A Cross Layer Study of Packet Loss in All-Optical Networks

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Abstract

A crucial issue in all-optical networks is packet loss. In this paper we evaluate sources of packet loss, comparing impact of effects at the physical layer and at the network layer. The study is compiled for optical packet, burst and circuit switched networks. We provide an analytical model that evaluates packet loss due to bit errors using bit-error rate, packet length distribution and network size as parameters. Bit errors at the physical layer set a lower limit to the aggregate packet loss and for some scenarios it overshadows packet loss at the network layer. For applications applied in the Internet today, bit error requirements may be considerably alleviated as compared to those of synchronous digital hierarchy (SDH) systems without degrading the perceived quality of service for the end-user. By considering recommended packet loss rates for future Internet services we evaluate the usefulness of different techniques for reduced packet loss.

1. Introduction

Historically, wavelength division multiplexing (WDM) has proved to be an efficient method to increase the transmission capacity in optical fibers. Although the data is transported in the optical domain it is usually processed in the electronic domain when traversing a switching office. However, with a continued growth in transmission capacity it will be technologically simpler and more economic to reduce the amount of electronic processing, thus leaving more tasks to the optical domain [1]. These future networks are referred to as all-optical networks and can be divided into three main categories; wavelength routed optical networks (WRON) [2], optical packet switched networks (OPS) [3] and optical burst switched networks (OBS) [4].

In WRON the optical wavelengths are used to simplify switching in the optical domain. A wavelength can be thought of as a transparent end-to-end connection passing through several switches without any processing between ingress and egress nodes. Alternatively, the wavelengths can be used in an OPS network to obtain a multiplexing gain. With OPS the payload is transparently routed through the optical network according to information contained inside its optical header. Some OPS schemes route individual data units (usually Internet Protocol packets) while other schemes aggregate packets destined for the same egress node inside the payload. OBS networks are characterized by a higher level of packet aggregation and the control information is sent ahead of the payload inside a control-packet.

When digital data is routed through any of these networks the bit pattern will be distorted due to addition of noise along the optical path or due to imperfections in network equipment. This article will quantify the effect of physical impairments on end-to-end packet loss in future all-optical networks using bit-error rate (BER), packet-length distribution and network size as parameters. We also find analytical expressions for the performance gain involved when using 3R-regeneration [5] and functionality for locating bit-errors inside a payload.

The article is structured as follows. First we introduce our system model and state the necessary assumptions used in subsequent sections. Then we provide expressions for packet loss rate (PLR) due to physical impairments, compare these to other sources of packet loss and establish limits on the PLR based on quality-of-service (QoS) recommendations. Finally, we present graphs illustrating limits on BER and payload length for different networking schemes, as well as a numerical example quantifying the usefulness of error-limiting techniques.

2. System model

We consider a network consisting of optical switches interconnected by optical fibers. The expressions for end-to-end PLR are developed by considering the path of a packet being routed from its ingress node to its egress node in the network. Figure 1 represents an arbitrary end-to-end path Π_k in an optical network that traverses H+1 nodes from its source node to destination node, i.e. H hops. Since the path Π_k begins at the exit of the ingress router and ends at the entry of the egress router we only consider sources of packet loss in the optical path.

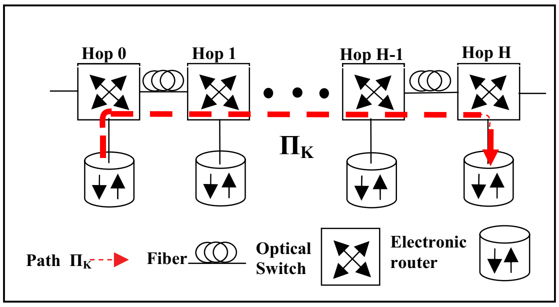

Figure 1. The optical burst/packet in the path Π_K may be corrupted during any of its H hops starting at the electronic ingress node and ending at the electronic egress node.

The three network types considered in this article (WRON/OPS/OBS) may transport Internet-Protocol (IP) packets in different ways. It is therefore useful to relate the different packet/burst lengths to potential networking schemes.

- A WRON may e.g. transport Ethernet frames of maximum 1518 bytes [6] which corresponds to $\approx 1.2 \cdot 10^4$ bits.
- One OPS scheme is described in [7] and uses a fixed slot of 1.35µs which fits $1.35 \cdot 10^4$ bits at a bit rate of 10 Gbps.
- For OBS the bursts can be several orders of magnitudes longer than OPS. One paper suggests 100µs as frame size for fixed sized bursts [8].

The packet/burst consists of a payload containing one or more IP-packets and it is associated with a packet-header or control-packet with information about the next or final destination. For simplicity we hereby refer to packet-header and control-packet using the term "control-field". Let the control-field contain C bits and let the payload consist of N IP-packets of length m_i, the index "i" ranging from 1 to N. M denotes the average packet-length, and the parameters related to the payload are linked by the following relation; $P = \sum m_i = N \cdot M$ bits. Total packet/burst length is L=C+P. Table 1 summarizes the notations used in this article.

Table 1. List of parameters used in article

Symbol	Symbol/parameter description
Π_K	Optical path where PLR is computed
PLR_T	Total packet loss rate (PLR) along Π_K
PLR_{PHY}	PLR due to physical impairments
H	Number of hops in path Π_K
m_i	Length of IP-packet labeled "i"
M	Average length of IP-packets m_i
P	Length of payload (fixed)
N	Average number of IP-packets inside the payload
C	Length of control-field
L	Total length of packet/burst. L = P+C
R_P	Number of regenerative points for payload along path Π_K
R_C	Number of regenerative points for control-field along path Π_K
BER	Bit error rate
B_P	BER for payload
B_C	BER for control-field
B	BER if $B_P=B_C$

3. Packet loss due to physical impairments

For both WRON and OPS/OBS, packets can be corrupted due to bit errors at the physical layer. We assume that there is a probability for a bit-error in every bit, and that bit-errors are independently and identically distributed. The PLR is computed for payloads of fixed size. Schemes for variable length payloads are not treated in this article and are identified as a subject for further study.

The number of lost packets caused by a single bit-error depends on two factors; detection of the error and the system's capability to locate it. For instance, when a bit-error occurs in the control-field it will cause the whole payload to be lost. But, for bit-errors in the payload this is not necessarily the case. If the system can locate the affected IP-packet it is possible to discard the damaged packet instead of the whole payload.

We study systems with three different types of error detection. (i) Errors are detected but not located. Detection of bit-errors can be performed using a cyclic redundancy check-sum contained e.g. in the control-field. (ii) Bit-errors are detected and located to the affected IP-packet and/or the control-field. One method to implement error locating code is to include one checksum per IP-packet inside the control-field. (iii) Bit-errors are detected and located to the affected bit thus enabling correction of the error. This can be implemented using forward error correction (FEC) which adds redundant information in the control-field and serves to reduce the system's BER. For instance, 7% redundancy applied to a 64 byte control-field will result in a dramatic reduction of its BER, e.g. from 10^{-4} to 10^{-15} [9].

In section 3.1 we develop an expression for PLR for systems with error detection only, and in 3.2 we give an expression for systems with the additional functionality of error location.

3.1 PLR due to physical impairments for systems without error locating code

Regardless of the regenerative method used, opto-electronic conversion or all-optical 3R-regeneration [5], there is a probability of misinterpreting the value of a bit. The probability for this event is given by the bit-error rate estimated between two regenerative points. Depending on the system under study, the number of regenerative points in the path Π_k may be superior or inferior to the number of nodes traversed by the packet/burst. For some networking schemes the number of regenerative points and BER may be different for payload and control-field. We denote B_C as the BER for the control-field and B_P as the BER for the payload. Similarly, R_P and R_C represent the respective number of regenerative points seen by the payload and control-field in the path Π_k. The chance of **not** observing one or more bit errors in the payload when traversing the path Π_k is given by (1), and similarly for the control-field in (2):

$$(1-B_P)^{R_P \cdot P} \tag{1}$$

$$\left(1-B_C\right)^{R_C \cdot C} \tag{2}$$

The probability of observing one or more bit errors in the payload or in the control-field is then:

$$PLR_{PHY} = 1-\left[\left(1-B_P\right)^{R_P \cdot P}\left(1-B_C\right)^{R_C \cdot C}\right] \tag{3}$$

Equation (3) is valid for all networking schemes studied in this article, but some restrictions apply.

- For OPS/OBS with electronic processing of the control-field there is necessarily 3R-regeneration of the control-field at each node such that $R_C \geq H$.
- For WRON architectures the control-field and the payload follows the same path through the OXCs, so $R_C = R_P$ and $B_P = B_C$.

One common regenerative strategy is to perform 3R-regeneration at each node for payload and control-field and to aim for $B_P = B_C$. Then (3) simplifies to the expression in (4):

$$PLR_{PHY} = 1-\left(1-B\right)^{L \cdot H} \cong L \cdot B \cdot H \tag{4}$$

where $B_P = B_C = B$. The approximation is found using the Taylor expansion to first degree, and deviates from the true value with less than 10% for $PLR_{PHY} < 10^{-1}$, i.e. for realistic values of B the packet loss rate is directly proportional to these parameters, cf. Figure 2.

3.2 PLR due to physical impairments for systems with error locating code

We use the same rationale as in section 3.1, but this time a bit error in the payload will only cause the affected IP-packet(s) to be discarded. This technique is therefore useful for networking schemes with a high degree of packet aggregation in the payload, e.g. OBS.

The PLR due to physical impairments is the average rate of packet loss in the payload plus N times the chance of having errors in the control-field. Again, considering 3R-regeneration at each node for payload and control-field we obtain

$$\begin{aligned} PLR_{PHY} &= \left\{1-(1-B)^{H \cdot C}\right\} \\ &\quad + \frac{1}{N} \cdot \sum_{i=1}^{N} \left\{1-\left(1-B\right)^{m_i \cdot H}\right\} \end{aligned} \tag{5}$$

This expression can be simplified with the Taylor series to first degree,

$$\begin{aligned} PLR_{PHY} &= B \cdot H \cdot C \\ &\quad + \frac{1}{N} \cdot B \cdot H \cdot \sum_{i=1}^{N} m_i \end{aligned} \tag{6}$$

$$\text{where,} \quad \sum_{i=1}^{N} m_i = P = N \cdot M \tag{7}$$

Substituting the sum in (6) with the expression in (7) gives the final result for PLR due to physical impairments with error locating code.

$$PLR_{PHY} = \left(1 + \frac{C}{M}\right) \cdot M \cdot B \cdot H \qquad (8)$$

If IP-packets were routed individually through the network we could set C = 0 and (8) would be equal to (4) with L = M. The first factor in (8) can then be viewed as expressing the penalty for using a control-field that might cause other packets to be lost.

From (8) and (4) we observe that a system with error-locating code performs better than a system uniquely based on error-detection as long as M < P, which always is true. The influence of C can be eliminated by adding FEC in the control-field. With a sufficiently low B_C after error-correction the first factor in (8) simplifies to unity. Equation (8) then compares to (4) and the performance gain is expressed by the ratio P / M. Figure 3 in section 6 discusses this in detail.

4. Unified view of packet loss at the network layer

Several sources of packet loss at the network layer have been extensively investigated and are well documented in literature. The most commonly encountered effects for OPS/OBS are contention of packets/bursts at the output port [10] and failure to configure the switch before arrival of the payload [11] [12]. For some WRON networking schemes one may encounter the situation where a lightpath request is rejected [13], possibly resulting in massive packet loss. Table 2 lists the mentioned sources of packet loss and where they might be encountered.

Table 2. Overview of various sources to packet loss in WRON and OPS/OBS

Source of packet loss	WRON	OPS/OBS
PLR due to BER	Yes	Yes
PLR due to rejected lightpath request	Yes	No
PLR due to contention	No	Yes
PLR due to early-arrival	No	Yes

In the following paragraph an analytic model for the total packet loss is developed using the following notation. We consider a network with S different sources of packet loss where P_j is the probability of losing a packet due to this particular effect at node indexed "j" being part of the path Π_k. PLR_i represents the chance of losing a packet along the path Π_k where the index "i" represents one specific source of packet loss and takes any natural number in the interval [1,S].

$$PLR_i = 1 - \prod_{\forall j \in \Pi_k} (1 - P_j) \qquad (9)$$

In order to clarify later discussions, we assume that P_j is identical all along the path Π_k, i.e:

$$PLR_i = 1 - (1 - P)^{H+1} \qquad (10)$$

When a packet/burst travels along its path Π_k there is a possibility of encountering more than one effect at a time, e.g. a packet with one or more bit errors being blocked due to contention. By considering each effect as an independent phenomenon this possibility is ignored and the total packet loss would be overestimated. For most practical cases however, as will be shown, each individual source of packet loss will be limited by QoS considerations to values well below 10^{-3}, a fact that effectively limits the chance of multiple faults. Using this approximation each source of packet loss can be treated independently and yields the following expression for the total network layer PLR:

$$PLR_T \cong \sum_{i=1}^{N} PLR_i \qquad (11)$$

One consequence of (11) is that PLR_T is restricted by the packet loss rate due to physical impairments, PLR_{PHY}.

$$PLR_T \geq PLR_{PHY} \qquad (12)$$

The practical implications related to (12) are discussed in section 6. However, first we define limits on PLR_T and PLR_{PHY} based on a QoS point of view.

5. Limits on packet loss due to quality of service requirements

Standardization organizations have suggested maximum limits on end-to-end PLR based on QoS considerations for different applications. For instance, the ITU-T recommendation Y.1541 defines six different classes of service, each service being characterized by different delay and packet loss requirements. Class 0 is the service putting the strictest demands on PLR, and specifies a maximum value for packet loss due to bit errors and another for the total packet loss rate, cf. Table 3. These values have been set to allow for satisfactory quality for IP-telephony and should be computed between the user network interfaces involved in the call. Our model accounts for the part of the network where the payload is transported in the optical domain and does not necessarily cover the stretch as defined above. The PLR due to bit errors computed for the path Π_k should therefore be limited to one tenth of the prescribed limit to allow for errors in uncovered domains.

Table 3. Estimated maximum allowable PLR for current and future Internet applications

Service	Measure	Measured between	Max PLR
IP-telephony	PLR_T	UNI-UNI	$< 10^{-3}$
IP-telephony	PLR_{PHY}	UNI-UNI	$< 10^{-4}$
IP-telephony	PLR_{PHY}	Path Π_k	$< 10^{-5}$
HDTV/Interactive games	PLR_T	Server-User	$< 10^{-5}$
HDTV/Interactive games	PLR_{PHY}	Path Π_k	$< 10^{-7}$

In the future, supporting real-time delivery of high-definition television (HDTV) and interactive games can become additional sources of income for Internet service providers. Following the same reasoning as above, an end-to-end $PLR_T < 10^{-5}$ [14] necessitates a value for PLR_{PHY} at least two orders of magnitude below this level.

The limits on PLR_{PHY} listed in Table 3 serves as examples of error-performance at lower layers and are therefore used as reference points for the plots presented in next section.

6. Graphical representation and discussion of results

In Figure 2 we plot packet loss rate due to bit-errors, named PLR_{PHY}, as function of BER with total packet/burst length L and number of hops H as parameters. The plots are derived from (4) which assume that the whole packet/burst will be discarded in presence of one or more bit-errors. Compared to the effects of BER and packet/burst length we observe a limited sensitivity regarding number of hops.

Since the majority of experimental studies and system designs aim for BER $\leq 10^{-12}$ [15], achieved with or without FEC, this is a point of interest on the graph. At this point $PLR_{PHY} \geq 10^{-10}$ irrespective of the networking scheme being used. Literature often presents PLR due to network layer effects in the order of 10^{-20} and below, e.g. [16], but according to (12) this will have no perceivable effect on the total PLR. We therefore argue that future research on network-layer effects in optical networks should be focused around or above this level.

When considering realistic values for network size and packet length, both WRON and OPS schemes at BER = 10^{-12} support even the toughest requirements on packet-loss. A system designed to support Class 0 traffic can accept bit-error rates approaching 10^{-9} without affecting the perceived quality of service for the end user. This puts less stringent demands on components and may lead to reduced capital expenditures and reduced operational expenditures of the system.

OBS of moderately long burst lengths also supports the limits on packet loss imposed by Class 0 services, but only at BER = 10^{-12}. However, at this BER we notice that PLR_{PHY} exceeds the upper limit for real-time high-quality broadcast. If this service is to be supported, either lower BER has to be achieved or we must reduce the effect of burst size by adding error-locating code in the control-field, cf. figure 3.

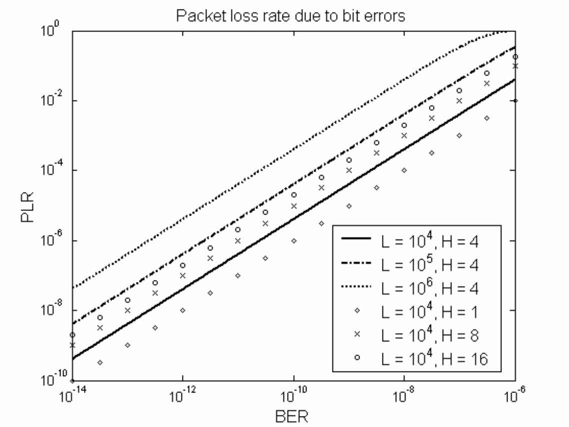

Figure 2. Packet loss due to physical impairments as function of BER for systems without error locating code in header/control-packet. 3R-regeneration is applied to payload and control-field at each node.

Plots in figure 3 are based upon equations (4) and (8). It is a comparison of PLR_{PHY} performance for network schemes with and without error-locating code in the control-field. The length of the control-field was set constant and equal to 64 bytes.

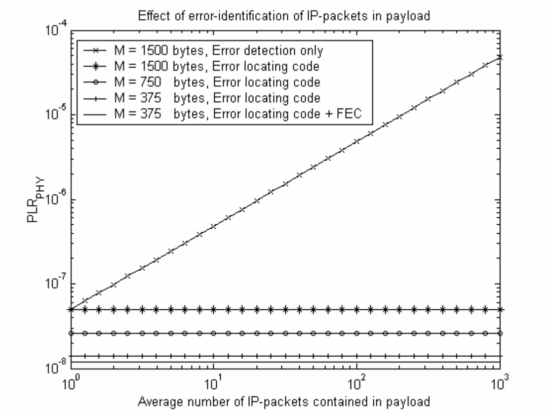

Figure 3. Comparison of PLR performance for OBS schemes with and without error-locating information in control-packet and for different average IP-packet lengths M. The burst size equals N times the average number of packets contained in the payload. For all plots C=64 bytes, BER=10^{-12} and H=4.

The upper curve illustrates that for a given average IP-packet length the system without error locating code is less effective than a system with error locating code. That is the price paid for reduced complexity.

The three middle plots use error-locating code in the control-field, each curve assumes a packet length distribution with mean M for the packets contained inside the payload. There is a clear performance difference with respect to average IP-packet length. This should not be surprising; a payload containing N long IP-packets will contain more bits than a payload with N smaller packets, hence higher PLR for the system carrying longer packets. M is significantly larger than C in the example above, thereby limiting the penalty involved when bit-errors occur in the control-field. However, for OPS systems carrying IP-packets of lengths that are similar to the control-field length, the packet loss rate will significantly increase.

Still using error locating code, but adding FEC to the control-field we can ignore the negative effect associated with bit errors in the control-field, cf. lower curve in figure 3. With regard to PLR_{PHY} it would be as if IP-packets contained in the payload were sent individually, i.e. replacing L in (4) with the average IP-packet length M.

Figure 4 shows possible values for payload length and BER when a given value of PLR_{PHY} is required.

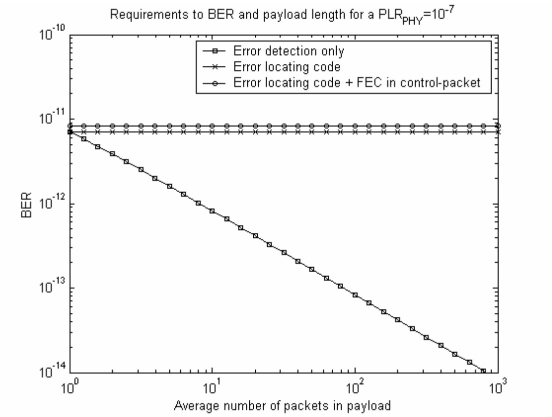

Figure 4. Targeted PLR_{PHY} =10^{-7}, the curves illustrate required BER and maximum number of packets inside the payload to achieve this. M=375 bytes =3000 bits, C=64 bytes =512 bits and H=4.

An example calculation illustrates the usefulness of error-locating code and FEC in the control-field. We assume a future OBS network aiming at supporting real-time HDTV with a limit on PLR_{PHY} around 10^{-7}. The payload size of this network is fixed to 10^6 bits and the mean length of the packets forming the burst is 375 bytes. For a path Π_K with H = 4 hops and only using error detection this requires a BER of $2.5 \cdot 10^{-14}$ to satisfy the limit on PLR_{PHY}. Such values for BER are difficult to achieve without applying FEC in the payload. To reduce the requirements on BER we can introduce error-locating code in the control-field. Solving (8) yields a maximum BER = $7.12 \cdot 10^{-12}$. With error-locating code and FEC in the control-field the maximum BER is further increased to $8.33 \cdot 10^{-12}$. Hence, FEC on the payload might not be necessary and the technological requirements on network equipment are reduced.

It should be remembered that the results were obtained assuming a relatively short control-field thereby yielding an important gain using error locating code. For OBS schemes with large bursts it is not necessarily trivial to achieve high gain, and efficient implementation of error locating code is required.

7. Conclusion

We derived analytical expressions for packet-loss rate due to bit errors in all-optical networks using bit-error rate, network size and packet-length distribution as variables. Assuming realistic network parameters we found that packet loss due to bit errors may be the dominant source of packet loss on the network layer.

We therefore investigated two methods capable of diminishing the effect of bit error rate on network performance, i.e. error-locating code and forward error-correction in the header/control-packet. Using error-locating code without any form of forward error correction the performance gain exceeded one order of magnitude for relatively long payloads. This was found true for a wide range of realistic packet-length distributions and network sizes. With the additional effect of error-correction we found the performance gain to increase by a factor two or more for systems carrying shorter payloads. We also showed that the performance gain of error-locating code is improved as the header/control-field length is reduced, thereby motivating research on efficient implementation of error-locating code. Finally, the analytical expressions in this article were derived for payloads of fixed length motivating further studies using variable payload length.

8. Acknowledgement

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9. References

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