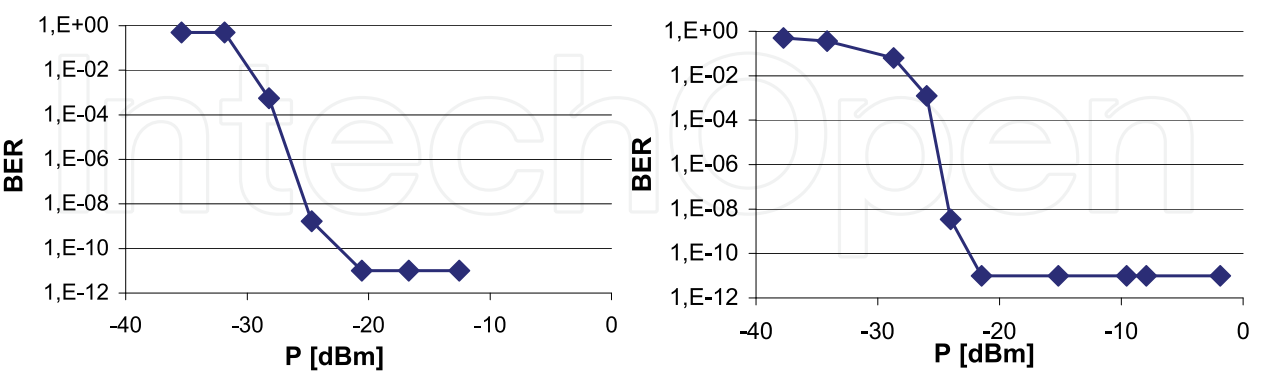

Fig. 16. BER measurements for two different wavelengths 850 nm (a) and 1300 nm (b) for speed transmission 100 Mbps as a function of attenuation obtained by including following couplers in optical path.

In order to construct the electro-optical transceiver working in 1GHz range we chose the byte method. The block diagram of the E/O transceiver working in the byte mode was shown in the Figure 17.
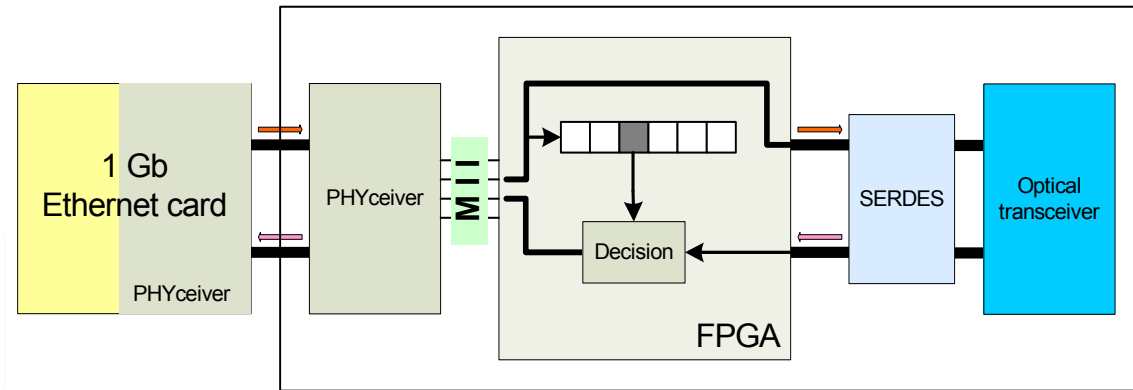

Fig. 17. E/O transceiver working in the byte mode.

In the byte mode, the Ethernet frame is decoded only into small pieces, i.e. nibbles for 100 Mbps and bytes in 1Gbps network speed. The bytes are sent in parallel to the SERDES (*serializer/deserializer circuit*). Although this makes frame end detection more troublesome (5 bit or 10 bit long words have to be analyzed), it offers faster collision detection, higher network throughput and a possibility of using the XC3S200 chip in 1Gbps networks.

Fig.18 shows WER (*Word Error Rate*) as a function number of coupler. Multimode GI coupler cascade measurements show that the tested off-the-shelf transceivers make it possible to build 1Gb optical networks with up to three coupler levels in optical path (Fig.18).

4.2 Bandwidth measurement

We've designed media converters for bandwidth measurement purposes. Transceivers AFBR-53D5Z, HCDTR-24 and PIN diodes have been used to build media converters. The bandwidth measurements were performed for different network configurations, including the GI patchcord cascade, GI coupler cascade and a complete optical path. The measurements were performed in the measurement setup shown in Fig.19 (for patchcord cascade).
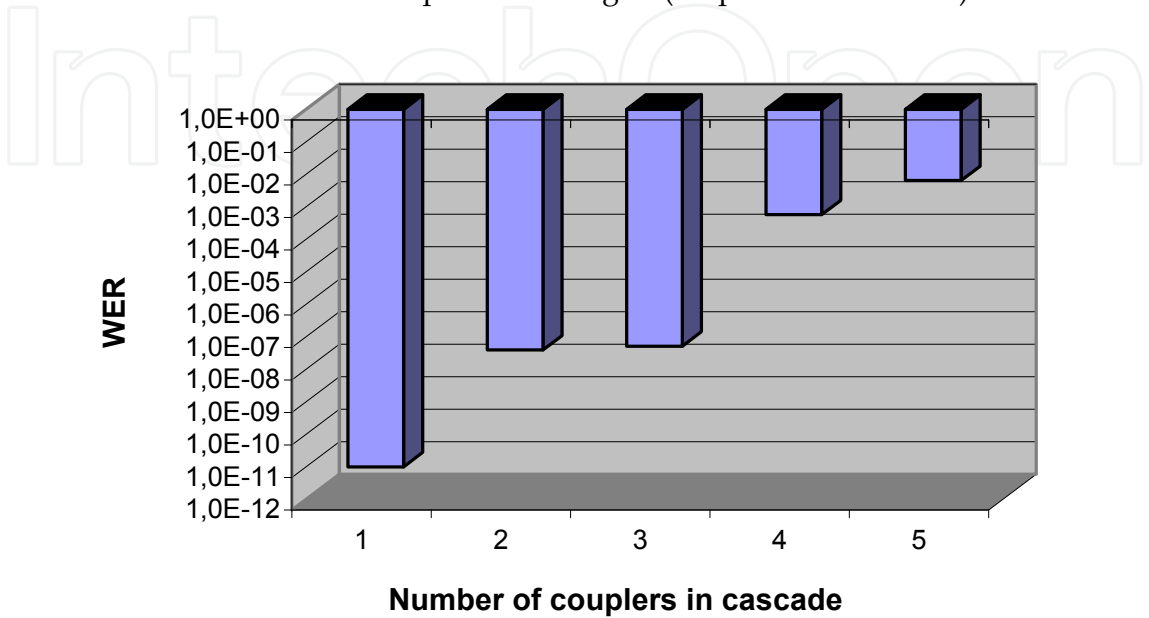

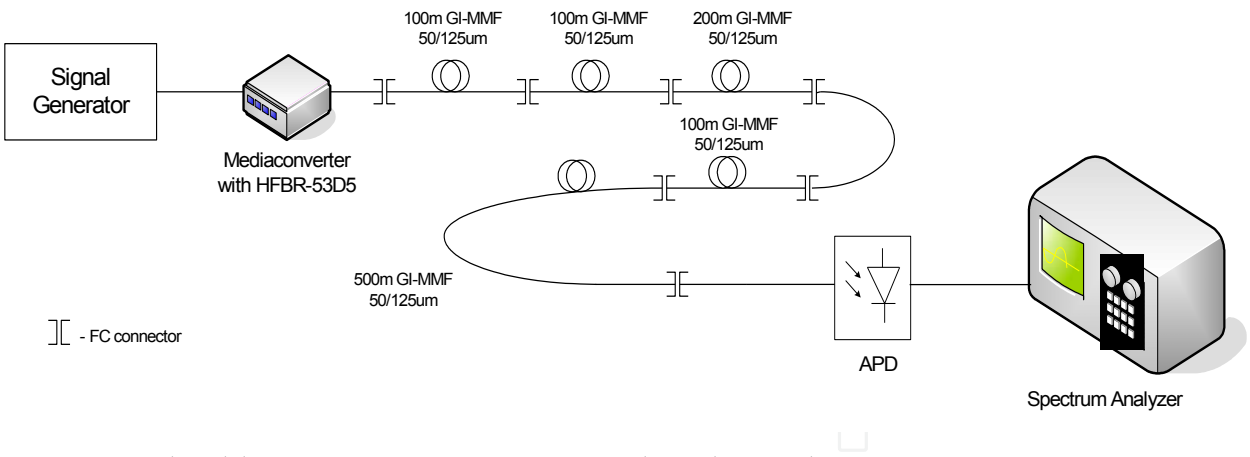Fig. 18. WER of transmission through cascade of couplers at 1,25GHz.

Fig. 19. Bandwidth measurement setup – a patchcord cascade.

Measurements were performed at various frequencies within the 10 MHz -1 GHz range. Similar to the setup where BER measurements were taken the network elements (GI patch-cords and GI couplers) in this setup were also joined using FC connectors. Fig.20 presents the transmission spectrum for a patchcord cascade and Fig.21 - for the complete optical path. One can notice that if the path attenuation does not exceed the dynamics of the transceivers, then the attenuation does not depend on the transmitted signal's frequency. On the other hand, if the optical path attenuation exceeds the system's dynamics, then the transmission bandwidth becomes significantly reduced.
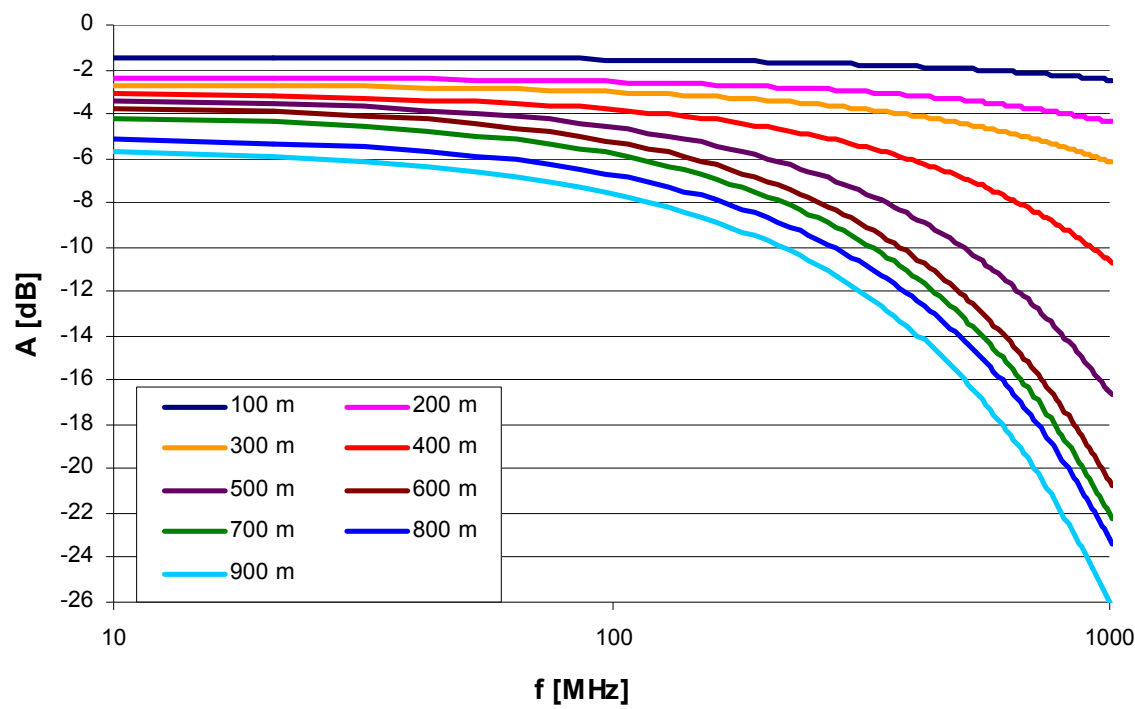
Fig. 20. Frequency response of the fiber optic patchcord cascade (850 nm).
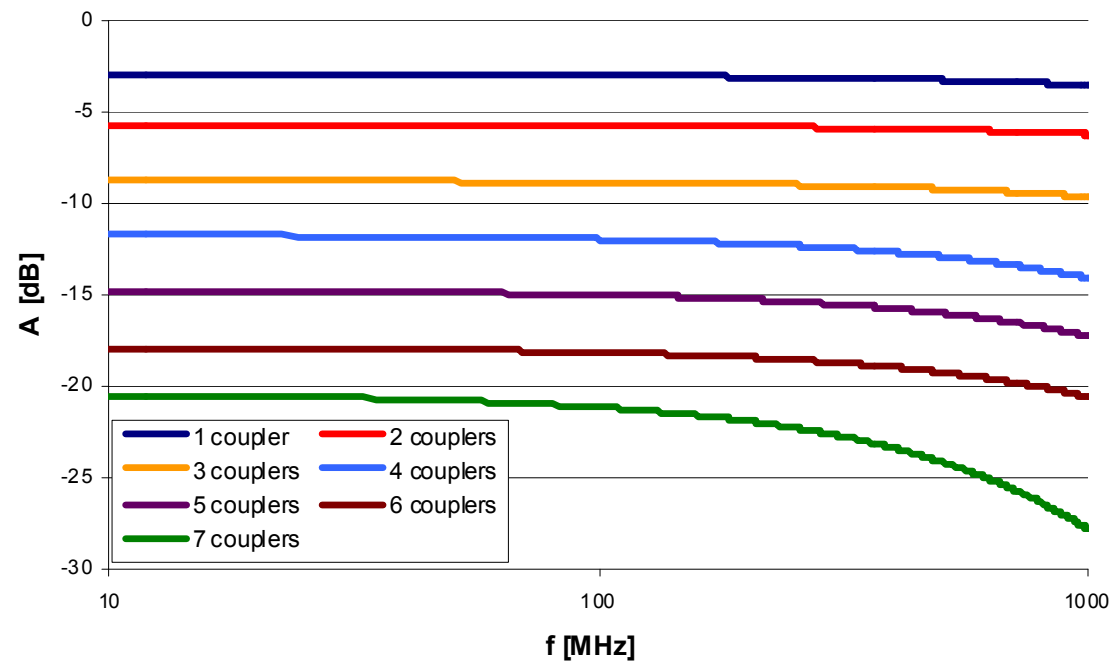

Fig. 21. Frequency response of the optical path (850 nm).

5. Network's size estimation

Parameters for a 1Gbps PON network can be assessed based on the passive structures measurements. The parameters presented in Table 1 were determined for an optical path with 100m fiber optic patchcords connecting nodes with the structure. In the table, we present projects of structures and parameters possible to achieve based on the data from our measurements. There are also proposals of suitable protocols for the chosen structures.

The number of nodes in a network depends significantly on the dynamics of available electro-optical converters. For the 850nm bandwidth the normal off-the-shelf transceivers usually offer dynamics only slightly above 15dB, while the dynamics in 1300nm and 1550nm windows can exceed 25dB.

Dynamic	15 dB		25 dB	
Type of structure	Transmissive star	Directional star	Transmissive star	Directional star
Number of nodes	16	6	64	12
Number of couplers in the network	32	9	192	21
Bandwidth	1 Gbps	1 Gbps	1 Gbps	1 Gbps
Method of collision detection	Comparison of streams	Directional coupling	Comparison of streams	Directional coupling
Necessary Hardware	Ethernet card with MII interface + FPGA programmed structure	Standard Ethernet card + converter NRZI <=> MLT-3	Ethernet card with MII interface + FPGA programmed structure	Standard Ethernet card + converter NRZI <=> MLT-3

Table 1. Parameters of the network topologies

6. The possibilities of applying CWDM method in a multimode structure

Transmission of different wavelengths in the optical passive structure allows obtaining more effective and quicker communication between nodes. We propose installation of a few different wavelength transmitters (T1-1310 nm, T2-1330, T3-1350 and T4-1370 nm) and receivers with CWDM multimode couplers in receiving stations, working as optical filters. Such installation allows the given structure to simultaneously transmit different wavelengths while giving transmission speeds proportional to the number of introduced wavelengths.
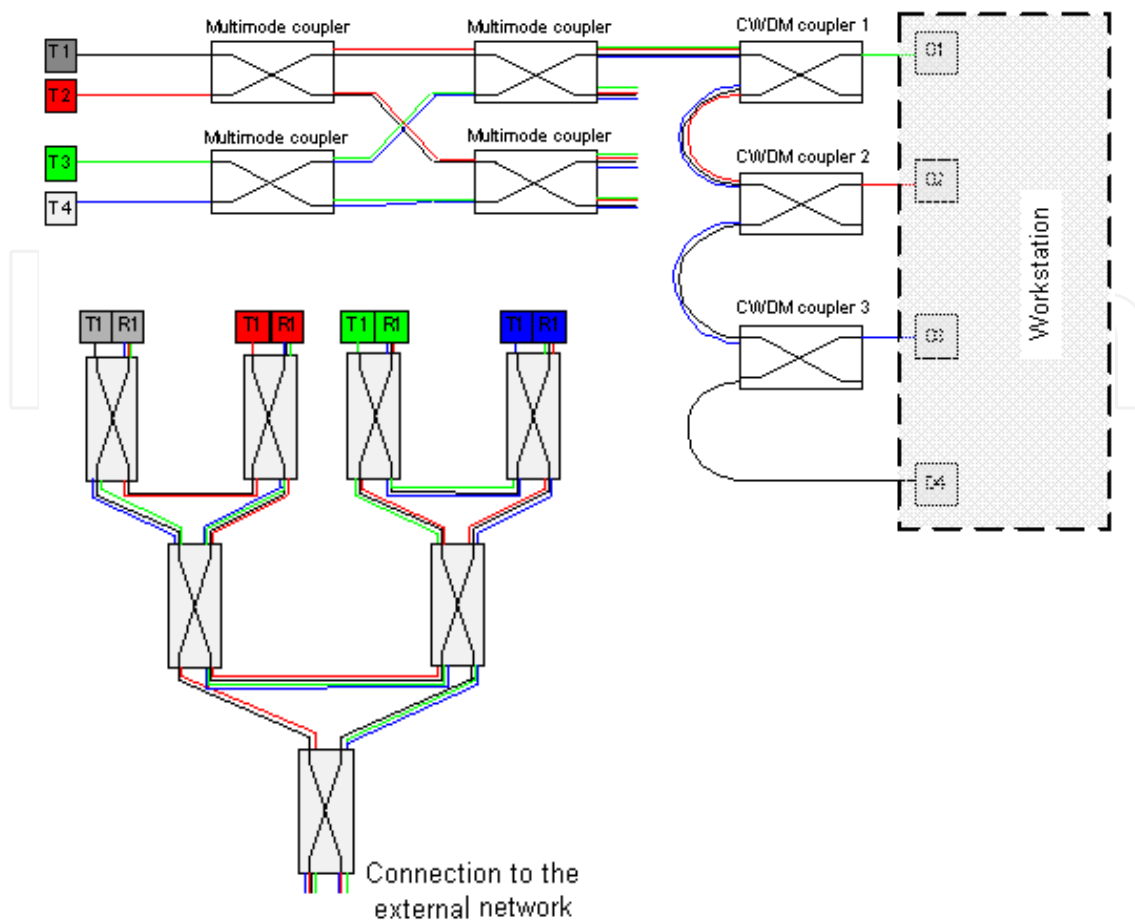
Fig. 22. Proposal of various CWDM PON structures

7. Conclusions

In this chapter we've proven feasibility of constructing Ethernet type local area networks based on multimode fibers working in either 850nm or 1300nm windows. Bandwidth, BER and WER analyses demonstrated possibility of building efficient networks with many GI 50/50 couplers in the optical path. Within the analyzed network types, the most promising for implementation at this point seems to be the transmissive star structure. Although the electrical part is complicated, much higher network capacity at relatively low cost per unit is well worth the tradeoff.

The available network structure size also greatly depends on the structure type. Out of the structures chosen for analysis, the transmissive star seems to offer much larger network size than the directional star structure. The advantage of transmissive star is its simpler collision detection method. Implementing directional coupling can be faster than the other streams because it's easier. Nodes based on directional coupling will be slightly cheaper, also there is no need for additional, complicated logic.

8. References

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