Integrating Optical and Mobile Networks: A Comprehensive End-to-End Simulation Platform

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***Abstract*—Communications are crucial in human interactions, the economy, education, and accessing and democratizing various services and information. With a vast physical infrastructure deployed, optical networks have been fundamental in end-to-end broadband communications. They are considered the foundation for future communications in modern society. Next-generation optical networks are expected to provide broadband services with massive capacity, lower latencies, and improved reliability, supporting various ultra-high bandwidth applications: cloud/edge networking, 8K video services, and digital twins. Optical networks have been playing an increasingly important role in mobile communications. They will be key for 5G/6G networks, given their bandwidth, coverage, synchronization, and low latency requirements. Various technologies are being developed for the convergence of optical-mobile networks to enhance performance, improve energy efficiency, and simplify the network's design, implementation, and operation. Researchers, vendors, and operators must be able to evaluate these new solutions effectively. They require a robust simulation framework that seamlessly implements the mobile and optical domains and their interactions. As far as we know, no open-source simulator has fulfilled these requirements to date. For this reason, in this paper, we present an optical-mobile unified simulation platform that addresses the convergence of 5G/6G technology and optical networks. This tool enables academia and industry members to test new optical-mobile network architectures and end-to-end (multi-technology domain) algorithms for dynamic resource allocation or restoration, advancing the capabilities and understanding of next-generation network technologies.**

***Index Terms*—5G, 6G, Network Simulation, Optical-Mobile Networks.**

I. Introduction

We are in an era where traffic growth, driven by high-definition video streaming, multimedia file sharing, and other information technologies, is increasing faster than the system's capacity. Mobile and optical communications are integral to everyday life in today's society. Not only does day-to-day communication rely on it, but industrial and critical applications also require a stable and reliable network. For instance, self-driving vehicles and remote surgical procedures demand low latency and reliable networks. It is estimated that in the near future, more than 30 billion devices will be connected to a 5G-enabled Internet of Things [1]. This combination of broadband services and a vast scale of end devices connected to the network will soon lead to high demand for optical network capacity that supports the 5G/6G infrastructure [2].

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Establishing test environments for controlled experiments before commercial integration is essential, enabling the exploration and validation of novel solutions [3]–[6]. For operators, developers, and academics, simulators, and testbeds are crucial, providing platforms to test mobile and optical networks' capabilities and limitations. A multi-domain simulation framework, covering mobile and optical aspects, is vital for evaluating solutions pre-deployment, automating processes, and using machine learning with realistic data, ultimately saving costs and improving design [7].

Some open-source simulators centered in 5G networks are available [8]–[10]. They are discrete event simulators that enable users to experiment with realistic scenarios of 5G networks to varying degrees. These simulators do not consider the aspects corresponding to the optical network and even less so considering elastic optical networks. If one wishes to model these aspects, simulators devoted specifically for that purpose should be used [11]–[13]. As far as we know, no open-source end-to-end simulator allows users to test 5G and optical networks simultaneously. In this paper, we introduce a unified optical-mobile simulation platform that facilitates the convergence of 5G/6G technology and optical networks. This tool allows academics and industry professionals to evaluate new optical-mobile network architectures and end-to-end, multi-technology domain algorithms for dynamic resource allocation and restoration, enhancing the capabilities and comprehension of next-generation network technologies.

The rest of this paper is structured as follows. In section II, the existing 5G simulator used in this project is introduced. We also present the main characteristics of our optical simulation environment. Additionally, the general characteristics of the end-to-end simulation platform are presented in section III. A summary of the experiments demonstrating the tool's functionality is provided in section IV. We conclude our work in section V.

II. Simulators: characteristics and architecture

A. Platform and libraries

Different platforms were evaluated to create an easy-to-use end-to-end simulator. Simu5G [9] stood out because of its characteristics. It has a wide set of options that can be configured, such as numerologies and carrier aggregation; it also counts with a user-friendly display. It enables the simulation of network scenarios where 4G and 5G coexist, both in StandAlone (SA) implementations and E-UTRA/NR Dual Connectivity (ENDC), which will be predominant in the near future.

Simu5G is a library inside the simulation environment OMNeT++ [14]; consequently, it carries all of its advantages. It is based on the object-oriented programming paradigm, which allows for a simple way of using the already implemented functionalities and adding new ones. It enables the depiction of realistic scenarios for studying performance and behavior in communication systems. In addition, it introduces a graphical simulation tool to visualize various simulations and employs sophisticated methods for statistical calculations. Being part of the OMNeT++ platform introduces the advantages of compatibility and interoperability with the other libraries it contains. For instance, INET Framework [15] includes common protocols, agents, and other models particularly useful for communication networks.

With the Simu5G and INET libraries, the mobile part of the end-to-end simulator can be easily implemented. Consequently, we focused on the optical network implementation and its subsequent adaptation and integration with the rest of the communication network. This allowed for creating different architectures and a clear path for future implementations.

B. *OpticalNetworks*

OpticalNetworks is the library developed in this paper to implement the different aspects of the optical domain. It is built on top of OMNeT++. It is defined by various modules, each playing a crucial role in its operation. These modules will be detailed below.

The first element needed is a module that creates traffic to travel through the optical network. *TrafficGenerator* was created for this purpose and will be followed by an *OpticalTransmitter*. The *TrafficGenerator* is used when simulating a purely optical network. As will be seen later, when integrating with Simu5G, this traffic generator is unnecessary, as the traffic routed through the optical network originates from or is destined for the mobile network. The *OpticalTransmitter* is responsible for transferring traffic to other modules (usually through an *OpticalFiber*), which will enable the data to continue its journey through the optical network. *OpticalFiber* block simulates an optical fiber. Even though OMNeT++ allows the use of personalized channels, a module was chosen instead to simulate a fiber. This was done to simplify certain operations and the acquisition of parameters. *OpticalFiber* connects various optical devices such as switches, transmitters, and receivers. To calculate certain parameters like delay and effective throughput, *OpticalReceiver* was created. This block simulates the behavior of an optical receiver. It was designed to be used in a fully optical context.

To send the messages to the correct destination and to check consistency on the switching tables, the *OpticalSwitch* was created. This block can have several input and output gates connected to an *OpticalFiber* and is responsible for the routing on the optical network. In this first stage of development, the

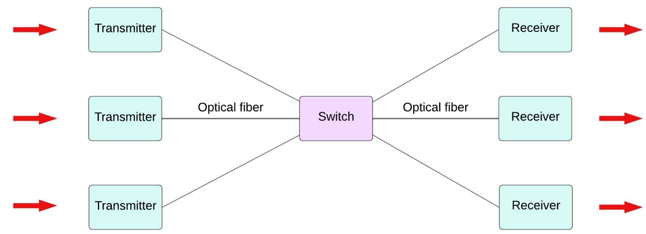

Fig. 1. Example of a fully optical network that can be implemented with the blocks designed in OpticalNetworks.

OpticalSwitch needs to receive the corresponding wavelength mapping to the corresponding output gate as input. A similar block was implemented called *OpticalSwitchFlexi*. This block implements the same functionalities as the *OpticalSwitch* but allows messages to have variable wavelengths. In this case, when a new mapping on the switching table needs to be added, the block checks for enough space available in the spectrum.

With the described blocks, somewhat complex architectures can be built, like the one in Fig. 1. In this figure, each *OpticalTransmitter* is connected to a *TrafficGenerator*, which is the source of the messages that go through the network. The *OpticalSwitch* has several transmitters connected and can switch the message to the corresponding destination accordingly.

III. MOBILE-OPTIC INTEGRATION

To achieve end-to-end simulations encompassing both optical and mobile domains, it was necessary to develop a new structure facilitating communication between the Simu5G blocks and the OpticalNetworks blocks. The mobile domain contains elements that create traffic of their own, such as gNodeB (gNB) or user equipment (UEs), which means that the *TrafficGenerator* is not needed in a mobile-optical topology. The natural way to pass the mobile traffic through the optical network is to connect the gNB with the *OpticalTransmitter*. However, the messages transmitted through the OpticalNetworks network contain specific values representing the physical characteristics of the involved elements, enabling the calculation of relevant network parameters. Therefore, they differ from those used in Simu5G. Ultimately, a translation between the two worlds is required.

To allow a correct communication between both domains, a new block was created. This block, “Node”, performs mobile-optic translation and vice-versa. Two Node blocks are needed since the optical network is used in the SP architecture. Once is placed between the gNB that transmits information and the optical network (in charge of mobile-optic translation) and the other one between the optical network and the receiving gNB (in charge of the optic-mobile translation). This is shown in Fig. 2.

The whole message received from the gNB is encapsulated in a new message to enable a correct translation of mobile messages. The corresponding parameters are added to allow the message to go through the optical network without

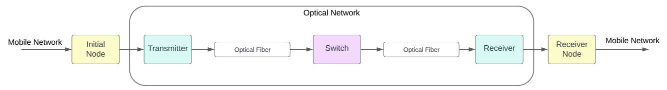

Fig. 2. Example of an end-to-end network showing the connections of the Nodes with the OpticalNetworks network.

affecting the encapsulated content. At the other end of the optical network, the *OpticalReceiver* was modified so that messages are not discarded after calculating the relevant data but are sent to the Node. This Node is in charge of extracting the encapsulated message and sending it to the receiving side of the mobile network. This makes the optical network transparent for mobile devices, and data can go from one UE to another. This allows the calculation of relevant parameters inside the optical network and of the end-to-end network as well.

IV. Experimentation and Results

Full end-to-end architectures were implemented, integrating mobile and optic domains. Experiments were conducted within different topologies to analyze delay, throughput, and lost packages. These values were calculated within the optical network and for the end-to-end topology, allowing us to know the delay in the mobile network as well (the translations are assumed to take a negligible amount of time).

It is worth emphasizing that the optical network implemented contemplates only unidirectional communication. To allow UEs to exchange messages between each other, two optical networks were needed, one for each possible direction of the messages. Since messages do not go through the same optical network in both directions, different delay values, throughput, and lost packages can occur. To avoid this unfair comparison, the values are calculated for each packet similarly, regardless of its path. In some simulations, only a one-way path is considered.

To demonstrate and evaluate the performance of the end-to-end multi-domain technological simulation tool, experiments corresponding to different simulations were carried out, and two will be presented. The results will be shown and briefly analyzed. However, the objective of this section is not to view the performance of the network itself but to show that the simulation tool works correctly.

A. First simulation: one-way path

Only one path is considered in the first simulated case (see an example in Fig. 3). The simulation consists of 15 UEs sending different types of traffic (uplink traffic). At the start of the simulation, only one UE sends VoIP traffic. After approximately 0.2 seconds, another 14 UEs start sending CBR traffic and stop at the simulation time of 1.5 seconds. The UE sending VoIP traffic never stops sending messages until the simulation ends.

In Fig. 4, a scatter plot is used to visualize better when messages arrive and how long it takes from their creation time.

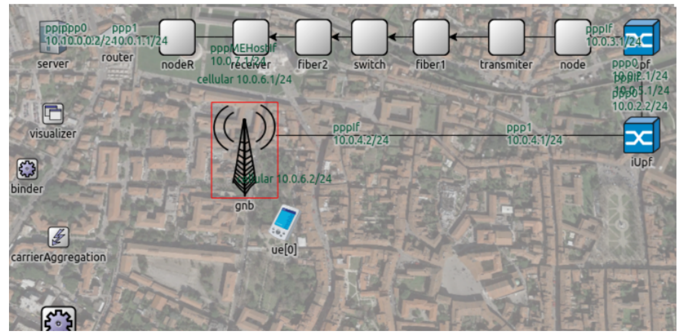

Fig. 3. Example of one-way path topology (OMNeT++ graphical interface). In this topology, one UE is represented.

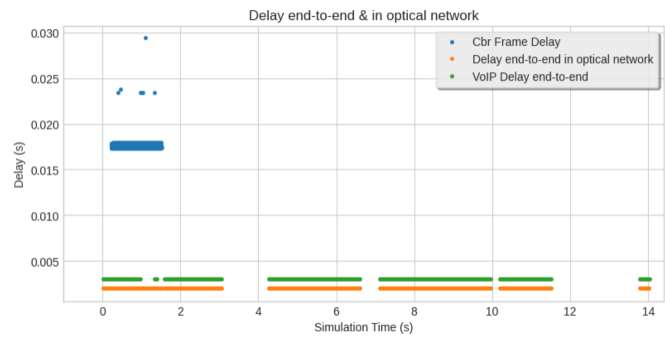

Fig. 4. Graph showing the end-to-end delay and the optical network delay for both traffic profiles: VoIP and CBR.

Additionally, it compares the delay in the optical network, which refers to the time from when the message enters the optical network until it exits. Observing the graph, the first noticeable aspect is that neither the end-to-end delay nor the optical network delay increases significantly, and both remain almost constant in VoIP. It is worth noticing that the delay is higher in the case of end-to-end, which makes sense considering that traffic has to go through a longer path. On the other hand, the CBR delay is slightly higher and varies a bit more during the period of higher traffic.

Given that the delay is almost constant throughout the simulation and the size of the packages does not vary throughout its duration, the throughput behaves very similarly. This means that the graph shows an almost constant curve in the case of VoIP traffic. This result also makes sense and shows that the throughputs are correctly calculated.

B. Second simulation: two-way path

This simulation was done in the case in which messages are sent from UEs on one side of the optical network to UEs on the other and vice versa. It aims to analyze how the values of delay and throughput vary when the network is congested. In this scenario, the traffic-sending UEs send only VoIP traffic, but in this case, the inter-arrival time of packets will be varied. At the start of the simulation, only one UE sends traffic in the form of packets of 300 bytes. This is done with an inter-arrival time of 0.01 seconds. After approximately 2.2 seconds,

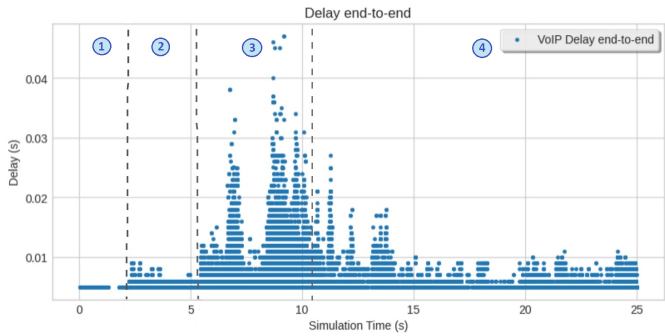

Fig. 5. Graph showing the delay of the congested UE.

another 4 UEs begin sending traffic with packets of 600 bytes at a frequency of 0.005 seconds, doubling the packet size and the transmission speed. Additionally, at 5.4 seconds of the simulation, another 5 UEs start sending traffic in the form of 600-byte packets but further decrease the inter-arrival time to 0.001 seconds. Up to this point, all the traffic is directed towards the same UE to congest it as much as possible and analyze the results. Finally, at 10.6 seconds of the simulation, the remaining 10 UEs start sending 600-byte packets with an inter-arrival time of 0.0005 seconds to different UEs (and different from the already congested one).

In Fig. 5, the delay of the congested UE is presented. It should be noted that the graphs have been divided into segments to visualize better when the traffic increases. A total of four segments that correspond to the four different instances described above are distinguished. This means that in each division, new devices start sending packets toward the analyzed UE. In the last segment, the traffic in the network is increased, but the traffic towards the analyzed UE is maintained. It is observed in 5 that the delay starts at low values in the first segment but then increases slightly in the second segment as more packets arrive with shorter intervals. When the third segment begins, the delay varies much more, even reaching values four times higher than in the first segment. This is due to the much higher traffic volume received. Finally, in the fourth segment, the delay decreased slightly, even though the traffic received by the UE had not changed. Interestingly, during this last segment, the overall network traffic increased. Intuitively, one might expect the delay to remain the same or even increase compared to the third segment. However, what actually happens is that as the network becomes saturated, many packets begin to get lost, resulting in fewer packets reaching. This is confirmed when analyzing the total packets sent and received by every UE. Consequently, the packets that do reach their destination arrive with less delay, but many other packets are lost. Once again, the simulation behavior is that of a real network, in which packets are discarded once the network reaches its maximum capacity. This shows that the end-to-end simulation platform works as expected.

V. Conclusions

The developed tool has practical applications in understanding network behavior under different resource allocation systems and in emulating various network architectures. These were the main motivations behind the tool's development. Its utility extends to evaluating resource allocation algorithms in a multi-technological approach, which can enhance the performance of optical-mobile networks in real-world scenarios.

The results obtained from this project contribute to the advancement of research and technological development in mobile and optical networks. A simulation tool for optical-mobile networks has been successfully developed, opening new possibilities for an in-depth study by providing precise statistics on the simulated networks.

The simulations conducted show that the message traffic flowed end-to-end without issues, and the whole process was transparent to the mobile network. However, the simulations could be conducted in an even more complex way to achieve results that are more faithful to reality.

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