5G-IoT Architecture for Next Generation Smart Systems

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2021 IEEE 4th 5G World Forum (5GWF) | 978-1-6654-4308-1/21/$31.00 ©2021 IEEE | DOI: 10.1109/5GWF52925.2021.00049

***Abstract*—Next Generation 5G networks are of prime importance to meet the increasing demands of emerging IoT applications and industry verticals for high throughputs and ultra-reliable low latency communication. Future IoT services also require high scalability and Internet connectivity for a wide range of applications, including various mobility scenarios. Communication systems developed so far have not been able to fully address the requirements of IoT applications. However, 5G has the capability to satisfy these needs and provides key enabling technologies for ubiquitous deployment of the IoT technology. We propose and evaluate a novel 5G-IoT architecture using Simu5G network simulator for enabling future IoT systems to support next generation applications. The proposed 5G-IoT architecture is shown to achieve high throughputs of around 1 Gbps with sub-millisecond latency and ultra-high reliability for scalable next generation smart systems.**

***Index Terms*—5G, IoT, emerging applications, enhanced Mobile Broadband, Ultra-Reliable Low Latency Communication, massive Machine Type Communication, architecture, Network Simulator, Simu5G**

I. Introduction

Internet of Things (IoT) is an emerging and promising technology with the potential to revolutionize the global world through connected physical objects. There were over 1.6 billion cellular IoT connections in 2020, and in a recent study, Ericsson forecasts that there will be around 5.4 billion connections by 2026 [1]. Research shows that a large majority of these devices will be connected by cellular technologies such as 4G and 5G, which are currently being used for IoT but are not fully optimized for IoT applications. Thus, the next generation of cellular networks needs to address the increasing traffic demands of such future applications and industry verticals. The fifth generation (5G) mobile network, in particular, aims to address the limitations of previous cellular standards and will be a key enabler for future IoT. However, 5G systems developed so far have not been able to fully address the needs of IoT applications, such as simultaneously achieving high reliability, low latency, and high data rates.

3GPP specifies three different classes of services: Ultra-Reliable Low Latency Communication (URLLC), enhanced Mobile Broadband (eMBB), and massive Machine Type Communication (mMTC). Thus, 5G-IoT use cases can be classified into three categories: critical IoT, broadband IoT, and massive IoT. Critical IoT requires high reliability and very low latency and includes applications such as industrial automation (Industry 4.0), tactile Internet, medical diagnosis, robotic surgery, etc. Broadband IoT requires high throughput and capacity, and examples of such applications are AR/VR, Ultra High Definition (UHD) video streaming, among others. Massive IoT needs scalability and includes applications such as smart cities, remote monitoring, etc. Additionally, IoT requires high scalability and Internet connectivity for a wide range of applications.

5G networks are of prime importance to realize the needs of the future IoT. It enables us to leverage its attributes, such as high bandwidth, low latency, high reliability, and massive connectivity, which are critical for IoT. The 5G New Radio (NR) [2] is a new air interface developed by 3GPP and operates over two frequency ranges, FR1 (sub-6 GHz) and FR2 (above 24 GHz). Massive data rates can be provided by the large amount of spectrum in the mmWave bands along with massive MIMO. On the other hand, using sub-6 GHz, 5G can provide higher coverage and expand the connectivity of IoT devices for various mobility scenarios. 5G can support large numbers of IoT connections with higher data rates, and better coverage [3]. Furthermore, IoT devices are often resource-constrained with low computational and energy capabilities.

To address these requirements, we develop a 5G-IoT architecture where an NR UE is enhanced to act as an IoT gateway that manages the data flow between IoT devices and the 5G base station. Using the UE as an IoT gateway improves the mobility and coverage of the network. Multiple UE/IoT gateways can be connected to a base station to maximize the benefits of 5G networks. Additionally, multiple IoT devices can be connected to an IoT gateway over wired Ethernet links to ensure higher reliability and security with low latency. In this work, we implement and evaluate the performance of such a scalable 5G-IoT system, which enables high throughput along with high reliability and low latency. We study the performance of such a system using Simu5G [4], which is a 5G simulation library based on the OMNeT++ framework [5]. Using Simu5G, we simulate the data plane of an end-to-end standalone 5G network that transmits packets between a remote server via the User Plane Function (UPF) in the 5G core and a UE that is connected to a gNodeB. Throughput, latency, and packet loss were used as metrics to evaluate the performance of the system. Also, the impact of scalability, mobility, numerologies, etc., was investigated for these networks.

The major contributions of this paper are summarized as follows:

- We propose a novel architecture for a 5G-IoT system

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DOI 10.1109/5GWF52925.2021.00049

using Simu5G network simulator, which has not been addressed by any prior work.
- We systematically evaluate and make improvements to the architecture, which improves the performance of the system.
- Finally, we validate the proposed architecture and achieve significant improvements for 5G enabled IoT use cases with realistic, scalable applications and mission-critical scenarios.

The remainder of the paper is organized as follows. Section II discusses the related work done in the areas of 5G-IoT and 5G network simulators. We present a novel 5G-IoT architecture with the simulation environment in Section III. Section IV evaluates and validates the performance of our 5G-IoT architecture for scalable, high throughput, and ultra-reliable low latency applications. Section V concludes the paper.

II. Related Work

IoT architecture in a 5G system is shown in Figure 1. In [6], [7], the authors discuss a 5G IoT architecture where smart IoT sensors for different applications could be connected to an IoT gateway through different wired and wireless networks. This gateway has the task of collecting and forwarding all the information between the IoT devices and the 5G base stations through a wireless link. 5G communication links provide the much needed URLLC and eMBB capabilities to the IoT system through the use of 5G NR technology with efficient numerology selection and mmWave communication technology [8]. However, network mobility, coverage, and reachability remain open research areas that needs to be addressed for ubiquitous communication. Also, as discussed by authors in [9], 5G standards are still evolving to address the challenges related to scalability, latency, and reliability. In [10], the authors discuss that achieving stringent performance requirements for diverse IoT applications is a major challenge to be resolved. Thus, there is a critical need for studying and developing the systems that provide these capabilities.

Given the wide range of services and performance offered by 5G networks, it is paramount that any development and study of 5G system is done on a platform that offers end-to-end simulation capabilities. Building a real-world cellular network for testing is often associated with infrastructure complexities. The Platforms for Advanced Wireless Research (PAWR) program has helped build one such wireless testbed at the University of Utah in Salt Lake City called POWDER [11], that offers a remotely accessible end-to-end software-defined platform to conduct such research. However, discrete-event network simulators offer a better and more scalable alternative for analyzing complex networks and developing new protocols. In this paper, we develop a 5G-IoT architecture by extending the functionality of the Simu5G simulator that provides a 3GPP compliant 5G simulation model library based on the OMNeT++ framework. Such end-to-end network simulators are great for performance analysis of 5G systems as they allow full-stack simulation using models for every

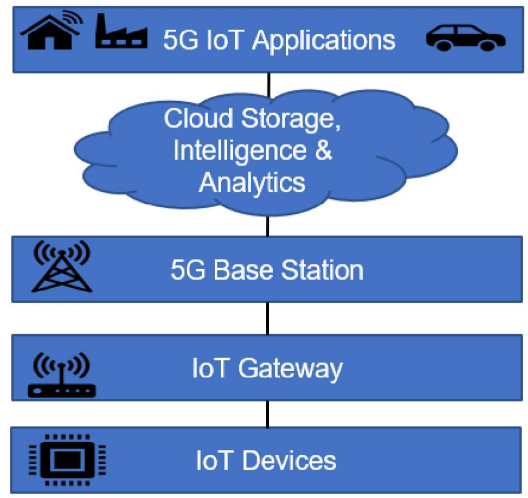

Fig. 1. 5G-IoT Architecture

layer of the protocol stack, network equipment, as well as application logic. This ability to simulate the whole network stack plays a crucial role in understanding many new features of 5G networks.

Along with OMNeT++, another widely used network simulation framework is ns-3 [12] that allows users to develop their own model libraries. Apart from Simu5G, which is based on the OMNeT++ framework and discussed in more detail in the next section, the other popular end-to-end simulation tools for 5G networks are based on ns-3. The 5G-LENA [13] model library uses the ns-3 framework and builds upon the LENA (LTE-EPC Network Simulator) 4G LTE library [14]. However, the 5G-LENA library mainly focuses on implementing the MAC and PHY layers of the 5G network stack. The ns-3 mmWave module [15] was developed before 3GPP 5G standards were finalized and thus is not fully compliant with the current standards. Also, both 5G-LENA and mmWave modules only support the Time Division Duplexing (TDD) mode. Thus, in our work, we develop a novel 5G-IoT architecture using Simu5G, which is a 3GPP compliant 5G network simulator.

III. 5G-IoT Architecture and Simulation Environment

This section briefly discusses the OMNeT++ framework and the Simu5G model that can be used for 5G New Radio (NR) user plane simulations. We also discuss the specifics of the proposed architecture to support IoT experiments in the 5G system along with our simulation design.

Simu5G is built on a widely used discrete-event simulation framework called OMNeT++ that can be used to model both wired and wireless networks, among others. *Modules* are the basic building blocks in the OMNeT++ framework and can be simple modules, or they can be combined to create more complex compound modules. They can also be linked through their interfaces called *gates* with links that are

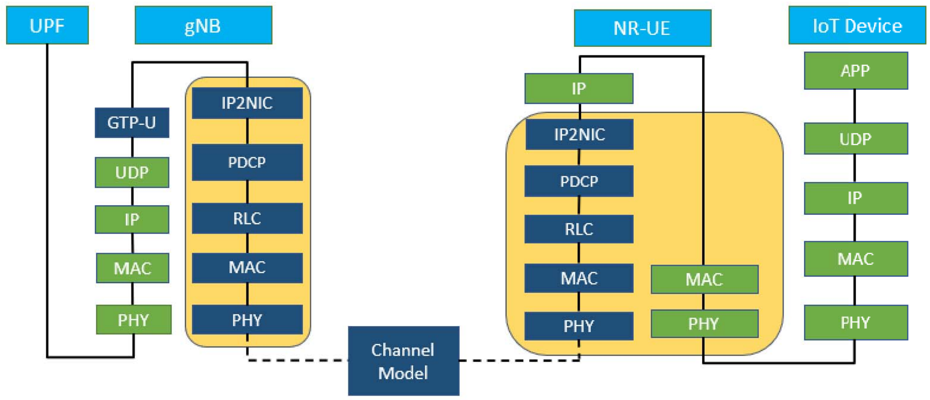

Fig. 2. 5G-IoT Architecture using Simu5G

known as *connections*. Modules use *messages* to communicate with each other, and simple modules are programmed to exhibit a specific behavior on receipt of these messages. This model behavior is written and programmed in C++. OMNeT++ uses NED or Network Description language to define the modules along with their gates and connections. The parameter values needed to initialize a model are defined in an initialization (INI) file. It also provides an Eclipse-based Integrated Development Environment (IDE) to facilitate editing and debugging. Simu5G makes use of the popular INET model library in OMNeT++ that implements models for various communication protocols, network nodes, connections, among others. Thus, by leveraging features of the OMNeT++, INET, and Simu5G libraries, one can simulate complex end-to-end scenarios using different networks with 5G systems.

Figure 2 shows the 5G-IoT Architecture using Simu5G. The NR capabilities of the 5G RAN in Simu5G are simulated in two main compound modules NrUe and gNodeB. The functionalities of the RAN are implemented as a stack of four protocol layers, which are the Packet Data Convergence Protocol (PDCP) layer, Radio Link Control (RLC) layer, Media Access Control (MAC) layer, and Physical (PHY) layer. Thus, the NrUe and gNodeB modules consist of four sub-modules (NrPdcp, NrRlc, NrMac, NrPhy), each representing a layer in the protocol stack. They also consist of an Ip2Nic submodule that can act as a bridge between the IP layer and the PDCP layer. The five submodules combined together make a compound module called NrNic representing the radio network interface. The NrUe module also implements the upper layers (UDP and IP layers) of the protocol stack using the INET library.

The Simu5G model library offers highly realistic and customizable channel models for modeling physical transmission. The carrierAggregation module in Simu5G can be used for simulating communication on multiple carrier component frequencies. We can vary key parameters like the carrier frequencies, bandwidths, number of resource blocks, etc., using the NED and INI files. Using this module, we can also adjust the numerology that varies the subcarrier spacing and the slot duration of 5G signals which is critical for enabling URLLC and eMBB services.

As part of the 5G core implementation, Simu5G provides a UPF module that is responsible for routing IP packets between the data network and the gNodeBs through the GTP (GPRS Tunnelling Protocol) tunnels. The UPF module can be directly connected to a gNodeB resulting in the standalone architecture deployment scenario.

The 5G-IoT architecture, as shown in Figure 1 consists of a mobile IoT gateway that can be used to connect the 5G base station to the end IoT devices, which often have very constrained capabilities. These gateways could also perform data aggregation on the packets coming from the various sensors, actuators, etc., in the IoT network [8]. The radio functionalities of the IoT gateway closely resembles that of a UE module in the 5G system. However, the gateway has the additional responsibility of forwarding packets to and from the IoT devices that are attached to it. As discussed above, the Simu5G library implementation of the NrUe module includes only the radio interfaces and lacks additional network interfaces for connecting to IoT devices in the network. Hence, the NrUe module was extended, and wired network interfaces were added parallel to the existing radio interface as shown in Figure 2. We also introduce a new compound module to represent the IoT devices attached to the IoT gateway. This new module emulates the protocol stack of a standard host module in INET. It also includes a novel submodule responsible for associating itself with a gNodeB and registering its IP address in the system. Our implementation is capable of handling multiple IoT gateways with multiple IoT devices connected over Ethernet links for network scalability and performance.

The standard implementation of Simu5G uses the address of the destination UE at the UPF to find out the connected gNodeB in the downlink direction. The UPF then uses this gNodeB address as the tunnel end-point identifier (TE-ID) to create the GTP-U tunnel. However, in an IoT scenario, the end devices are no longer the UEs but are the IoT devices that have no direct connection to the gNodeBs as shown in Figure 3. Thus, the system is enhanced such that each IoT device in the system has an associated gNodeB, depending on the IoT gateway/UE to which it is connected. The UPF can now know which IoT device is connected to which IoT gateway and hence to which gNodeB. Also, the gNodeB uses the information about its connected IoT gateways/UEs for scheduling in the MAC layer but does not have information about the IoT devices. Thus, the system is further developed, such that the gNodeB can now know which IoT device is connected to which IoT gateway and can use that information for scheduling. We also enable IP layer forwarding at the IoT gateway such that the packets are routed to the correct IoT device.

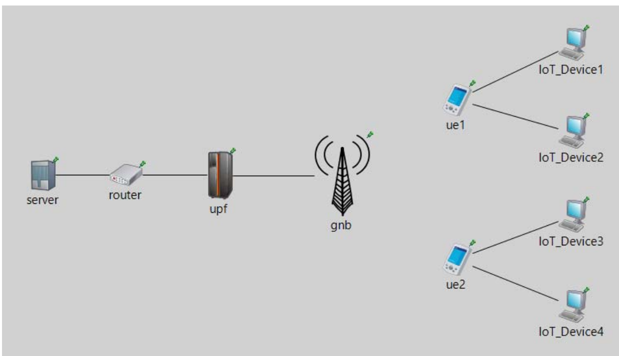

Fig. 3. Example of a Simu5G simulation scenario with two IoT gateways each connected to two IoT devices

IV. Evaluation

Systematic evaluation of the 5G-IoT system was conducted for critical IoT, massive IoT, and broadband IoT type applications. We simulate a standalone 5G architecture where the gNodeB is connected to the UPF in the 5G core network. A server is connected to the UPF via a router and sends data packets to the IoT devices in our system using their IP addresses. IoT devices are connected to the 5G system through an IoT gateway. For evaluating the system, parameters like frequency, bandwidth, packet size, packet interarrival time, number of IoT devices in the system, number of UEs, and numerology index were varied. Stationary as well as mobile IoT systems are considered, where the IoT gateways/UEs along with the attached IoT devices are both moving at the same speed. The UE is located at (500m, 350m) for the stationary use cases, and the coordinates for the gNodeB are (450m, 300m). Additional simulation parameters are provided in the sections below.

A. Critical IoT

The system was evaluated for critical IoT type of applications. Latency and packet loss were used as metrics to evaluate the performance of the system. Experiments were conducted for both stationary and mobile UEs. For the mobile scenario, the UE moves along the x-axis with the initial and final coordinates being (500m, 350m) and (1000m, 350m), respectively. The simulation parameters are shown in Table I.

TABLE I
SIMULATION PARAMETERS FOR CRITICAL AND MASSIVE IOT USE CASES

Parameter	Value
Carrier frequency	2 GHz
Bandwidth	0.5 MHz
UDP Packet Size	32 B
UDP Packet Interarrival Time	1 ms

The experimental results indicated that the proposed 5G system achieved ultra-high reliability and very low latencies for varying numerologies, as shown in Table II. The numerology values were chosen to be 0, 1, 2, and 3, corresponding to subcarrier spacings of 15 kHz, 30 kHz, 60 kHz, and 120 kHz, respectively. The system is able to realize sub-millisecond latency of 0.68 ms for a numerology value of 3. High reliability with zero packet loss and low latencies is observed for all the numerologies. Additionally, the latency and reliability improve with an increase in numerology. The latency improves significantly by 93.50 % for a numerology value of 3 as compared to a numerology value of 0. It is shown that the system can address the stringent requirements for URLLC, which needs a reliability of 10^{-5} in terms of packet loss rate for a 32-byte packet with a user plane latency of 1 ms. System is also evaluated for mobility scenarios for a numerology value of 3 with UE speeds at 5 m/s, 10 m/s, 15 m/s, and 20 m/s, as presented in Table III. As the speed increases, a slight increase in latency is observed. The system performs well for all the mobility scenarios, and zero packet loss with very low latencies is observed.

TABLE II
LATENCY AND PACKET LOSS FOR VARYING NUMEROLOGIES WITH 10 STATIONARY UES

Numerology	Latency (ms)	Packet Loss (Ratio)
0	10.46	0
1	3.40	0
2	1.45	0
3	0.68	0

TABLE III
LATENCY AND PACKET LOSS AT VARYING SPEEDS WITH 10 MOBILE UES FOR A NUMEROLOGY VALUE OF 3

Speed (m/s)	Latency (ms)	Packet Loss (Ratio)
5	0.6987	0
10	0.7028	0
15	0.7029	0
20	0.7042	0

B. Massive IoT

The system was also evaluated for massive IoT type of applications. Latency and packet loss were used as metrics to evaluate the performance of the system. The simulation parameters are shown in Table I. Experiments were conducted by varying the number of IoT gateways/UEs and IoT devices up to 50 in the 5G system, for a numerology value of 3. Here, a single IoT device is attached to each IoT gateway. As shown in Table IV, zero packet loss with very low latencies is observed for the network. The latency increases with an increase in the number of UEs, but still remains below 2.3 ms for up to 50 UEs.

TABLE IV
LATENCY AND PACKET LOSS WITH VARYING NUMBER OF UES FOR A NUMEROLOGY VALUE OF 3

Number of UEs	Latency (ms)	Packet Loss (Ratio)
10	0.68	0
20	0.88	0
30	1.22	0
40	1.69	0
50	2.29	0

Additionally, the system was also evaluated for scenarios with multiple IoT Devices connected to multiple IoT gateways, for a numerology value of 3. Two scenarios were tested, the first one with a single IoT gateway and the second one with two IoT gateways. In both cases, the number of IoT devices attached to the gateways were varied up to 20 to measure the average latency of the system. High reliability with zero packet loss and very low latencies is observed as shown in Figure 4. The latency increases with an increase in the number of IoT devices but still remains below 2.7 ms for the one IoT gateway scenario and below 3.8 ms for the two IoT gateways scenario. Additionally, for any number of IoT devices, the system with one IoT gateway gave lower latencies than the system with two IoT gateways. Thus, the system performs well with scalability and achieves high reliability with zero packet loss and very low latencies.

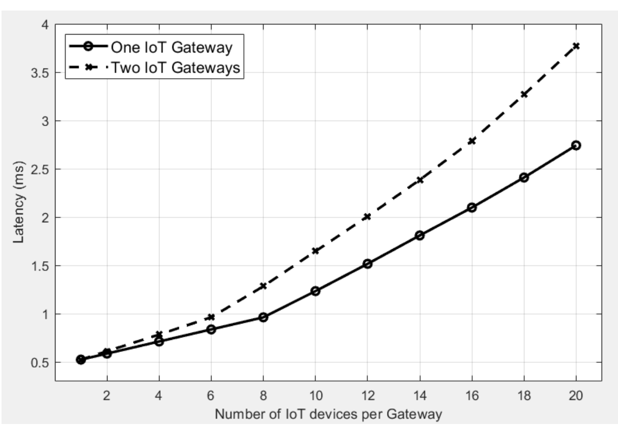

Fig. 4. Latency with varying number of IoT devices connected to one and two IoT gateways for a numerology value of 3

C. Broadband IoT

The performance of the 5G-IoT system was also evaluated for broadband IoT type of applications. Applications with large packet sizes and low packet interarrival times, were considered for these experiments. Throughput, latency, and packet loss were used as metrics to evaluate the performance of the system. The simulation parameters are shown in Table V.

TABLE V
SIMULATION PARAMETERS FOR BROADBAND IOT USE CASES

Parameter	Value
Carrier frequency	28 GHz
Bandwidth	100 MHz
UDP Packet Size	4096 B
UDP Packet Interarrival Time	0.05 ms, 0.03 ms

The system was first evaluated for varying numerology values with a stationary UE and a packet interarrival time of 0.05 ms. It is observed that the system is able to achieve high throughputs of up to 657.11 Mbps with a latency of 0.58 ms and a packet loss of zero, as shown in Table VI. The latency improves significantly by 87.28 % for a numerology value of 3 as compared to a numerology value of 0. This enables it to meet the requirements for eMBB applications, which require a user data rate of 100 Mbps with a user plane latency of 4 ms. Additionally, it is observed that increasing the numerology value improves the performance of the system.

Simulations were also conducted for a stationary UE with a packet interarrival time of 0.03 ms for varying numerology values. As shown in Table VII, the system is able to achieve very high throughputs of 1036.39 Mbps with a latency of 16.1 ms and a packet loss of 0.01 for a numerology value of 0. A decrease in the packet interarrival time results in higher throughput for the system, as more data can now flow through the system. As the numerology value is increased up to 3, further improvement is seen for the throughput, latency, and packet loss. The throughput increases to 1095.02 Mbps with a latency of 0.59 ms and zero packet loss for a numerology value of 3. The latency improves significantly by 96.34 % as compared to a numerology value of 0. Thus, the system is able to meet the stringent requirements of ultra-fast speeds with ultra-high reliability and very low latency.

TABLE VI
THROUGHPUT, LATENCY AND PACKET LOSS FOR VARYING NUMEROLOGIES WITH A STATIONARY UE FOR A PACKET INTERARRIVAL TIME OF 0.05 MS

Numerology	Throughput (Mbps)	Latency (ms)	Packet Loss (Ratio)
0	643.87	4.56	0
1	650.92	2.30	0
2	654.89	1.16	0
3	657.11	0.58	0

The 5G-IoT system developed performed well for scalable URLLC, eMBB, and mMTC types of applications. The system achieved high throughput and reliability with very low latency for all three IoT use cases. Thus, the proposed 5G-IoT system improves the performance of next generation IoT networks significantly and shows great potential for achieving

TABLE VII
THROUGHPUT, LATENCY AND PACKET LOSS FOR VARYING NUMEROLOGIES WITH A STATIONARY UE FOR A PACKET INTERARRIVAL TIME OF 0.03 MS

Numerology	Throughput (Mbps)	Latency (ms)	Packet Loss (Ratio)
0	1036.39	16.1	0.01
1	1084.68	2.30	0.0002
2	1091.36	1.16	0.00006
3	1095.02	0.59	0

high throughput and ultra-reliable low latency communication, which are critical for emerging IoT applications.

V. CONCLUSION

In this paper, we present and evaluate a novel 5G-IoT architecture for scalable, high throughput, and ultra-reliable low latency communication in next generation IoT networks using Simu5G network simulator, which to the best of our knowledge, has not been addressed in any prior work. The proposed 5G-IoT architecture performs well for all the three types of 5G-IoT use cases: critical, massive, and broadband, and can enable next generation smart systems. The architecture was shown to significantly increase the throughput and reliability of the system while simultaneously improving the latency. Our work focuses on developing novel real-world solutions for addressing the challenges involved in building scalable next generation cellular IoT networks. In the future, we plan to further develop our system by leveraging 5G and beyond networks as an enabler for deploying next generation services in large city-scale environments.

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