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Linear Crosstalk for Impairment-based Optical Routing

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1. Abstract

Optical in-band crosstalk between interfering optical channels has been identified (see [ITC-DIL]) as one of the major limitations to the diameter and the performance of photonic (or all-optical) networks. In this context in-band crosstalk remains a cause of optical signal degradation in switching elements included in a Photonic Cross-Connect (PXC).

The aim of this draft is to extend the previous work dedicated to routing impairments [IPO-IMP]. It seeks to determine which are the additional linear crosstalk effects that need to be considered and which kind of engineering rules may be used to take these effects into account in constraint-based optical routing.

Moreover, we propose to introduce IGP routing protocol extensions to transport information related to linear crosstalk relevant for

wavelength routing decisions (i.e. the route of the wavelength throughout the optical network).

2. Conventions used in this document

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC-2119 [2].

3. Introduction

[IPO-IMP] states that Optical crosstalk refers to the effect of other signals on the desired signal. It includes both coherent (i.e. intrachannel) crosstalk and incoherent (i.e. interchannel) crosstalk. Main contributors of crosstalk are the OADM and OXC sites that use a DWDM multiplexer/demultiplexer (MUX/DEMUX) pair. For a relatively sparse network where the number of OADM/OXC nodes on a path is low, crosstalk can be treated with a low margin in OSNR without being a binding constraint. But for some relatively dense networks where crosstalk might become a binding constraint, one needs to propagate the per-link crosstalk information to make sure that the end-to-end crosstalk which is the sum of the crosstalks on all the corresponding links to be within some limit, e.g. 25dB threshold with 1dB penalty ([Goldstein94]). Another way to treat it without having to propagate per-link crosstalk information is to have the system evaluate what the maximum number of OADM/OXC nodes that has a MUX/DEMUX pair for the worst route in the transparent domain for a low built-in margin. The latter one should work well where all the OXC/OADM nodes have similar level of crosstalk.ö

While the above description proposes alternatives to overcome crosstalk impairments in all-optical environment, it doesnÆt propose a clear method to process this information in the context of constraint-based wavelength route computation, selection and allocation.

The corresponding conclusion expressed in [IPO-IMP] is 'Crosstalk and effective passband narrowing due to filtering effects can be treated approximately as a constraint on the maximum allowable number of Optical Add-Drop Multiplexers (OADMs) and Photonic Cross-Connects (PXCs) in the transparent segment of the lightpath or optical channel.'

Therefore, the aim of this memo is to provide a definition for the crosstalk constraint and to propose an efficient way to take these effects into account for dynamic constraint-based routing in

Wavelength Switched (all-)optical Networks (WSoNs).

In WSoNs, unicast connections carried on lightpaths are optical point-to-point connections between two nodes. Such connection can span one or more network nodes and is used to transport packets or TDM circuits from source node (ingress) to destination node (egress). The network nodes can be Optical Cross-Connects (OXC) with non-transparent O-E-O interfaces or Photonic Cross-Connects (PXC) with transparent interfaces. PXCs do not perform any conversion of

the optical signal into the electrical domain or vice-versa (such devices are also referred to as All-Optical Cross-Connects). Optical networks comprised of OXCs only are referred to as 'non-transparent' WsoNs, while networks built of PXCs only are known as 'all-optical' or 'transparent' WSoNs.

In WSoNs spanning a large geographical area, an optical signal (the wavelength) may traverse a number of intermediate nodes and long fiber segments. In order to enable the signal to flow over the desired wavelength in the optical domain, each intermediate PXC uses passive and lossy switching elements (i.e., power leaking due to isolation) using active electrical control mechanisms.

The progressive losses experienced by the signal in all these nodes and long fiber segments necessitate the use of optical amplifiers (usually, erbium-doped fiber amplifiers (EDFAs) or Raman amplifiers) at strategic locations in the network, possibly at each node and within the fiber segments.

Unfortunately, the PXCs and EDFAs, while offering transparent switching and loss compensation respectively for optical signals, may introduce significant transmission impairments, such as:
- in-band crosstalk generation when two or more optical signals propagate through the same PXC
- generation of Amplifier Spontaneous Emission (ASE) noise in EDFAs while providing signal amplification and wavelength dependence of EDFA gain

These impairments, in the absolute sense, make the optical signal power gain a traffic-dependent and non-deterministic quantity. The in-band crosstalk and the ASE noise, generated at every intermediate node, propagate along with the optical signal over the assigned carrier wavelength; and all of them undergo variable gains at various wavelengths because of the traffic-dependent, non flat gain spectra of EDFAs.

Thus, a signal degrades in quality as it traverses through switches and fiber segments while propagating along its assigned lightpath toward its destination, and the OSNR continues to decrease. When the signal finally arrives at the destination, the crosstalk and ASE noise that have accumulated along with the signal may result in significant degradation of the OSNR, which in turn might increase the receiver bit error rate (BER) beyond its acceptable threshold.

In order to examine the reliability of the physical layer, one needs to capture all of these physical-layer limitations together and evaluate the achievable BER for a given lightpath.

Note: considerations related to ASE noise are fully detailed in [IPO-IMP]

4. Linear crosstalk

In addition to non-linear crosstalk (described in [IPO-NLI]), some crosstalk occurs even in a perfectly linear optical channel because of the imperfect nature of various optical components such as filters, demultiplexers, and switches.

4.1 Out-of-band crosstalk

Out-of-band crosstalk (also referred to as hetero-wavelength crosstalk) results from the leak of a fraction of the optical signal power from neighboring channels that interferes with the detection process in optical filters and demultiplexers.

To maintain a given value of the Bit Error Rate (BER), the corresponding power penalty must be kept below a certain threshold. For instance, the power penalty can be limited around 0.3 dB when maintaining a BER of 10^(-12) and 0.2 dB when maintaining a BER of 10^(-9). Notice that this threshold is dependent on the refinement of the filter.

The out-of-band crosstalk induces at the receiver side a penalty on the required power to maintain a given value of the BER. The specification of a maximum acceptable penalty gives a maximum admissible crosstalk value. Moreover, the out-of-band crosstalk can always be further reduced at the receiver side using an enhanced filtering.

However, this technique can not be applied to the in-band crosstalk. Consequently, in-band crosstalk is a critical parameter to be taken into account as impairment in constraint-based optical routing.

4.2 In-band crosstalk

In-band crosstalk (also referred to as homo-wavelength crosstalk) occurs during the switching of the optical signal in multiple devices such as PXCs, including (N x N) spatial switches. The in-band crosstalk for a given lightpath in the (N x N) switch is induced by the (N - 1) other lightpaths carried over the same wavelength due to the loss of the switch.

Note that the out-of-band crosstalk may be transformed into in-band crosstalk in a PXC, when multiplexing optical signals coming from different demultiplexers through a switching stage.

By definition (ITU-T G.692), the optical crosstalk is defined as the ratio of the combined total disturbing power due to signal power from all other channels, operating under all specified conditions, relative to the nominal signal power level in the desired channel, at the single-channel signal output reference points SD1 ... SDn according to Figure 1 (in G.692), within the resulting bandwidth of the optical demultiplexer and optical receiver, expressed in dB.

Therefore, the in-band crosstalk induced by an (N x N) switching element can be formulated as the fraction F (also referred to as the crosstalk level) of power leaking through the switch. When assuming equal power for all (N - 1) sources of coherent in-band crosstalk (due to the incomplete filtering caused by the partial overlap among the N channels), this leads to the r^2 factor: r^2 = F x (N - 1); where r^2 is defined as an intensive noise.

Notice that this formulation of the induced in-band crosstalk reflects an ideal system where each of the N sources provides the same contribution to the in-band crosstalk.

As described in [AGR-FOCS], the impact of the in-band crosstalk on the system performance can be evaluated by using the power penalty. When the in-band crosstalk is treated as an intensive noise, the power penalty D can be expressed as follows:

D = - 10 log (1 - (r x Q)^2) where Q is the Q factor

For instance, to keep the power penalty below 2dB when the Q factor = 8.6, the factor r must be such that r < 0.07, thus limiting the crosstalk level below û23dB when N = 2, below -36dB when N = 16 and -43dB when N = 100. Alternatively, giving a power penalty of 1dB

(2dB) and a Q factor = 7 (BER = 10^(-12)), the crosstalk level must be maintained below -24dB (-21dB respectively).

Note: this memo considers only first order crosstalk, i.e., the crosstalk flowing through propagating in the downstream direction (from ingress to egress) and producing in its turn additional crosstalk or higher order crosstalk) is not considered in this memo..

However, the above formula is only valid when there is no optical noise within the system as detailed in [OFC-XTD]. It is demonstrated therein that the power penalty simulated and experimentally measured depends on the optical noise: a 1dB penalty for a low OSNR value induced -30dB crosstalk compared to the -24dB crosstalk without optical noise.

5. Impact on optical routing

This section describes the impact of in-band crosstalk on optical routing.

5.1 Crosstalk computation for an optical channel

Considering the establishment of an optical channel within a network, this channel will be a succession of ôjö different switching elements, each switching element (SE) having a XT(SE).

Then, the total cumulated crosstalk over the whole optical channel or path, XT(path), is given by:


```
XT(path) = Sum(XT(SE)[j])

where XT(SE)[j] is the XT induced by the switching element 'j'
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With this simple formula, it is possible to compute the total cumulated XT for any optical channel switched through a sequence of S switching elements.

If the (N x N) switch element is composed of n x (M x M) switching sub-elements (M < N) then simply XT(SE) = Sum(XT(SSE)[i]), where XT(SSE)[i] is the XT induced by the switching sub-element 'i'.

However, in real systems, the individual XT(SSE) values will be difficult to measure; this aspect is not considered in the remaining sections of this document.

5.3 Crosstalk constraint

In Section 4, we have demonstrated that the crosstalk is an additive variable along an optical path (including several nodes) which depends on the Q factor and the channel spacing (more precisely the number of channels). Therefore, the cumulative XT value over the whole optical path (XT(path)) can be used to determine the maximum number of hops (i.e., PXCs) that this channel can traverse.

Consequently, the crosstalk routing constraint can be expressed as follows: after switching an optical channel through a sequence of PXCs the total cumulative crosstalk XT(path) must be such that:

- 10 log (1 - Q^2 x XT(path)) < D

When XT(path) fulfills this constraint, the corresponding optical channel is not limited by the in-band crosstalk induced by the switching elements of the PXCs along the optical path (though depending on the OSNR). This suggests a limiting D factor compatible with the OSNR margin. Using a conservative value for the power penalty limit guarantees the feasibility of the optical channel in the worst OSNR case; however, this will lead to reject some feasible paths.

Therefore, by applying the above formula which does not take into account OSNR effects, when the Q factor is known and using D as a constraint (usually 1 or 2dB power penalty), one can determine with the above formula the maximum number of switching elements (and subsequently the maximum number of PXCs) that a given optical channel can traverse.

Another approach would be to have a table, based on measurements or simulations, giving the different XTmax values as a function of the targeted Q (since a single Q value could not be sufficient for all optical channels when providing QoS differentiation for instance) and cumulative OSNR per channel (OSNR(path)). XT(path) would then be

compared to the proper XTmax retrieved from this table. As such, this approach works without any complex formula.

Remember also that any PXC will be designed to limit as much as possible the in-band crosstalk.

6. Traffic-engineering routing protocol extension

Using the approach initiated in [IPO-ORI], the in-band crosstalk constraint can be integrated into the OSPF-TE Link-State Advertisement (LSA) or ISIS-TE Link State PDU (LSP). As mentioned here above, the XT(SE) parameter may be flooded using a dedicated extension to the Router TLV defined for IGP TE-Routing protocol.

In OSPF, this XT(SE) parameter is included in a common sub-TLV of the Router TLV in the Traffic Engineering LSA since this parameter defines a node (and not a link) TE attribute. The Type value of this sub-TLV is to be attributed (TBA). The length of this sub-TLV is 4 octets and the corresponding value specifies the XT(SE) value (in IEEE floating point format) per switching element. The format of the XT(SE) sub-TLV is shown below:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Type = TBA                   |          Length = 4           |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                             XT(SE)                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

In IS-IS, the XT(SE) parameter is included in a sub-TLV (whose type is TBA) of the Traffic Engineering router ID TLV (type 134). The length of this sub-TLV is 4 octets and the corresponding value specifies the XT(SE) value (in IEEE floating point format) per switching element. More precisely, the following sub-TLV is added:

- Sub-TLV type: TBA
- Length (in bytes): 4
- Name: XT(SE)

7. Security Considerations

This memo does not imply additional security issues than the one considered in [ISIS] and [OSPF].

8. References

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