Analysis of a New Signaling Method at the Physical Layer for Optical Packet Switched Networks

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Abstract. For the implementation of IP over fiber concept, the All Optical Label Swapping (AOLS) technique is proposed, where the packet routing and forwarding functions are carried out directly in the optical domain. The proposed method is based on the combination of the optical frequency shift keying (OFSK) modulated label with the on–off keying (OOK) modulated payload on the same optical carrier. This orthogonal modulation scheme, for the label encoding onto the intensity modulated payload is studied for the first time via extensive simulation of a network system where the abovementioned functions are taken place.

Keywords: AOLS, MPLS, FWM, SOA, XPM, optical FSK, ER, MZI wavelength converter, 2R regenerator

1 Introduction

1.1 Overview of the problem

The rapid growth of packet based Internet traffic, has fully overtaken circuit switched traffic and has imposed the need for ultrahigh link capacities and ultrahigh packet switching speeds, at network nodes. Multiprotocol label switching (MPLS) technology has been introduced, as a solution for packet routing and forwarding functions, and it is based on label swapping mechanisms. Instead of reading huge route lookups, a single label is read, on each packet [1]. In today's approach, IP packets are mapped to ATM cells, which in turn mapped to SONET frames. However, by carrying the IP packets directly over the WDM layer, we overcome the need of transportation over the two intermediate layers, resulting in an all optical

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Dissertation Advisor: Dimitris Syvridis, Professor process and increased network throughput. The above mentioned trend is supported by the generalized MPLS (GMPLS) protocol, where λ (wavelength) switched channels play the role of the label switched paths in MPLS protocol[2]. Apart from the λ labeling, additional label information can be encoded and attached to the IP packet, via various label encoding methods, at the edge nodes before entering the WDM core network, thus creating an adaptation-encapsulation layer, lying between IP and WDM layers. All optical label swapping (AOLS) is the method of coding the optical label onto the packet, after having removed the old one, for all optical packet routing and forwarding. It directly determines the structure and performance of the optical core node (router), and it is strongly related to the channel bandwidth efficiency and the transmission quality of the packet and the label.

Our method relies a proposed IM/FSK (Intensity modulated-Frequency shift keying) scheme [3], with the label-payload encoding based on four wave mixing (FWM) process in a semiconductor optical amplifier (SOA).

A detailed numerical simulation analysis is carried out, for the investigation of the limits of the method, concerning the propagating distance, the extinction ratio of the IM signal, the modulation index of the FSK header, the number of successive label swapping nodes with their corresponding fiber spans, as well as an optimization of the system critical parameters in order to maximize the above limits. The architecture of the intermediate node assumed in this work is based on two main units, a typical Mach Zender interferometer MZI- SOA based module for the FSK header removal and payload regeneration, and a SOA based FWM module for the label encoding on the IM payload.

1.2 Alternative label coding techniques

In the past few years, many methods have been proposed and studied for all optical labeling. According to the way optical label is attached to the datagram, there are four main categories: i) optical subcarrier multiplexed (SCM) header ii) bit serial header iii) optical orthogonal modulation and iv) wavelength labeled WDM.

The optical SCM method accommodates both, the label and the data payload on the same wavelength, considering the payload as the baseband and modulating the label on an RF frequency subcarrier channel [4]. However, during the propagation of the DSB (double side band) signal through a dispersive fiber, upper and lower SCM side bands will undergo different phase shifts, due to different phase velocities. There are two solutions that can handle it, one concerns the carrier suppressed label extraction, via a fiber Bragg grating (FBG) or a fiber loop mirror [5-6], while the other concerns the single sideband (SSB) transmission via a notch filter [7]. Another drawback of the above mentioned modulation method is that SCM can not support, adequately, high bitrate systems (40Gbps and above) due to electronic components limitations.

The label wavelength method uses a separate wavelength for the transmission of the optical label [8], making inefficient use of the bandwidth and underutilizing the label channel capacity. Moreover, as payload and label propagate through a dispersive fiber, on separate wavelengths, they would have different speeds due to chromatic dispersion, resulting in a walk off between them.

As far as bit serial method is concerned, many interesting approaches have been proposed, for the optical label processing (extraction and reinsertion) from the payload. These concern the usage of time to wavelength, or inversely mapping, via FBG optical correlation [9], the usage of time gated, wavelength shifting PPLN waveguides [10], a XOR logic [11], a continuous wave tag [12], or other interesting optical pulse code correlation methods[13]. However, bit serial method may require strict synchronization and timing control. Moreover, it sometimes demands different power levels or coding formats (eg RZ payload with NRZ header), in order to distinguish between label and payload.

Two more, interesting approaches concern header separation, using different states of polarization and separate header and payload generation on two symmetrical beat longitudinal modes, caused by original carrier suppression[14].

Finally, the orthogonal modulation and its binary representative (IM/DPSK or IM/FSK) has received major interest. The data payload is intensity modulated, while the label is represented by either the phase or the frequency information of the optical carrier[15]. The crucial point here, is the low extinction ratio, required for proper operation of the label receiver. It has been shown that strong intensity modulation of the payload introduces crosstalk and deteriorates the label quality. As a solution, Manchester coding (instead of NRZ) of the payload pulses is strongly recommended, to suppress the crosstalk term, thus providing better results [16].

2 Orthogonal Label Coding Technique Analysis

This section covers a description of the system, its components, and its importance in an AOLS structure, followed by a theoretical description of the SOA model, used for the implementation of the FWM scheme. Finally an individual investigation and optimization of the critical parameters of the orthogonal IM/FSK scheme, and the limitations imposed on the AOLS network system for a high bit rate propagating IM/FSK signal, are analyzed via numerical simulations.

2.1 Description of the IM/FSK orthogonal scheme and the AOLS network

The whole network system as can be seen in fig.1 is consisted of three kind of nodes: The starting node, the intermediate node and the end node. The starting node is responsible for the generation of the IM payload signal and the FSK modulated header signal, by the corresponding transmitter units, and their combination onto a common wavelength carrier. The most crucial block for the system operation, is the intermediate node which is responsible for the old label extraction and removal, the payload wavelength conversion and regeneration, and the new label generation and insertion with the bare payload, onto an optical carrier.

Fig.1 shows analytically the components that implement each of the above functional blocks. At the starting node, a 625Mbs or a 2,5Gbs NRZ, optical FSK label is combined with the intensity modulated IM 10Gbs or 40Gbs NRZ data payload respectively. This FSK modulated label, has been realized by chirping, through direct modulation, a laser transmitter, at a low modulation index, according to a typical optical FSK scheme. An FSK compensation scheme has been added on the FSK transmitter. According to the scheme, an electroabsorbsion (EA) modulator,(any AM modulator would do),accepts the optical FSK data, while at the same time is driven with the inverse electrical data, hence the intensity variations at the laser output have been completely removed and furthermore the residual IM has been minimized. At the same time, IM packet payload is generated by externally modulating a MZ amplitude modulator at low extinction ratio (3dB). Both signals enter the SOA after being amplified in such a way, that payload is the pump and label is the signal, according to a typical FWM scheme. Spectra of the IM payload, the FSK modulated header and the conjugate signal at the output of the FWM module are shown in fig 2. In fact, the starting node accomplishes the IP packet and header encapsulation function, generating an optical labeled packet, while the end node strips the packet from the label, thus giving back the pure IP packet.

Before entering the intermediate node, the signal propagates over a span of single mode (SMF) fiber, followed by the proper dispersion compensation (DCF) fiber. Dispersion compensation is required for proper FSK operation, due to the walk off effect between the two FSK tones. The FSK tone spacing is also a crucial matter.

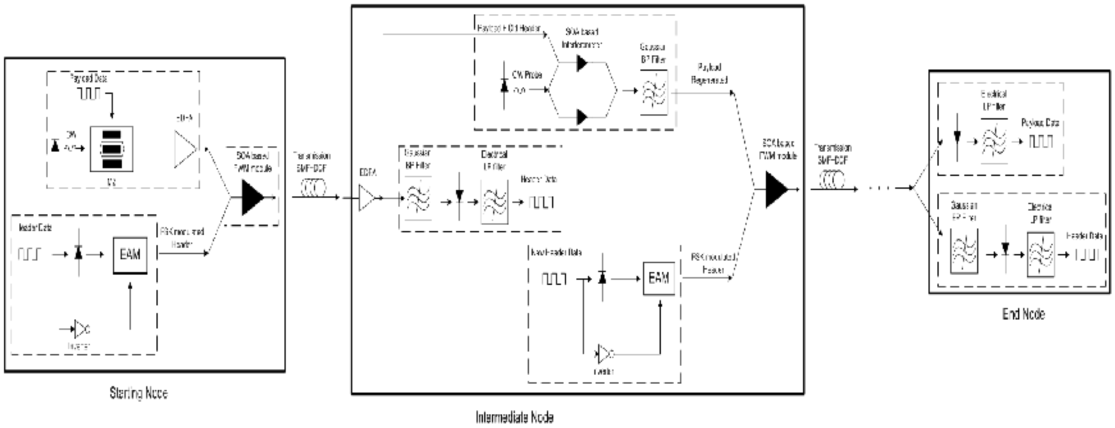

Fig. 1. Detailed schematic representation of the proposed method.

The intermediate node which possesses the functionalities of the AOLS core router consists of three subunits: the label extraction unit, the label removal and payload regeneration unit, and the label insertion unit.

The label extraction module, is a typical optical FSK receiver, composed by a Gaussian 10GHz optical bandpass filter, a PIN photodiode and the appropriate electrical lowpass filter. The same module also applies to the end node, for the final label extraction. The label removal and 2R regeneration module consists of a typical co propagating Cross Phase modulation (XPM) based MZI-SOA model followed by the appropriate optical Gaussian bandpass filter. Due to the XPM process, all the coherently encoded information (FSK modulation) is not transferred to the output of the module, while the IM payload is not only preserved but also 2R regenerated.

Finally, it is worth mentioning that, sometimes, core routers need to change only the wavelength of the labeled packet and not the encoded label itself, since it is about a two level label encoding. In such case, XPM based interferometric wavelength converter IWC-SOA devices cannot be applied, and instead some transparent wavelength conversion scheme, that preserves FSK modulation, should be used. The appropriate device is then the SOA based FWM scheme, where the IM/FSK signal is the pump and a CW laser is the signal input. Hence, the IM/FSK input will be copied, without a change in the encoded label.

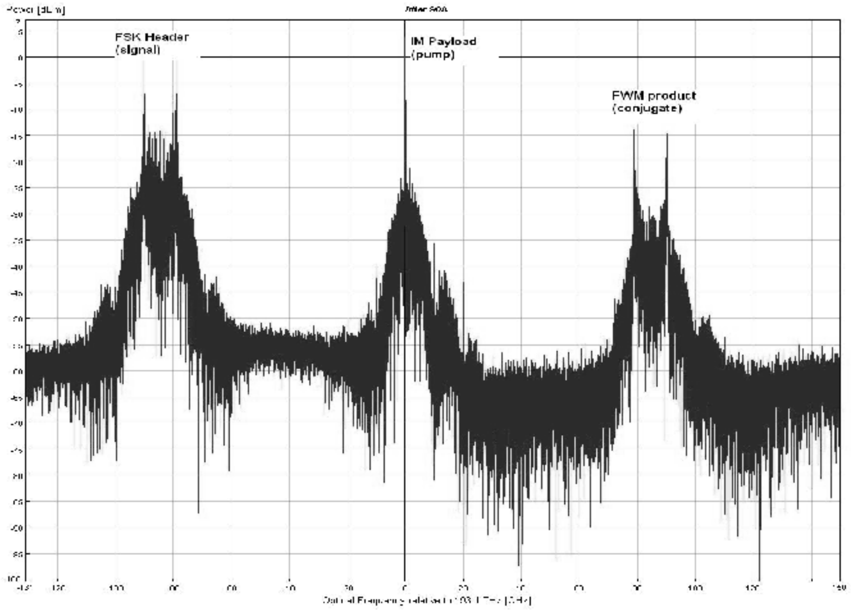

Fig. 2. Spectra of the IM payload (pump), the FSK modulated header (signal) and the conjugate signal at the output of the FWM module.

2.2 SOA model

In the model presented [17], interband and intraband carrier dynamics mechanisms, such as carrier density pulsation (CDP), carrier heating (CH) and spectral hole burning (SHB) have been taken into account. SOA model is described by the following coupled mode rate equations:

(1)

$$\frac{\partial A_1}{\partial z} = \frac{1}{2}\left[g(1 - i\alpha) - \alpha_l\right]A_1$$

$$-\frac{1}{2}\left(n_{1,2}\left|A_2\right|^2 + n_{1,3}\left|A_3\right|^2 + n_{1,4}\left|A_4\right|^2\right)A_1$$

$$-\frac{1}{2}\left(n_{2,1} + n_{3,1}\right)A_2 A_3 A_1^* - \frac{1}{2} n_{2,4} A_2^2 A_4^* + ASE_1$$

(2)

$$\frac{\partial A_2}{\partial z} = \frac{1}{2}\left[g(1 - i\alpha) - \alpha_l\right]A_2$$

$$-\frac{1}{2}\left(n_{2,1}\left|A_1\right|^2 + n_{2,3}\left|A_3\right|^2 + n_{1,4}\left|A_4\right|^2\right)A_2$$

$$-\frac{1}{2}\left(n_{1,2} + n_{4,2}\right)A_1 A_4 A_2^* - \frac{1}{2} n_{1,3} A_1^2 A_3^* + ASE_2$$

(3)

$$\frac{\partial A_3}{\partial z} = \frac{1}{2}\left[g(1 - i\alpha) - \alpha_l\right]A_3$$

$$-\frac{1}{2}\left(n_{3,1}\left|A_1\right|^2 + n_{3,2}\left|A_2\right|^2 + n_{3,4}\left|A_4\right|^2\right)A_3$$

$$-\frac{1}{2}\left(n_{1,4} + n_{2,4}\right)A_1 A_2 A_4^* - \frac{1}{2} n_{1,2} A_1^2 A_2^* + ASE_3$$

$$\frac{\partial A_4}{\partial z} = \frac{1}{2}\left[g(1 - i\alpha) - \alpha_l\right]A_4 \tag{4}$$

$$-\frac{1}{2}\left(n_{4,1}\left|A_1\right|^2 + n_{4,2}\left|A_2\right|^2 + n_{4,3}\left|A_3\right|^2\right)A_4$$

$$-\frac{1}{2}\left(n_{1,3} + n_{2,3}\right)A_1 A_2 A_3^* - \frac{1}{2} n_{2,1} A_2^2 A_1^* + ASE_4$$

where Ai (i =1,2,3,4) is the propagating optical field, ASEi is the Amplified Spontaneous Emission (ASE) noise, α_1 the internal linear loss, τ_s is the carrier lifetime of the SOA and g the signal gain, given by:

$$\frac{\partial g}{\partial t} = \frac{g_s - g}{\tau_s} - g\frac{P_{tot}}{P_{sat}\tau_s} \tag{5}$$

where gs is the small signal gain, Ptot the total power, Psat the SOA saturation power. The coefficients nij represent the three diffusion contributions, from the nonlinear processes, CDP, CH and SHB given by the following:

$$n_{i,j} = n_{i,j}^{CDP} + n_{i,j}^{CH} + n_{i,j}^{SHB} \tag{6}$$

$$n_{i,j}^{CDP} = \frac{g(1 - i\alpha)}{P_{sat}} \times \frac{1}{\left[1 - i\left(\omega_i - \omega_j\right)\tau_s\right]\cdot\left[1 - i\left(\omega_i - \omega_j\right)\tau_{SHB}\right]} \tag{7}$$

$$n_{i,j}^{CH} = \varepsilon_{CH}\, g\left(1 - i\alpha_{CH}\right) \times \frac{1}{\left[1 - i\left(\omega_i - \omega_j\right)\tau_{CH}\right]\cdot\left[1 - i\left(\omega_i - \omega_j\right)\tau_{SHB}\right]} \tag{8}$$

$$n_{i,j}^{SHB} = \varepsilon_{SHB}\, g\left(1 - i\alpha_{SHB}\right) \times \frac{1}{1 - i\left(\omega_i - \omega_j\right)\tau_{SHB}} \tag{9}$$

where ε and α are the gain compression factors and linewidth enhancement factors respectively, for the CH and SHB phenomena.

2.3 Numerical results and discussion

At first in this section, a proper value for the FSK modulation index, (spectral spacing), between the two FSK tones of the header, at the FSK transmitter, is determined. At second, system's limitations are examined, without including intermediate label swapping nodes, only the starting node with its transmitters, the FWM based combination scheme, the transmission module, and the end node with its corresponding receivers. This investigation is carried out for the determination of the optimum values of critical system parameters, such as the extinction ratio of the signal for different bit streams, the dynamic range of the FWM module and the transmission distance effect on the propagating signal. The above research is done for 10Gbs NRZ IM payload signal, with 625Mbs NRZ FSK modulated header. Next, we continue on testing the system limitations by searching for the optimum values of the above critical parameters, when successive intermediate label swapping nodes with their corresponding transmission spans, are included, according to a typical network route. Hence it's the number of cascaded label swapping nodes that determines system limitations. Finally, the possibility of the system to operate at 40Gbs NRZ IM payload with a 2.5Gbs NRZ FSK modulated header, is investigated.

Optical FSK header transmitter investigation. Advantages and disadvantages for large and small frequency spacings are mentioned. On one hand, a large frequency spacing, with a proper optical bandpass filter would seem to be desired for proper FSK demodulation at the receiver. It is common truth that the more we modulate the signal, the larger frequency deviations we achieve, and the better results we get at the receiver for a constant bit rate. Another benefit of the large frequency spacing is related to the chirp characteristics of the total signal (IM combined with FSK). Chirping generally results in a broadening of the signal spectrum, so if this broadening is too large, the FSK modulated label will be influenced. Luckily, there's no degradation of the FSK signal as long as chirp falls within the bandwidth of the filters used for direct detection of the FSK tone.

On the other hand, in the case of dense WDM networks, with small channel spacing would impose a small frequency deviation between the two FSK tones. Secondly, there is the residual amplitude modulation of the payload, imposed by strong FSK modulation, which has also been removed, due to the applied FSK compensation scheme at the FSK transmitter, otherwise it would require a weak modulation and consequently small spacing.

It is obvious that, the greater FSK tone deviation we get, the better performance we achieve, since it is easier and more efficient to demodulate the header. On the contrary, payload's performance is deteriorating, as the FSK tone deviation increases because the residual intensity modulation effect imposed by the stronger FSK modulation becomes more pronounced. FSK values around 12-20GHz could be the perfect choice for combined acceptable payload and header performances, at the receivers.

Investigation on system limitation without intermediate label swapping nodes. There are some critical parameters, that directly or indirectly, affect system's performance, such as the extinction ratio (ER) of the externally modulated payload, the width of the optical filter of the label receiver, and the dynamic range of the FWM. The IM modulated payload's ER trade off, is one of the most crucial points, for the proposed encoding method. High ER ensures high performance for the payload, but it is catastrophic for the header while, low ER continues to support optical FSK, even during the zeros of the payload at the expense of the lower IM modulated payload performance. Good performance above BER threshold can be achieved for the 10Gbs payload and 625Mbs header in the back to back configuration with ER values not higher than 4dB. Such an ER is not sufficiently high to ensure high performance in a network configuration and is one of the weak points for the IM/FSK technique as well as for other orthogonal techniques proposed in the literature.

It is also shown by our simulation runs, that the header sustains a good performance for transmission distances up to 80km, while the corresponding maximum transmission distance for the payload is not higher than 60km, which therefore is the maximum distance between two successive nodes for the complete system.

Finally, one of the most important operating parameters to characterize, is the dynamic range of the SOA based FWM module. The data signals do not always have the same power level when they reach the FWM module. The dynamic range, for various pump power levels at the input of FWM module, is around 8.84dB.

Investigation on system limitation when intermediate label swapping nodes are included. At first, system performance is examined, as concerns the number of intermediate nodes, for a constant ER of the signal, of 3dB, and 50km, dispersion compensated SMF fiber span. The maximum number of label swapping nodes that can be supported by the system is five. It is worth noticing that, header preserves an almost steady behavior, due to the constant ER, while payload decreases gradually as the number of the spans and the nodes across the route increases.

System limitation, concerning the number of intermediate nodes, continues by varying the distance per span, for a constant ER, and inversely, varying the ER, for a constant 50km span distance. Three different span values have been assumed of 30, 50 and 70km, for a constant ER value of 3dB. The total length of the network path reduces as the number of the intermediate nodes increases, thus the payload signal of the system survives after a four node route of 70km span distance, in between nodes, or a five node route of 50km span distance, or finally a six node route of 30km span distance. As concerns header performance, all the above mentioned system configurations, have the same behavior. The reason is that, at each node the header is extracted and a new one is inserted.

Finally system's limitation is also examined, concerning the number of cascaded intermediate nodes, for a constant distance span of 50km, with the ER signal values of 3dB, 8dB, and 12dB. The payload signal of the system, survives after a ten node route, when it is IM modulated with 12dB ER, or after a six node route, when it is IM modulated with 8dB ER, or after a five node route with 3dB ER.

40Gbs IM payload with 2.5Gbs FSK header for AOLS applications. The two critical functions which should respond at these high bit rates are the header erasure XPM unit and the FWM based combiner of IM modulated payload with FSK modulated header. As already mentioned above both these modules use as a key element a SOA. The ability of XPM unit to operate at 40Gbs has been already proved experimentally[18]. Concerning the FWM unit, it would be expected to have no problem in operating at high bit rates, since the FWM phenomenon based on ultrafast nonlinear processes in the SOA has much higher frequency limitations. Unfortunately, the numerical simulations proved that this is not the case, mainly for the FWM unit. The reason is due to the pump modulation scheme needed for the FSK/IM combination, and is related to the long free carrier relaxation times.

3 Conclusion

An orthogonal IM/FSK encoding scheme, with the label–payload coupling based on FWM in a SOA, and the label removal with payload wavelength conversion and regeneration, based on XPM in a SOA-MZI module, has been investigated on its limits, via extensive simulation. Many critical parameters of the system have been tested and optimized, in order to determine these limits, and concern almost all the functional blocks of the configuration, starting from the FSK transmitter module individually, the back to back edge node configuration with and without propagation DCF fiber span, and the complete configuration, with the inclusion of intermediate label swapping nodes and their corresponding transmission spans, according to a typical network route. The system has been tested mostly for 10Gbs NRZ IM payload with 625Mbs FSK modulated header, which appear to be the upper limits for the bit rate of the two bit streams (payload and header).

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