SIMTON: A Simulator for Transparent Optical Networks

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***Abstract*—In this article we present a software to simulate Transparent Optical Networks (SIMTON). SIMTON is an event-driven simulation software implemented in C++ which takes into account optical device characteristics for the evaluation of network blocking probability in wavelength routed transparent optical networks. The simulator uses a physical layer model that considers the following effects: device losses, fiber attenuation, four wave mixing, residual chromatic dispersion and polarization mode dispersion in optical fibers, gain saturation in optical amplifiers (Erbium Doped Fiber Amplifier), dependence of the amplified spontaneous emission noise with the input power in EDFA, in-band crosstalk in optical switches, and source spontaneous emission noise of the laser transmitter. By using SIMTON it is possible to adjust the parameters of the optical devices, as well as to choose the routing and wavelength assignment algorithm. Moreover, the tool has a graphical interface. We also present some examples of network analysis results obtained from SIMTON.**

I. Introduction

Optical networks are currently the most used technology by the telecommunications carriers for the implementation of their backbones. The main reason for this is that the optical communications systems offer, at the same time, the possibility to expand the transmission capacity allied to a high availability and reliability [1], [2].

The optical networks can be classified in three categories: opaque, all-optical and translucent networks [3]. In the opaque networks, the optical layer is used only for transmission. All network operations, such as switching and management, are carried out by electronic circuits. In these networks, at each network node along the lightpath, the optical signal undergoes optical-electronic-optical (O/E/O) conversions [4]. On the other hand, in all-optical networks the optical signal propagates along the network, from the source node to the destination node, in the optical domain without experiencing O/E/O conversions [4]. The translucent networks are optical networks that use the concept of islands of transparency. These networks are divided in many transparent islands and these islands are interconnected by electronic regenerators [3].

Although the all-optical networks are less expensive than the opaque ones, in these networks there is no signal regeneration along the lightpaths. Thus, the signal is degraded during transmission, and the quality of transmission of the lightpath can not reach acceptable levels (*e. g.* leading to a high bit error rate) [5]. Therefore, for the implementation of such networks, it becomes necessary to estimate the degradation of the optical signal along the possible lightpaths [5]. In order to estimate the impacts of signal degradation in the optical layer, three strategies can be adopted: the use of numerical calculations for wave propagation in optical fibers and devices (numerical solution), the implementation of an optical testbed (experimental solution) or the use computers to simulate the network operation. Despite being very accurate, the first one is impracticable for large networks evaluation due to the high computational complexity of the problem, specially if the target is to assess the dynamic behavior of the network. The second option is particularly expensive due to the high cost of the optical devices deployed in the networks. As a good alternative, the network designers can use computational simulations with simplified analytical models. Using these models, it is possible for a simulator to test, compare and evaluate the performance of devices, algorithms, protocols and topologies used in the network.

Following the third strategy (the simulation idea), some simulators of optical networks have been developed. These tools can be divided in two groups. In the first group, the tools do not consider the degradation of the signal in the optical layer, which means that they can only be applied to opaque networks. In this first group the following projects can be listed: OWNS [6] (extension of the Network Simulator [7]), OPNET [8], NIST Merlin [9], and TONetS [10]. In the second group, the tools take into account the degradation of the signal quality in the optical layer along the optical signal propagation process, and for this reason, they are able to simulate the behavior of transparent all-optical networks. The simulator SIMON [11] is classified in this group and considers the effects of attenuation of the optical signal in optical fibers and in other devices, gain saturation in optical amplifiers and in-band crosstalk in the optical switches.

The simulation tool presented in this paper (SIMTON) considers, in addition to the effects considered by SIMON, the following optical layer impairments: polarization mode dispersion (PMD), residual chromatic dispersion (RCD), four wave mixing (FWM) and the dependence of amplified spontaneous emission noise (ASE) with the Erbium doped fiber amplifier (EDFA) input optical power [12], [13].

This paper is organized as follows: in Section II we declare the SIMTON implementation assumptions; in Section III we show the SIMTON graphical interface; in Section IV we present the statistical analysis of the simulator, in Section V we list its cases of use; in Section VI we show some examples of simulation results and, finally; in Section VII we give our conclusion.

II. Implementation Assumptions

The simulation tool allows one to adjust the parameters of the optical devices, as well as choosing the routing and wavelength assignment (RWA) algorithm to be used in the simulation. SIMTON was implemented in C++ programming language and was divided in two modules: the simulator of optical network and the graphical user interface (GUI).

In this Section some aspects considered in the implementation of SIMTON are shown.

A. Physical Layer

The physical layer of the network is composed by optical devices such as optical amplifier and optical switches. Moreover, an optical network is represented by a set of nodes and a set of links interconnecting the nodes. SIMTON assumes that a pair of optical fibers is deployed in each link, one for transmission and the other for reception. Thus, each fiber has an unidirectional traffic. In SIMTON, each connection is established in a bidirectional way. Despite we have assumed this, it is easy to set an unique fiber for transmission and reception.

This first version of SIMTON does not support the wavelength conversion capability in the nodes along the ligthpaths. Therefore, each connection is carried out in the same wavelength from the source to the destination node. SIMTON uses an optical circuit switching approach. The optical amplifiers gains can be easily adjusted to exactly compensate for the total link losses.

The link architecture and optical devices assumed by SIMTON are shown in Fig. 1. From the left to the right we have the following devices: laser transmitter, optical switch, optical multiplexer, optical fiber, optical demultiplexer, optical switch and optical receptor. Each device has a set of parameters that can be adjusted by the SIMTON user. The set of parameters for each network device is listed in Table I, which also shows the standard preset values used in the simulations described in Section IV and in Section VI.

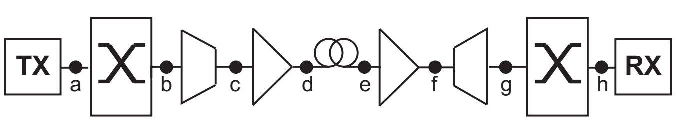


Figure 1. The link architecture and optical devices assumed by SIMTON.

In order to take into account the physical impairments the SIMTON uses a physical layer model developed by our research group [12], which evaluates the optical signal-to-noise ratio (OSNR) of the lightpath. The model evaluates the optical signal-to-noise ratio of each lightpath and it considers the following impairments: ASE noise, amplifier gain saturation effect, saturation of ASE noise in EDFAs, homodyne crosstalk in optical switches, the losses, FWM and PMD effects in the transmission fibers [12]. The verification of the quality of signal (QoS) of one lightpath is made by comparing the $OSNR_{\text{out}}$ in the output of the lightpath with the predefined minimum OSNR ($OSNR_{\text{Th}}$). Thus, in order to satisfy the QoS requirement, the $OSNR_{\text{out}}$ of the lightpath must be greater than $OSNR_{\text{Th}}$. Moreover, we also consider the effect of residual chromatic dispersion, as described in [14].

Table I
List of the optical devices and parameters adjustable by the SIMTON user.

Device	Parameter	Standard value
Network	Load	70 Erlang
	Maximum temporal broadening	10 %
	Minimum acceptable signal-to-noise ratio	23 dB
Laser transmitter	First used wavelength	1528.78 nm
	Laser power	0 dBm
	Linewidth	0.0045 nm
	Output signal-to-noise ratio	30 dB
	Transmission bit rate	40 Gbps
Optical switch	Insertion loss	3 dB
	Isolation factor	−40 dB
Multiplexer	Insertion loss	3 dB
Optical amplifier	Noise figure	5 dB
	Non-saturated gain	Compensate for the losses
	Output saturation power	19 dBm
Optical fiber	Channel spacing	100 GHz
	Loss coefficient	0.22 dB/km
	Number of wavelengths per link	36
	Transmission fiber dispersion coefficient (@1544.53 nm)	−0.75 ps/km.nm
	Transmission fiber slope (@1544.53 nm)	0.06 ps/km.nm^2
	Zero dispersion wavelength for transmission fiber	1557 nm
	Compensating fiber dispersion coefficient (@1544.53 nm)	−99.77 ps/km.nm
	Compensating fiber slope (@1544.53 nm)	−1.87 ps/km.nm^2
	Zero residual dispersion wavelength	1544.53 nm
	PMD coefficient for NZ-DSF	0.04 ps/$\sqrt{\text{km}}$

B. Routing and Wavelength Assignment Module

Our network simulation engine follows the flowchart shown in Fig. 2. A candidate lightpath for the incoming call request is searched by the RWA module. The output of the RWA module feeds the call admission control (CAC) module. The CAC is responsible for the decision whether a given call request can be established or not in the network. If the RWA module can not find a lightpath for a requested call, the CAC blocks it.

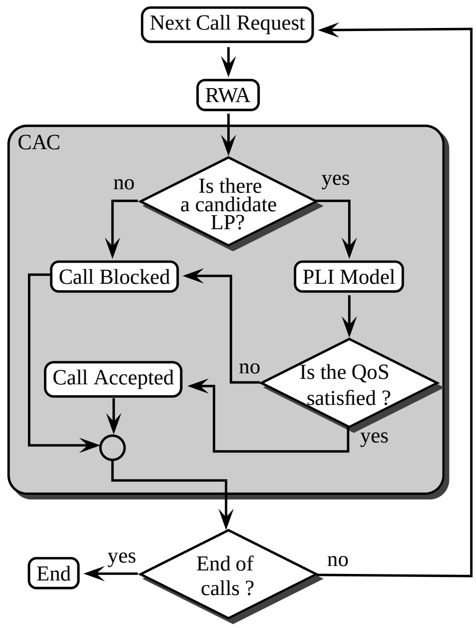


Figure 2. Flowchart used by SIMTON for the solution of the RWA problem.

If the RWA algorithm returns a candidate lightpath (CLP), then the CAC evaluates its Δt_{CLP} and $OSNR_{\text{CLP}}$ using the physical layer impairments (PLI) model (Section II-A). The current state of the network is considered in this evaluation. The CAC checks if both QoS constraints are satisfied: $\Delta t_{\text{CLP}} \leq \Delta t_{\text{Th}}$ and $OSNR_{\text{CLP}} \geq OSNR_{\text{Th}}$, where Δt_{Th} is the maximum pulse broadening and $OSNR_{\text{Th}}$ is the minimum acceptable OSNR value for the QoS requirements. If either inequality does not hold, then the requested call is blocked by the CAC. Otherwise, the request is accepted. An accepted call results in the establishment of a circuit switched bidirectional connection in two different fibers between the selected source and destination nodes.

C. Traffic Generation and Network Load

To simulate the dynamic behavior of the network, the call requests are generated dynamically following a stochastic process. This approach is also known as dynamic lightpath establishment (DLE) [15]. For each call request, two network nodes are raffled, randomly, following an uniform probability density function. Thus, all the nodes in the network are equally probable to be selected. These two selected nodes are assigned as the source and destination nodes of the call. The generation process of call requests follows a Poisson process: the time interval between calls is exponentially distributed with average μ and the duration of each call also follows an exponential distribution with a mean value equal to $\frac{1}{H}$. With these two parameters, one can define the network load L as $L = \mu H$, in which, H is the mean time, on average, that the call is active and μ is the mean rate for the call requests generation. The network load L is given in Erlang.

D. Blocking Probability Evaluation

The network blocking probability estimates the relative amount of not accepted calls by the network. As it was discussed before, a blocked call can occur either by the lack of available network resources to establish the call or for inadequate quality of signal for the found route. Thus, a higher blocking probability means that a larger number of users could not make use of the network resources, which indicates a worse network performance. The blocking probability is estimated by evaluating the ratio between the number of blocked calls and the total number of call requests to the network.

III. Simulator Implementation

Fig. 3 shows the main screen of the developed graphical interface (GUI). By using this SIMTON interface one can create and save a new network topology, or edit a saved network.

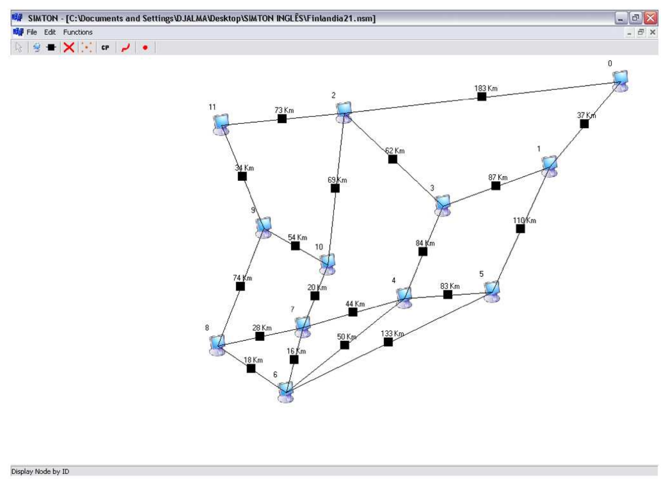


Figure 3. SIMTON main screen showing the network topology being edited by the user.

The user is allowed to configure all nodes, all links or an specific node or link parameter by selecting the desired element. Link lengths and node numbers are shown in Fig. 3. In each link, the following parameters can be modified: optical fiber length and loss coefficient, insertion losses in the optical multiplexers and demultiplexers, number of fibers in a link, optical amplifiers gain, saturation power and noise figure. All these options are illustrated in the parameters configuration screen shown in the Fig. 4. In each node the following configuration options are available: switch insertion loss, optical signal-to-noise ratio of the transmitter and laser output power as illustrated in Fig. 5. SIMTON also allows the user to configure all amplifier gains to compensate for the losses or to set each EDFA gain of the network.

Fig. 6 illustrates the screen where the user can define the simulation parameters. Some examples are: the number of generated calls, the value for $OSNR_{\text{Th}}$, which impairments should be considered or not during the simulation, the RWA algorithm, types and range of parameters in the considered

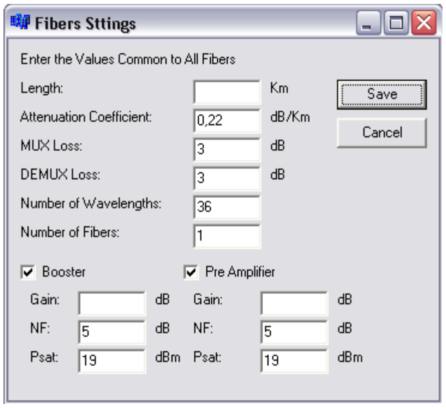


Figure 4. Configuration screen of the optical devices parameters in network link.

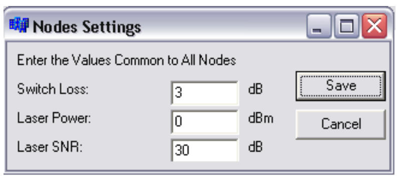


Figure 5. Configuration screen of the optical devices parameters in network node.

analysis. The simulation process starts upon clicking the "Simulate" button.

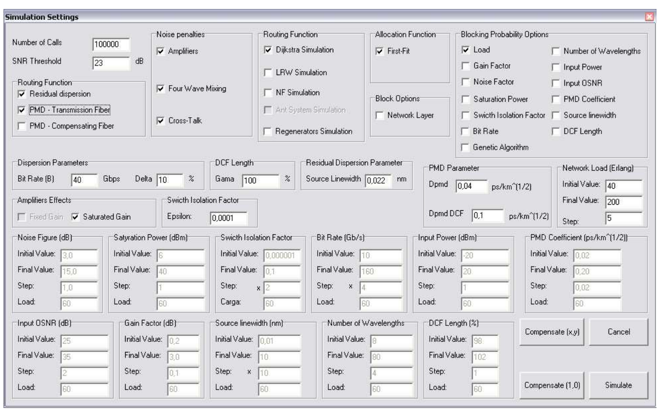


Figure 6. Simulation setup screen - configuring the simulation parameters.

During the simulation process, the SIMTON shows a screen indicating the simulation evolution. Upon the end of the simulation, the SIMTON shows a screen with the result, which is shown in Fig. 7. This screen always shows the blocking probability as function of the optical devices parameters or network load. In addition, the software also generates a log text file in which all the data about the simulation are recorded. Thus, it is possible to export the simulation results to another plotting software.

IV. Statistical Analysis of the Simulator

The main result generated by SIMTON is the network blocking probability as a function of some parameters as discussed in the previous sections. In order to verify the

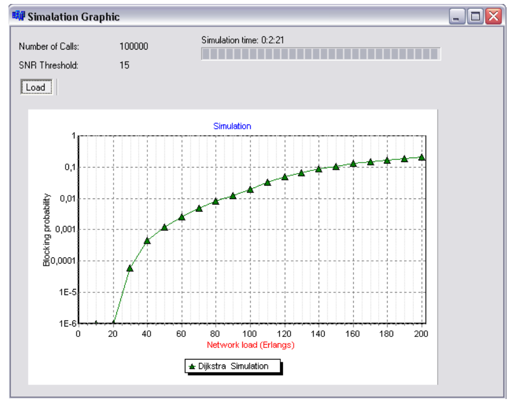


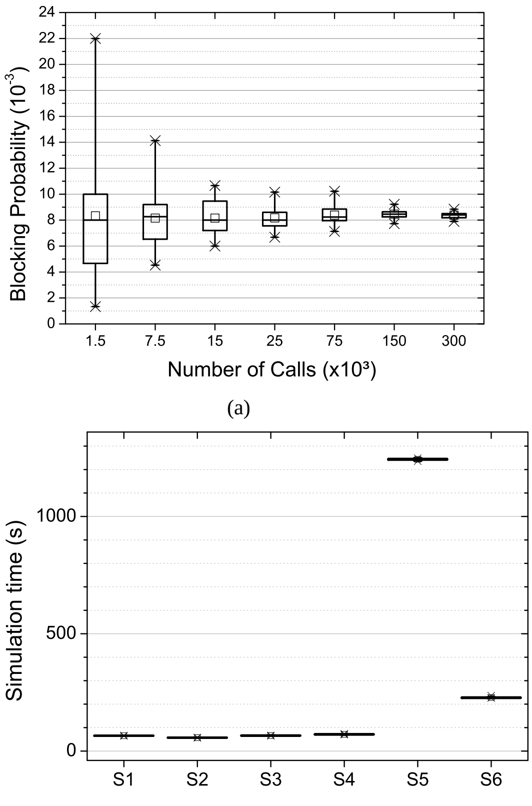
Figure 7. Simulation screen showing results.

reliability of the results given by SIMTON we performed a statistical analysis of the results. The blocking probability returned by SIMTON is a random variable that is obtained as the ratio between the number of blocked calls and the total number of call requests to the network. The simulation software generates a finite set of call requests. It is expected that the variance of the blocking probability results decreases as the number of call requests increases. In order to analyze the statistical behavior of the blocking probability results, we performed a set of 30 simulations using the parameters listed in Table I with a network load of 70 ErlangS in the Finland topology [16], which is shown in Fig. 3.

Fig. 8(a) shows the box plot of these results as a function of the number of call requests. The open square and the horizontal line inside the box represent the mean and the median of the results obtained from the 30 simulations, respectively. The box stands for the 25th and 75th percentile, whereas the whisker stands for the 1st and 99th percentile, which means that the region in the whiskers delimitates the confidence interval of 98 %. As one can note from Fig. 8(a), as the number of simulated call requests increases the confidence interval of 98 % becomes narrower, as expected. The width of the whiskers and the boxes obtained for $1,5 \times 10^5$ and 3×10^5 call requests are almost the same. It indicates that for this level of blocking probability (8×10^{-3}) a number of call requests higher than 3×10^5 will not lead to a narrower 98 % confidence interval.

Fig. 8(b) shows the simulation time of the SIMTON, considering different scenarios of simulation. For every scenario we used the simulation tool running in an Intel Core2 Duo @2.13 GHz with 3 GB of RAM computer. We performed a set of 30 simulations using the parameters listed in Table I, considering a set of 10^5 call requests in the Finland topology [16], which is presented in Fig. 3. Table II describes the physical impairments considered in each scenario.

In the scenarios $S1$ to $S4$ the FWM effect is not considered. Note from the Fig. 8(b) that, for these scenarios, the time spent by the SIMTON to perform the simulations are practically in the same order of magnitude (around 80 s). When the FWM effect is also considered ($S5$), the simulation time increases by



(a)

(b)

Figure 8. Statistical analysis of the simulator: (a) convergence aspects and (b) simulation time for different scenarios.

Table II
DESCRIPTION OF DIFFERENT SCENARIOS CONSIDERED.

Scenario	Impairment
$S1$	PMD effect only.
$S2$	PMD and RCD effects only.
$S3$	Amplifier impairments only.
$S4$	Amplifier and optical switch impairments only.
$S5$	Amplifier, optical swith and FWM effect only.
$S6$	All physical impairments.

a factor of almost 16 times (around 1270 s), compared to the other scenarios. It allows one to conclude that the evaluation of the FWM effect is very time consuming, compared with the other physical impairments. In $S6$, all impairments are considered including the FWM. The main difference between the scenarios $S5$ and $S6$ is that the pulse broadening impairment is taken into account in $S6$, whereas it is not in $S5$. Note from Fig. 8(b) that the simulation time for the $S5$ is considerably higher than for the $S6$ scenario. It can be explained by the implementation of the CAC module (described in details in Section II). The CAC verifies the pulse broadening impairments before the other physical impairments. For this reason, when a call does not meet the pulse broadening criterion it is blocked without any further evaluation of the other physical impairments, reducing the total simulation time.

V. SIMTON CASES OF USE

In order to illustrate how SIMTON works, this section presents a brief description of the software cases of use. SIMTON is divided in two modules: the optical network simulator and the graphical user interface. Fig. 9(a) shows the cases of use diagram of the graphical user interface. The options available to the user are:

- **Create network**: Allows the user to design a new network topology.
- **Save network**: Allows the user to save a designed network into a file.
- **Open network**: Allows the user to open a previously saved network.
- **Modify network**: The user can edit a network by adding or removing links or nodes of the active network topology.
- **Compensate for the losses**: Setup the optical amplifiers gains to compensate for the losses along the links.
- **Configure the devices**: Allows the user to configure the parameters of network devices. There are two options to configure the devices:
  - *All devices*: Changes simultaneously the values of the parameters for all the devices in the network.
  - *Single devices*: Changes the value of a specific device parameter.
- **Run a simulation**: Starts a simulation with the parameters configured by the user.
- **RWA algorithm**: Allows the user to choose the RWA algorithm used during the simulation. There are four possible choices implemented for the routing algorithm: shortest path (SP) [15], least resistance weigth (LRW) [17], optical signal-to-noise ratio (OSNR-R) [12] and minimum number of hops (MH) [15]. The wavelength assignment algorithms implemented are: first fit, random, most used, least used, best fit and just enough [15]. Other RWA algorithms can be easily implemented.
- **Select results**: SIMTON gives, as a result, the graph of the network blocking probability as a function of some predefined parameters. The following parameters can be chosen by the user: number of wavelengths per fiber, amplifier saturation power, amplifier noise figure, laser transmitter power, network load, switch isolation factor, transmission fiber PMD coefficient and the output OSNR of the transmitter laser.
- **Select impairments**: Allows the user to select which impairments SIMTON should take into account during the simulation. The possible choices are: PMD, RCD, FWM, dependence of ASE with the EDFA input power, EDFA gain saturation and switch crosstalk.
- **Show graph**: Plots the simulation results in a graph of blocking probability as a function of devices parameters or network load. The devices parameters choices are: amplifier noise figure, amplifier saturation power, transmission laser power, switch isolation factor, number of wavelengths, network load and PMD coefficient of the

fiber, for example.

Fig. 9(b) shows the cases of use diagram of the simulation module. The options available to the user are:

- **Simulate**: Starts a network simulation.
- **Connection request generator**: Simulates the call requisition patterns in the network, according to the description in Section II-C.
- **Evaluate the OSNR**: Evaluates the output OSNR of the lightpath, as described in Section II-A and the set of impairments chosen by the user.
- **Call manager**: This module handles the connections in the network, setting up connection and removing inactive calls, releasing its resources for new assignments.
- **Establishment of the calls**: Establishes the calls in the network and reserves network resources for the calls. Moreover, it evaluates and stores the optical powers in each network point.
- **Release calls**: Releases the network resources used by the ended connections.
- **RWA algorithm**: Runs the routing and wavelength assignment algorithm.

VI. Examples of Simulation Results

By using the SIMTON, it is possible to perform a variety of studies concerning to the network performance (in terms of blocking probability) and to make performance comparisons of networks using different optical devices characteristics. As an example, some of the possible studies and analysis that can be performed using SIMTON are shown in this section. The detailed discussion about the simulation results presented here and their implications on network performance are not in the scope of this paper and it can be found in [12].

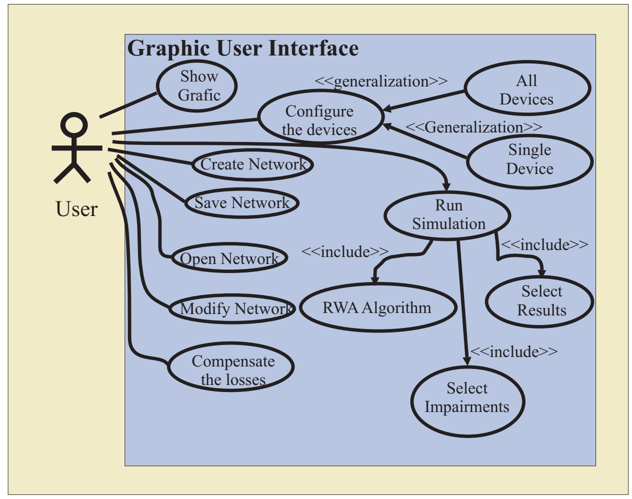
Fig. 10(a) shows the network performance (blocking probability) as a function of device parameters, for different network loads. It indicates that there is an optimal value for the laser power, since for low powers the blocking probability is high due to amplifier noise, and for high powers the blocking probability increases due to the non-linear effect, in-band crosstalk and amplifier saturation effects [12]. This simulation could be used by a network designer to specify the device characteristics for the optimization of network operation. For example, Fig. 10(b) shows the impact of different amplifier saturation powers and noise figures, and Fig. 10(c) shows the impact of optical switches with different isolation factor values on network performance.

Besides the analysis of network performance as a function of device characteristics, SIMTON is also able to analyze and compare the network performance for different RWA algorithms. As an example, Fig. 11 shows the network blocking probability as a function of network load for three different RWA algorithms [12], which are: SP, LRW and OSNR-R.

VII. Conclusions

This paper presented a computational simulation tool named SIMTON designed for the simulation of wavelength routed optical networks. SIMTON can be used to investigate the impact of physical impairments in the performance of all-optical networks. SIMTON takes into account more physical impairments than the other similar simulation tools found in the literature.

We believe the SIMTON is a powerful tool for optical network simulations, to evaluate the network performance for different RWA algorithms, different device specifications, different network topologies and traffic loads. The possible users include network designers and operators, equipment vendors and network researchers, to perform network analysis, update and planning.



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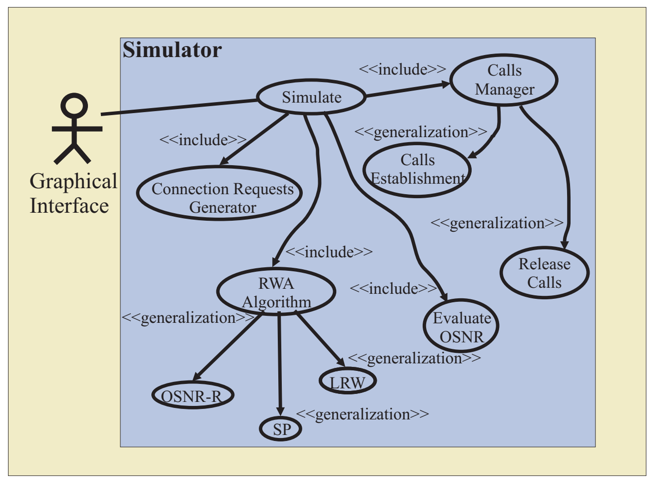

(b)

Figure 9. Cases of use diagram for the SIMTON: (a) GUI module and (b) simulation module.

Acknowledgments

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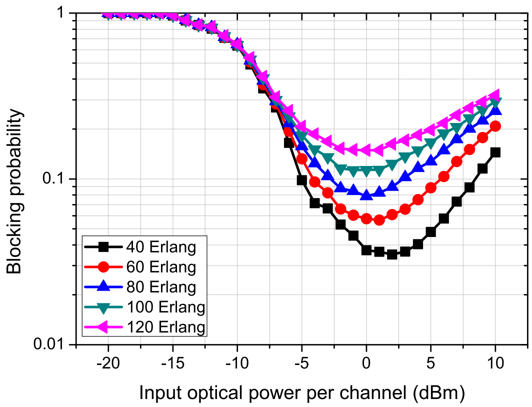

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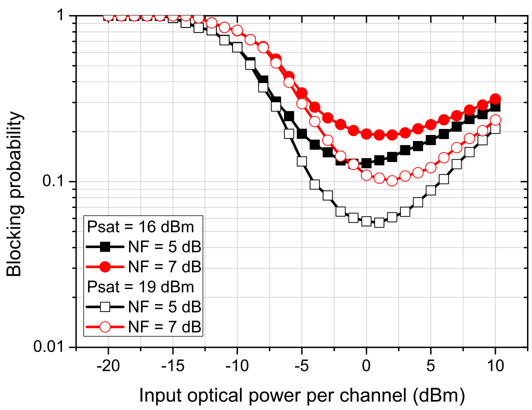

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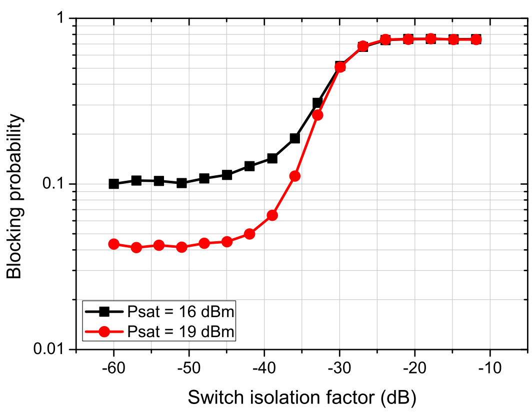

(c)

Figure 10. Simulation example of blocking probability as a function of different: (a) network loads; (b) amplifier saturation powers and noise figures and (c) isolation factor values for optical switches.

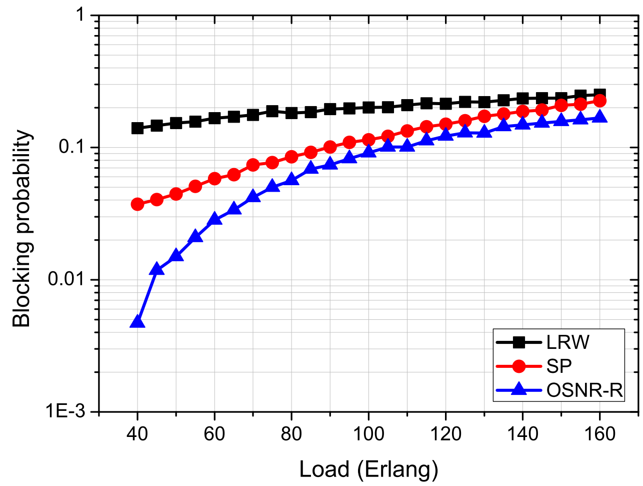

Figure 11. Simulation example: network blocking probability as a function of network load for three different RWA algorithms (SP, LRW and OSNR-R).

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