OPTICAL TRANSPARENCY AND OPTICAL OPACITY IN FUTURE ALL-OPTICAL PACKET SWITCHED NETWORK

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ABSTRACT

"Transparent network" and "all-optical network" are not synonyms. Optical transparency has to be sacrificed in optical logic elements. The paper presents author's original view on future (all) optical packet-switched network which is based on a clear distinction within dual nature of optical signals: analogue and transparent features of the signal in optical frequency domain from one side, and digital characteristics of temporal signals and opaque solutions for all-optical logics from the other one. The imminence of breakdown of the "transparency paradigm" in the all-optical packet switched network for a variety of networking functions is pointed out.

INTRODUCTION

The introduction of Erbium-Doped Fibre Amplifiers which replaced electronic regenerators in fibre based transmission links in early 90s resulted in optical transparency of the links [1]. The evolution of actual telecommunication networks towards transparent and/or all-optical network started at that time. Transparent networks at regional and global scale with transmission speed exceeding one terabit-per-second became a reality, the networks are commonly referred to as "terabit networks" [2].
One of the most promising and cost effective ways to increase the transparent network throughput is the Wavelength Division Multiplexing (WDM) technique. In WDM systems many information channels are transmitted simultaneously through every single fiber of the system using different optical wavelengths modulated by independent data streams. Using WDM enables one to increase easily the capacity of already existing fiber links what is of particular interest especially in the cases when placing new optical cables is impossible or too expensive. This is especially attractive in view of future information society needs for exchange of enormous information streams, resulting from a general use of multimedia and hypermedia services. WDM offers the orthogonality between wavelength and time, so they can be processed independently and simultaneously [3].

A wide commercial deployment of WDM systems with hundreds of transmission channels is foreseen in the near future. WDM requires sophisticated narrow-band light sources with extreme wavelength stability, as well as a variety of photonic devices for all-optical signal processing. The future technology has to meet new demands especially in the field of optical digital signal processing, including full 3R regeneration. Moreover, a concept of the 4R regeneration has been introduced with the fourth "R" standing for regeneration of the optical signal spectrum [4]. The optically transparent transmission is expected to be of essential advantage in actual "IP over Optical" networks [5].Transparent networks offer an additional degree of freedom that is the optical wavelength. Consequently, wavelength converters are developed in order to allow the realization of wavelength routing functions.In order to profit fully from optical signal processing it is essential to develop advanced devices with novel materials and concepts as optical nonlinearities or photonic bandgap structures [6].However, significant research challenges still remain to exploit fully the transparency of the optical networks, and a resource to basic electromagnetic research approach is needed for realization of qualitatively new classes of devices [7].
Moreover, the expected introduction of optically transparent fiber links to subscriber loop will allow to take advantage from WDM technology also in that area. New ways of providing access are emerging based upon the need for interactive broadband services. A combination of various signals (i.e. analogue or digital radio and television, interactive broadband services, Internet traffic) could then be transmitted simultaneously.
Unfortunately, in real systems one is faced to the lack of the ideal transparency rather than to the transparency itself. Namely, the signal quality suffers from physical limitations even of an ideal fiber which are the attenuation, chromatic dispersion, and nonlinear distortion. What makes things even worse, the deterministic DGD (Differential Group Delay) and statistic PMD (Polarization Mode Dispersion) resulting from it are introduced in real systems due to non-ideal fibre geometry and stress caused by cable layout. The result is that the bit-error-rate of the system can surpass the usual 10^{-11} limit, especially in the fast transmission systems. Consequently the nonlinear crosstalk, optical noise and PMD are main problems to be coped with in the actual links. Consequently, the optical signal can be transmitted successfully only at

certain distance, this distance is called transparent length and it needs to be investigated carefully. Therefore, a realistic system modelling and design are of crucial importance in order to overcome multichannel signal degradation due to a variety of impairments [8].

In the paper we discuss in detail the transparent features of the network and we point out that that "transparent" and "all-optical" does not mean necessarily the same [9]. Indeed, the optical transparency has to be sacrificed when we add some optical logic elements e.g. for signal processing packet switching, etc. The impact of optical transparency on a successful deployment of future optical packed switched networks is discussed. The talk is expected to clarify much of the future network understanding since actually people consider the opacity of a network comes from conversion to electronics only, thus they obviously disregard the "optical opacity" that is inherent to a number of all-optical solutions. Realisation of networking functions with photonic components is summarised and directions of future development are pointed out.

NOTION OF TRANSPARENCY

Before we enter in a detailed discussion of transparency and lack of it, let us specify what characteristics of transparent link we would like most to have. So in an ideal case we would like to have the signal at the output exactly the same as in the input, obviously with acceptation of time delay caused by finite value of light velocity, and eventually of attenuation of the signal power but without degradation of its other characteristics.
Unfortunately that ideal situation is not realisable in an optical network since even in an ideal glass fibre exhibits attenuation, chromatic dispersion of the first and higher orders, and glass optical nonlinearities. Moreover, Polarisation Mode Dispersion (PMD) results from random local lack of circular symmetry of the fibre due to technology imperfections and local stresses caused by cable layout. The term "PMD" is used both in the general sense of two polarization modes having different group velocities, and in the specific sense of the expected value of differential group delay <??> between two orthogonally polarized modes. PMD causes the spreading of a pulse in the time domain and it is actually the main transmission distance-limiting factor in 40 Gbit/s systems and above, and as such it became recently a subject of intense research both for fibre optimisation and characterization as well [10].
It should be noted here that the notion of transparency has already been applied also to metallic cable based electrical links: those links are so called transparent if the output signal is proportional to the signal at the input. This suggests that the transparency is rather an analogue feature of a link [1]. That is in contrary to digital transmission schemes and logic elements like electronic regenerators in early binary fibre communications: the output signal has mainly two levels (zero or one), depending on the decision of the logics.
Transparency in optical domain has also its common sense: the medium is transparent if the light goes through. The advent of Erbium-Doped Fibre Amplifiers resulted in an elimination of optoelectronic regenerators, therefore in transparency of optical link, and thus in a possibility of WDM transmission.

The optical signal is characterised by temporal characteristics: shape, absolute and relative (instantaneous power), and spectral characteristics. So what we do in order the output signal resembles the input one as much as possible, or at least it is detectable properly?

- To compensate for attenuation, optical amplifiers and especially Erbium-Doped Fibre Amplifiers are already a well-developed solution.
- To compensate for chromatic dispersion, dispersion-compensating modules are developed with dispersion compensating fibres and fibre gratings as typical examples.

Similarly, fibre dispersion can be compensated by Kerr-like nonlinear index increase in glass, leading to temporal solitons that are special pulses with perfect compensation of dispersion and self-focusing effects.
Unfortunately, it is especially difficult to compensate for nonlinear distortion and interactions. The common way is to avoid them by keeping optical power low enough or developing new fibres with low value of nonlinear coefficient. Using non-equidistant WDM channel frequency grid spacing allows avoiding cross-talk due to Four-Wave Mixing. A positive way to exploit nonlinearity for soliton transmission is another classical example.

Now we can admit that the free-space is the only medium ideally transparent: no attenuation, no dispersion, and no nonlinear interactions. However, even in free-space optical beams are subjects of diffraction, what causes sending optical signals through the free-space not an efficient communication means.

Nevertheless, the problem of diffraction is overcome in an elegant way in optical-fibre based one-dimensional telecommunication links. In a fibre the diffraction of the beam is compensated with the guiding core focusing properties, leading to fibre modes that can be defined as special beams having unique property of perfectly vanished total effect of diffraction and focusing interplay.

Similar way spatial solitons' stability is a result of perfect compensation of diffraction and self-focusing in the nonlinear medium, while in the case of temporal solitons a perfect compensation of dispersion and nonlinear index increase occurs.

In the case of dark solitons, both spatial and temporal, self-defocusing effects play an essential role. Continuing the analogy, one can imagine "dark modes" representing plane wave with light intensity locally decreased within an "anti-guiding" core region with lower refractive index than in the surrounding cladding.

Why transparency is so important issue? In Dense-WDM systems wavelengths of the optical channels has to be assigned to specific values with separation of 0.8 nm, 0.4 nm, 0.2 nm or as little as 0.1 nm for 100 GHz, 50 GHz, 25 GHz or 12.5 GHz optical carrier frequency spacing. The fundamental requirement of a typical WDM network is to assure very high wavelength stability of optical sources. Therefore a precise adjustment of a particular wavelength to its proper value is a sophisticated and costly process. Consequently it is wise not to loose that precious wavelength in the network as long as possible, and in particular do not convert the signal to electrical domain for as long as possible. Nevertheless this could be done at some extend only which is referred to as "transparency length" [11].

Fibre itself and other optical components as well produce, in addition to attenuation, also an optical crosstalk in temporal and spectral domains, temporal and spectral noise, especially in optical amplifiers, in fibres due to nonlinear interactions, and in WDM multiplexers/demultiplexers as phased arrays. Moreover, optical nonlinearities in fibres and amplifiers influence both temporal shape and spectrum of the signal.

Therefore, if we insist the network behaves transparent way, this simply means that we allow attenuation and / or amplification, and eventually wavelength conversion. Transparent wavelength conversion assumes the conservation of temporal signal shape, which is superimposed to a different wavelength.

OPTICAL SWITCHING & ROUTING

Degrees of freedom of an optical network are, in addition to 3-D space co-ordinates, also time (and resulting possibility of Optical Time Domain Multiplexing, OTDM), wavelength (WDM), and polarisation with some attempts done in the past in order to exploit polarisation multiplexed transmission. Consequently, the above degrees of freedom provide opportunities for optical switching in space domain, in temporal domain, wavelength switching, and polarisation switching. In addition to that, a logical on/off switching is performed in optical logic elements.

Optical routing can be realised as wavelength routing in a transparent way. This is an analogue and passive solution, or an analogue and active one if wavelength conversion is applied.

All-optical packet routing involves some intelligence of the router and some decision based on the information included in the packet. It is a digital action and as such it is not realisable transparent way [9]. Even though all-optical routing element involves optical logics, optical memory, etc., nevertheless it is not optically transparent and it exploits optically opaque elements. The signal remains in optical domain, but digital operations result in that the fundamental transparency condition of proportionality of output and input signals is not satisfied.

Therefore, the actual state of optical network infrastructure and its emerging evolution direction can be summarised as follows:

- from circuit switched optical networks, with analogue processing of carrier frequency i.e. in spectral domain, the transparency is a positive characteristics here,

- to packet switched network, with direct digital processing of temporal signals, realising all-optical switching and in particular exploiting optically opaque routing devices.

Ten years ago the networks entered a stage of "electronic islands" emerged in an optically transparent network, with electronic islands standing for opaque digital signal processing equipment [12]. It seems that during next ten years we will witness a network consisting of "optical islands" emerged in a transparent network, where islands will realise digital signal processing in an all-optical fashion.

What would happen later? Some combination of both? Last decade has demonstrated that it is very risky to make forecasts in telecommunications for more than ten years [12].

CONCLUSIONS

After a decade of triumph of optically transparent WDM transmission opaque optical elements will be introduced in mass in the next stage of network development, in view of imminent network evolution towards optical packed-switched networks. The optically opaque elements will be necessary especially for all-optical signal processing in general, and all-optical routing functions in particular.

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REFERENCES

1]. M. Marciniak, "Transparency of optical networks: How to manage it?" *International Conference on Transparent Optical Networks* ICTON'99, Kielce, Poland, June 9-11, 1999.

2 M. Marciniak, "The impact of optical transparency on the successful development of all-optical terabit networks," *5th World Multi-Conference on Systemics, Cybernetics and Informatics SCI 2001*, Orlando, Florida, USA, July 22-25, 2001.

3 R.C. Alferness, "Research challenges in optical networking", *ECOC'98*, Madrid, Spain, Sept. 1998.

4 L.Thylén, "Some aspects of photonics and electronics in communications and interconnects", *International Conference on Transparent Optical Networks* ICTON'99, Kielce, Poland, June 9-11, 1999.

5 M. Klinkowski and M. Marciniak, "Development of IP/WDM Optical Networks," *International Workshop on Laser and Fiber Optic Network Modelling*, Kharkov, Ukraine, May 22-24, 2001.

6 M. Marciniak, "Solving present and future problems in optical telecommunications with PBGs," in: *Nanoscale Linear and Nonlinear Optics*, American Institute of Physics, Conference Proceedings Vol.560, pp. 77-88, Melville, New York, 2001.

7 A. G. Nerukh, I. S. Scherbatko, and M. Marciniak, *Electromagnetics of Time-Varying Media with Applications to Photonics*, National Institute of Telecommunications, Warsaw 2001.

8 M. Marciniak and A. Sedlin, "Numerical analysis of optical nonlinearities in multispan DWDM fibre transmission systems", in: *Nonlinear Optics for the Information Society*, Edited by A. Driessen, pp. 113-121, Kluwer Academic Publishers, Dortrecht, The Netherlands, 2001.

9 M. Marciniak, "Transparent versus opaque issues in an all-optical packet switched network" (Invited), *10th International Workshop on Optical Waveguide Theory and Numerical Modelling,* Nottingham, UK, April 5-6, 2002.

10 IEC Technical Committee 86 "Fibre Optics", New Work Item Proposal on Test procedures for fibre optic cable plant and links – Polarization mode dispersion measurement for installed links, September 2001.

11 P. Lagasse et al. "Photonic Technologies in Europe", ACTS Infowin 1998.

12 J.E. Midwinter. "Photonic in switching: the next 25 years of optical communications?" *IEE Proceedings-J*, Vol. 139, No.1, pp.1-12, 1992.