Analysis of Blocking Probability in Noise and Crosstalk Impaired All-Optical Networks

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***Abstract*—In all-optical networks with no wavelength converters, signals are switched optically inside the nodes and therefore propagate over hundreds or thousands of kilometers with no electrical regeneration. Over such distances, physical impairments, such as intersymbol interference (ISI), amplifier noise, and leaks within nodes (crosstalk), accumulate and can lead to serious signal degradation, resulting in poor quality of transmission (QoT) as measured by signal bit-error rates. The role of Routing and Wavelength Assignment (RWA) algorithms is to accommodate incoming calls in optical networks over a route and a wavelength. RWA algorithms block calls if a continuous wavelength from source to destination cannot be found (wavelength blocking), or when the quality of transmission (QoT) of the call is not acceptable (QoT blocking). Evaluating RWA algorithms via simulations is possible but time consuming and hence analytical methods are needed. Wavelength blocking has been studied analytically in the past, but QoT blocking has never been analytically modeled. In this paper, we present an analytical method to evaluate blocking probability in all-optical networks, accounting for physical layer impairments. Our physical layer model includes ISI and noise, two static effects that only depend on the network topology, and also crosstalk, which depends on the network state. Simulations on three different topologies with various number of channels, representing small to large scale networks, show that our technique is suitable for quick and accurate dimensioning of all-optical networks: the accuracy of the blocking rates computed with the analytical method, taking only seconds or minutes to run, is the same as that of simulations, which take hours to run.**

***Index Terms*—Optical Networks, Routing and Wavelength Assignment, Physical impairments, Analytical Modeling.**

I. Introduction

All-optical networks have emerged as a solution to keep up with the always increasing throughput demand. In today's transport networks, data is transmitted over optical fibers and optical-electro-optical conversion is needed at the nodes to perform routing. These networks can achieve a throughput of up to several hundreds of Gbits/s using Wavelength Division Multiplexed (WDM) channels. Yet optical fibers have a potential capacity of several tens of terabits/s. Although, as noted in [2], all-optical connections are not currently common service offerings, they offer significant infrastructure benefits in their ability to reduce cost, space, and power dissipation. Even in the case of current/near-future all-optical networks, where some regeneration may be desirable, an architecture using "islands of transparency" has been proposed, whereby a large network is split into smaller fully transparent networks separated by electrical regenerators. Each smaller transparent optical network is called an "island of transparency" [3]. Deploying such all-optical, dynamic networks where calls arrive and must be provisioned on-demand in near real-time, is promising but also challenging and novel issues have to be anticipated at the physical layer. Indeed, while perfect transmission and negligible bit-error rates (BER) are valid assumptions for optical networks with electrical regeneration, large all-optical networks, with paths that can reach several hundreds or thousands of kilometers with no regeneration other than amplification, are impaired by non-negligible physical layer degradations [4], [5]. Some of these impairments depend on the instantaneous traffic, and hence cross-layer techniques are needed to study them.

The role of RWA algorithms is to assign a route and a wavelength — the combination of which is called a *lightpath* [6] — to incoming calls in a network, in order to satisfy an optimization goal, such as the minimization of the average call blocking probability in the network [7]. Since wavelength conversion is not yet mature for commercial deployment, a call in an all-optical network must use the same wavelength from source to destination, a constraint known as the *wavelength continuity constraint*. Failure to find a lightpath that meets the wavelength continuity constraint for an arriving call results in *wavelength blocking* for the call. Moreover, all-optical networks are subject to physical impairments that are static and depend on the network topology only, and to other physical impairments that are dynamic and vary with the network state. Static impairments include ISI caused by the interplay between linear (chromatic dispersion) and nonlinear (Self Phase Modulation, SPM) propagation effects on signals, as well as filtering at the receiver, and Amplified Spontaneous Emission (ASE) noise due to amplifiers [8], and causing signal OSNR reduction. Dynamic impairments include signal leaks within the nodes and that co-propagate from the node where the leak occurs until the end of the lightpath; these leaks are called crosstalk and are described in [9]. Because of these impairments, the Quality of Transmission (QoT) of lightpaths assigned to incoming calls, as measured by their BER, may be beyond a threshold set by the network operator (typically the BER threshold is set between 10^{-9} and 10^{-15}), depending

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on the network state. If, at admission time, the BER of a tentative lightpath assigned to a call is beyond the threshold, or if establishing the call would inject too much crosstalk and cause the BER of a lightpath already established in the system to cross the threshold, then the call cannot be accepted: it has to be rejected due to the *QoT constraint*, resulting in *QoT blocking*.

Evaluation by simulation of RWA for non-trivial network topologies such as general mesh topologies was done in [5], where the impact of each of the aforementioned impairments (ASE noise, chromatic dispersion/SPM interaction, node crosstalk) was shown to strongly impact call admission blocking rate, is a time-consuming process. For this reason, alternate analytical methods are needed. Although the problem of analytically computing blocking probability in all-optical networks has been studied in the past, using various models and assumptions, the physical layer has never been accounted for to this point in any analytical work. In this paper we present the first analytical method to evaluate QoT blocking in all-optical networks. The technique can be attached to any technique for calculating the wavelength blocking, which are numerous. In [10], a reduced load approximation scheme is developed and is applicable only to small networks due to its exponential computational complexity with the number of nodes in the network. Also, in [10], wavelength utilizations on different links are assumed to be independent. This independence assumption is oversimplifying, especially for sparse networks where nodal degree is low. The independence assumption is relaxed in [11]–[15]. However, other oversimplifying assumptions are made in [11]. The technique presented in [12], based on path decomposition, tackles fixed and alternate routing schemes, possibly with the presence of wavelength conversion in the network. In [13], the authors extend results from [15] and are able to determine the blocking due to outdated information in the network.

In [14], the problem of partial wavelength conversion is touched upon, and the wavelength blocking computation procedure is shown to be accurate for a variety of topologies. The iterative algorithm presented in [15] also yields very accurate results, while only making a two-link correlation assumption, that is, the wavelength utilization on a link of a given route depends only on that of the one previous or next link of the route. The wavelength blocking computation techniques presented in [14] and [15] are relatively simple and yield accurate results for large arbitrary topologies. To compute QoT blocking, our technique assumes that we can compute wavelength blocking for each route; however, our technique does not make assumptions on how this is done. For these reasons, and in order to demonstrate the independence of our algorithm with respect to wavelength blocking computation techniques, we use in turn those two different wavelength blocking computation algorithms [14], [15] to compute QoT blocking in arbitrary networks. We show that our technique can be easily and independently combined with each of these techniques, yielding similar numerical results.

In this paper, we tackle the problem of analytically computing blocking probabilities in networks subject to both wavelength blocking and QoT blocking caused by static (ISI, ASE noise) and dynamic (crosstalk) effects. The model is applicable to metropolitan and regional all-optical networks, and, for very large scale networks divided into "islands of transparency", to each of the islands. As in [14], [15], we consider a single instance of routing and wavelength assignment, namely, fixed routing where routing tables are precomputed and contain a single path between any two nodes, and random wavelength assignment. Indeed, as is seen in [7] for instance, the impact of wavelength assignment on network performance as measured by blocking probability is less than an order of magnitude. The goal of the paper is to present a fast algorithm that can be used to dimension the performance of a network, rather than computing exact blocking probabilities for specific RWA algorithms.

This paper is organized as follows. In Section II, we present our model and state the assumptions used throughout the paper. We present our technique to compute QoT blocking (including ISI, noise, and crosstalk) in Section III. In Section IV, we show how our QoT blocking algorithm integrates with a specific instance of wavelength blocking computation algorithm. Our technique is validated by simulations on various network topologies for realistic physical layer parameters and we present a time complexity analysis in Section V.

II. Network and crosstalk model

We present here our assumptions concerning the network, traffic, and crosstalk models used throughout this paper. In the all-optical networks modeled here, links represent unidirectional optical fibers. The number of wavelengths per link is fixed to a constant number C across the network and wavelength conversion is not available. Call durations are exponentially distributed with mean rate $M_{R(n_1,n_2)} = 1$ and call arrivals follow a Poisson process with mean rate $\Lambda_{R(n_1,n_2)}$ for route $R(n_1, n_2)$ from node n_1 to n_2. Since $M = 1$, the offered load in Erlang on a route R is Λ_R. Denoting by V the set of nodes in a network, the total offered load in Erlang in that network is $\sum_{\substack{n_1,n_2 \in V \\ n_1 \neq n_2}} \Lambda_{R(n_1,n_2)}$.

The physical layer and crosstalk in particular are modeled as follows. When a call is accepted in the network, it is assigned one lightpath, as shown in Fig. 1. Because of the physical impairments sustained by signals during their transmission on a lightpath, a signal may be too degraded at reception to ensure a minimal QoT as defined by the network operator. Denoting by μ_1 and μ_0 the means of the received "1" and "0" samples after electrical filtering and by σ_1 and σ_0 their respective standard deviations, the *Q factor* of a signal is defined as $Q = (\mu_1 - \mu_0)/(\sigma_0 + \sigma_1)$. Using a Gaussian assumption [8], the BER and the Q factor of a signal are related by $BER = 0.5\mathrm{erfc}\big(Q/\sqrt{2}\big)$ for uncoded on-off keyed (OOK) signals. For instance, a BER of 10^{-9} corresponds to a Q factor of $Q = 6$.

In this paper, we account for three main physical impairments that are known to affect lightpaths in all-optical networks [16]: intersymbol interference, amplifier noise, and crosstalk. Each of these effects is accounted for as a noise variance in the Q factor of the lightpath, that is, for a given

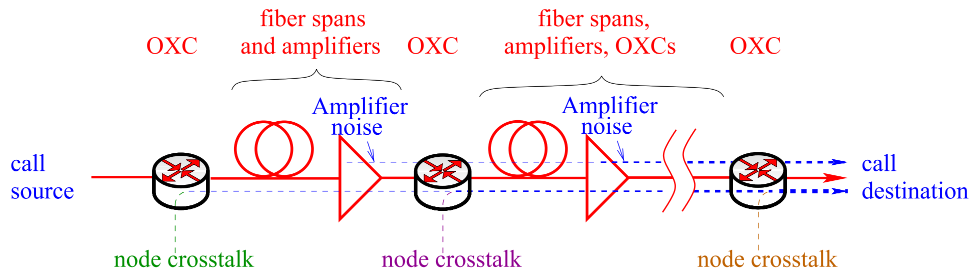

Fig. 1. Model of a transmission lightpath (plain line) used to compute the Q factor. Each node can inject one or more crosstalk components (dashed lines), and ASE noise can originate from each amplifier (dotted lines).

route R:

$$Q_R = \frac{\mu_{1,R} - \mu_{0,R}}{\sigma_{0,R} + \sigma_{1,R}} = \frac{\mu_{1,R} - \mu_{0,R}}{\sigma_{0,R} + \sqrt{\sigma_{i,R}^2 + \sigma_{n,R}^2 + \sigma_{X,R}^2}} \quad (1)$$

where $\sigma_{1,R} = \sqrt{\sigma_{i,R}^2 + \sigma_{n,R}^2 + \sigma_{X,R}^2}$, and $\sigma_{i,R}^2$, $\sigma_{n,R}^2$, and $\sigma_{X,R}^2$ are the variance contributions due to intersymbol interference, amplifier noise, and crosstalk, respectively. Here we make the (usual) assumption of a high transmitter extinction ratio, such that ASE noise and crosstalk impairments can be ignored for the "0" bits. In addition, we assume that all signals are in the same polarization state, a worst-case scenario typically used to design networks (see for instance [9] in the context of crosstalk modeling).

We introduced ISI and ASE noise in Section I as static effects. Node crosstalk originates from signal leaks in the nodes, either at the demultiplexing stage or inside the switching fabric. The model for the origin of crosstalk we use here, "self-crosstalk", was first detailed in [17], and we restate it here for clarity. In the "self-crosstalk" model, crosstalk is created by two lightpaths on different wavelengths entering an optical cross-connect (OXC) by the same (input) port and exiting the OXC on the same (output) port. Because of imperfections at the input demultiplexer, a small part of the signal of each lightpath leaks onto the other.

Contrary to ISI and ASE noise, crosstalk is a dynamic effect, depending on what lightpaths are established in the network. We compute $\sigma_{X,R}$ accounting for all crosstalk components on a lightpath by summing the variance contributions for each crosstalk term:

$$\sigma_{X,R}^2 = n\sigma_{x,R}^2, \quad (2)$$

where n is the number of crosstalk terms injected along route R and $\sigma_{x,R}^2$ is the variance contribution of each of these crosstalk signals, assuming these are all equal.

Other types of crosstalk, which were presented in [17], are ignored here. For instance, crosstalk due to leaks in the switching fabric is generally weaker than crosstalk originating from the demultiplexers. Also, we do not distinguish between crosstalk coming from adjacent or non-adjacent channels. This assumption is accurate when the demultiplexer frequency response is flat in the cut-off region. Our method can be easily generalized to more than just the crosstalk model described above. For instance, a small modification of how crosstalk components are counted permits the accounting for switching fabric crosstalk. Such a modification is useful in cases where the primary source of crosstalk is the switching fabric, in the case of non-MEMS switches for instance [18]. Furthermore, our analytical method can compute blocking probabilities if both demultiplexer and switching crosstalks are present in the case where both crosstalk attenuations are the same. If non-adjacent crosstalk is actually weaker than adjacent crosstalk, then our technique actually would result in over-dimensioning, as the weaker non-adjacent channel crosstalk components would then be on an equal footing with the stronger adjacent channel crosstalk. Because our technique takes *dynamic* effects into account, all in all it reduces the amount of over-dimensioning required at network design time.

In addition, although the work considers single channel nonlinear effects, namely, the interaction between SPM and chromatic dispersion, we do not account here for nonlinear interchannel effects (XPM, FWM), which could be limiting impairments in certain next-generation all-optical networks. This assumption, however, is valid for metro or regional networks where routes are not more than a few hundreds of kilometers, and where crosstalk is a major impairment [19].

III. Performance Analysis Under QoT Constraints

A. Overview

In this section, we assume that wavelength blocking probabilities are known, and we compute QoT blocking rates. More specifically, we compute the QoT blocking probability $B_R^{(q)}$ due to ISI, noise, and crosstalk blocking for every route R. Recall that a new call is blocked due to insufficient QoT if, at admission time, the Q factor of a tentative lightpath assigned to a call is beyond a predefined threshold, or if establishing the call would inject too much crosstalk and cause the Q factor of a lightpath already established in the system to cross the threshold.

To compute the blocking probability due to QoT, we first assume that the wavelength blocking probabilities $B_R^{(w)}$ are known and we determine the distribution of the number of crosstalk components XT_R that impair each route R in Section III-B. Then, we relate the blocking probability due to QoT to the crosstalk distributions in Section III-C.

The QoT computation algorithm is largely independent of the algorithm used to compute wavelength blockings $B_R^{(w)}$ for every route R. However, some algorithms, e.g. that presented in [15], rely on the computations of *conditional blocking probabilities*: let $B_{R|X_j=m}^{(w)}$ be the blocking probability due to lack of wavelength for route R given m wavelengths are

Algorithm 1 Blocking probability computation: main algorithm when **no** conditional blockings are used by the wavelength blocking computation algorithm.

Initialize $B_R^{(w)}$ for all R: using for instance [14].
Initialize $B_R^{(q)} = 0$ and $B_R = B_R^{(w)}$ for every route R.
repeat
  Let $\tilde{B}_R = B_R$.
  Compute $B_R^{(q)}$ for all R: using Equations (3), (4), (5), (6), (7), (8), as described in Sections III-B and III-C.
  Compute B_R for all R: using (9).
until $(B_R - \tilde{B}_R)/B_R < \epsilon$ for every route R

free on link j. We provide the necessary steps to interface with such algorithms as well in Section IV.

An overview of the algorithm used to compute blocking probabilities in all-optical networks with physical impairments is given in Alg. 1. In each case, the QoT blocking computation algorithm is iterative and stops when a convergence criterion (e.g., blocking rate difference for each route between two consecutive iterations lower than a preset threshold) is met.

Before we exhibit the details of the QoT blocking computation algorithm, we also make the following assumptions concerning the traffic model. These assumptions make analysis tractable and fast, yet approximate well the behavior of all-optical networks:

(A1) routing is fixed with no alternate paths and wavelength assignment is random pick, such that all wavelengths are statistically equivalent;
(A2) wavelength occupancies on disjoint routes are independent of each other;
(A3) the establishments of lightpaths on two different routes are independent events.

Assumptions (A1) and (A2) are made in other papers focusing on wavelength blocking, most notably, in [14], [15]. In particular, the wavelength equivalence assumption (A1) prevents the inclusion of cross-channel effects (XPM, FWM, differentiation between adjacent and non-adjacent crosstalk); the removal of this assumption is left for future work and this paper is applicable to cases where cross-channel effects are not limiting factors in the quality of transmission of signals. We would like to emphasize, however, this wavelength independence assumption can be mitigated; for instance accounting for XPM and FWM could be done by assuming a worst-case, static case, whereby all channels are in use, although this would result in network over-dimensioning. Hence, our technique could also be applicable to more general network scenarios than small or medium scale metro/regional networks, at the expense of the accuracy of the dimensioning. In addition, our analysis can be extended to the case of dynamic routing where the route is not dependent on network state, e.g., when probabilistically picking routes from a set of candidate, but analyzing state-dependent routing requires new methods. Assumption (A3) is used further in this work; numerical results show that the resulting approximations do not affect much the accuracy of the method.

In addition, we consider that the system is ergodic. The blocking probability for a route in a network is actually a time average (average of blockings per unit of time), but the analytical method computes ensemble averages (average of blockings over the set of possible network states). Therefore, the blocking probabilities we compute are equivalent to blocking rates. Moreover, event orders are not important to compute these rates. More specifically, in a real network, if call C_1 arrives and is blocked because establishing C_1 would cause the QoT of some other call C_2 already established to drop below the predefined threshold, then C_1 is rejected; in our analysis, since it is the QoT of C_2 that drops below threshold, C_2 is rejected. Averaging over all network states in the analysis yields the blocking rate in the real network. This ergodicity principle does not hold if more than 2 connections are involved simultaneously; for instance it could be argued that if C_1, C_2, C_3 arrive, C_1 can be established but C_2 and C_3 would drive the QoT of C_1 beyond threshold if they were established, and are hence blocked. Our analysis counts only the blocking of C_1 rather than the 2 blockings of C_2 and C_3, leading to a QoT blocking probability under-estimation. However, such very specific situations where 3 connections or more arrive almost concurrently and share the same resources, and where the QoT of one of them is close to the threshold are likely to be much less probable than the concurrent arrival of only 2 connections as described above, where ergodicity holds; hence the impact of this under-estimation can be expected to be limited, as will be seen with numerical results in Section V.

B. Distribution of the number of crosstalk terms

Denote by $U_R(k)$ the probability that $k = 0, \ldots, C$ calls are established on route R; $U_R(k)$ accounts only for calls that use *exactly* route R, not for calls that use only part of route R or that use a route that includes R. To determine the distribution U_R for each route R, using assumptions (A1) and (A2), we approximate U_R as a binomial random variable. Then, the utilization of a wavelength on some route R can be viewed as a Bernoulli trial with probability of success p_R, the probability that the corresponding call is established.[1] The probability that a call is established on route R is the per-wavelength arrival rate for calls on route R, multiplied by the probability that a call is actually accepted on R, that is:

$$p_R = \frac{\Lambda_R}{M_R} \frac{1 - B_R}{C} = \Lambda_R \frac{1 - B_R}{C} \tag{3}$$

since, with no loss of generality, the service rates M_R are assumed to be unity.

The probability that exactly k calls are established on route R is therefore:

$$U_R(k) \approx \binom{C}{k} p_R^k (1 - p_R)^{C-k}, k = 0, 1, \ldots, C. \tag{4}$$

Let $I_R^{xt} = \{R_1, \ldots, R_p\}$ be the set of the routes that are potential sources of crosstalk for lightpaths established on route R. The set I_R^{xt} is determined for each route R as follows.

Consider route R consisting of the sequence of s nodes $(r_1, \ldots, r_s)$. Consider a route R' consisting of the sequence

[1] The wavelengths statuses are statistically identical but not independent, hence the binomial distribution we use is an approximation.

of nodes $(r'_1, \ldots, r'_l)$. Route R' can inject self-crosstalk at node r_n ($n = 1, \ldots, s$) of R if the input ports for R and R' at node r_n are the same, or if the output ports for R and R' at node r_n are the same. That is, $R' \in I_R^{xt}$ when:

- $n = 1$ (if r_n is the first node of R): R and R' start with the same link, i.e., $(r_1, r_2) = (r'_1, r'_2)$. In this case, crosstalk occurs at the multiplexer used to add wavelengths to the network.
- $n = s$ (if i is the last node of R): R and R' end with the same link, i.e., $(r_{s-1}, r_s) = (r'_{l-1}, r'_l)$.
- $1 < n < s$ (the other cases): R and R' share two consecutive links separated by node r_n, i.e., there exists $v \in \{2, \ldots, \min(s-1, l-1)\}$ such that $(r_{n-1}, r_n, r_{n+1}) = (r'_{v-1}, r'_v, r'_{v+1})$.

Call $n_{xt}(R, R')$ the number of common nodes between routes R and R' where crosstalk can occur. Suppose k lightpaths use exactly route R', that is, those k lightpaths are not using only a part of route R' nor are they using a route that includes R'. Then, the number of crosstalk components injected by R' on R is $kn_{xt}(R, R')$. Calling $U'_{R,R'}(k')$ the probability that some route R' injects k' crosstalk components on route R, we therefore obtain:

$$U'_{R,R'}(kn_{xt}(R, R')) = U_{R'}(k). \tag{5}$$

Let $XT_R(k)$ be the probability that route R is subject to exactly k crosstalk components. The total number of crosstalk components k seen by route R is the sum of all crosstalk components injected at each node of R by all routes that intersect R. Using assumption (A3), the probabilities for establishing lightpaths on different routes are independent such that $U'_{R,R'}$ describe independent random variables. Therefore, $*$ denoting the convolution operator, and with $I_R^{xt} = \{R_1, \ldots, R_p\}$, the distribution of XT_R can be computed as follows:

$$XT_R = U'_{R,R_1} * \ldots * U'_{R,R_p}. \tag{6}$$

C. Blocking probability due to QoT

In this section, we exhibit the relation between the physical layer (impact of crosstalk on QoT) and the network layer (distribution of the number of crosstalk components). Assuming that physical layer impairments are due to ISI, noise and self-crosstalk only, the Q factor Q_R for a route R is given in (1).

Using the techniques described in [19], we can precompute $\mu_{1,R}$, $\mu_{0,R}$, $\sigma_{0,R}$, $\sigma_{i,R}$ and $\sigma_{x,R}$ for all routes in the network. Since the quantities $\mu_{1,R}$, $\mu_{0,R}$, $\sigma_{0,R}$, $\sigma_{i,R}$ and $\sigma_{x,R}$ are known for each route in the network, we can compute the maximum number of crosstalk components $N_R^{\max}$ a route R can accommodate to maintain a Q factor above a predetermined threshold Q_{th} using (1) and (2):

$$N_R^{\max} = \left\lfloor \frac{\left(\frac{\mu_1 - \mu_0}{Q_{th}} - \sigma_{0,R}\right)^2 - \sigma_{i,R}^2 - \sigma_{n,R}^2}{\sigma_{x,R}^2} \right\rfloor. \tag{7}$$

Therefore, the probability that a lightpath is blocked because it does not meet the QoT constraint is the probability that this lightpath is subject to $N_R^{\max}$ crosstalk components or more, that is:

$$B_R^{(q)} = \sum_{k > N_R^{\max}} XT_R(k). \tag{8}$$

The blocking probabilities due to wavelength continuity and due to QoT are related by:

$$B_R = B_R^{(w)} + (1 - B_R^{(w)}) B_R^{(q)}. \tag{9}$$

Indeed, a call can be blocked due to QoT only if a wavelength is available on the route the call is assigned, that is, when the call is not blocked due to the wavelength continuity constraint.

IV. Integration with a Wavelength Blocking Analytical Model Requiring Conditional Probabilities Computations

Our QoT blocking analytical model is general and can be adapted to various wavelength blocking analytical models. In the previous section, we described how to compute QoT blocking in all-optical networks, assuming that wavelength blockings $B_R^{(w)}$ are known. The integration of our QoT computation techniques with certain wavelength blocking computation algorithms, such as that of [14], is straightforward, as is seen in Alg. 1. However, certain wavelength blocking computation algorithms, such as that of [15], are more complex to integrate with our QoT computation technique because a) the wavelength blocking algorithms itself is iterative, rather than sequential; and b) it relies on the computation of wavelength blockings conditioned on the number of free wavelengths on a given link: $B_{R|X_j=m}$, which in turn depend on QoT conditional blockings ($B_{R|X_j=m}^{(q)}$).

A. Overview of the integration

Now consider the model described in [15]. This model makes the following assumptions, in addition to the assumptions already outlined in Section II:

- given m wavelengths are free on link j, the time until a call that uses j arrives is assumed to be exponentially distributed [20], such that the number of free wavelengths on link j is modeled as a *birth-death process*;
- the state of wavelength i on link j of a route R is independent of the state of some other wavelength $k \neq i$ on the previous link $j-1$ on the same route, given the state of wavelength i on link $j-1$ or given the state of wavelength k on link j (a two-link correlation assumption).

Unlike the algorithm proposed in [14], the wavelength blocking algorithm proposed in [15] is iterative. It is articulated around the computation of the state-dependent arrival rates $\alpha_j(m)$; assuming $\alpha_j(m)$ is known, a number of quantities are computed, ultimately leading to the computations of $B_R^{(w)}$ and $B_{R|X_j=m}^{(w)}$, and to the update of the $\alpha_j(m)$, which depend on $B_{R|X_j=m}^{(w)}$. The process is repeated until both $B_R^{(w)}$ and $B_{R|X_j=m}^{(w)}$ satisfy a convergence criterion for each route R, each link j and each number of wavelengths m.

Therefore, we combine the wavelength computation algorithm with QoT blocking computation technique as shown in Alg. 2 and in Fig. 2. The $\alpha_j(m)$ are initialized and we obtain $B_R^{(w)}$ and $B_{R|X_j=m}^{(w)}$ using [15]; we use these as inputs to out technique to obtain $B_R^{(q)}$ and $B_{R|X_j=m}^{(q)}$, and hence B_R and $B_{R|X_j=m}$; then the $\alpha_j(m)$ are updated and the loop repeats until convergence of the quantities B_R and $B_{R|X_j=m}$ for each route R.

B. State-dependent arrival rates

We now show how to compute the conditional blockings $B_{R|X_j=m}^{(q)}$, which are needed to compute the blockings $B_{R|X_j=m}$ in [15].

In [15], state-dependent arrival rates $\alpha_j(m)$ are defined as:

$$\alpha_j(m) = \sum_{R:j\in R} \Lambda_R \left(1 - B_{R|X_j=m}\right), \tag{10}$$

where $B_{R|X_j=m}$ are blocking probabilities conditioned on the number of free wavelengths on a given link. We show here how these conditional blocking probabilities $B_{R|X_j=m}$ should be updated to account for (conditional) QoT blocking.

Similarly to (9), the total conditional blocking probabilities depend on the conditional blocking probabilities due to QoT:

$$B_{R|X_j=m} = B_{R|X_j=m}^{(w)} + \left(1 - B_{R|X_j=m}^{(w)}\right) B_{R|X_j=m}^{(q)}. \tag{11}$$

We now determine the conditional probabilities $B_{R|X_j=m}^{(q)}$, which are needed to compute the state-dependent arrival rates $\alpha_j(m)$ through (10) and (11). First, we compute the probability $p_{R|X_j=m}$ that a given lightpath is established on route R given m wavelengths are free on link j, and the probability $U_{R|X_j=m}(k)$ that R is used by exactly k lightpaths given m wavelengths are free on link j.

If j is not a link of R, then $p_{R|X_j=m} = p_R$ and $U_{R|X_j=m} = U_R$. If j is a link of R then at most m wavelengths are free on R. Consider the case where j is a link of route R. The probability that a given lightpath is established on route R given m wavelengths are free on link j is now:

$$p_{R|X_j=m} = \frac{\Lambda_R}{M_R}\frac{1 - B_{R|X_j=m}}{C} = \Lambda_R \frac{1 - B_{R|X_j=m}}{C} \tag{12}$$

since $M_R = 1$ for each route R.

We adapt (4) accounting for the fact that m, not C, wavelengths at most can be used by a lightpath on R:

$$U_{R|X_j=m}(k) \approx \begin{cases} \binom{m}{k} \left(p_{R|X_j=m}\right)^k \left(1 - p_{R|X_j=m}\right)^{m-k} \\ \qquad\qquad\qquad \text{if } k = 0, \ldots, m, \\ 0 \qquad\qquad\quad \text{if } k = m+1, \ldots, C. \end{cases} \tag{13}$$

The probability that route R' injects k crosstalk components of route R, given m wavelengths are free on j, follows from (5):

$$U'_{R,R'|X_j=m}(kn_{xt}(R,R')) = U_{R|X_j=m}(k). \tag{14}$$

The distribution of XT_R given m wavelengths are free on R is:

$$XT_{R|X_j=m} = U'_{R,R_1|X_j=m} * \ldots * U'_{R,R_p|X_j=m}, \tag{15}$$

Algorithm 2 Blocking probability computation: main algorithm when conditional blockings are used by the wavelength blocking computation algorithm.

Initialize $B_R^{(w)} = B_R^{(q)} = B_R = 0$ for every route R.
Initialize $\alpha_j(m) = \Lambda_R \cdot$ (number of routes using link j), $\alpha_j(0) = 0$ for every route R, every link j, every wavelength count $0 < m \le C$.
repeat
  Let $\tilde{B}_R = B_R$.
  Compute $B_R^{(w)}$ for all R: using for instance [15].
  Compute $B_{R|X_j=m}^{(w)}$ for all R, j, m.
  Compute $B_R^{(q)}$ for all R: using Equations (3), (4), (5), (6), (7), (8) as described in Sections III-B and III-C.
  Compute $B_{R|X_j=m}^{(q)}$ for all R, j, m: using Equations (12), (13), (14), (15), (16), as described in Section IV-B.
  Compute $B_{R|X_j=m}$ for all R, j, m: using (11).
  Compute B_R for all R: using (9).
  Compute $\alpha_j(m)$ for all R, j, m: using (10).
until $(B_R - \tilde{B}_R)/B_R < \epsilon$ for every route R

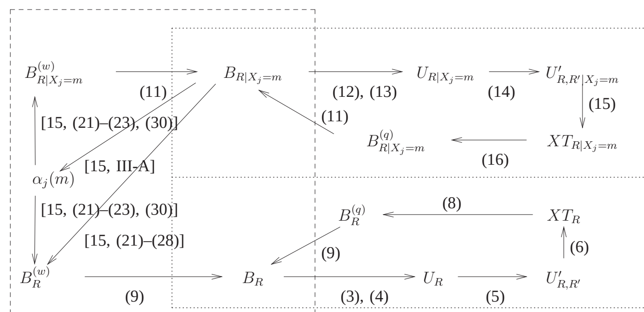

Fig. 2. Iterative algorithm to compute blocking probability of an all-optical network using the wavelength blocking probability computations algorithm described in [15] (dashed box), which requires the computations of state-dependent arrival rates. Our extensions to compute the blocking probability due to QoT are in the dotted boxes. The edges are labeled by the corresponding equation numbers in the body of this paper, or in [15] when indicated.

and the blocking probability due to QoT conditioned on the state of link j is:

$$B_{R|X_j=m}^{(q)} = \sum_{k > N_R^{\max}} XT_{R|X_j=m}(k). \tag{16}$$

The state dependent arrival rates $\alpha_j(m)$, which depend on $B_{R|X_j=m}^{(q)}$, can then be updated, using (11), (16), and for instance [15, Section III-A].

V. Performance

A. Validation by simulation results

In this section, we evaluate our analytical model for blocking probability in all-optical networks impaired by crosstalk. Evaluation is performed on three different topologies of increasing complexity: a ring of 6 nodes, a mesh of 8 nodes (Fig. 3), and the NSFNET topology (Fig. 4). The physical parameters are chosen to emulate regional-sized networks; in particular, as in [5], we scaled down the length of each link of the originally continental-sized NSFNET network by a factor of 10 in order to obtain a fully transparent topology with a diameter of a few hundred kilometers, where the shortest path between any two nodes is short enough such that any node can be reached (without regeneration) from any other node. Unless otherwise stated, we used the parameters given in Table I. Let B, $B^{(w)}$, and $B^{(q)}$ be the mean (taken over the set of the node pairs) blocking probability, blocking probability due to the wavelength continuity constraint, and blocking probability due to QoT, respectively. The analytical results are obtained by stopping the iterative algorithm when the difference for the blocking probabilities between two successive iterations differ by less than 1% for each route. The simulation results are obtained by simulating the routing and wavelength assignment of 10^5 calls. We use separate counters to determine blocking due to wavelength and due to QoT to compute B_w, B_q, and B using (9). Each data point is obtained by repeating this process 10 times in order to compute 95% confidence intervals, which are shown on the plots.

Similar to the analysis, simulations use precomputed tables to compute Q factors; however, in the simulation, we consider that crosstalk is propagated from the node where the leak occurs to the end of the considered lightpath, while in the analysis we assume that crosstalk is propagated on the whole considered lightpath, irrespective of where the leak occurs, as can be seen in (2). With the physical parameters given in Table I, it can be shown that the crosstalk variance decreases slowly with the propagation distance [19]; therefore, our analytical method tends to underestimate crosstalk variances by assuming longer propagation distances, and hence to underestimate QoT blocking.

We first present results for the ring of 6 nodes topology with 32 wavelengths per link ($C = 32$) in Fig. 5. For this set of parameters, blocking probability due to wavelength continuity is several orders of magnitude lower than that due to QoT, and therefore $B^{(q)} \approx B$. Our technique estimates accurately blocking probability in a wide operation range (blocking probabilities varying over 4 orders of magnitude). Notice here that, since $B_w \ll B_q$ for all routes, in practice our technique does not rely at all on any underlying wavelength blocking computation technique for the set of parameters utilized here. The two techniques described in Section IV yield identical results.

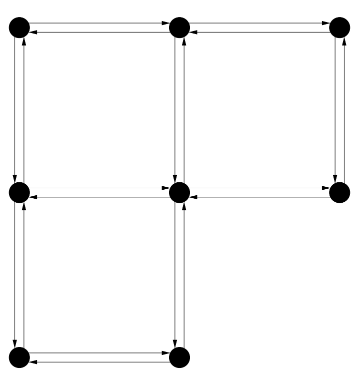

Fig. 3. Mesh of 8 nodes. Each link is a span of 70-km of fiber.

In Fig. 6, we show the blocking probability due to QoT for the mesh of 8 nodes with 16 wavelengths ($C = 16$) for 2 levels of crosstalk: -25 dB and -30 dB. Again, in this case, blocking probability due to wavelength continuity is very small compared to that due to QoT and hence we do not report it. Therefore, the choice of underlying wavelength continuity computation algorithm does not impact on the QoT computations here, since wavelength blocking is negligible compared with QoT blocking.

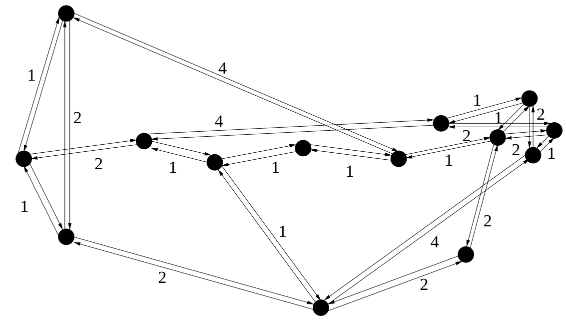

Fig. 4. Down-scaled version of the NSFNET topology (scaling factor: 1/10). In the figure, the weights represent the number of 70-km long spans for the links.

TABLE I
PHYSICAL PARAMETERS FOR THE SIMULATED NETWORKS.

Description	Value
Span length	70 km
Signal peak power	2 mW
Bit rate	10 Gbps
Pulse shape	Super-Gaussian NRZ
Port crosstalk	-30 dB
WDM grid spacing	25 GHz
Optical filters bandwidth	25 GHz
Fiber loss	0.22 dB/km
Nonlinear coefficient	2.2 (W km)$^{-1}$
Chromatic dispersion	17 ps/nm/km
Dispersion compensation	100% post-compensation
Noise figure	6 dB
Receiver electrical bandwidth	7 GHz
Minimum Q factor	6

We define the gain in load of a network as follows: given a target blocking probability B_t, a reference crosstalk level η_r, and a crosstalk level η, the gain in load for crosstalk level η is the ratio between the offered network load such that the total blocking probability in the network for crosstalk level η is B_t, and the offered network load such that the call blocking probability in the network for crosstalk level η_r is B_t. It can be seen in Table II, which was obtained using our analytical method, and where B_t was fixed to 0.001 and η_r to -25 dB, that crosstalk level has a dramatic influence on the admissible load in the network. For instance, if crosstalk level drops by only 5 dB from -25 dB to -30 dB, then the network can be loaded 16 times more while still achieving a 0.001 average total blocking probability.

In Fig. 7, we report blocking probability for the scaled NSFNET topology with 16 wavelengths ($C = 16$). Again $B^{(w)}$ is negligible compared to $B^{(q)}$ and we report $B^{(q)}$ only. Our model is very accurate over more than 3 orders of magnitude in terms of blocking probability.

Figs. 8 and 9 depict the scenario where the number of

TABLE II
GAIN IN LOAD (WITH RESPECT TO THE -25 dB CROSSTALK LEVEL CASE) FOR THE MESH NETWORK OF 8 NODES FOR A TARGET BLOCKING PROBABILITY OF 10^{-3}.

Crosstalk (dB)	25	26	27	28	29	30
Gain in load	1	2.1	3.8	5.9	10.1	15.9

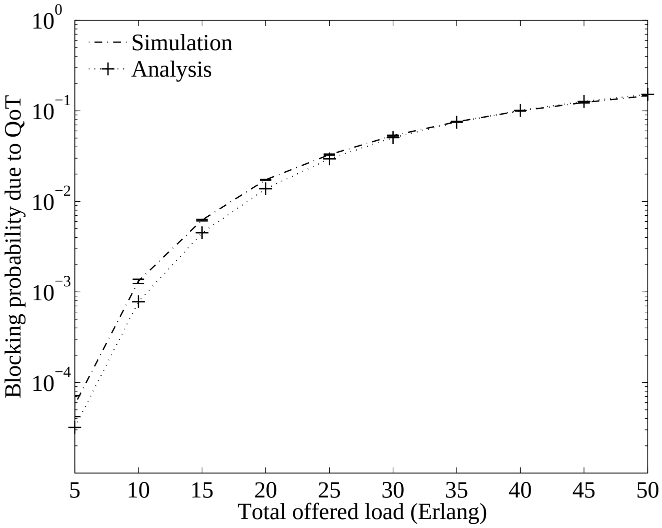

Fig. 5. Blocking probability for the ring of 6 nodes, 32 wavelengths, -30 dB crosstalk; 95% confidence intervals are given for the simulation curve.

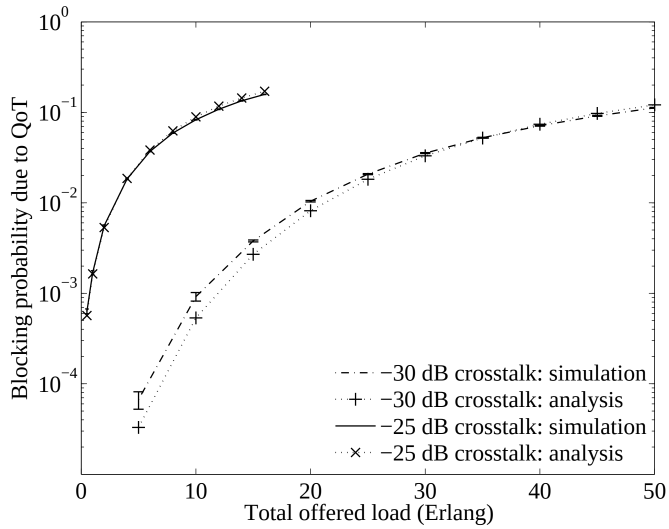

Fig. 6. Blocking probability for the mesh of 8 nodes, 16 wavelengths, -25 dB and -30 dB crosstalk; 95% confidence intervals are given for the simulation curve.

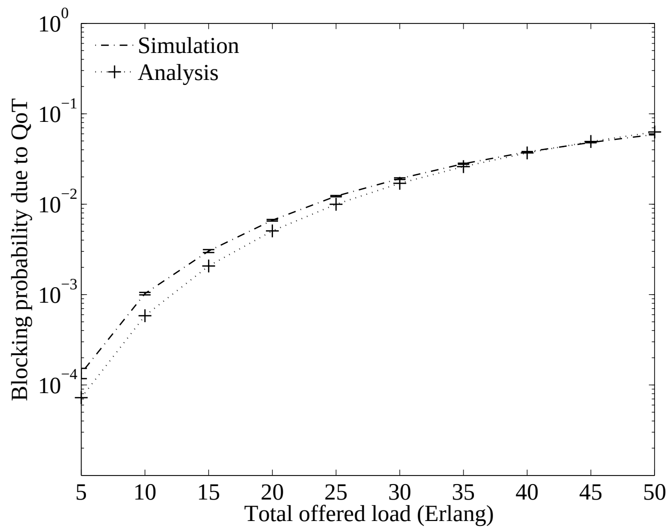

Fig. 7. Blocking probability for the NSFNET topology, 16 wavelengths, -30 dB crosstalk; 95% confidence intervals are given for the simulation curve.

wavelengths is 8 ($C = 8$) instead of 16. Here, blocking due to wavelength continuity is not negligible. Fig. 8 assumes that the underlying wavelength blocking model is that of [14] while Fig. 9 assumes that the underlying wavelength blocking model is that of [15]. In each figure, we report total blocking probability, as well as blocking probabilities due to wavelength continuity and due to QoT. The wavelength blocking probabilities returned by the two underlying wavelength blocking computing algorithms are very close one from another, with results obtained with the wavelength blocking model from [15] slightly more accurate than those obtained with the model from [14]. As a consequence, QoT and overall blocking rates obtained analytically in Fig. 9 obtained with the model from [15] are also slightly more accurate than those in Fig. 8 obtained with the model from [14], especially for the higher load values. However, this accuracy advantage comes at a computational complexity cost, as explained in Section V-B. In either case, for loads lower than 30 Erlangs, QoT blocking dominates wavelength blocking, and the converse is true for loads above 30 Erlangs. Our analytical results predict this behavior accurately.

B. Computational complexity

We determine here the computational complexity of our technique for one iteration of the algorithm. Because our algorithm relies on another algorithm to provide wavelength blocking probabilities, we perform a complexity analysis for each of the wavelength blocking algorithms outlined above. In practice, the algorithm runs through just a few iterations before the blocking probabilities converge and the algorithm terminates. Denote by N the number of nodes in the network, L the number of links, A the maximum number of nodes on a route, D the maximum number of routes intersecting any given route ($D = \max_R |I_R^{xt}|$), C the number of wavelengths. The number of routes is $N(N-1) = O(N^2)$.

Consider first the combination of our QoT blocking computations with the wavelength blocking computations of [14]. In this case, QoT computations dominate the time complexity; more specifically, the evaluation of the multiple convolutions in (6) is $O(N^2(AC)^D D \log(AC))$. This is also the complexity of the overall blocking probability computation algorithm.

Consider now the combination of our model with the wavelength blocking algorithm presented in [15].

Computation of $B_R^{(w)}$*:* it can be shown that the time complexity needed to compute all $B_R^{(w)}$ as in [15] is $O(N^2CA(N^2 + C^2L))$.

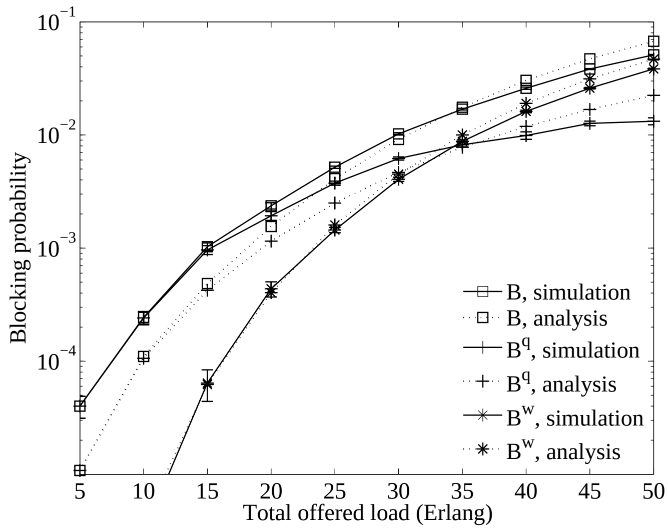

Fig. 8. Blocking probability for the NSFNET topology, 8 wavelengths, -30 dB crosstalk; 95% confidence intervals are given for the simulation curve. Underlying wavelength blocking algorithm from [14].

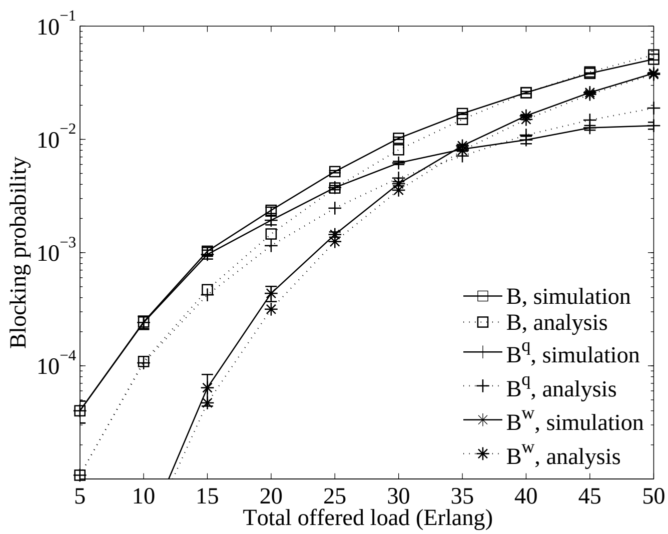

Fig. 9. Blocking probability for the NSFNET topology, 8 wavelengths, -30 dB crosstalk; 95% confidence intervals are given for the simulation curve. Underlying wavelength blocking algorithm from [15].

Computation of $B_R^{(q)}$*:* the statistics required to compute the Q factors are precomputed. The complexity of the computations that lead to $B_R^{(q)}$ is dominated by the computations of (15). Each $U'_{R,R'|X_j=m}$ can be represented as a vector of at most AC elements. To compute each $XT_{R|X_j=m}$, we need to convolve at most D of these vectors, which can be done in time $O((AC)^D D \log(AC))$ using FFTs. The time complexity of (15) and thus of our extensions is $O(N^2LC(AC)^D D \log(AC))$. The time complexity of the full algorithm is hence $O(N^2C(A(N^2 + C^2L) + L(AC)^D D \log(AC)))$. Notice here that, because of the conditionals computations, the QoT computations are a factor LC more complex if the underlying wavelength blocking model is [15] rather than [14]. Also, when used in conjunction with [15], the time complexity of our technique is not dominated by QoT blocking computations: both wavelength and QoT blocking have an impact on the overall computational complexity.

On comparable hardware, computing blocking probabilities through simulations typically took several hours, while analysis took only a few minutes at most — a gain of one to three orders of magnitude in running time.

VI. Conclusions and Future Work

We presented an iterative technique to compute the blocking probability in all-optical networks impaired by ISI, noise, and channel crosstalk. Starting from published methods that compute blocking probability due to wavelength continuity only, we were able to compute blocking probability due to QoT. Our technique was evaluated on various topologies for realistic physical layer parameters and shown to closely match simulation results. Our technique can be used to predict impact of physical impairments on the network behavior in terms of lightpath rejection rate, and hence to dimension medium or large-scale all-optical networks.

This paper is the first work to analytically model blocking behavior of all-optical networks subject to Quality of Transmission impairments; however, the technique relies on several restrictive assumptions, in particular, fixed routing and first fit routing. The authors believe that, although changing the routing or wavelength assignment schemes does impact blocking rate, and in particular wavelength blocking rate, the technique developed in this paper is sufficient for quick dimensioning of all-optical networks. In addition, our technique is independent of the algorithm used to compute wavelength blocking, and can be extended to account for different routing schemes (e.g., fixed alternate routing is investigated in [15] for wavelength blocking modeling) and more crosstalk models; however, differentiating between adjacent and non-adjacent channel crosstalk requires the removal of a key assumption, namely, equivalence of wavelengths in the system, and is left for future work. Although our model is applicable to the "island of transparency" architecture for very large, continental all-optical networks, it does not account for other architectures with sparse regeneration. In addition, the wavelength equivalence assumption does not allow the inclusion of interchannel effects (XPM, FWM), which could be limiting impairments in certain next-generation all-optical networks. Finally, Polarization Mode Dispersion (PMD), which will be a major impairment in future, very high speed optical networks, is a statistical impairment of a different nature than ISI, ASE noise and crosstalk, and hence needs to be studied separately.

Acknowledgment

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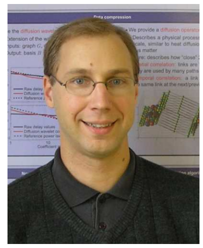

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