Towards Large-Scale Wireless Network Simulations for Hybrid Data Centers

Arno Troch*, Shvan Karim†, Vinay B. Y. Kumar†, Michael Peeters*, Johann Marquez-Barja*
*IDLab, University of Antwerp - imec, 2000 Antwerp, Belgium
†imec, 3001 Leuven, Belgium

***Abstract*—The deployment of high-capacity wireless communication technologies within Data Center Networks (DCNs) holds significant potential to alleviate the issues typically associated with conventional wired DCNs, such as limited scalability, high cabling costs, and traffic hotspots. However, it is currently unclear how and in what capacity these wireless connections will be incorporated into existing DCNs. To enable extensive design space exploration, using simulation tools such as the Structural Simulation Toolkit (SST), an open-source simulation framework commonly used for modeling next-generation High-Performance Computing (HPC) systems, is required. However, most open-source tools do not provide libraries for simulating wireless DCNs. In this paper, we describe our work towards extending SST with wireless network models. Our objective is to leverage SST as a system-level network simulator capable of simulating large-scale DCN topologies and protocols with both wired and wireless communication links, allowing rapid prototyping of next-generation hybrid data centers.**

***Index Terms*—Data center networks, DCN, hybrid data center, wireless networks, modeling, simulation, parallel simulation, SST**

I. Introduction & Motivation

Data centers have traditionally relied entirely on wired network infrastructure. However, as the scale of these data centers continues to grow, the fixed and uniform nature of fully wired Data Center Networks (DCNs) poses significant challenges. The costs and complexity associated with cabling increase with the size of the cluster, and the highly dynamic traffic patterns generated by data center workloads often lead to network congestion, commonly known as hotspots [1], [2].

The integration of wireless links into DCNs has emerged as a promising solution to address these challenges. By leveraging high-frequency millimeter wave (mmWave) and (sub)-terahertz wireless links, traditional wired DCNs can be complemented with dynamic and high-capacity on-demand connectivity. However, several unsolved challenges remain in integrating wireless communication into existing DCNs, including 1) determining the optimal placement of wireless radios; 2) defining which communication types to support (inter-rack, intra-rack, etc.); and 3) developing novel network protocols that take into account the hybrid nature of the DCN.

For the design and validation of these new hybrid DCN topologies and protocols, a parallel discrete-event simulation framework such as the Structural Simulation Toolkit (SST)[1] is an extremely valuable tool. While SST is widely used to model and simulate High-Performance Computing (HPC) architectures and is therefore equipped with basic wired network models, it currently lacks wireless communication models.

[1] sst-simulator.org

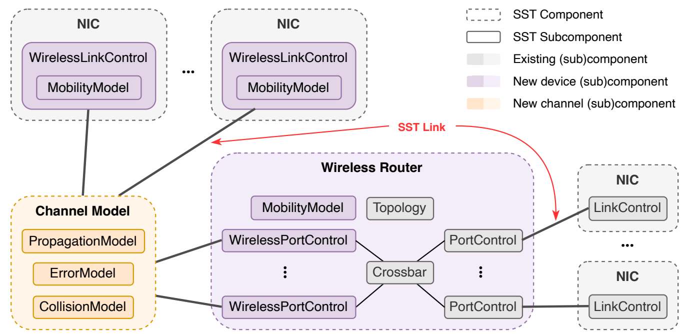

Fig. 1: Architecture of SST with wireless models and interfaces.

In this paper, we present our efforts toward expanding SST with wireless models and interfaces. The choice of SST comes from two main reasons. First, the focus on parallel simulation enables us to conduct network simulations on a much larger scale compared to existing network simulators. Past studies have shown SST's ability to handle exascale network simulations, with certain studies even simulating data center networks with more than 100 000 nodes [3]. Second, SST also offers various non-network models for simulating HPC hardware. The integration of network and hardware models within SST provides a unique platform for exploring hybrid DCNs, allowing simulation of both connectivity and compute within a single environment.

II. SST Models & Architecture

Within SST, the existing wired network module known as Merlin is often used to create Network on Chip (NoC) interconnects and to model intra- and inter-rack communication. In this section, we describe the wireless network models we created to enable wireless communication within Merlin. As shown in Fig. 1, we designed and developed several novel components and subcomponents.

- `WirelessLinkControl`/`WirelessPortControl`: based on the existing Merlin `LinkControl` and `PortControl` components, these subcomponents serve as a wireless interface for Network Interface Controllers (NICs) and routers, respectively. They enable devices to communicate over the wireless medium and implement basic physical (PHY) and Medium Access

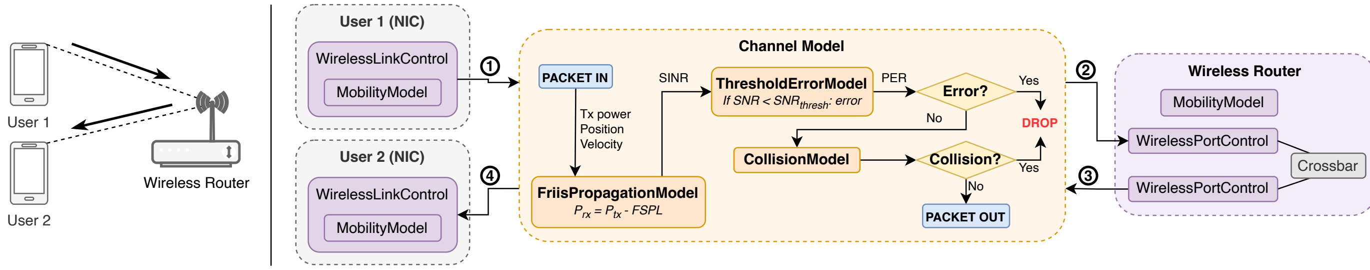

Fig. 2: Example scenario and accompanying flow diagram showing the interactions between wireless SST components and subcomponents. In the scenario shown on the left, User 1 sends packets to User 2 through the Wireless Router. The packet flow throughout the SST components is then shown on the right.

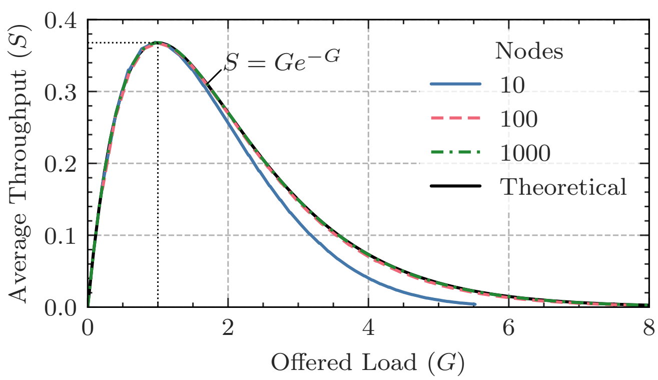

Fig. 3: Results of Slotted ALOHA simulations in SST. The results with 10 nodes show a significant deviation, which is expected, since the theoretical model assumes an infinite number of nodes. However, the results with 100 and 1000 nodes show that our system converges.

Control (MAC) layer functionality, such as packet transmission, reception, and buffer management.

- `MobilityModel`: based on existing mobility models from the ns-3[2] network simulator, we integrate the position and velocity of wireless devices for use in the channel model.
- `ChannelModel`: the channel model component represents the wireless medium. It performs calculations for path loss, packet reception errors, and packet collisions through the `PropagationModel`, `ErrorModel`, and `CollisionModel` subcomponents, respectively.

Fig. 2 provides a more detailed overview of the currently implemented channel components, as well as the interactions between them. The `FriisPropagationModel` computes the received power of a packet based on the Friis transmission equation, which is then used to calculate the Signal to Interference plus Noise Ratio (SINR). The `ThresholdErrorModel` then checks for packet errors based on this SINR, by checking whether it exceeds a predefined threshold value. Finally, using the knowledge of all packets transmitted over the channel, the `CollisionModel` checks for packet collisions at each receiver.

[2]nsnam.org

III. Preliminary Results

To validate our wireless models, we conduct preliminary simulations using a slotted ALOHA system and compare the results with the expected theoretical throughput. Our experimental setup resembles the scenario depicted in Fig. 2, with multiple users connected to a wireless router, operating on a shared channel. For each simulation run, we use a channel frequency of 2.4 GHz with 1 MHz bandwidth and transmit 100 packets of 1 B (same as the slot size) from each user to the wireless router. We vary the number of users $N \in \{10, 100, 1000\}$ and the packet arrival rate, following a Poisson distribution with parameter $\lambda \in \{0.2, 0.3, \ldots, 8\}$, across simulation runs. Then, using the statistics embedded in our channel model, such as the number of successful receptions and the number of collisions, we capture both the offered load G over the channel and the relative average throughput S. The resulting curves shown in Fig. 3 for 10, 100, and 1000 users validate the correctness of our wireless system, as they converge towards the theoretical curve with increasing users.

IV. Conclusion & Future Work

Our work lays the foundation for performing wireless network simulations with SST, thus advancing the development of a system-level network simulator for hybrid data centers.

Moving forward, we will focus on further expanding the simulator's wireless capabilities. This includes incorporating directional antenna models to enable simulations at mmWave and (sub-)terahertz frequencies, integrating small-scale fading into the channel model, and expanding the PHY/MAC capabilities of the wireless devices.

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