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Search for Ultimate Throughput in Ultra-Broadband Photonic Internet

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***Abstract*—A review of our today's understanding of the ultimately broadband photonic Internet is presented. A simple calculation is presented showing the estimate of the throughput of the core photonic network branches. Optoelectronic components, circuits, systems and signals, together with analogous electronic entities and common software layers, are building blocks of the contemporary Internet. Participation of photonics in development of the physical layer in the future Internet will probably increase. The photonics leads now to a better usage of the available bandwidth (increase of the spectral efficiency measured in Bit/s/Hz), increase in the transmission rate (from Gbps, via Tbps up to probably Pbps), increase in the transmission distance without signal regeneration (in distortion compensated active optical cables), increase in energy/power efficiency measured in W/Gbps, etc. Photonics may lead, in the future, to fully transparent optical networks and, thus, to essential increase in bandwidth and network reliability. It is expected that photonics (with biochemistry, electronics and mechatronics) may build psychological and physiological interface for humans to the future global network. The following optical signal multiplexing methods were considered, which are possible without O/E/O conversion: TDM-OTDM, FDM-CO-OFDM, OCDM-OCDMA, WDM-DWDM. The Polish perspective closes the review.**

***Keywords*—Optical networks, Internet, global network, photonic Internet, future Internet, optoelectronic networks.**

I. INTRODUCTION

PHOTONIC Internet comprises the core transport network of the ultimate capacity [1]–[48] and numerable access networks (and its components) of large variety and changing capacity – heavily depending on the specific application [49]–[118], [118]–[171].

The development of electronic and optoelectronic technologies, micro-systems and information technologies, for more than three decades, in combination with a new psychological and sociological understanding of the global network, has been creating a stable background for very fast evolutional changes of the Internet [1]. The global network is researched in a much wider context than only as an advanced technical infrastructure. Particular role in the development of the technical, hardware and software layers play optics, photonics and optoelectronics [2]–[5].

It seems now that the photonics, together with electronics and mechatronics (micro-systems), will be able in the future to create something more than only the advanced technical infrastructure, in a form of a completely new kind of interface of psychological and even physiological nature. It would be a sort of a more direct interface of human senses to the global network. The necessary condition is existence of a virtual infrastructure of the throughput non confining the applications, including fast, real-time transmission of the contents as hi-res 2-D and 3-D images. The 100GbE, which is close to standardization [6] has recently been commercialized [7], [8].

Next logical step, which is unavoidable, is the 1 Tb/s photonic Ethernet [9]. This is an extension to the standard IEEE 802.3. The backbone network of the future Internet with access links 1Tb/s, which is now researched, goes into the throughputs of 100 Tbit/s [10]. The next step, out of easy reach yet, is a network of the throughput reaching 400 Tbit/s and 1Pb/s. Today a stabilized standard for a single fiber in a core network, taking into account the costs seems 10 Tbit/s. The throughput of 1 Tbit/s seems also justified economically and technically, for major Ethernet access links. The emphasis is put on a deeper 'photonization' of the Internet, and full in the future. This stems from the development of the optical fiber communication, all optical integrated optics processors and big costs of manufacturing high speed electronics, entering the domain of THz.

The electronics is a bottle neck in the domain of digital signal processing at these speeds, which includes application of advanced modulation schemes of very high spectral efficiency. The fastest commercial (thus relatively cheap) DAC/ADC integrated circuits work at the speeds not very much over 20 GHz. Today the solution is proper granularity of the electronic bandwidth and the last km, broadband access link to the user.

II. FUTURE PHOTONIC INTERNET ENGINEERING

The EU participates in the development of the future Internet [6], via actions of the Future Internet Assembly FIA. The broadband TCP/IP networks are subject of interest of the Internet Society [7], Gigabit Internet Alliance [8] and many more. Also in Poland, there are coordinated efforts for the development of the ICT sector. The first work was done by the Pioneer network. Now a project is carried out on the "Future Internet Engineering". It is coordinated by the FE&IT of WUT in cooperation with several telecom institutions like the Institute of Communications (governmental laboratory). The project has more than 10M Euro from the European Funds on Operational Programs (POIG) [9]. Participation of optoelectronics, next to the wireless data transmission technologies, in the construction of the physical layer of the Internet, increases very fast together with the traffic intensity in the core and access networks.

The contemporary Internet uses widely optoelectronics, optics, photonics and related branches for the following purposes:

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data transmission, transmission multiplexing, switching of data streams, building of all optical sectors in the network, effective usage of accessible bandwidth, bandwidth division and granularity, making the bandwidth accessible for users, bandwidth management, increasing of spectral and energy efficiency of the network, increase of the network reliability and flexibility, lowering of costs, etc.

Many of the above components of the optical (and associated radio) networks under development contribute evolutionarily to a new quality which one calls virtualization. The virtualization leads to completely arbitrary usage of the network transport layer for dynamic realization of tasks or temporary configuration of functional networks. Arbitrarily configured transport layer of practically unconfined throughput realizes distributed high performance computing equally easily and at low cost as any other task to transport large amount of data. Assuming, that such dynamically configured virtual network has an optimal structure for the task.

III. AVALIABILITY OF NONCONFINED BANDWIDTH

Today's research on optical fiber links, residing on a single filament, of ultimate throughputs go into at least two major directions:

- maximum throughput of a short to medium range link realized between big core network nodes; these links are of several hundred km in length and of throughputs closing to 100 Tbit/s;
- maximum throughput of very long optical links, like transcontinental or transatlantic; these links are of 10000 km in length and of throughputs closing to 10 Tbit/s.

Here we will confine the analysis to the applications of photonics and optoelectronics in the Internet with the emphasis on the availability of the ultimate transmission parameters. The availability of unconfined bandwidth and unlimited flexibility in granularity allocation of this bandwidth is the basis of the future Internet development and guarantees its full virtualization. Technical components of this basis are as follows: core and access networks use the same (common) transmission technologies like optical Ethernet, the optical and electronic methods of bandwidth multiplexing, concatenation, demultiplexing are TDM in ETDM and OTDM versions, FDM in OFDM and CO-OFDM versions, the bandwidth is used at high spectral efficiency presumably over 10 bit/s/Hz, the network is optimal considering technology, bandwidth and energy usage, reliability.

IV. OPTOELECTRONICS IN CONTEMPORARY INTERNET

Today, the optoelectronics fulfills the following functions in the Internet:

- links for gigabit and terabit data transmission in the core network; the links consist of optical cables, cooperating with optoelectronic transceivers or optical amplifiers;
- optical fiber links for ISP networks, local and access;
- optical fiber links for users of FFTX type, like fiber to the home or premises FTTP, FTTH;
- optoelectronic user interfaces O-NIC;
- optoelectronic standard Ethernet interfaces: 1, 10, 40 and 100 GbE;
- optoelectronic signal multiplexing CO-OFDM, OTDM, as differentiated from electronic analogs of these methods: ETDM, EFDM, EOTDM;
- photonic switching of light paths in transparent optical networks, O/O switching without O/E/O switching;
- amplification and regeneration of digital optical signals in semiconductor optoelectronic or active optical fiber components, for trunk transmission.

Optoelectronics technologies are also used for building plasma and LCD displays, and 2D, 3D projectors, including holographic.

V. OPTOELECTRONICS IN FUTURE INTERNET

Optoelectronic technologies will be used in the future Internet systems:

- further increase of the throughput of optical transmission channels, up to Pbps, and very effective management of the burst traffic and irregular demand for bandwidth;
- building of all optical networks, practically with not confined bandwidth;
- building of intelligent photonic physical networks with arbitrarily and dynamically configured virtual networks oriented optimally for particular tasks;
- projection of 3D image in free space and creation of virtual reality for full submerging of a human being, generation of feeling of full presence and participation;
- building of flexible displays and transparent illuminators integrated with civil engineering infrastructure;
- building of new generation of personal digital assistants, which are integrated image interface of an individual to the virtual world; this interface may (what is today difficult to imagine) fulfill the basic needs of a human being like nutrition, physiology, health, safety, communication, transportation, education, creativity, economy and business, culture, entertainment, relaxation, etc.;
- organization of the closest human vicinity; embracing an individual with a broadband (including RF, IR and optical bands) interactive cloud, working as a kind of an interface to our senses and our organism and to the global network.

The fully photonic network is a term describing a really future network, which is expected to emerge during the next several decades. A transparent network does not require intermediate signal transformation O/E/O. Intelligent light paths of different colors are configured dynamically between the relevant users. The paths are opened without collisions in the complex network structure. The network transmits ultra – fast optical signals of arbitrary rate and arbitrary format of modulation. Generation of optimal networks for particular sub-tasks, with reserved relevant transmission and processing resources is done on demand of the user. The users are virtual entities, infrastructure, things, machines, and human beings. Direct usage by humans is much smaller than by things. The network is fully virtual, it means that the physical layer is practically invisible and does not influence its activities.

Today, such a network is tested physically in laboratories on the level of its single components, functional circuits and single links. The tests concern ultimate performance of these components in terms of signal transmission, data aggregation – concentration, multiplexing data processing and acquisition. The rates for a single optical fiber link has recently crossed a mark of 50 Tb/s and will soon cross 100 Tbit/s. The used transmission techniques are concatenated OTDM/WDM and CO-OFDM/WDM.

VI. HOW DO WE UNDERSTAND TODAY THE FUTURE INTERNET

The future Internet (according to our today's evaluation) is mainly a machine environment. The human Internet, as we understand today, consists of three layers: contents, services and social. The Internet of things, it is mainly communication of machines (M2MC) and some machine interface to the Internet of humans. Different references, very numerable concerning this subject, say that the Internet of things will occupy from 70% even to 95% of all the network. The machines (things) are understood here as civilization infrastructure, industry, production, environment monitoring, safety, human vicinity, but also automated research and knowledge discovery, automated space exploration, etc. Machine communications creates aggregated, massive data streams. Human – human communications and human – machine communications are data, sound, images and text. The Internet of things will use optical links and transmission networks nearly unconfined in the bandwidth. The mobile access networks will serve mobile machines like cars, mobile robots, autonomous vehicles, robotic safety structures, etc. The stationary reconfigurable networks will serve, apart from massive transport, also FTTH, radio access, distributed environmental sensors and RFID devices. The Internet of humans provides mobile access to three layers – contents, services and social, via a broadband virtual reality environment dynamically created on demand (or existing permanently) around each individual. The role of photonics is data transmission, generation of 3D images and sounds, signal processing, creation of virtual reality with the impression of full immersion.

The man – machine interface will be incomparably more complex and functional than today, with the development of photonics technologies. Further development in the submerging technologies will be combined with the development of such tools like: very effective on-line 3D imaging, monitoring of human well being (including monitoring and interaction with physiological and psychological parameters), body area network (BAN, WBAN) – personal psycho-physiological network [10], [11]. Some simple versions of such tools and networks are now under development for mobile, remote, medical monitoring purposes. The surface of human body will be used for an intelligent interaction with the network. Such interaction may evolve to a sort of additional artificial sense of humans. It may include generation of images directly on a retina, but the potential extent of these technologies is much broader. Some of these techniques may be not very safe, as we evaluate them today, and awake a lot of anxiety. An individual is expected to be surrounded by his/her own optical and RF interacting and computing cloud, carrying and processing all necessary information.

Today we are speaking of avatars and avatarization of human beings. Further development of this direction will involve special kinds of social acceptance, or evolutionary redefining of the role of individuals, his/her autonomy and freedom as well as the society. This perspective is increasingly clearly visible today. The role of optoelectronics in this development direction of the future Internet are sensors, measurement techniques, image communication, and in the future much more – encircling human being with an intelligent EM cloud. This optical cloud, modulated by real and virtual senses, by speech, gestures, blinks of eyes, sweat on the skin, but also by physiology and psychology will be an interface of the individual and his/her organism to the global network.

VII. CORE AND ACCESS NETWORKS OF CONTEMPORARY INTERNET – THE IX

The Internet core is build by the major nodes of the Internet traffic exchanges IX and backbone links between them. The Internet exchanges IX are connected mutually now by multi-gigabit and multi terabit in the future optical links [12]–[14]. In Warsaw, the WIX organization is a formal agreement of Internet companies, which opened a common node for local Internet traffic exchanges. The agreement is a non-for-profit organization. This node provides fast and, from the assumption, free of charge (the subscription fees are very low) communications between all the users. The Warsaw IX has a dissipated structure, created by the proprietary networks of the users. Some nodes have aggregated nature like the London LINX. National and local nodes in Poland are: WIX in Warsaw, PLIX Poland in Warsaw, PIX in Poznań, LIX in Łódź. PLIX is the biggest IX in Poland and has two locations in Warsaw, in LIM building in the city center and in Telehouse Poland at ATM building. A nondependent PLIX location is in Katowice in the PSE building. The current aggregated average traffic (September 2011) is around 200 Gbps. For comparison, the relevant traffic at LINX is around 800 Gbps. PLIX has around 150 users, while LINX has over 300 users.

The users of IX are telecom operators, telecom entrepreneurs, Internet contents and service providers, together with their networks. The aim to build a local IX is to minimize the costs of local and trunk connections, increase the local and trunk throughput, open better inter-operator connections, increase the routing efficiency in metro connections, lighten the load on the intercity and international links, exchange of local resources, effective organization of the Internet resources. Europe possesses over 60 large IX of the average aggregated traffic bigger than 1 Gbps. The maximal (burst) traffic in these IX is from 3 to 10 times bigger than the average. IX of medium size have typically a few tens of users. The biggest IX in Europe is DECIX in Frankfurt of the maximum traffic around 2.5 Tbps [13]. The world has now around 150 very large IX of the traffic over 100 Gbps. It is predicted that the future IX, in the hardware layers, will be totally dominated by optoelectronics technology.

VIII. OPTICAL TERABIT LINKS AND RESOURCE GRANULARITY

An important issue while building a multi-terabit network of the future Internet is the flexibility of configuration. The network should be able to offer the resources in such a way, which is called the granularity, as to satisfy very different, and dynamically changeable demand for the bandwidth. Flexibility of the bandwidth supply, to balance the demand, decreases essentially the network exploitation costs and increases the throughput. 1 Tbps and multi Tbps links are justified between big IX. In such a case, each of the nodes has a full terabit transponder. Transmission system in a modern network is of multicast character (instead of broadcast) in order to save the bandwidth. The access to smaller nodes has to be ensured by the efficient usage of only part of the terabit data stream, without a need to possess the full terabit receiver (which is expensive) by the distant node. Application of the relevant splitting of the bandwidth enables usage of many receivers (also coherent ones) of the granularity 40Gbps. The 40Gbps receiver in a smaller node sees only its part of the whole terabit data stream and is fully compatible with the transmitter of the big node. Granularity in the optical network means also access (in a normalized way, concerning the bandwidth) to the whole fiber and the signal transmitted there, and to relevant part of this signal like a single wavelength, or only part of the load carried by a single wavelength. Granularity concerns also the issue of O/E/O and E/O/E conversion in a hybrid electronic and optical network, due to a confined bandwidth of the involved electronics.

IX. OPTICAL AND HYBRID CONCATENATED MULTIPLEXING

An important issue to build networks of ultimate throughput is the ability to efficiently manage very large natural bandwidth which is available in either free space or in an optical fiber. This is connected with the necessity to split and multiplex this immense resources in such a way as to increase considerably the spectral efficiency of the bandwidth usage. Two steps lead to efficient optical spectrum management. The bandwidth has to be split, in a fully normalized way (to lower the costs of hardware) to elementary partial bands with insulating gaps. These elementary bands have to be modulated in the most efficient way so as to multiply the transmission. The criteria of applicability for the photonic (but also electronic) transmission multiplexing are: implementation costs, realizability and technical complexity, signal uniformity and homogeneity, spectral efficiency, manageability of data streams, existence of modulation methods compatible with the multiplexing schemes, susceptibility to concatenation of modulation and/or multiplexing, etc. Here, there are listed some methods relevant to optoelectronic high throughput networks.

The multiplexing methods used in optical and optoelectronic networks can be divided to several fundamental classes, depending on the domain they are realized in: time domain TDM, frequency domain FDM, wavelength domain WDM, polarization state domain PDM, space domain SDM, and coding domain CDM. Some of these domains may be realized in electronics or in photonics spaces leading to ETDM and OTDM in time domain, EFDM and O-FDM in frequency domain, etc.

The next criterion to divide the multiplexing method is a signal, its kind and way of processing.

- transmission method – electronic, optoelectronic, optical, mixed;
- coding – RZ, NRZ;
- processing method – generation, amplification, regeneration, routing, clock recovery, 3R, digital processing;
- signal detection – in particular parts of the transmission system – transmitter, linear regenerator, network node, transceiver, receiver – which may be electronic, optoelectronic, optical, hybrid, integrated.

The next criterion to divide the transmission multiplexing methods is bandwidth, its kind, domain, way of management, technical realization of bandwidth splitting. The following multiplexing systems may be distinguished:

- with single bandwidth or multiple bandwidth;
- with single carrier of multiple carriers;
- optoelectronic or fully optical.

The most important multiplexing methods used for optical fiber transmission systems are:

- classical WDM method (with its dense variant DWDM, super-dense variant UDWDM) with direct detection and intensity modulation (IM DD);
- coherent WDM, single carrier [1];
- orthogonal WDM, single carrier [2];
- fully optical OFDM, with direct detection, single carrier, (O-OFDM and CO-OFDM) [3];
- coherent optical OFDM, CO-OFDM) [4], [5];
- OFDM with electro-optically modulated subcarriers, with direct detection, single carrier [6];
- multiband MB-OFDM, with a single band in single time, (multi-band version) [7];
- OFDM with non-orthogonal direct sub-carrier multiplexing [8];
- band multiplexing BM-OFDM with non-orthogonal splitting to sub-bands [9];
- orthogonal band multiplexing OBM-OFDM with orthogonal splitting to sub-bands, multiple carriers, hybrid optoelectronic method of relatively small granularity of electronics, due to splitting of the whole band to narrower sub-bands which in turn are subject to easy and cheap O/E conversion, [10].

The multiplexing methods are subject to concatenation. Now it is a concatenation of electronic methods, or optoelectronic and optical. In the future, all optical methods will be concatenated. The following methods are added:

- classical electronic and optical TDM – WDM and its optical – optical version OTDM – WDM,
- OFDM – WDM, and – OCDM – WDM.

The optoelectronic methods offer now quite high spectra efficiency of digital transmission, over 5b/s/Hz. This allows not to resign from very high rate of elementary data streams, of the order 100 Gbps, at the granularity of electronic bandwidth equal to 20 Gb/s. This granularity of electronics is obtained now at not too high cost (for the conditions of industrial telecom standards). Splitting to sub-bands is performed by anti-aliasing filters. In these conditions, a single ADC circuit of 20 GS/s is satisfactory to receive 100 Gb/s OFDM signal. Direct work with 100 Gbps electronics now increases the system costs dramatically, outside the area of cost-effectiveness. It does not mean that such systems are not researched intensely in laboratory conditions, to replace 20 and 40 GHz granularity with 100 GHz one in the future.

X. MULTIPLEXING: WDM, DWDM, SDWDM (UDWDM)

A natural method of signal multiplexing in a single optical fiber transmission channel is application of several wavelengths (colors) – WDM wavelength division multiplexing. The WDM, in different variants of color density distribution like standard WDM, and dense WDM – DWDM, is now the basic transmission method for optical signals in optical fiber communication networks. A single source optical carrier wave is quasi monochromatic, and has narrow spectral width. Each color is subject to modulation by a transmitted data signal. The modulation process broadens the width of an individual channel. The bandwidth of a single color channel, a single WDM channel, depends on the rate of modulation. These rates are standardized to the following numbers: 1 Gb/s, 2 Gb/s, 10 Gb/s, 40 Gb/s, 100 Gb/s, but also 160Gbit/s and more in the future, like 400Gb/s. The bandwidth of a single channel depends on the method of modulation and its spectral efficiency measured in B/s/Hz.

Distances between the colors must provide effective signal transmission of the rates listed above, and without distortions. The distortions include channel crosstalk causing intra-symbol interference and increase in the transmission errors. The distances between the colors are standardized and are equal to, depending on the kind of WDM system and modulation method and transmission rate in the channel: 100 GHz for WDM, 50 GHz, 25 GHz for DWDM, 12.5 GHz, 10 GHz, 8 GHz, 6.25 GHz, 5 GHz, 3.125 GHz for UDWDM and less for the next generation UDWDM. Individual channels are separated by optical filters, or are generated individually or in groups as optical combs. The optical filters are compatible with transmission channels. They are optical fiber Bragg filters. Filters provide isolation above 30 dB, at the wave separation of channels of the order of a small part of nm (even 0.01 nm). Small distances between the colors increase the spectral efficiency of the transmission measured in Bit/s/Hz. The spectral efficiency of WDM determines the ratio of the used natural transmission band to the non-used one. The efficiency goes to the unity. Now, in the exploited WDM systems is below 0.5. New systems have spectral efficiency bigger than 0.5.

The WDM system gives the simplest answer to a question how to divide the available, and vast optical bandwidth. The available bandwidth in a telecom optical fiber is from around 1200 nm to 1650 nm (the width 450 nm), assuming the losses below 0.5 dB/km. The bandwidth available for 1dB/km is from 1000 nm to 1700 nm (the width 700 nm). The local networks allow bigger fiber losses, due to short links between the nodes, resulting in an effective bandwidth more than 1 μm. The continuous natural band is divided to discrete, individual, adjacent carriers. Optical carriers in telecom fibers, for the 1500 nm window, have the frequency in the range 190 – 195 THz. For other applications this bandwidth is wider and extends over the range 180 – 220 THz. Calculation between frequency and wavelength, for a modulated optical carrier wave, is as follows, assuming a neutral value of 1 bit/s/Hz for the spectral efficiency of the transmission: 100 GHz is equivalent to 0.8 nm, and 12.5 GHz is equivalent to 100 pm. Transmission band in an optical fiber is traditionally divided to several sub-bands, like C (1530-1565 nm) and L (1565 – 1625 nm) which is equivalent in the frequency domain to 5 THz and 7 THz bandwidths. Together in this area there is 12 THz of natural bandwidth available. Tested small color separations may equal, for example, to 5 GHz, which is equivalent to 40 pm, and 1 GHz is equivalent to 8 pm. Spectral efficiency of the modulation methods inside a single color channel, which is larger than the unity, narrows proportionally the demand for bandwidth of this discrete channel. One may also define a natural spectral efficiency of the WDM system. It is always smaller than one, but for ultra dense UDWDM may be considerably bigger than 0.5.

The development of WDM system results in the increase of effective number of individual transmission channels, decrease of separations between the channels, lowering of the bit error rate, etc. The most dense WDM system in 2001 had 1000 channels of 12.5 GHz separation. Now the UDWDM systems can have one order of magnitude more 10Gb/s color channels or slightly less 40Gbit/s and 100Gbit/s channels. The total spectral width of a single 40Gbit/s transmission channel in classical WDM is 0.4 nm, together with adjacent inter-channel isolating separation space. The assumptions for this data are: separation space is 10GHz and the spectral efficiency is neutral. The polarization sensitivity of such a system is around 10 pm, and is not crossing the separation bandwidth, even for smaller separation equal to 5GHz. The polarization sensitivity stems from the polarization dispersion in optical fiber and from optical noise.

XI. COMMUTATION AND COLOR ROUTING

The WDM operator has to be able to manage passively or actively the colors. Several techniques may be used for this purpose as simple switching and complex routing. The role of an optical router in an optical network node is to receive many multicolor WDM signals, and analyzing them against the destination node. Full WDM signals are transmitted between large nodes of the optical transport network. The WDM signal is analyzed in the distribution node against the color contents and their destination. The WDM signals are unfolded and again entwined. But this is not the only possibility. Also, part of the load may be discharged in the node from particular color. The empty space is loaded with new data. Opening of a single color path between the source node and destination node has, in a certain sense, a character of passive commutation. Creation of an analogous multicolor path requires color commutation and routing in the nodes.

Active techniques of color commutation rely on change of the color carrying the same load. The wavelength of the carrier, subject to the same modulation as the previous carrier, is changed. The change of carrier color may be required by the router switching thousands of wavelengths of the incoming WDM signals, originating from source nodes, and building from these wavelengths new WDM signals to be transmitted to new destination nodes. In some cases such a color change may not be required and then the same color is routed by the node building a single color path. In the next node, however, before the next jump, the load is subject to analysis again and may be changed, recharged, discharged fully or partly. A router in a large node may be a destination of WDM signals of the same color but carrying different load (additionally of the same or different rate, and different data format), and aiming at the same or different destination nodes. The change of color or data rate may be sometimes necessary, under the condition that the color carrier is fully and effectively used for transmission purposes. In the opposite case the network throughput is not used optimally. From the point of view of the user, the network lowers the transmission rate.

Flexibility of the optical router will rely on simple assumption that all the options are possible. This means the following: a change of color without a change of load, a change of load without a change of color, loading a color with data of different rate, change of separation between colors, interleaving colors with different separations, change of signaling standard in WDM, building of integrated WDM signal with different data rates of data in different colors, densification or separation of colors in integrated WDM signals, simultaneous existence of asynchronous and asynchronous data transmission in the same WDM network. A simple example of this kind of signal transformation is that the integrated WDM data stream between large nodes consists for example from 100 channels of 12.5 GHz in separation. This stream is built of two ones consisting of 50 channels separated by 25 GHz.

The above data and examples of necessary properties of an optical router do not show all possibilities. Proceeding downlink, the router is supplied with a number of optical fibers. Each fiber can now carry many WDM signals in a number of OTDM time slots. Each WDM signal can carry the same or different colors. The colors carry load. The router should be able to switch the whole fiber, or a group of fibers, i.e. the whole signal carried by a fiber to a different fiber, etc. Descending downlink or down the bandwidth granularity, the switching may concern narrower entities than the fiber: a group of colors, a single color, a time slot, the load or particular part of the load.

XII. OPTICAL PACKET SWITCHING AOLS

The transmission technique in WDM systems relies on optical (the best solution, however now also electronics is involved) labeling (optionally, alternatively or conjunctively) of the source node, destination node, the path (intermediate nodes and signal jumps between the nodes), optical cable, a group of fibers, a single fiber, a group or a single time slot in the OTDM signal, a confined bandwidth – a group of wavelengths, a single color, an optical path, an electronic time slot ETDM or a single electronic carrier f_n in the OFDM system. The prevailing protocol; used in optical networks for label switching is GMPLS (generalized multi-protocol label switching), or as the variant concerning the wavelengths, it is GMPλS. The label is essentially equivalent to the allocated bandwidth, which is reserved in the infrastructure for certain labeled data stream.

One of the techniques researched for effective usage in the optical Internet is all optical label switching AOLS [15]–[18]. The technique increases the efficiency of the bandwidth utilization, allows for packet transmission, and acts only in the optical layer. A key issue is bandwidth efficient adding of the label to the packet (a stream of packets). There is a number of techniques of optical labeling. The simplest, though not the most efficient, is to add additional heading of the same color in the frame of certain packet stream. The same color of the label, as the load, makes it difficult to manipulate with it in the optical domain. The other method is application of a different color for the label. Label attachment is done in the core network router, and the way of this attachment influences the signal quality. The label and the signal have different but very close and adjacent colors. Attachment (gluing) and separation (erasure) of the label is done by means of optical filters. These processes are related with a small loss of the optical signal power. This loss should be as small as possible. In practice these losses are smaller than 1 dB at the label and packet separation around 0.1 nm in the spectral domain. Too small separation of the label and load causes signal distortion. Too big separation lowers the spectral efficiency of the WDM transmission. This means that at the same throughput of the channel, a bigger bandwidth is occupied.

The most frequently applied, full optical, thus keeping the signal and network transparency, techniques of label and load attachment is optical subcarrier multiplexing OSCM and labeling of the colors (LL-lambda labeling). The advantage of both methods is low rate required for the label signal. The disadvantage is the necessity to keep spectral distance in frequency domain between the label and load bands. After the label is erased, the load has to be kept for further distribution. This increases the signal bandwidth which is not necessary. For high speed loads of 40 Gbit/s, 100 Gbit/s, and 160 Gbit/s, a modified OSCM method is used. This method uses the WDM bandwidth more efficiently. Some of these bandwidth sparing methods are: attenuation and separation of the carrier, color conversion, and multi-node label exchange. The 40 Gbit/s or 100 Gbit/s WDM system may use the subcarrier frequency of 30 GHz, which causes nonlinear distortions in the frequency domain. An effective method for these rates of the load transmission is application of the vestigial sideband modulation VSB [19]. The optical signal destined for transmission is modulated in the RZ format with attenuated carrier (carrier suppressed RZ) CSRZ. The CSRZ is suitable for the vestigial modulation of the sideband. As a result, the format VSB-CSRZ is obtained.

The 40 Gbit/s or faster load is initially modulated as a CSRZ signal and then as VSB-CSRZ by the use of optical filtration (in a tunable optical filter). The label signal (around 1

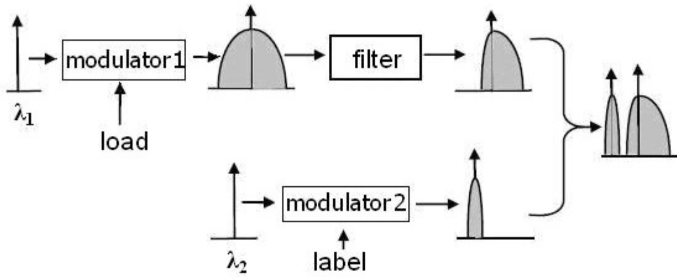

Fig. 1. Labeling of payload in VSB [18]. The load signal is transmitted by λ_1 carrier and after filtration the VSB signal is obtained. The label is transmitted by carrier λ_2, close to λ_1. Different colors of the label and the load facilitate the signal manipulation procedures by means of simple optical coupling and filtration.

Gbit/s) is modulated traditionally as NRZ (or in other arbitrary format) in different but adjacent color. Then, the label signal is joined with the VSB load signal. Alone, the NRZ signal is not appropriate for the VSB modulation. The CSRZ signal is created from two signals: 40 Gbit/s data and sinusoidal clock of 20Gbit/s. Both signals are joined in the Mach-Zehnder modulator MZM with the phase $\theta = \pi$. The load and the label are joined and separated easily by means of optical filtration. The algorithm of creation of the transmission signal does not depend on the formats of the label and load. The label signal of 1 Gbit/s is required for the load signal of 40 Gbit/s. The label and the load are combined to the format of transmission signal in a 3dB optical fiber, color neutral, coupler.

The modulator works as an optoelectronic, tunable Mach-Zehnder modulator (MZM). The total bandwidth of the load and the label is essentially smaller than in the classical OSCM labeling method. The channel crosstalk is also smaller. The 3dB bandwidth for 40Gbit/s signal and 1Gbit/s label is 0.3 nm. The 20 dB bandwidth for this case is 0.5 nm. The load and the label are separated from the optical transmitted signal in the receiver, particularly in the optical circulator by a tunable optical fiber Bragg grating. The grating has a bandwidth of 25GHz and reflects the 1Gbit/s label to the detector, letting the rest of the signal through, and allowing the load to be amplified by EDFA. The load is filtered optically for its bandwidth in order to block the wideband ASE (amplified spontaneous emission) noise and then is subject to detection in a receiver of digital bandwidth larger than 40Gbit/s. The analog bandwidth of the receivers, for the label and load, are respectively 30 GHz and 1 GHz. The amplitude separation coefficient of the load and the label is greater than 20 dB. The energy cost of load and label separation is 0.5 dB, for the optimal channel width, in the range of 0.46 – 0.5 nm. This means that the separation between the load and the label is 0.1 nm. For these parameters, the noise is low and the BER$< 10^{-12}$. For smaller channel widths, the separation cost increases. This labeling schema may be used for very high rate optical networks of 160 Gbit/s, where the channel width is smaller or comparable to 0.8 nm, which means is compatible with the separation standards of the WDM channels.

XIII. CDMA AND OCDM, OCDMA, OCDM-WDM

The CDMA protocol is popularly used in the LAN networks, also in the wireless communications. This method of transmission multiplexing provides multi-access. Application of the CDMA over the existing WDM brings a lot of advantages and shifts them to the optical domain. The input data stream is demultiplexed in the traditional WDM system in order to be transmitted by different colors. In the OCDMA, the data stream is, for example, split to N-bit frames using M-wavelengths. Each frame consists of NxM components representing a unique position in the time – wavelength coordinates.

XIV. OFDM, O-OFDM AND CO-OFDM

The OFDM modulation, which is described by the IEEE 802.11 standard, is now a foundation of many RF transmission systems, as in the cellular telephony. The OFDM symbol, in electronics domain, is generated by means of a fast inverse Fourier transform in order to be able to multiplex the data in parallel of lower rate to multiple sub-carriers. The sub-carriers are defined by orthogonal frequency components of the symbol. Such an electrical signal is subject to E/O conversion building the optical O-OFDM signal ready for transmission. In the receiver, a photodiode performs the O/E conversion. The converted signal is subject to FFT. The data are recovered for particular sub-carriers. The throughput is confined by two factors in such a system: E/O/E conversion – the optical modulator in the transmitter and photodiode in the receiver as well as electronic DSP IC – which is an FFT processor. The aim of the system development efforts is to shift these processes, and particularly the FFT, into the optical domain. Optical FFT means that the optical data of small rate (from single sources) are directly multiplexed in the transmitter (to the form of transmission ready data stream) and next are demultiplexed in the receiver. Thus, the OFDM transmission rate may be considerably increased. A discrete optical Fourier transform (ODFT) and the inverse transform IODFT is performed, in an integrated photonic circuit – consisting of delays and phase shifters (which is called a time optical lens), much faster than in the electronic circuits. The ODFT and IODFT processes may be massively parallelized in a single integrated circuit. Channel equalization is done in a relatively simple way, in the frequency domain, by means of a matrix of tunable optical attenuators (TOA). This task would have been much more difficult in the time domain.

Transmission multiplexing by means of orthogonal frequency division multiplexing OFDM is used in optical systems due to several important advantages. These are: a relatively big immunity and tolerance of this system to the signal dispersion (small spectral width of the sub-band); tolerance to polarization mode dispersion PMD (in a coherent version); big spectral efficiency (small inter-channel separations); possible modulation of high order – enabling dynamic adaptation of transmission rate to the changing transmission conditions and to the channel parameters; big sensitivity of the optoelectronic receiver (for coherent transmission and reception). The ratio of the peak to average value of the O-OFDM signal (PAPR parameter) is big, thus, the system is relatively not resistant to fiber nonlinearities. CO-OFDM requires a complicated hardware in comparison with the O-OFDM with direct signal detection (DDO-OFDM). CO-OFDM is an alternative for a coherent, trunk transmission system with a single optical carrier. The speed of electronics is the major confinement of work for the direct detection CO-OFDM, despite its high spectral efficiency. The CO-OFDM system may avoid, however, the O/E/O conversion and thus DAC/ADC conversion, which is a bottle neck for the transmission rate. The solution is application of a multiband OFDM. The whole available OFDM band is divided to multiple orthogonal sub-bands. The technique is a concatenation of systems analogous to WDM and O-OFDM and is called as orthogonal band multiplexed OFDM (or OBM-OFDM). The CO-OFDM signal may be modulated as QPSK. Multiple OFDM bands of small or none isolation bands, which gives high spectral efficiency, are multiplexed and demultiplexed without any inter-band interference due to the orthogonality between the bands.

XV. OBM-OFDM

Multiple bands are transmitted simultaneously in certain moment of time in the OBM-OFDM (called also as cross-channel XC-OBDM) system. The principle of OBM-OFDM is a division of the whole, assumed and available, spectrum to orthogonal OFDM sub-bands. The consequence of OFDM multiplexing with multiple carriers is: the orthogonality of bands improves the spectral efficiency, because small or none insulation band may be used between the transmission bands, two OFDM sub-bands may be demodulated simultaneously by means of a single FFT (the classical OFDM requires three functions FFT and IFFT), there is used a cyclic prefix in order to facilitate the strict synchronization confinement on the bit level, to modulate and demodulate there is used the effective IFFT and FFT transform, the spectrum of multiband OFDM is more confined than in OFDM with a single carrier, the band may be divided conveniently be electronic anti-aliasing filters, the narrow band may be processed by DAC/ADC of smaller rates.

The whole OFDM band includes N sub-bands. Each sub-band includes M sub-carriers f$_i$. Each sub-carrier inside a sub-band is distant from the adjacent sub-carriers of a constant value Δf. The sub-bands are mutually isolated by the isolation band Δf$_g$. The separation of sub-carriers is identical for each sub-band due to a common sampling clock for the whole system. The orthogonality condition between particular sub-bands is determined by the relation Δf$_g$=mΔf, means that the isolation band is m-times multiple of the distance between the sub-carriers. This condition guarantees that each sub-band is an orthogonal extension of the other. The orthogonality condition is fulfilled not only for the sub-carriers in each sub-band but also for two sub-carriers from different bands. The sub-carriers f$_i$ and f$_j$ from bands I and J are mutually orthogonal, despite they originate from different bands.

XVI. MB-OFDM

The development of MB-OFDM technique is coordinated by the MBOA Collaboration (Multiband OFDM Alliance) in order to introduce the ultra-wideband transmission systems UWB. The MB-OFDM system transmits a single band in a particular while. This band is used for building a full frequency variety of the signal and for multiple access.

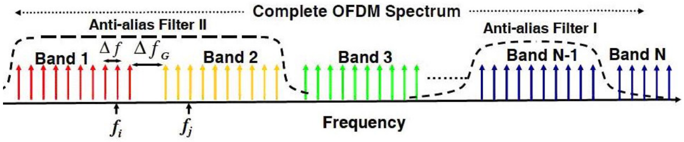

Fig. 2. Schematic division of the bandwidth in the OBM-OFDM system.

The modulation methods in the optical fiber transmission systems are evolutionary nearing to some of the advanced and classical techniques used from some time in the RF systems.

XVII. PDM-OFDM

The PDM-OFDM relies on concatenation of the OFDM in the frequency domain and doubling it in the polarization domain by PDM method [18] (polarization division multiplexing). The PDM system may relatively easily, and at low cost, double the transmission rate using two orthogonal polarizations of the transmitted optical wave in the fiber. Realization of bigger multiplication in the polarization domain, though possible, is difficult and does not provide sufficiently big channel separation.

XVIII. OPTICAL TIME LENS

Spatial distribution of the EM field on the back focal plane of a conventional lens is the Fourier transform of the field distribution on the forward focal plane. An analogous, dual solution to a classical lens – which is acting in parallel in the space domain (space frequencies), is a time lens, which is acting in series in the time domain. The time lens is a cascade combination of a dispersive component, a phase modulator and again a dispersive element – all in a form of optical fiber or compatible with optical fiber (like Bragg grating fiber). Optical time lens is a combination of optical delays and phase shifters. Formal translation into a dual component is done by exchange of the space variables with the time variables. This means that the diffraction is exchanged by dispersion, and the space chirp of a conventional lens is exchanged by time chirp introduced by the phase modulator. Such a lens, inherently of a very broad bandwidth, performs a discrete, direct or inverse, Fourier transform (DFT or DFT^{-1}) of the optical time signal in a form of a data stream rather than an image. The transformation is done fully in the optical domain without any need for O/E/O conversion.

The direct and inverse Fourier transform is defined as:

$$E_k = 1/N \sum_{m=0}^{N-1} \epsilon_m e^{i2\pi km/N}, \quad \epsilon_m = \sum_{k=0}^{N-1} E_k e^{-i2\pi mk/N}, \tag{1}$$

where E_k and ϵ_m are samples in the frequency and time domains for k-th and m-th position. N is a natural number of the samples, and the following condition holds $0 \leq k, m < N$. Respective positions of frequency and time are: $t_m = m\tau$

and $\omega_k = k\delta$, where τ and δ are distances of the samples in time and frequency, such as the following condition is fulfilled $\delta\tau = 2\pi/\mathrm{N}$. The values ω_k are optical color frequencies (sub-carriers). Optical implementation of DTF is obtained by phase delays realized by precise choice of the optical path lengths and the output signal reconstruction in the output coupler. Realization of the inverse DTF is performed in an analogous circuit to a WDM demultiplexer, with exception of precise tuning of the time delays and phases for each optical path, in such a way that all components of a wavelength respective to the OFDM sub-carrier are orthogonally multiplexed to a single output port. The phase delays are defined in reference to the frequency of optical carrier.

XIX. TDM and OTDM

Optical networks work with optimally concatenated modulation and transmission multiplexing – TDM and WDM. TDM multiplexing is performed in electrical domain – ETDM, or in optical domain – OTDM. Exploitation, or highly standardized ETDM systems of the highest rates work at the throughputs of 40 Gbit/s and 100 Gbit/s. The standard of 160 Gbit/s is under tests, as well as 320 Gbit/s. Laboratory systems work at even higher rates, exceeding 500 Gbit/s. The bottleneck is electrical bandwidth. The development of sub-terahertz and THz electronics may cause that these rates increase to the full THz range. The OTDM systems do not have such confinement. The throughput of OTDM systems may now reach over 10 Tbit/s, which is today out of range for integrated electronics. For the competition between the ETDM and OTDM (and generally electronics – photonics) we do not know the answer for such questions as: which system will be cheaper, more energy efficient, less technically complicated, simpler in long time exploitation, more reliable?

Physical and technical confinements of the OTDM are not combined with the terminal equipment, as is the case of the ETDM system, but with the link itself and its components – optical fiber, photonic amplifiers, all optical signal regenerators. When the TDM rate grows, what is equivalent to larger bandwidth, and when the transmission distance between the network nodes increases, the digital optical data transmission is subject to the following factors: chromatic dispersion (CD) and polarization mode dispersion (PMD), optical fiber nonlinearity, bandwidth and noise confinements of the line devices like amplifiers. OTDM multiplexing requires very precise synchronization in time domain of the channels and signal components. It is necessary to compensate in the fiber not only the basic dispersion but also the components of higher order, which is relatively expensive in the hardware realization. Now, the OTDM system, as a generator of an optical signal of nearly arbitrary rate, is used as a tester of the absolute transmission capacity of ultimately broadband single channel optical fiber transmission links. Due to this reason, the OTDM systems do not use standard fibers (SSMF) but only dispersion managed optical fibers (DMF). The DMF link consists of concatenated lengths of optical fibers of a set and usually compensating the levels of dispersion. The aim is to obtain a desired level of the aggregated dispersion for the whole length of a link.

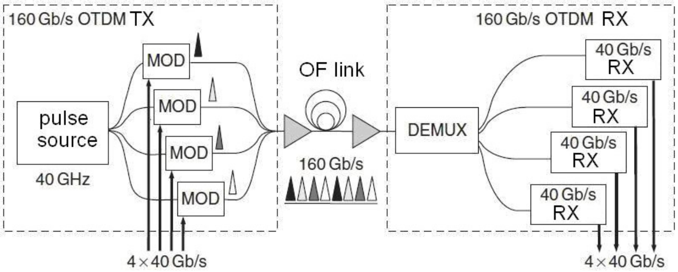

Fig. 3. The principle of OTDM transmission [33].

XX. Coherent Transmission

Optical coherent transmission allows for more distance between the repeaters and lowers the line noise. It was introduced to optical fiber communication systems in 1981, together with the development of optical fiber single mode single polarization (or polarization maintaining) systems. The transmission system uses the coherence of optical carrier wave. The optical wave is modulated in frequency or in phase, and the receiver works in a homodyne or heterodyne mode. The advantage of the method is the possibility to use very dense optical OFDM. It is possible in the system, on the level of the intermediate frequency, to condition the transmitted signal, distorted in the optical domain. The conditioning is performed in electronics domain [15]–[18].

XXI. Ethernet 1 Tb/s

The research work on the Future Ethernet is going in two essential and different directions. Both directions use optoelectronic technologies and both aim at the increase of the link and network throughput and at the increase of transmission reliability. There are two options for the future Internet high quality transmission mode: asynchronous and synchronous.

The first option is an ultrafast photonic Ethernet of the asynchronous transmission, in agreement with the IP/TCP standard and the Best Effort service provisioning rule. The system should be back compatible with previous generations of the classical Ethernet and the Internet. At the increased network capacity, it is perhaps easier to provide high values of the QoS parameter. It is impossible, however, to eliminate the inherent latencies. The extension of the Ethernet Standard IEEE 803.2 allows fully to use the existing optical fiber cable infrastructure. Some of these old optical cables are even not optimized for the third transmission window.

The second option is an ultrafast photonic Internet of synchronous transmission, so called the High Quality Ethernet. This solution aims at providing very small signal delays, of the order of ns, and very high values of the QoS parameter. Today, the Internet does not have the ability to transmit synchronously, thus, to transmit with arbitrarily small latency. The Future Internet allows for the transmission of both types of signals simultaneously, one side with the other, with the possibility of free choice by the user. The choice may be done automatically by the network, depending on the task superimposed by the user or communicating machines (with the networks or between themselves). The ultra-broadband synchronous Internet of high quality may require a new kind of network consisting of dispersion compensated optical fiber cable infrastructure.

Experimental links and networks of ultra-broadband, photonic synchronous Internet are now tested by laboratories in big telecom operators and by large research laboratories like CERN. CERN has an advanced group working on the High Quality synchronous Ethernet dedicated for control of future large research infrastructures, for example for the upgrade of the LHC to the status of Super LHC (sLHC). The description of the open White Rabbit project is fully accessible in the Internet [white rabbit/cern]. In parallel, an international technical group, in cooperation with the IEEE works on a standard of an ultra-broadband photonic synchronous Ethernet.

Experimental transmission links of 1Tbit/s Ethernet (classical and synchronous) are tested in academic laboratories and in the industry. Standardization centers and vendors are predicting the introduction of 1Tbit/s Ethernet around 2015. Other sources shorten even this period to 2013. The obtained results today for the 1TbE are very promising, with the following parameters: modulation OTDM or CO-OFDM, reach for over 500 km without Raman amplification and dispersion compensation, compensating EDFA amplifiers, spectral efficiency over 2 to 4 bit/s/Hz, applied standard singlemode telecom optical fiber SSMF, electronics granularity 40 Gbit/s. Assuming the spectral efficiency for 3.3 bit/s/Hz, to carry the 1 Tb/s data stream, it is necessary to use a homogeneous optical band of 300 GHz or 2.5 nm in the width. The spectrum may be positioned in an arbitrary place of the C or L band. Granularity of electronics equal to 40 Gbit/s requires application, in the 1 Tb/s system, around 25 to 30 non-correlated carriers (tones, colors) positioned homogeneously inside the 300 GHz bandwidth. The inter-carrier distance is then 8 to 10 GHz. The granularity of electronics equal to 10 Gbit/s requires the usage of over 100 colors in the same conditions.

One of the basic technical problems of 1 TbE, which bases on the OFDM, is broadening of the OFDM signal to the level of 300 – 400 GHz. This may be done using many narrow band sources, a single wideband source, but also by other methods like applying a circular frequency shifter with a step making the neighboring frequencies partially overlapping with each other. The required bandwidth is filled fully and uniformly after a set number of repeated circles. A photonic, circulating, frequency shifter consists of a fiber optic loop, quadrature modulator I and Q, and two EDFA amplifiers – in order to compensate for the losses of frequency conversion. A band pass filter gives the required shape to the formed band. Sub-bands f_i are formed from f_o in the successive loops and are non-correlated. The loop delay is tailored to a natural number of the OFDM symbol period. Thus, the neighboring sub-bands are synchronized in the OFDM frame. The signal generated in such a way fulfills the conditions of OBM-OFDM (orthogonal band multiplexed) [4]. In practice, meant for the industrial conditions, a multi-band O-OFDM optical signal is generated in a photonic integrated circuit. A source of the signal is a laser generating an optical frequency comb. In the latter case, the O-OFDM sub-bands are mutually frequency coupled. The OFDM signal, in the time domain, for a 1TbE link, assuming the electronics granularity as 20 Gb/s, and spectral efficiency above 3 bit/s/Hz, has to include over 100 sub-carriers. To obtain a transmission system of these parameters, a few thousand of uncorrelated, overlapping frequency component sub-carriers is required, filling in a continuous way spectrally the whole 300 GHz band. Now the obtained bit error rate for optical noise parameter OSNR, in experimental laboratory systems of similar parameters is expected to approach soon acceptable levels [10].

XXII. INTERNET 100 TBIT/S

There are a few examples of laboratory systems working in the transmission rate area nearing to 100 Tb/s. NTT demonstrated, in March 2010, during the OFC, a transmission WDM system realized on a single fiber, 240 km in length, of aggregated throughput over 69 Tbit/s. The WDM signal consisted of 432 wavelengths with 25 GHz of inter-channel separation. Each color carried an effective OTN standard signal of 171 Gb/s. An increased spectral efficiency of optical transmission was obtained by application of 16 QAM signal format. A demodulation algorithm was applied without additional signal redundancy. Coherent detection, and advanced DSP techniques were applied in the optical receiver. Sensitivity of the coherent receiver is over 3dB bigger than when a conventional direct detection of the NRZ signal was applied. The DSP algorithm in the receiver equalizes the color distortions caused by chromatic dispersion and polarization mode dispersion during the signal transmission. The band of 1527 – 1620, or nearly 100 nm, was used for the transmission. Thus, the transmission band occupies jointly the C and enhanced L bands of optical fiber. A low noise wide-band optical amplifier was applied of a flat amplification characteristic over the whole 11 THz band. The amplifier, due to high power level, had a mechanism to control the nonlinearities. The SNR parameter was increased by application of distributed Raman amplification. The format of transmission, which was 16 QAM, in combination with double PDM, resulted in eight fold reduction of the symbol transmission rate. The eventual result was the reduction of the demands on the cooperating electronics to the technically acceptable level and reduction of the required optical bandwidth.

The 171 Gbit/s signal is in agreement with the OTN standard (Optical Transport Network by ITU-T). The transmission rate of the load is 160 Gbit/s in this standardized signal. Apart from the load, the package contains signalization and management parts, and has the ability of error correction through the FEC mechanism. The OTN signal, which modulates a single color, was generated by combination of 16 QAM and 2 PDM modulation and multiplexing. The rate of symbols (equivalent to the maximum rate of electronics) was over 20 Gbaud (171:8). The 16 QAM signal was built by joining, in the QAM modulator, two QPSK signals of the amplitude rates 2:1. The source was a narrow-band DFB semiconductor laser of the spectral width 100 – 200 kHz. The laser was hybrid integrated with an optoelectronic circuit of QAM modulator and two polarization coherent detector.

XXIII. PHOTONIC NETWORK MONITORING

Monitoring of optical parameters OPM (optical performance monitoring) is one of necessary automatic operator functionalities of the photonic, transparent, future Internet. During the photonic network exploitation, especially a network of ultimate throughput, its parameters may change in time. The following parameters are prone to aging or climatic changes: wavelengths of generated carriers in the WDM system, separations between the transmission channels, nonlinear phenomena may be enhanced which is caused by filling the fiber with large optical power. All of these detuning phenomena may cause inter-symbol interference and similar effects. It is necessary to monitor on-line, in the real time, such parameters like: dispersion, optical noises via the OSNR parameter, time jitter, etc. Some parameters, like OSNR, have to be measured with sufficiently dynamic range, usually larger than 30 dB. Some parameters, like dispersion, have to be measured with sufficiently large sensitivity. The role of an OPM sub-system is continuous support for the QoS mechanisms, and management of the network reliability. The OPM monitors all transmitted optical signals and evaluates, in quality and quantity, their degradation. Monitoring results are used to avoid the degradation of transmission quality, or to trigger alarms and reroute the traffic. Summing these features up, the OPM system should be characterized by:

- Large dynamic range – larger than 30 dB, and large sensitivity – larger than 100 fs/nm, and large time resolution – larger than 10 fs. All these transmission parameters of optical signals are measured for the network throughputs larger than 1 Tbit/s;
- Large bandwidth of an optical spectrum analyzer of the RF bandwidth, of the order of several THz;
- Monitoring capability of the degradation processes for many network parameters simultaneously, the best way by means of a single CW type of measurement;
- Flexibility of the OPM towards changes of the optical bandwidth and wavelength, covering all the transmission spectrum;
- Simplicity of configuration of the optical measurement circuit, without a complex adjusting of the interferometric set ups.

Usually, the measurement of a single and even two signal parameters is not enough.

The OPM systems in usage now are usually not fully compatible with a photonic, transparent network of the Future Internet of the fluencies well above 1 Tbit/s. The methods of measurement of signal and network parameters degradation base usually on conventional procedures and optoelectronic devices, like: coherent detection, asynchronous sampling of signal delay by means of optical decoupling, tone monitoring in the bandwidth, homodyne with orthogonal delay, monitoring of sub-carrier for a single tone in the bandwidth. These methods are technically mature and quite efficient in reference to the current optical fiber networks with O/E/O conversion. A part of the monitoring process in the above methods is O/E conversion. When the transmission rate grows over 40 Gbit/s (time duration of the transmitted signal is around 500 fs), or even above 100 Gbit/s. Then, these methods turn impractical, due to the confinement of the electronic bandwidth. The 40 Gbit/s signal (for a single electronic TDM channel) may be generated in optoelectronic domain by a fiber optic MLFL laser with mode coupling (mode locked fiber laser), a nonlinear circuit of pulse compression and optoelectronic MZ modulator, all transmitter excited with a digital signal designed for transmission. Rising the throughput to the level above 1 Tbit/s of optical fiber transmission is done in the OTDM multiplexer, of the multiplicity at least 25 times.

A fully photonic OPM system may base on nonlinear optics solutions. The advantage to use for this purpose the nonlinear Kerr effect is the time constant of the order of femtoseconds which does not confine resolution of the measurements in the optical domain. There are tested the following, fully optical solutions of monitoring of the optical transmission signal: measurement of the spectrum of RF signal with the usage of cross phase modulation XPM, cascade mixing of four waves FWM, optical signal regeneration in a semiconductor optical amplifier, nonlinear optical fiber loop mirror, intensity autocorrelation of the data stream. Usually these techniques have confined dynamic range, and only a single parameter is measured at a time.

The following conditions and methods are used for the measurement of the RF spectrum of the transmitted f_s signal: photonic nonlinear component is used, cross phase modulation effect is used (the sampling signal is two times weaker – to calibrate the measurement system), the CW sampling signal f_p is co-propagating with data (and is distant from the transmitted signal of a few tens of nm). Such measurement conditions allow for simultaneous monitoring of group velocity dispersion GVD, thus the dispersion of the transmitted energy (second derivative of the fundamental modal refraction in a fiber) and optical noise coefficient OSNR in the band, but also the time jitter, of the transmitted optical signal of the rate even higher than 1 Tbit/s. The XPM effect generates, between the f_s and f_p signals, the side-bands proportional to the power density spectrum of the signal. The signal spectrum, after passing through the nonlinear component, consists of two autocorrelation maxima of the transmitted signal and cross-correlation maximum of the sampling signal. This spectrum may be recorded in the OSA (optical spectrum analyzer). The autocorrelation function in time domain is obtained from the full spectrum by numerical reverse Fourier transform (Weiner-Khintchine theorem). The period T of transmitted bits is recovered from the autocorrelation signal. The autocorrelation function has maxima for the delay times equal to 0, T, 2T, ... The autocorrelation function has minima for delay times equal to T/2, 3 T/s, ...

The monitoring parameters: dispersion, noise (amplitude, ASE) and jitter (phase noise) are obtained from their different influence on the transmission signal deterioration and from their characteristic shapes of the RF spectrum of the autocorrelation function. It is usually done assuming a simplification of the signal to the Gaussian shape. The dispersion causes broadening of the autocorrelation signal, reduces the intensity of its maximal value and causes interference between the neighboring pulses. The ASE noise diminishes the efficiency

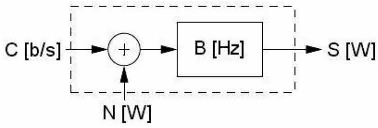

Fig. 4. Shannon-Hartley law and relevant block diagram of transmission channel, where, C-channel capacity, B-bandwidth, S-output signal power, N=gB-noise power, f-frequency, g-noise spectral density, R[b/s]-line rate (throughput), SNR[dB]=$10\log_{10}$(S/N).

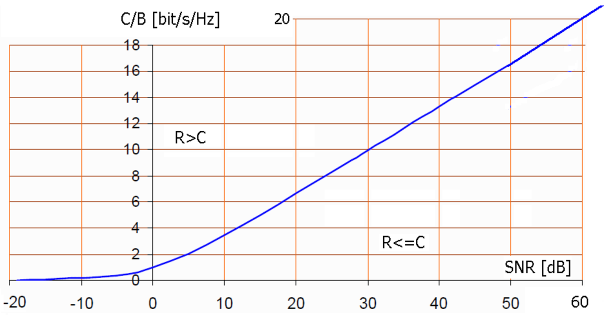

Fig. 5. Shannon-Hartley diagram: spectral efficiency C/B of (photonic) transmission vs. signal to noise ratio. Function is also presented for bit energy E_b=S/C [W/b/s], or E_b/g [dB]

of the cross-correlation process and increases the noise background in the RF spectrum, increasing everywhere the level of the autocorrelation signal. The time jitter of the transmitted signal causes the phase noise, reduces the power of higher harmonics in the RF spectrum, broadens the cross-correlated pulses, does not change the autocorrelation function for zero delay. To manage the measurements and the working of the OPM system on line, it is necessary to create algorithms which extract the mentioned parameters from the described characteristics and their influence on the signal, its spectrum and autocorrelation function. The dispersion is obtained directly from the autocorrelation function. The OSNR is obtained from the measurement of the optical clock in a photonic analyzer of the RF spectrum. The mean square value of the jitter J_{rms} (fluctuation) is calculated from the reduced autocorrelation function, assuming the Gaussian pulse and the widths of the autocorrelation T_a and cross-correlation T_c in 90% height equal to: $J_{rms} = [4(-\ln 0.9)^{1/2} \cdot (T_k^2 - T_a^2)^{1/2}]^{-1/2}$.

The nonlinear component may be a strongly nonlinear optical fiber. The fiber has to be made of different glass than silica, like chalcogenide (As_2S_3). Even strongly nonlinear silica fiber has the nonlinearity not enough. Its length to be effective has to reach hundreds of m if not km to accumulate the optical nonlinearity. This long length causes time parting of the signal with the CW probe, and in consequence is a reduction of the measurement bandwidth. The best solution seems to apply a strongly nonlinear component which is simultaneously of small dispersion (of shifted dispersion on the level of 10 ps/nm/km in the middle of the C band), in the C and L bands, in the form of a chalcogenide glass waveguide. The waveguide is contained in an integrated planar photonic circuit acting as a fully optical RF spectrum analyzer. For large glass nonlinearity $\gamma > 10^4$ [km/W], of small effective modal field TM $A_{eff} < 1\mu m^2$, the required waveguide length is of the order of a few cm, which largely increases the measurement bandwidth. Adding an EDFA amplifier before such an integrated circuit, and minimization of the insertion losses (via antireflection coating, which eliminate Fabry-Perot resonances), eliminates the optical power problems (power budget) in the OPM circuit.

XXIV. PETABIT, PHOTONIC, FUTURE INTERNET?

Let us assume the following technical data of hypothetical photonic link of the future Internet: transmission system with WDM – CO-OFDM concatenated modulation and multiplexing scheme; the used optical fiber bandwidth is inside the loss window l<0.5 dB/km with the usage efficiency of 90% (natural spectral efficiency of WDM) or equal approximately to 400nm; equivalent natural bandwidth in frequency domain is 50 THz; spectral efficiency of transmission (today attainable with difficulty in optical domain, but available in the RF domain and used in cellular telephony systems) of the order 10 bit/s/Hz; easily obtainable polarization multiplexing 1:2 with acceptable SNR values. Using this data, the following throughputs are obtained: around 1Pbit/s for trunk optical fiber systems, and 2–3 Pbit/s for local area network systems. Assuming an optical fiber cable between very large IX of the future Internet containing 100 lighted and 100 dark fibers in each direction, for full duplex transmission, the following hypothetical parameter is obtained of the core transport network – 100 Pbit/s. This value of data rate is five orders of magnitude faster than the planned development of the standardized, guaranteed throughput equal to 1 Tbit/s offered today for the core network of the photonic Internet.

XXV. SHANNON-HARTLEY CONFINEMENT IN OPTICAL DOMAIN

For colored noise, the S-H law is:

$$C = \int_0^B \log_2\left(1 + \frac{S(f)}{N(f)}\right) df \qquad (2)$$

For AWGN noise, C=B$\log_2$(1+S/N). Two approximations hold: C=0.33B(SNR[dB]) for S/N>>1 and C=1.44B(S/N)=1.44gS, S/N<<1, what is shown in fig.5.

Assuming a low-noise channel SNR=30dB for trunk photonic transmission and B=50 THz, one obtains C = 0.5 Pb/s and the spectral efficiency C/B = 10 b/s/Hz. For a noisy photonic channel the transmission does not depend on the bandwidth, and the solution are LDPC or Turbo-FEC codes.

WDM has covered a distance during the two decades. The bandwidth reserved for a single channel is: CWDM – 20 nm, WDM – 0.8 nm (100 GHz), DWDM – 50/25 GHz, UDWDM – 6/3 GHz, NG-UDWDM 1.5/075 GHz. Assuming L<2.0 dB/km, $\Delta\lambda \approx 1.2\mu$m, one can accommodate 64 channels in 100 GHz, fig.6. The optical band has 1200 nm: 0.8 nm = 1500 channels. UDWDM system capacity is: 1500*64=96000 colors with separation 1.5 GHz. Assuming 1 Gb/s/color, the aggregated traffic reaches 100 Tb/s. Assuming 5 Gb/s/color and adding 2: 1 PDM we obtain the same value of 1Pb/s for the ultimate throughput.

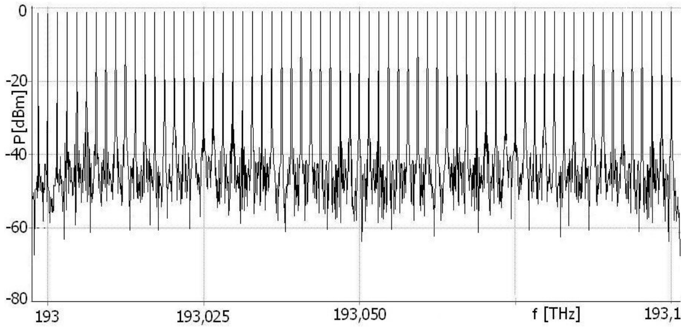

Fig. 6. Optical spectrum for 64 NG-UDWDM channels: 100 GHz: 64 = 1.5625 GHz.

The DWDM system shown by NTT during the OFC2010 has the following parameters: R≈70 Tb/s, modulation 16 QAM with 2 PDM, band 1527–1620 nm, D = 25 GHz, E = 6.4 b/s/Hz. Electronics worked at an acceptably low rate of >20 Gbaud. Squeezing the 25 GHz standard to 1.5 GHz, or interleaving the colors 16 times, one obtains 70 Tb/s * 16 ≈ 1.1 Pb/s. Again the same number of previously calculated ultimate throughput is obtained from these estimates basing on the realistic expansion of the existing system.

XXVI. POLISH PERSPECTIVE

The daily statistics of DE-CIX (Frankfurt, September 2011) display peak traffic around 2.5Tb/s. Similar traffic is at LINX (London). Prime private users obtain there 1Gb/s or 10Gb/s. PLIX (Warsaw) shows traffic around 200Gb/s. Big PLIX participants own 40Gb/s and 10Gb/s ports. The best ISP provide in Warsaw area 120Mb/s via cable/FTTH for private users.

The Internet develops locally quite intensely, using richly the international experience. Own research is concentrated at universities [36]–[171] mainly in international cooperation, with some support of the European Operational, Structural and Framework Programs [172]. The research concerns also a variety of the access networks to the Internet high throughput backbone.

XXVII. CONCLUSIONS

The optoelectronics offers now high spectral efficiency of digital transmission, over 5 b/s/Hz. The number is to be doubled soon. This allows not to resign from very high rate of elementary data streams, equal to 100 Gbps, at the granularity of electronic bandwidth 20 Gb/s. This granularity of electronics is obtained now at low cost. Splitting to sub-bands is performed by anti-aliasing filters. A single ADC circuit of 20 GS/s is satisfactory to receive 100 Gb/s OFDM signal. Direct work with 100 Gbps electronics increases the system costs. Such systems are researched in laboratory conditions, to replace 20 and 40 GHz granularity with 100 GHz in the near future. The ultimate throughput for a single optical fibre, as calculated today, seems to be around 1Pb/s for trunk systems and 2-3 times more for LAN. Internet 2025, according to today's predictions, will carry several tens of Pb/s of aggregated traffic (three orders of magnitude more than today), will need several tens of TW of electrical power and will employ tens of millions of us.

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