

Integrating physical layer modeling in the simulation of dynamic WDM optical networks with direct and coherent detection

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Abstract—In this paper, we enhanced the capability of SIMON (Simulator for Optical Networks) by considering different modulation formats. This is achieved by integrating a new physical network model that can support both direct and coherent communication data in SIMON. SIMON is implemented in C++ and previously supported only Wavelength Division Multiplexing (WDM) with direct optical network simulation. It measures the network blocking probability by considering various optical device characteristics. SIMON model was adept at capturing the most significant impairments that affect the Bit-Error Rate (BER). This study introduces refinements in SIMON, considering the fiber dispersion and non-linear effects compensated using digital signal processing. This paper extensively compares Direct Optical Networks (DONs) and Coherent Optical Networks (CONs) regarding their performance, efficiency, and reliability. We analyze the performance of both types of networks towards two different network topologies under diverse conditions. The results from our simulations underscore both network types' strengths and weaknesses and provide a foundation for making informed decisions on network deployments.

Keywords—Optical network simulation, Performance measurement, Direct Optical Network, Coherent Optical Networks

I. INTRODUCTION

Optical fiber networks are often the backbone of today's internet and telecommunication systems. As the demand for faster network speeds escalates and new business requirements emerge, network engineers and designers face the growing challenge of crafting innovative algorithms and protocols to modernize and enhance existing communication infrastructures. Developing and evaluating such features or algorithms on a physical platform is often complex and time-consuming as it requires significant financial investment and poses challenges regarding adaptability and scalability. Given the constraints in accessing real-world testbeds or networks, simulation tools have become indispensable during the planning and design stages. Network simulation is a cost-effective and highly versatile approach for planning and designing communication infrastructures. It offers a pragmatic alternative, providing robust, scalable network design flexibility. This methodology has gained widespread acceptance in both industrial and academic settings.

Accurate modeling in network simulations is essential to ensure the reliability and performance of real-world networks. Precision in modeling guarantees that the network's simulation behavior closely mirrors its operation in real scenarios. This helps predict potential issues, optimize performance, and ensure efficient use of resources. Furthermore, when designing new network topologies or protocols, accurate simulations can guide decisions, avoiding costly mistakes and downtime. In essence, the credibility of network design, testing, and forecasting hinges on the accuracy of the underlying simulation models.

Integrating physical layer modeling in network simulations is crucial for capturing real-world complexities such as signal degradation, noise, and interference. These factors directly impact network performance metrics like throughput, latency, and reliability. Without accounting for the physical layer, simulations may produce overly optimistic results that could lead to incorrect decision-making. Including physical layer characteristics allows for more precise evaluation and optimization of network protocols and configurations, thereby enhancing the credibility and usefulness of the simulation outcomes.

Over the past several decades, optical network communications have evolved from experimental technologies to the backbone of global data transmission. Initially focused on long-haul connections, the deployment of fiber optic cables dramatically enhanced the capacity and reach of networks. Technological milestones like WDM and dense WDM (DWDM) multiplied the data-carrying capabilities of these fibers. In the early 2000s, introducing optical cross-connects and switching technologies brought more flexibility to network designs, allowing for smarter, more efficient data routing. Direct Detection, one of the earliest techniques to gain prominence, is characterized by its simplicity and cost-effectiveness. In recent years, digital signal processing and miniaturization advances have made Coherent Detection increasingly cost-competitive, even for applications where Direct Detection was traditionally dominant. This development has further blurred the lines between the optimal use cases for each detection technique, making the comparison

between Direct Detection and Coherent Detection a subject of ongoing research and development [1]. Innovations like software-defined networking (SDN) promise even greater network agility, opening doors for more dynamic, programmable infrastructures.

This study presents a refined version of the SIMON simulator [2] that now accounts for fiber dispersion and non-linear effects to improve network simulations' accuracy. Our work provides an in-depth comparative analysis of Direct-/Coherent Optical Networks, evaluating key metrics such as performance, efficiency, and reliability.

The paper is organized as follows: Section II delves into the background of our research. This includes exploring direct and coherent detection mechanisms in optical networks, reviewing related works, and an overview of existing optical network simulators. Section III focuses on the physical layer model within SIMON. It covers the various components of the wavelength routing node, the Amplified Spontaneous Emission (ASE) model for Erbium-Doped Fiber Amplifiers (EDFA), and Bit Error Rate (BER) estimation techniques. Section IV outlines our simulation architecture and setup, providing the context and parameters for our experiments. Section V presents and discusses our simulation results and key findings, offering insights into the study's implications. Finally, Section VI concludes the paper, summarizing our contributions and outlining directions for future research.

II. BACKGROUND

A. Direct and Coherent Detection

To meet the requirements of high data rates, the information can be encoded in the amplitude/phase/polarization of the electric field. One such modulation scheme is termed as On-Off keying (OOK), where an electrical binary bit stream modulates only the intensity of the optical carrier. Intensity-modulated schemes are detected directly using a photodiode and are referred to as direct detection schemes. Alternative modulation approaches, such as Quadrature phase shift keying (QPSK) and Quadrature amplitude modulation (m-QAM), utilize both the phase and amplitude of the optical carrier to transmit information. These modulation schemes are detected by mixing the received signal with another optical signal termed as local oscillator to preserve the phase and amplitude of the optical carrier. These types of detection schemes are termed coherent detection systems. An optical network can support any of these modulation/detection systems, depending on the applications, requirements, transmission distance, data rate, and cost. With increased demand for capacities, most optical networks use advanced modulation formats with coherent receivers [1].

Any fiber optic link/network can cause dispersion and attenuation, which needs to be compensated [1]. Dispersion is usually compensated by performing digital signal processing (DSP) [3] whereas attenuation is compensated by adding inline amplifiers such as Erbium doped fiber amplifiers (EDFA). EDFA adds noise and amplifies the optical signal; hence, the optical signal-to-noise ratio (OSNR) degrades. Apart from

these coherent optical networks are affected by several impairments such as frequency offset, laser phase noise, and polarization mixing [3]. In this paper, we consider all these impairments to be compensated by DSP in case of coherent systems. For direct detection systems, we assume the sufficient length of dispersion compensating fiber is used to compensate for the accumulated dispersion. We also consider a wavelength division multiplexed (WDM) network, which is typically used to increase the data rates in networks.

B. Related Work

In the study by Bu et al. [4], an OSNR-aware Routing and Wavelength Assignment (RWA) strategy is proposed for wavelength-convertible networks. While the network topologies in their work differ from those examined in this paper, both studies employ the same EDFA model for optical amplification. Notably, the work by Bu et al. does not compare the blocking probability associated with different modulation and detection schemes in the absence of wavelength conversion—a gap that our study aims to fill.

The study by Pandya et al. [5] concentrates on all-optical wavelength conversion, employing semiconductor optical amplifiers for this purpose. In their research, Erbium-Doped Fiber Amplifiers (EDFA) serve as inline amplifiers, and they take multiple optical impairments into account. While we employ the same Indian network topology in our work, it's important to note that the Pandya et al. study does not address the blocking probability for various modulation and detection schemes—a subject area that our research aims to explore in detail.

C. Other Optical Network Simulators

Several open-source optical simulators are available in the community, each with specific features, capabilities, and limitations. Net2Plan, as discussed in [6], is renowned for its applications in WDM optical networks, aiding in design and performance simulation. It provides a flexible, modular framework for implementing and evaluating various network algorithms. Its robustness and flexibility make it a favorite among network designers. Yet Net2Plan may not be able to accurately replicate all the complexities and nuances of a real-world network environment. The study in [7] serves as an extension to Net2Plan. Its primary objective is to allocate resources equitably, contingent on service data rates. This approach ensures consistent blocking performance across varied services within the Elastic Optical Networks (EON) framework. OMNeT++ [8] is an extensible, modular, component-based C++ simulation library and framework, primarily used for building network simulators. Its generic and flexible architecture allows OMNeT++ to be used in various domains, not just networking. However, the native OMNeT++ package may lack certain domain-specific features or models, requiring users to incorporate additional frameworks like INET or create custom models. The simulator presented in [9] is based on the OMNeT++ platform for elastic networks. Its distinct feature is its dynamic adaptability; it can augment and diminish the

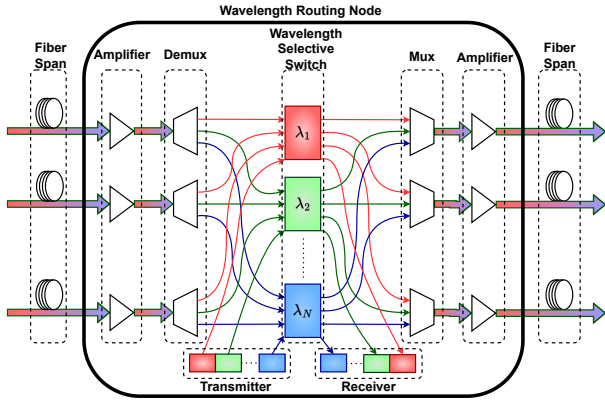


Fig. 1: Schematic of a wavelength-routing node (WRN).

spectrum allocated to a designated light path, showcasing flexibility crucial for various network scenarios. GNPY [10], based on the Gaussian Noise Model [11], is a newly developed optical network route planning and optimization tool that models real-world mesh optical networks. One limitation of GNPY is that the simulation is stateless and can only handle calls one at a time.

III. PHYSICAL LAYER MODEL IN SIMON

SIMON is an object-oriented, event-driven simulation package implemented in C++. It is capable of measuring the network-level blocking probability of WDM optical networks. The physical-layer models in SIMON consider signal attenuation in fiber and other components, amplifier gain saturation, and homowavelength crosstalk in switches. Simulation experiments can be performed with a user-specified bit-error-rate limit, which must be satisfied by any call set up in the network.

A. Components in Wavelength-routing Node

Fig. (1) shows the schematic of a wavelength-routing node, also referred to as a Reconfigurable Optical Add Drop Multiplexer (ROADM). This wavelength routing node acts as the stage between fiber spans and accounts for wavelength switching/routing. Typically, the attenuation coefficient of a single mode fiber is 0.2 dB/km at 1550 nm, thus resulting in a net loss of 16 dB for a span length of 80 km fiber. The span loss is compensated by optical amplifiers; which are the first component in the wavelength routing node. This is followed by an array of demultiplexers, separating incoming signals based on their wavelengths. These demultiplexed signals are then directed to the optical wavelength-routing switches/ wavelength selective switches (WRS). Each WRS is responsible for routing signals of a specific wavelength to the appropriate output port. The final stage consists of multiplexers, which combine signals of all wavelengths back together before sending them to the designated output fiber. The incoming signal experiences losses from the demultiplexer, wavelength selective switch, and the multiplexer, which is been compensated with the help of an amplifier

stage after these components. The amplified WDM signal is then transmitted through the next fiber span. There is also a provision to add and drop wavelengths to switch the data traffic from one wavelength to another. For this, the wavelength routing node has transmitters and receivers capable of transmitting/receiving specific wavelengths of interest. For the node in the source station, these transmitters initiate the call by transmitting all the desired wavelengths, whereas for the node in the destination station, these receivers terminate the call. In this cross-connect switch setup, the number of optical switches matches the number of incoming wavelengths. Additionally, each switch has a minimum number of input/output ports equal to the number of input/output fibers.

B. ASE model for EDFA

As mentioned in Section III-A, each node consists of amplifiers to compensate for the loss incurred during transmission. Moreover, inline amplifiers are essential if the fiber length exceeds 80 km. In our simulation, we employed EDFA as the amplifier in the architecture. Amplified spontaneous emission (ASE) is a limiting factor for EDFA as it adds noise to the amplified signal by which the OSNR of the amplified signal degrades. The power spectral density of ASE can be modeled as a function of frequency ν [1],

$$P_{ASE}(\nu) = 2n_{sp}h\nu_0(G(\nu) - 1)\Delta f. \quad (1)$$

In (1), n_{sp} refers to the spontaneous emission factor or the population inversion factor, ν_0 is the center frequency, $G(\nu)$ is the EDFA gain for ν^{th} frequency component and Δf is the bandwidth of the modulated signal.

C. BER Estimation

One of the critical parameters that determine the blocking probability is the bit-error rate (BER) at the destination (receiver) end. In coherent systems, the BER for any modulation format can be estimated from the received optical signal-to-noise ratio (OSNR) as [12],

$$\text{BER} = \frac{2}{M} \left(1 - \frac{1}{\sqrt{m}}\right) \text{erfc} \left(\sqrt{\frac{3M(E_b/N_0)}{2(m-1)}} \right) \quad (2)$$

where

$$E_b/N_0 = \frac{2B_{ref}\text{OSNR}}{pMR_s}. \quad (3)$$

OSNR is the ratio of output signal power to the output in-band noise power. The noise power is typically measured using the standard reference bandwidth of 12.5 GHz (0.1 nm). In (2) and (3), B_{ref} refers to this standard reference bandwidth = 12.5 GHz, p represents the number of polarization, M is the modulation order, m is the number of constellation points and R_s is the symbol rate. As an example, for 25 Gbaud single polarized 16 QAM modulation, $m = 16$, $M = 4$, $p = 1$, $R_s = 25$ Gbaud.

Fig. (2) shows the BER evaluated for different values of OSNR curve for different modulation formats such as single polarized quadrature phase shift keying (SP QPSK), single

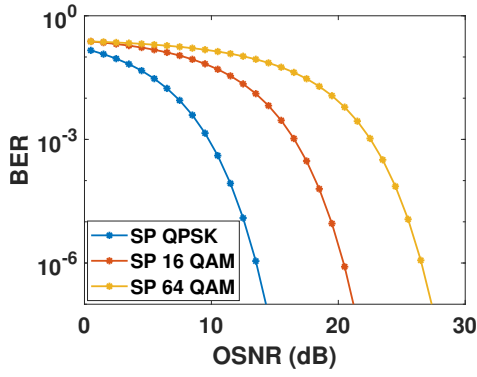


Fig. 2: BER - OSNR curve for different modulation formats (symbol rate fixed to 25 Gbaud).

polarized quadrature amplitude modulation with 16 constellation points (SP 16 QAM) and single polarized quadrature amplitude modulation with 64 constellation points (SP 64 QAM). This figure works as a reference point for further network simulations. The figure shows that to achieve a specific BER, say 10^{-3} , higher order modulation formats demand higher OSNR values

In direct detection systems such as On-off keying (OOK), the BER is estimated from the decision threshold I_D as [1],

$$\text{BER} = \frac{1}{4} \left[\text{erfc}\left(\frac{I_1 - I_D}{\sigma_1 \sqrt{2}}\right) + \text{erfc}\left(\frac{I_D - I_0}{\sigma_0 \sqrt{2}}\right) \right] \quad (4)$$

where

$$I_D = \frac{I_0 + I_1}{2}. \quad (5)$$

In Eqn. (4) and (5), I_1 and I_0 refer to the average value of currents corresponding to bit 1 and bit 0, which is the product of the responsivity of photodiode multiplied by the received power for the corresponding bits. σ_1 and σ_0 refer to the standard deviation for bit 1 and 0, respectively, estimated from the square root of variance. The variance corresponding to each bit is calculated by summing up the corresponding variance of thermal noise, shot noise, spontaneous emission, and cross-talk.

IV. SIMULATION ARCHITECTURE AND SETUP

A. SIMON Architecture

We explain our SIMON simulator architecture using the block diagram in Fig. (3). First, the SIMON simulator generates calls between the source and destination pairs. These calls also contain a holding time when initialized according to some distribution and will be released once the time expires. The event-driven simulation module will check for a route between the source and destination for each call request and then look for a free wavelength. The shortest-path routing algorithm determines the route, and a free wavelength is assigned based on the first-fit method. The call will be blocked if no route or wavelength is available; SIMON will work in direct or coherent detection mode, depending on

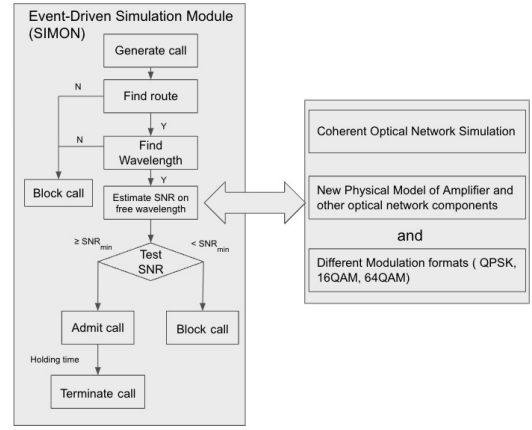


Fig. 3: SIMON simulator architecture.

the different simulation configurations. The Coherent Optical Network Simulation module will choose different modulation formats and continue the simulation. SIMON will calculate the estimated BER for each path request based on its physical model, which considers the amplified spontaneous emission (ASE) noise, nonlinear interference (NLI) accumulation, fiber dispersion, and other physical impairments. If the BER is above the pre-determined threshold (e.g., $1e-9$), the call will be admitted; otherwise, the call is blocked.

The blocking probability is given by (6).

$$P_b = \frac{\text{Number of blocked calls}}{\text{Total number of calls}} \times 100\%. \quad (6)$$

B. System Parameters and Simulation Setup

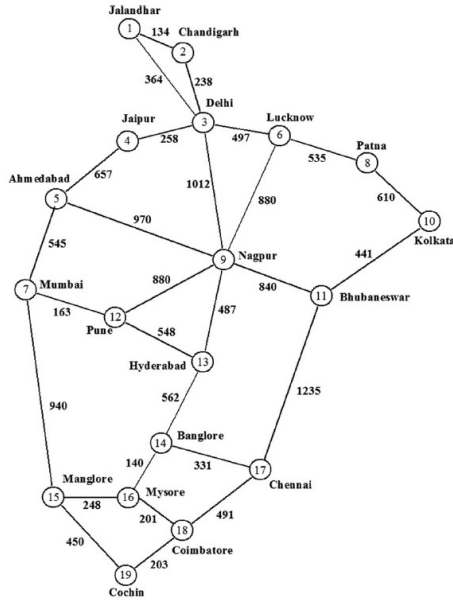
In this paper, we mainly analyze two network topologies [5] depicted in Fig. (4a) and Fig. (4b). These refer to a 19-node RailTel India network with 28 bidirectional links and a 24-node USNET with 43 bidirectional links (link length in kilometers). The required simulation parameters for the simulation study are given in Table I and Table II. Lambda is the arrival rate, defined as the number of calls arriving per second. The service rate denoted by Mu is the number of calls accepted per second. The ratio of the arrival rate to the service rate gives the load (in Erlang) of the network.

TABLE I: Network Simulation Parameters

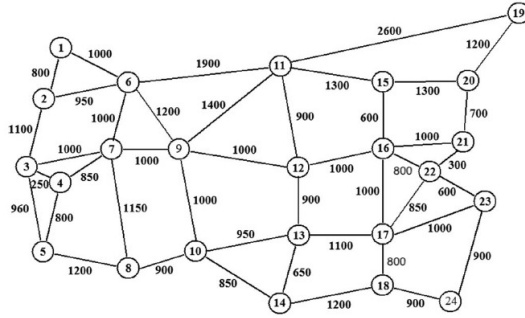
Parameter	Value
Lambda (arrival rate)	0.01/0.03/0.1/0.3/1/3/10/30/100
Mu (service rate)	1
# of Wavelengths	8
# of Calls	100,000
Assignment	First Fit
Routing	Shortest Hop Path
Gain Model	Homogeneous

V. SIMULATION RESULTS

This section presents a comparative analysis of Direct Detection (DD) and Coherent Detection (COH) optical networks, utilizing the refined SIMON model for our evaluation.



(a) 19-nodes RailTel Network



(b) 24-nodes USNET

Fig. 4: Network Topologies.

TABLE II: Physical Layer Simulation Parameters

Parameter	Value
Bitrate	10/25/40/100 Gbps
Thermal noise	$5.3e-12$ V/Hz
BER limit	1×10^{-9} (DD) and 3.8×10^{-3} (COH)
Length of fiber link segment	80 km
Small signal gain of amplifier	19.95 dB

Specifically, we investigate the blocking probability with network load under various scenarios. These include differing modulation formats, symbol rates, and Bit-Error Rate (BER) thresholds.

We used a modified Pacbell topology (see [13], Fig. (7)) consisting of 15 nodes and 52 links with 150km for each link to study the effect with/without inline amplifiers. Fig. (5) displays the blocking probability for Pacbell topology with inline amplifier for OOK at different symbol rates. Considering the OOK modulation format, the BER limit is set to $1e-9$. Fig. (5) reveals that as network load rises, blocking probability also goes up. Additionally, greater bit rates lead

to higher blocking chances because the corresponding OSNR requirements become more stringent. Fig. (6) displays the blocking probability for a Pacbell topology at 25 Gbaud for different modulation formats without inline amplifiers. Comparing Fig. (5) and (6), when inline amplifiers are used, the blocking probability starts as low as 0.002 and rises to about only 0.9 at 100 Erlangs of load; whereas blocking probability is nearly 100% without inline amplifiers. This highlights the effectiveness of using inline amplifiers to reduce the blocking probability. Fig. (6) also says that the blocking probability for QPSK is lesser when compared to the other coherent modulation formats.

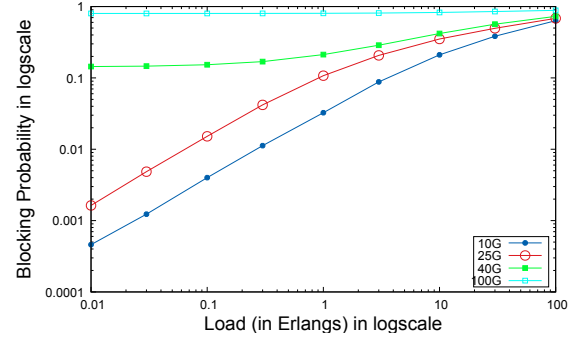


Fig. 5: Blocking probability for Pacbell topology with inline amplifier (BER limit = $1e-9$) for OOK at different symbol rates (150 km fiber with inline amplifier placed after 75 km).

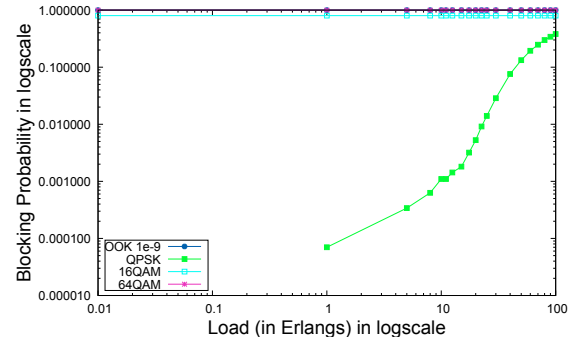


Fig. 6: Blocking probability for Pacbell topology without inline amplifier for different modulation formats at 25 Gbaud (150 km fiber).

Fig. (7) compares blocking probability in the RailTel Network for both DD and COH configurations, using inline amplifiers after every 80 km. Fig. (7) also says that QPSK modulation performs better than all other modulation formats. The reason behind this could be explained using Fig. (2), where we conclude that for a specific OSNR, the BER increases as we move onto higher modulation formats.

Fig. (8) contrasts the blocking probability in the USNET Network for both DD and COH setups, using 80 km-spaced inline amplifiers. Even here, the QPSK modulation is the best performer in these conditions. The blocking probability for each modulation format is higher for USNET topology

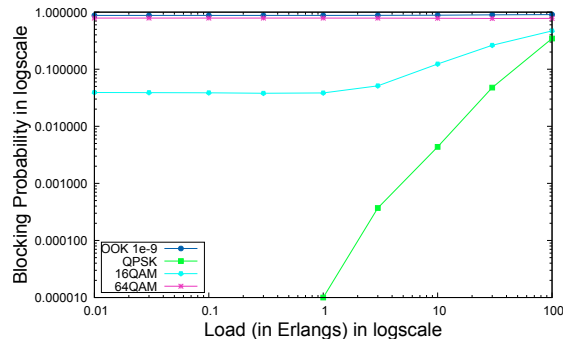


Fig. 7: Blocking probability for RailTel Network for different modulation formats (inline amplifier placed after 80 km).

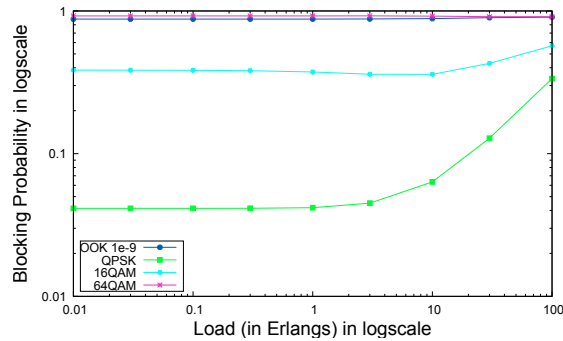


Fig. 8: Blocking probability for USNET Network for different modulation formats (inline amplifier placed after 80 km).

when compared to RailTel, which is primarily due to the greater number of nodes and links in the US network. Fig. (9) indicates that an increase in bit rates corresponds to a higher blocking probability, which is a pattern consistent with USNET Network observations.

In comparing the Pacbell topology to the other two, we observed that longer link distances lead to higher blocking probabilities. Our simulation does not account for regenerators, underscoring their importance for enhancing communication in actual networks.

VI. CONCLUSIONS AND FUTURE WORK

In this work, we presented an enhanced SIMON simulator with EDFA as amplifier. We implemented different modulation formats for coherent communication and provided an in-depth comparative analysis of Direct/Coherent Optical Networks, evaluating key metrics such as blocking probability, efficiency, and reliability. In our future research, we aim to expand SIMON's capabilities by incorporating additional amplifier models, such as Semiconductor Optical Amplifiers (SOA). We also intend to examine the impact of using regenerators in optical networks. Additionally, we plan to investigate the potential of applying machine learning techniques within the simulation environment.

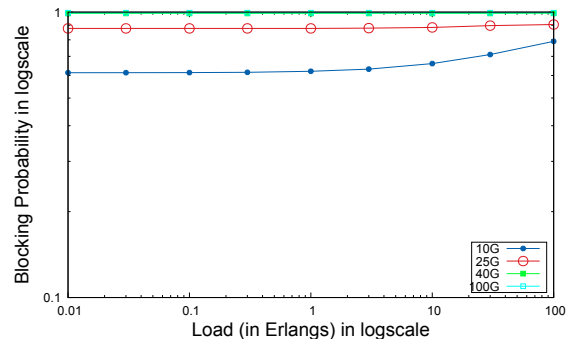


Fig. 9: Blocking probability for RailTel Network for OOK at different symbol rates.

VII. ACKNOWLEDGEMENTS

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