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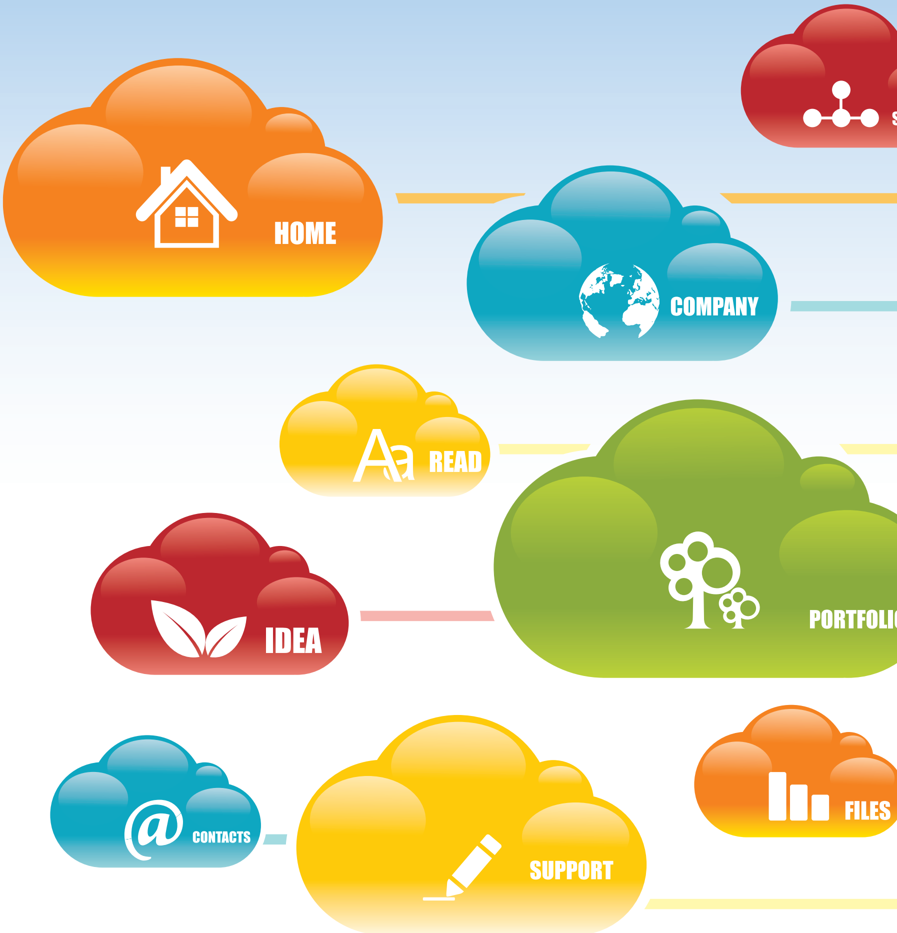

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The CTTC 5G End-to-End Experimental Platform

Integrating Heterogeneous Wireless/Optical Networks, Distributed Cloud, and IoT Devices

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The Internet of Things (IoT) will facilitate a wide variety of applications in different domains, such as smart cities, smart grids, industrial automation (Industry 4.0), smart driving, assistance of the elderly, and home automation. Billions of heterogeneous smart devices with different application requirements will be connected to the networks and will generate huge aggregated volumes of data that will be processed in distributed cloud infrastructures. On the other hand, there is also a general trend to deploy functions as software (SW) instances in cloud infrastructures [e.g., network function virtualization (NFV) or mobile edge computing (MEC)]. Thus, the next generation of mobile networks, the fifth-generation (5G), will need not only to develop new radio interfaces or waveforms to cope with the expected traffic growth but also to integrate heterogeneous networks from end to end (E2E) with distributed cloud resources to deliver E2E IoT and mobile services. This article presents the E2E 5G platform that is being developed by the Centre

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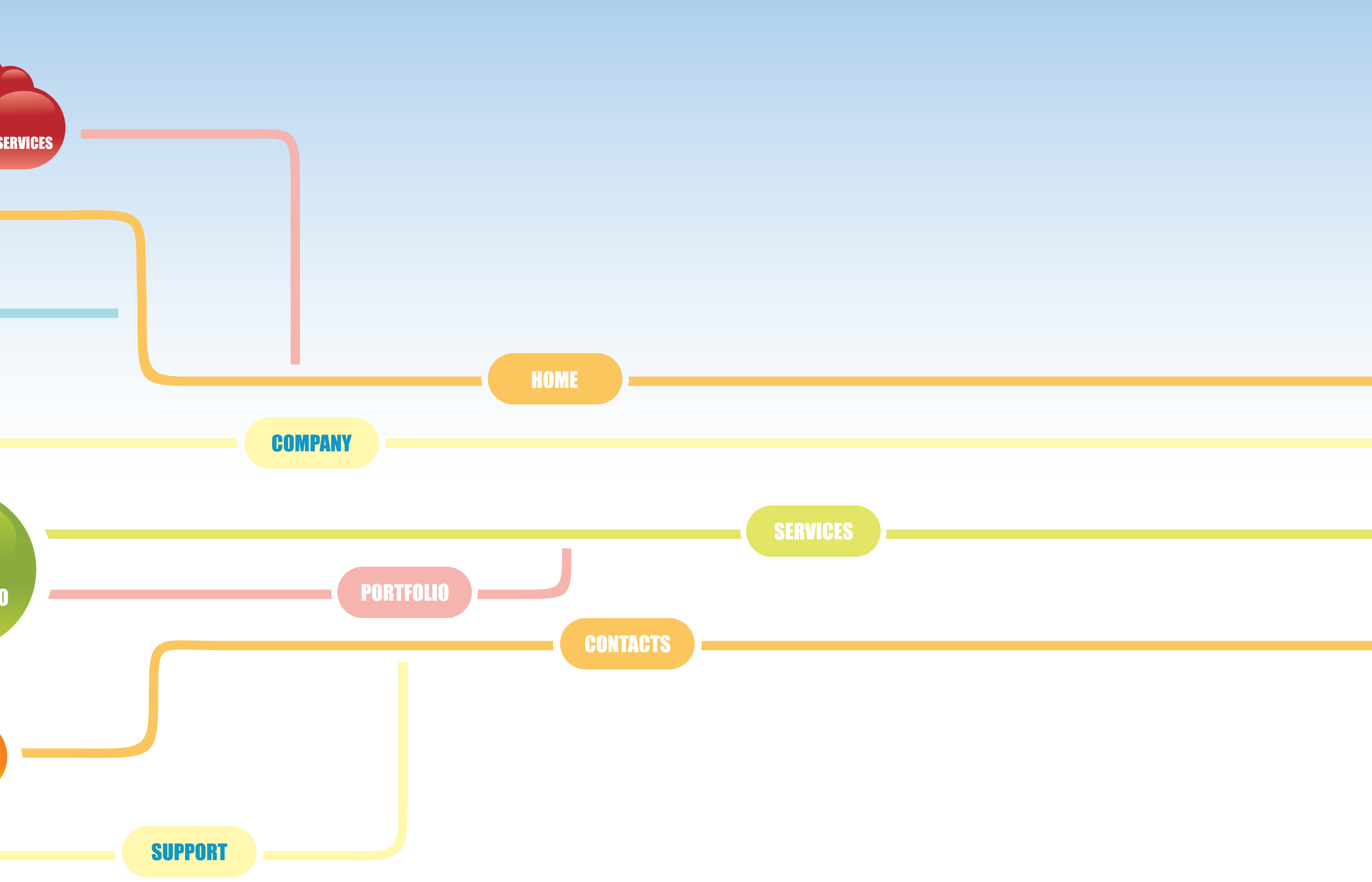

Tecnològic de Telecomunicacions de Catalunya (CTTC), the first known platform capable of reproducing such an ambitious scenario.

Introduction

The 5G of mobile network technology is more than the development of new radio interfaces or waveforms. It also deals with the design of E2E-converged network and cloud infrastructure to facilitate both the traditional human-based and emerging IoT services. This converged infrastructure (see Figure 1) is composed of E2E heterogeneous network segments covering radio and fixed access, metro aggregation, and core transport with heterogeneous wireless and optical technologies; massive distributed cloud computing and storage infrastructures; and large amounts of heterogeneous smart devices and terminals for traditional mobile broadband services (e.g., smartphones and tablets) and IoT services (e.g., sensors, actuators, robots, cars, and drones).

At the network level, the requirements for 5G include high flexibility, low latency, and high capacity to support the forecasted 1,000-fold growth in mobile data traffic with submillisecond latency [1]. On the control/management side, the 5G networks must also deliver E2E connectivity services among distributed cloud infrastructures and between any end user (i.e., devices and terminals) and the distributed cloud infrastructure. This requirement can only be met by efficiently integrating heterogeneous access [radio access networks (RANs), fixed access, satellites, Wi-Fi, and personal area networks], optical/wireless crosshaul (fronthaul/backhaul), metro aggregation packet networks, and high-capacity optical core transport networks.

At the cloud level, 5G requires massive computing and storage infrastructures. This is needed to store and process the data being generated by billions of connected smart devices, such as temperature monitoring, distance measurement, and energy consumption. In addition, the impending growth of NFV [2] and MEC [3] also requires cloud services for the deployment of SW functions [e.g., mobile evolved packet core (EPC), local cache, and firewalls]. Originally, cloud services have been implemented in core data centers (DCs) for high-computational or long-term processing. However, the cloud is being spread to the edge of the network (e.g., in edge DCs located in the metro network, or even in the network nodes or mobile base stations with cloud capabilities) to reduce the latency of services for the end user. This concept is referred to as *fog computing*. Therefore, 5G networks need a global orchestration for the distributed cloud implementation and the management of heterogeneous networks. This orchestration shall dynamically allocate computing and storage resources to deploy functions where needed and

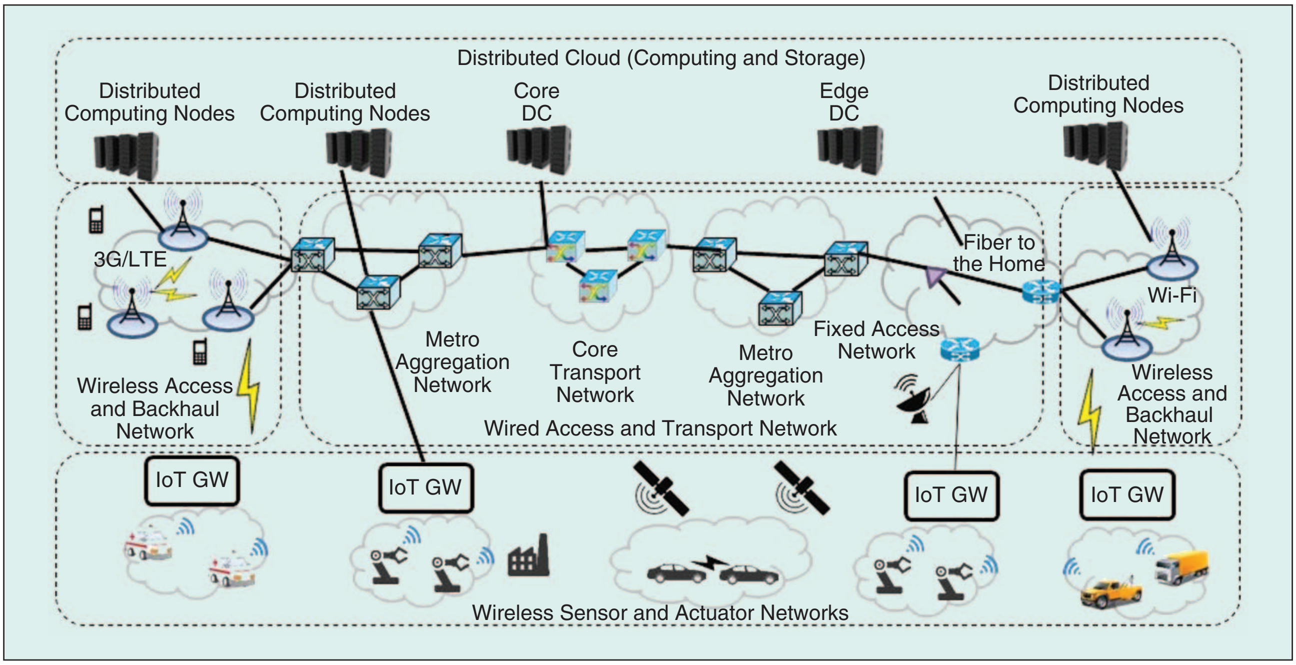

FIGURE 1 The 5G E2E scenario integrating distributed cloud, heterogeneous networks, the IoT, and mobile broadband services. 3G: third generation.

provide the required connectivity to achieve the desired E2E functionality or service.

Conducting real-life demonstrations of such a complex system is not easy. CTTC is working on the development of the first 5G E2E experimental platform for testing advanced E2E IoT and mobile services. The approach integrates various existing experimental facilities already available at CTTC, which cover activities from the physical layer (PHY) to the application/service layer for mobile networks. The building blocks of this demonstration platform are shown in Figure 2. These facilities cover complementary technologies ranging from terminals, sensors, and machines, to radio access networks, aggregation/core networks, and cloud/fog computing. Specifically, the five existing experimental facilities are involved:

- the ADRENALINE test bed [4] for wired fronthaul/backhaul [SW-defined network (SDN)-enabled packet aggregation and optical core network, distributed cloud and NFV services in core and metro DCs]
- the Experimental Test Bed for Research on Mobile Networks (EXTREME) [5] and LTE-EPC Network Simulator (LENA) long-term evolution (LTE)-EPC protocol stack emulator for wireless fronthaul/backhaul and mobile core (SDN-enabled wireless HetNet and backhaul, edge DC, and distributed computing nodes for cloud and NFV services)
- the GEDOMIS test bed [6] for LTE/5G PHY real-time prototyping based on field-programmable gate arrays (FPGAs) and SW-defined radio (SDR), and the CASTLE test bed, a highly configurable SW tool allowing LTE/5G/satellite PHY development and testing
- an LTE/5G analog front-end microwave and millimeter wave (antenna, power amplifier, filter, mixer, and so on), including digital predistortion (SHAPER) and energy-harvesting devices for the IoT
- the IoTWorld test bed [7] integrating sensors, actuators, and wireless/wired gateways (GWs).

The aim of this article is to describe how these facilities are integrated with each other to build a complete E2E 5G demonstration infrastructure.

Integrating Wireless and Optical Transport Networks for E2E Connectivity

Hierarchical SDN orchestration has been proposed as a feasible solution to handle the heterogeneity of different network domains, technologies, and vendors. It focuses on the network control and abstraction through several control domains while using standard protocols and modules. The need for hierarchical SDN orchestration has been previously justified with scaling and security.

The proposed hierarchical SDN architecture for the integration of wireless and optical transport networks is shown in Figure 3 [8]. In the wireless segment, implemented over EXTREME, an SDN controller is in charge of the programming of the wireless network (access and backhaul). This SDN controller tackles the specificities of the wireless medium, implementing the proper extensions to control wireless devices. In the optical segment, implemented over the ADRENALINE test bed, we consider an SDN-enabled multiprotocol label switching–transport profile aggregation network, while a core network uses an active stateful path computation element (PCE) on top of a generalized multiprotocol label switching (GMPLS)-controlled optical network.

In the proposed architecture, we introduce a global E2E SDN orchestrator, which is responsible for provisioning E2E connections through different network segments. It has been implemented using the parent application-based network operations (pABNO) in [9]. The pABNO is able to orchestrate several network segments: an SDN-enabled wireless segment and an optical transport network segment controlled by a child ABNO (cABNO). Application-based network operations (ABNO) is an Internet Engineering Task Force request for comments, which describes the internals of an SDN controller.

The proposed message exchange between a pABNO and a wireless SDN controller/cABNO is shown in Figure 4. It can be observed that an E2E connection is requested (POST call) to the pABNO. The pABNO computes the involved network controllers (wireless SDN/cABNO) and requests the underlying connection to them. We can observe how the workflow follows inside a cABNO, which is responsible for another level of hierarchical SDN orchestration.

Integrating the IoT and Optical Metro Aggregation Networks with Distributed Cloud Computing

The SDN is a key enabler technology to address all the technical challenges posed by the IoT. SDNs aim to overcome the limitations of the traditional Internet protocol (IP) networks, which are complex and hard to manage in terms of network configuration and reconfiguration due to faults and changes. An SDN can be viewed as a network operating system that interacts with the data plane and the network applications by means of

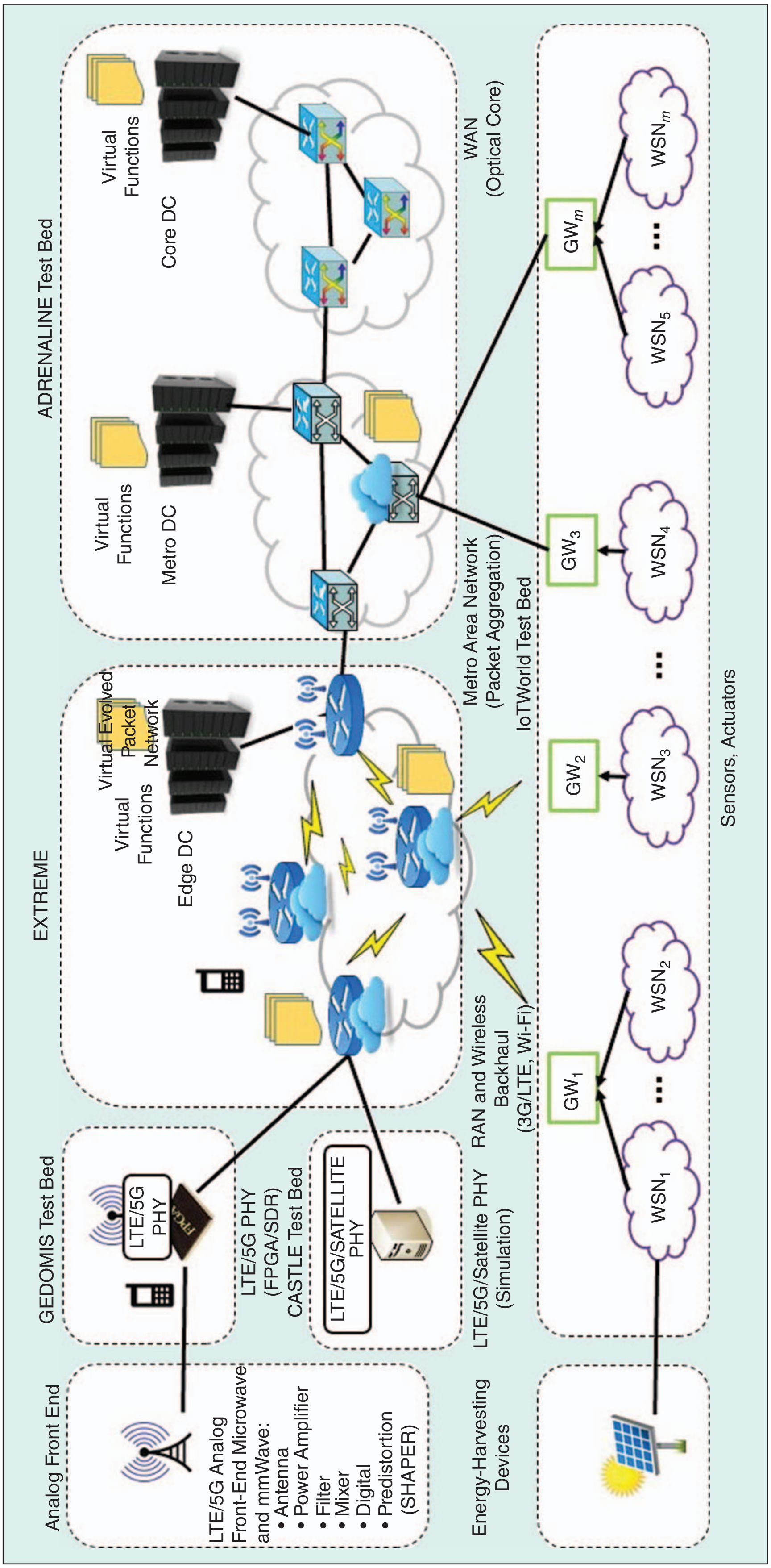

FIGURE 2 The CTTC 5G E2E experimental platform. WAN: wireless access network; WSN: wireless sensor network.

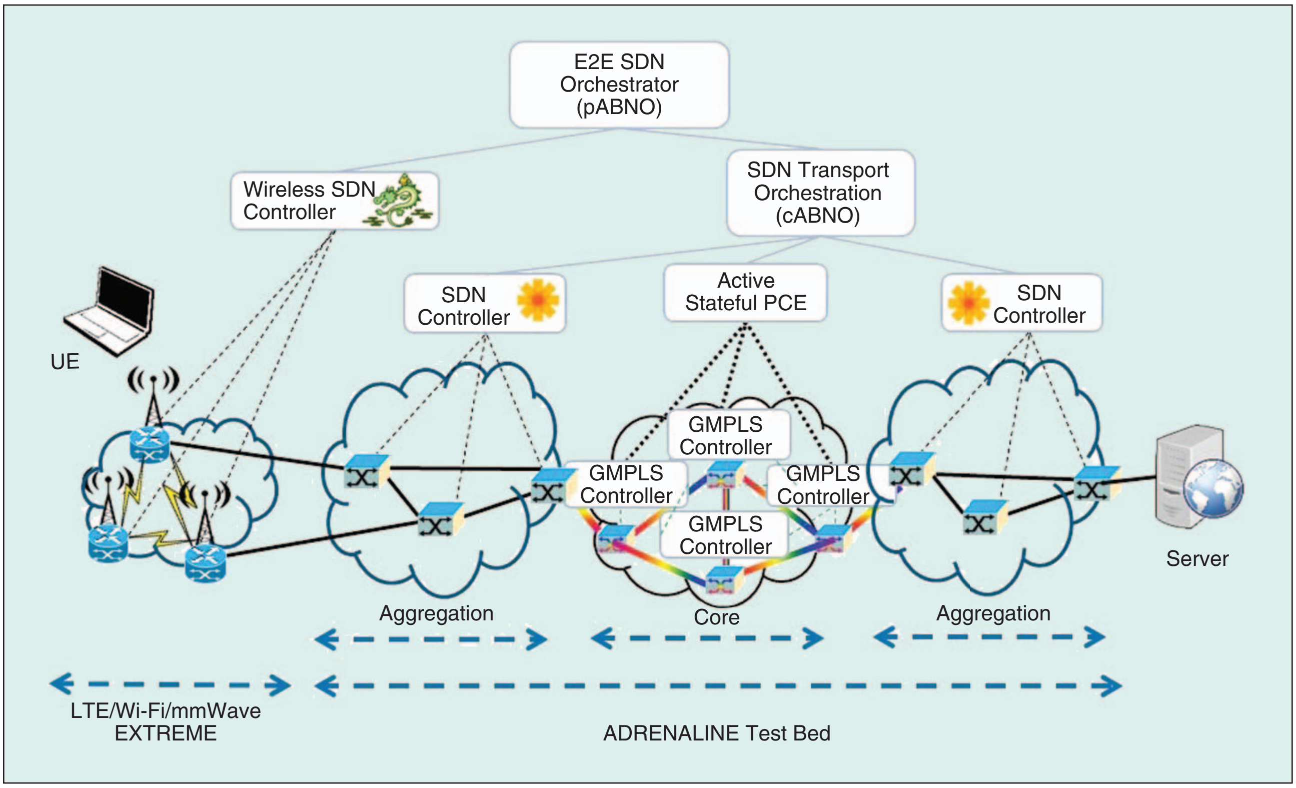

FIGURE 3 An integration of the ADRENALINE and EXTREME test beds.

application program interfaces (APIs). In this regard, the different needs in networking resources, such as bandwidth and delay, can be managed more easily thanks to the SW programmability approach facilitated by the SDN in the network control. Another important benefit of the SDN is that it paves the way for the integration of smart objects with fog and cloud computing. More specifically, thanks to the flexibility provided by the SDN, the data flows of information between IoT nodes and fog or cloud computing can be easily managed. This enables collaborative analytics among geodistributed smart things.

Integrating the IoT and SDN can also increase the efficiency of the network by responding to changes or events detected by the IoT, which might imply network reconfiguration. For example, the SDN can be used in IoT applications, where the data are transmitted from the sensors periodically in specific time frames to schedule the requested bandwidth on the transmission paths only during the active duty cycles. Such dynamic reconfiguration of the forwarding devices is only possible through centralized applications, which orchestrate IoT collected information and network resources information jointly. SDN security can also be applied to IoT GWs to enforce security at the network edges.

We deployed an SDN/NFV-enabled edge node in the ADRENALINE test bed for integrating wired IoT GWs from the IoTWorld test bed by means of the E2E SDN orchestration of integrated cloud/fog and network resources [10]. E2E SDN orchestration will provide network connectivity between IoT GWs and deployed virtual machines (VMs), which might be allocated in the proposed edge node or in a DC located in the core network.

The considered system architecture is shown in Figure 5. At the top of the figure, the integrated cloud/fog and network orchestrator [11] is responsible for handling VM and network connectivity requests, which are processed through the cloud and SDN orchestrators. The orchestration process consists of two different steps: 1) the VM creation and 2) the network connectivity provisioning. The integrated cloud/fog and network orchestrator requests the creation of VMs instances to the cloud orchestrator, which is responsible for the creation of the instances. It is also responsible to attach the VMs to the virtual switch inside the host node (at the edge node or in a core DC). When the VM creation is finished, the cloud orchestrator replies the VM's networking details to the integrated cloud/fog and network orchestrator [medium access control (MAC) address, IP address, and physical computing node location]. The SDN orchestrator is responsible for provisioning E2E network services. The SDN orchestrator will provide the E2E connectivity between the requested IoT GW and the deployed VM. Finally, data from IoT GW will flow to the processing resources located in the proposed SDN/NFV-enabled edge node.

The cloud and network topologies, as seen by the cloud/fog and network orchestrator, are shown in Figure 6. Each

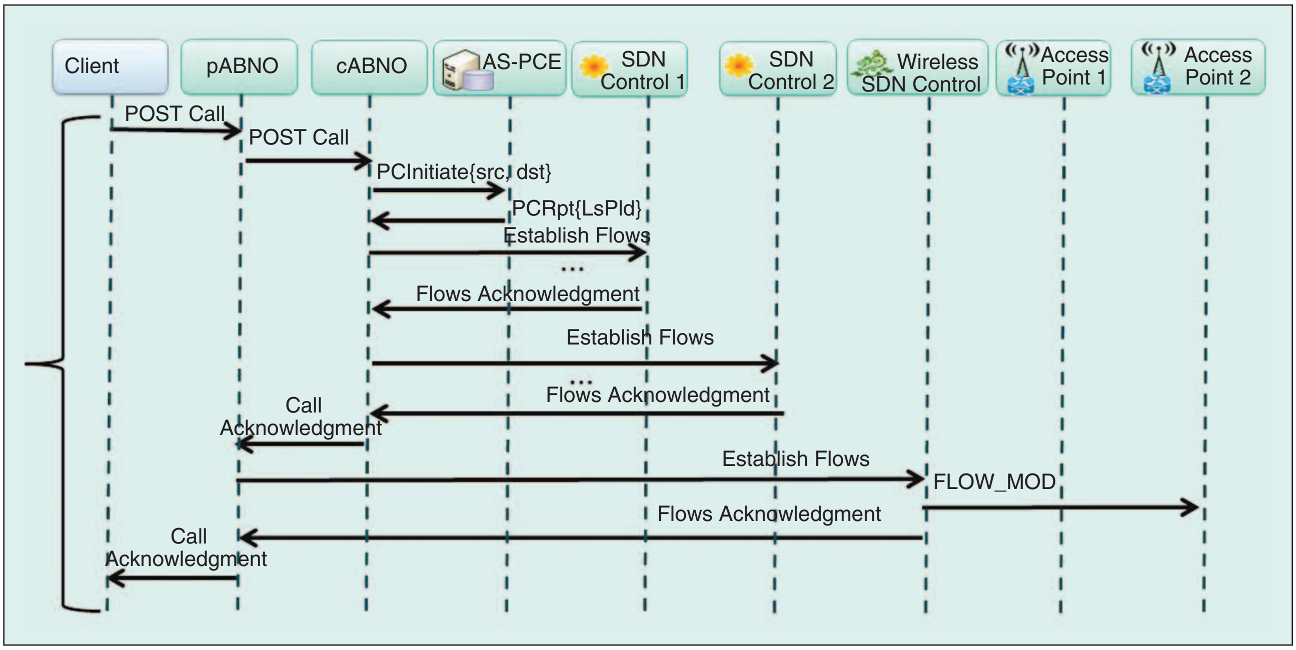

FIGURE 4 The message exchange diagram of E2E provisioning services between the ADRENALINE and EXTREME test beds.

network domain (network elements controlled by a single SDN controller) is abstracted as a single node (either packet or optical). It can also be observed that the provisioned VMs are connected to the packet network.

Integrating the IoT with Wireless Access and Backhaul Networks

Experimenting with cellular networks, including the wireless backhaul, and the IoT is a challenging venture. A powerful alternative for research purposes would consist of using SDRs to deploy an IoT network that is LTE enabled. This would mean that every single IoT device is equipped with an SDR LTE radio and connects with an SDR-based eNodeB. Then, the various eNodeBs could be interconnected using another SDR-based solution. Unfortunately, both the technical complexity and the cost of designing, deploying, and operating such a complex solution would become prohibitive, especially if the number of devices of the IoT network has to be large.

As an alternative, the solution presented in the E2E test bed of CTTC consists in connecting real IoT devices to EXTREME in various ways. To this end, it is first necessary to integrate the category-zero user equipment (UE) in the LENA modules. Such integration would then enable the following levels of connection between the IoTWorld test bed and EXTREME.

The first option would consist of running LENA in the GWs, e.g., raspberry-pi modules of IoTWorld. LENA could operate in the emulation with an instance of an UE fetching the data packets actually received via radio, routing them through the protocol stack of LENA, and emulating their transmission to the eNodeB. The EPC would also be emulated in LENA, thus offering an E2E solution. This approach is shown in Figure 7.

The main limitation of the first option is that it would only be possible to run a single GW connected to a single eNodeB, thus limiting the capability of the joint test bed to emulate a realistic IoT network where more than one machine-to-machine (M2M) GW is expected to be deployed at the same time to run an IoT application. To overcome this limitation, the second option would consist of setting up a central server where LENA runs with various instances of UE. Then, the data traffic actually received by each GW via radio, i.e., raspberry pi, would be connected to each of the UE instances of the server. Such interconnection would enable the emulation of various M2M GWs simultaneously connected to a common eNodeB and the EPC. This approach is shown in Figure 8. With either of the above two approaches, the IoTWorld test bed could also benefit from the existing connections between EXTREME and ADRENALINE, thus enabling a complete E2E experimentation of an IoT deployment. In this case, data would be transported via SDN-controlled wireless and optical backhaul networks acting as a heterogeneous multidomain transport layer, as shown in Figure 8.

Integrating 5G/LTE PHY and Virtual Mobile Protocol Stack for Flexible HW/SW Partitioning

The integration of a 5G/LTE PHY provided by either the GEDOMIS test bed or CASTLE test bed with the LENA LTE-EPC emulated protocol stack [12] running over EXTREME will allow the full-stack experimentation of multiple 5G use cases that exploit the flexibility of SDN/NFV when applied to mobile networks (e.g., virtual base

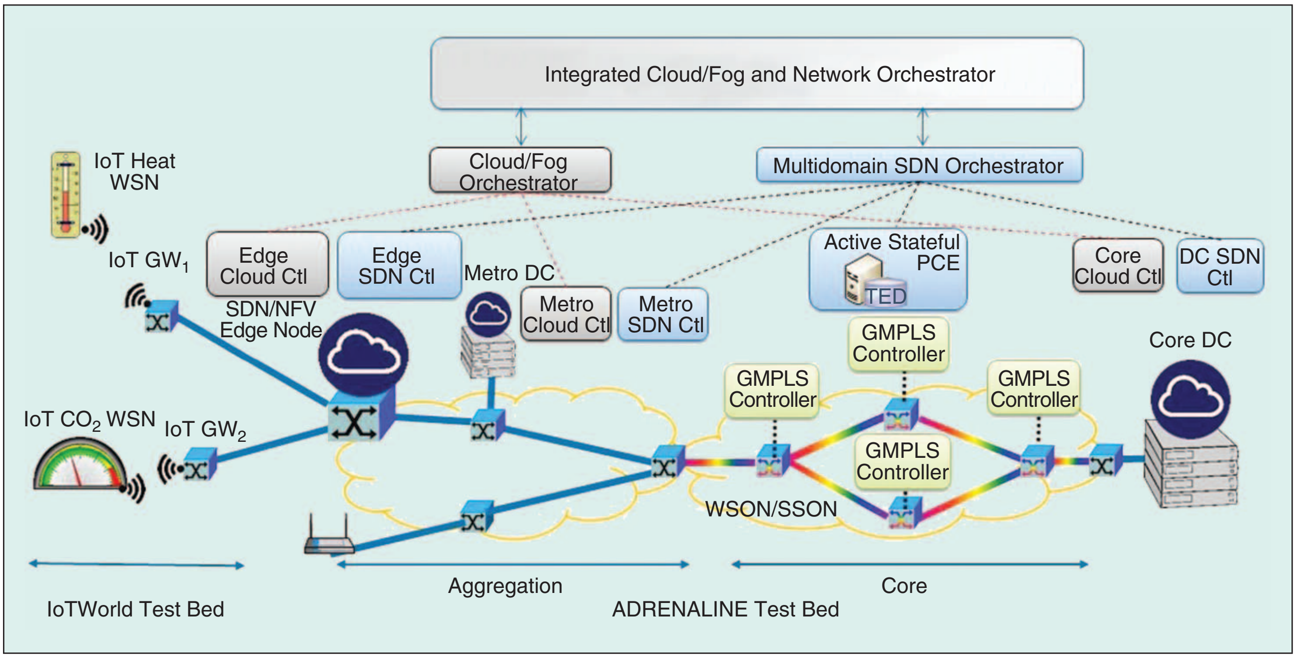

FIGURE 5 An E2E SDN orchestration of an SDN/NFV-enabled edge node for IoT services. TED: Traffic Engineering Database; WSON: wavelength switching optical network; SSON: spectrum switching optical network.

stations or self-organized networking). This may consider, for example, the virtual base station use case defined by the European Telecommunications Standards Institute NFV group, or experiments on coverage and capacity optimization involving the whole radio protocol stack and its interactions with core network elements and real applications. The availability of the full-stack mobile network test bed allowing experimentation from PHY up to applications and services is currently rare. In fact, experiments on these topics are often limited to either a PHY platform with minimal MAC layer support, due to the cost of commercial protocol stacks, and the limitations of open source ones, or IP-level test beds with limited access to low-level PHY configuration. In contrast, our integrated test bed will allow evaluating full-stack NFV solutions in a real wireless propagation environment with the GEDOMIS test bed, or in a real-time emulation environment with CASTLE emulator, with the possibility of combining both emulated and real (e.g., fiber) backhaul/aggregation network links and applications, and of including additional emulated cells to achieve a larger experiment scale.

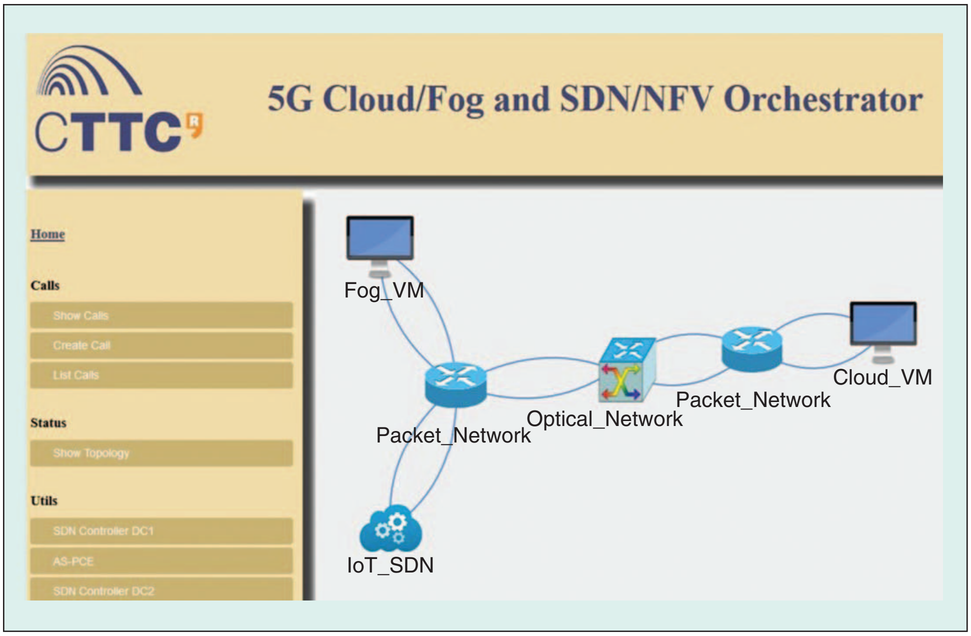

FIGURE 6 The view of the cloud and network resources from the developed cloud/fog and network orchestrator.

To realize this vision, development of tools that exploit the flexibility that NFV brings to mobile networks is essential. In this sense, it is important to underline that flexible hardware (HW)–SW partitioning is widely perceived as a key technology enabler for fully exploiting the network programmability brought by SDN and NFV. In this way, the SW programmable data plane combined with intelligent HW that dynamically

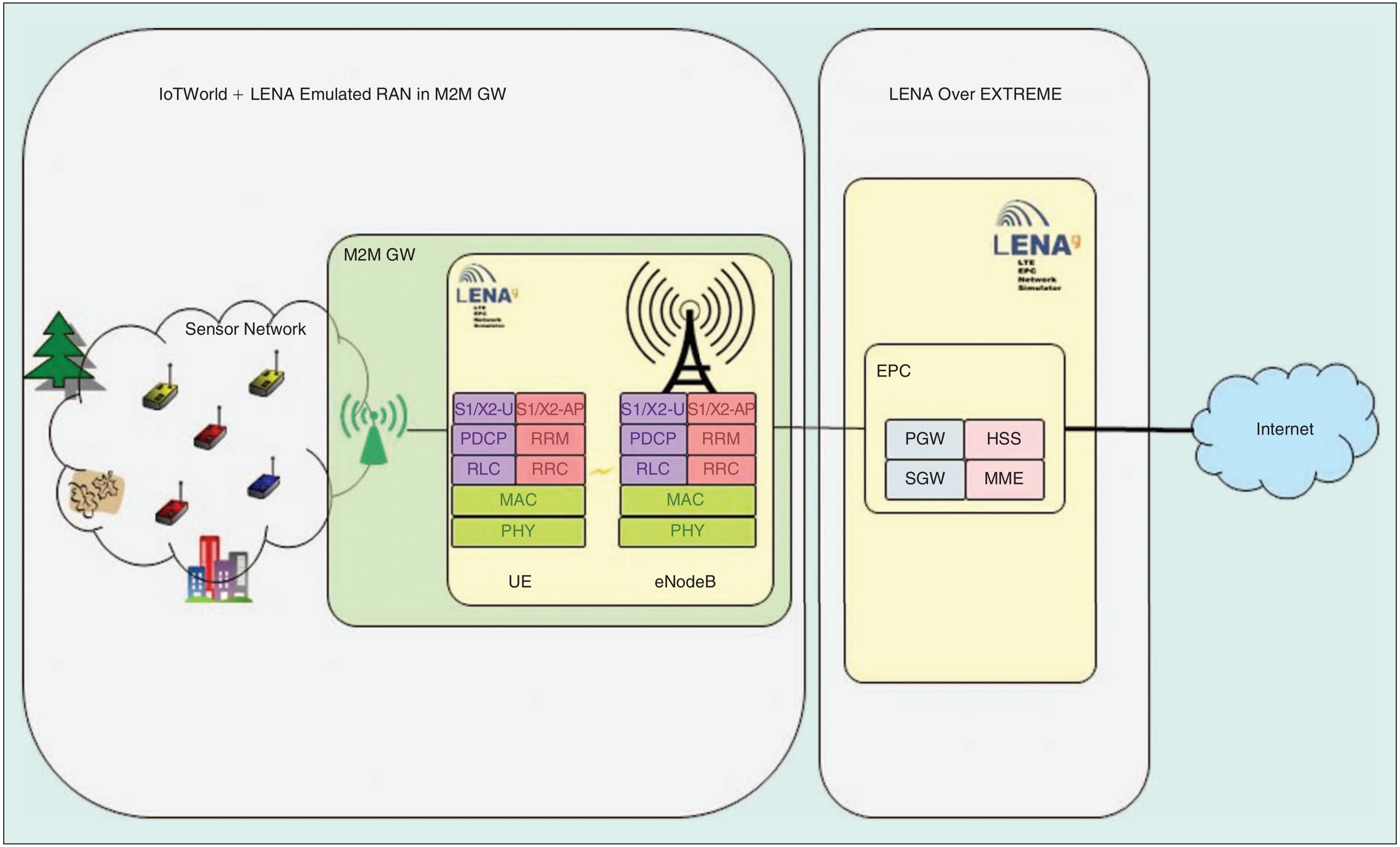

FIGURE 7 The M2M GW connected to a UE stack of LENA running inside a single LENA process that includes the eNodeB and the core network. PDCP: packet data convergence protocol; RRM: radio resource management; RLC: radio link control; RRC: radio resource control; PGW: packet data network GW; HSS: home subscriber server; SGW: serving GW; MME: mobility management entity.

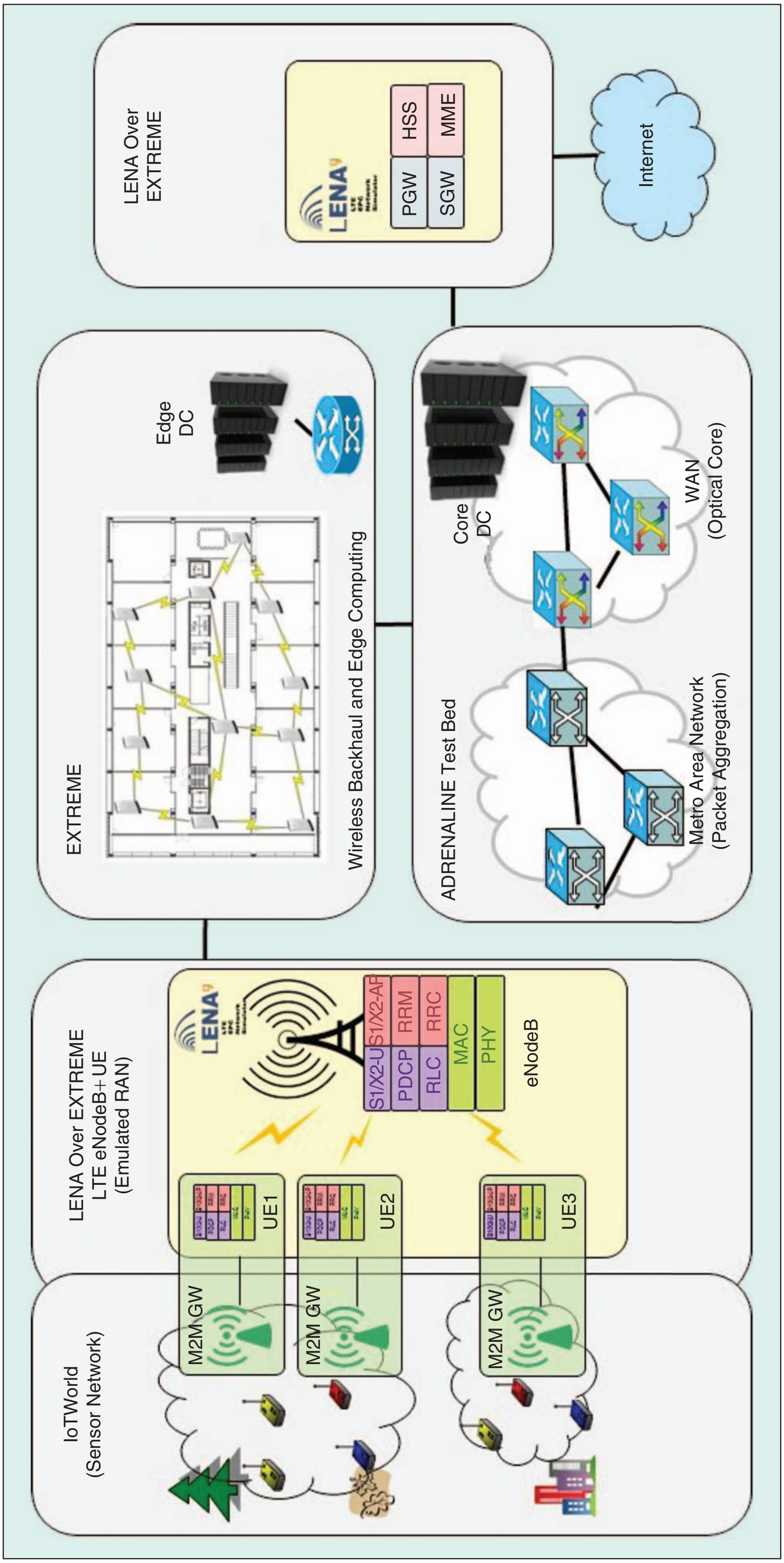

FIGURE 8 An E2E MTC test bed with emulated RAN and EPC with wireless and optical backhaul.

collaborates with control plane SW will allow addressing the performance, flexibility, and security challenges of 5G mobile networking. At the same time, the requirements for low latency communications (including signal processing), low-power operation, and high-performance parallel computation will be made more stringent, thus imposing dedicated HW solutions for some functions.

There are three main issues related to the HW–SW split: 1) the physical location where communication stacks are implemented (e.g., base station, cloud), 2) the technology of the processing elements that is used [e.g., entirely programmable system-on-chip (SoC), FPGAs, general-purpose processors (GPPs)], and 3) the granularity of the partitioning (e.g., at communication stack level, at function or process level). In this use case, the main idea is to flexibly distribute functions of the communication stack among different processing elements (e.g., SoCs, FPGAs, and GPPs), which are physically residing either in communication nodes (e.g., base stations) or in cloud/fog processing architectures, and to adaptively change processing topologies (e.g., base stations, intermediate nodes, or cloud processing architectures). The decision for the distribution of the HW–SW functions will be made based on experiments made at design time (static mode), which will reflect the specific 5G operating scenarios, as shown in Figure 9.

Such function distribution may be done based on multiple criteria, such as high performance, low energy, low communication latency, or a tradeoff of these. Apart from shifting functions from dedicated HW coprocessors to SW processing space to guarantee the performance goal of the identified scenarios, a number of baseband parameters will be tunable. The tuning of these parameters will be performed at system level and, potentially, could also be based on different criteria. Initially, for this particular use case, the decisions will be driven by energy-aware communications criteria. Essentially, these system-level decisions will be based on using different communication primitives that can adjust certain parameters associated with a given energy cost. Indicative parameters of this type might be the modulation and coding scheme, the use of single- or multiantenna configurations (e.g., improve signal-to-noise ratio or data rate), the signal bandwidth, the type of waveform (e.g., from 4G to 5G), the use of fragmented spectrum (e.g., coexistence of radio transmissions) [13], the type of digital predistortion and crest factor reduction applied for the linearization of the power amplifier output (e.g., affecting the baseband processing requirements, digital-to-analog converter and analog-to-digital converter usage and power amplifier energy cost), the energy consumption operation mode (e.g., switch off dynamic power consumption in portions of the FPGA baseband implementation), and the traffic volume density allowing to switch off parts of the network. The two examples of virtual mobile network function splitting and deployment developed in the GEDOMIS and EXTREME test beds are shown in Figure 10.

Integrating Analog Front-End and Energy Harvesting Devices

Wireless communication is ultimately demonstrated through analog front ends suitable to address the stringent requirements and diverse features of the PHY digital signal processing of 5G systems acquired through GEDOMIS and CASTLE test beds. At the same time, energy harvesting technologies exploiting existing light, thermal, vibration, and electromagnetic ambient energy availability can further extend the energy autonomy of low power, IoT communication, sensor and actuator devices, and improve the energy efficiency of the underlying analog front ends and digital circuitry [14], [15].

CTTC's test bed facilities span a diverse set of fabrication technologies, including the traditional printed circuit board milling, as well as laser prototyping and inkjet printing that provides the necessary resolution for low-cost prototyping of analog front ends up to mmWave frequencies and using different materials from flexible substrates suitable for wearables and IoT wireless sensor devices, to high-performance substrate materials suitable for mmWave applications. In addition, testing capabilities include signal generators, vector network analyzers, and an anechoic chamber suitable for testing wireless front ends under controlled propagation environments. The use of off-the-shelf circuit components, the traditional microwave substrate materials, and fabrication methods allow one to obtain low cost easily customized front-end designs, and in addition, they permit a fast turnaround time of high-performance prototypes.

5G NETWORKS NEED A GLOBAL ORCHESTRATION FOR THE DISTRIBUTED CLOUD IMPLEMENTATION AND THE MANAGEMENT OF HETEROGENEOUS NETWORKS.

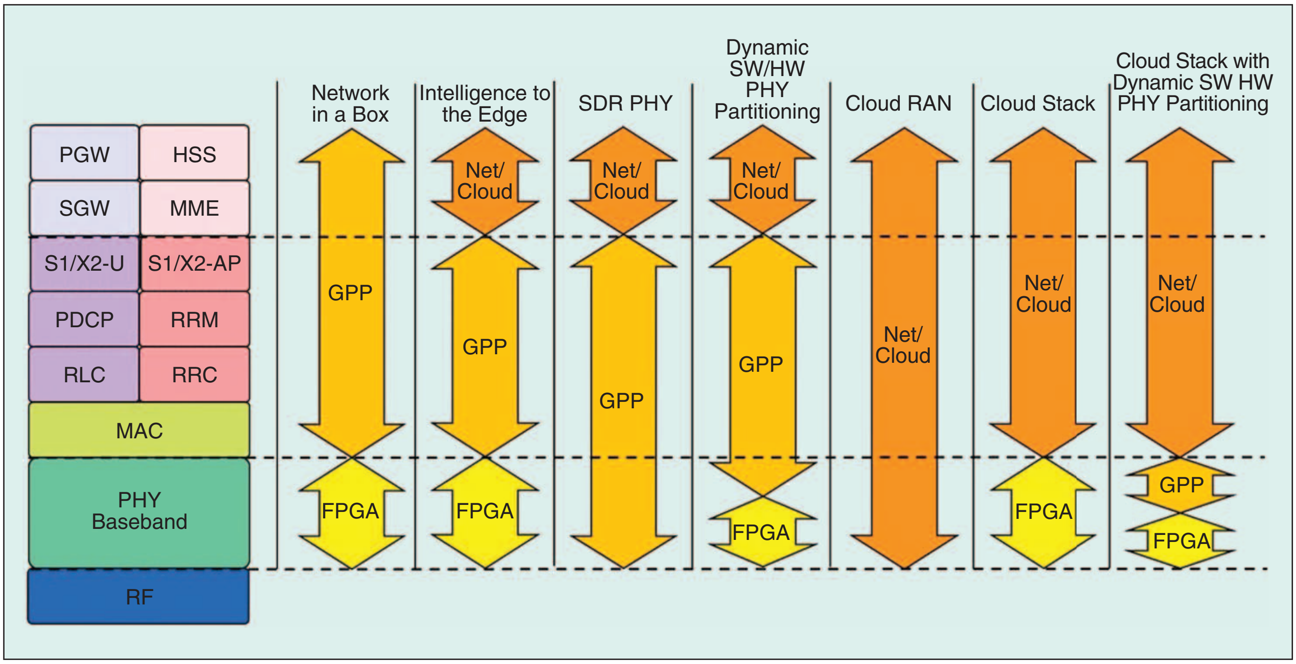

FIGURE 9 The virtual mobile network function splitting and deployment.

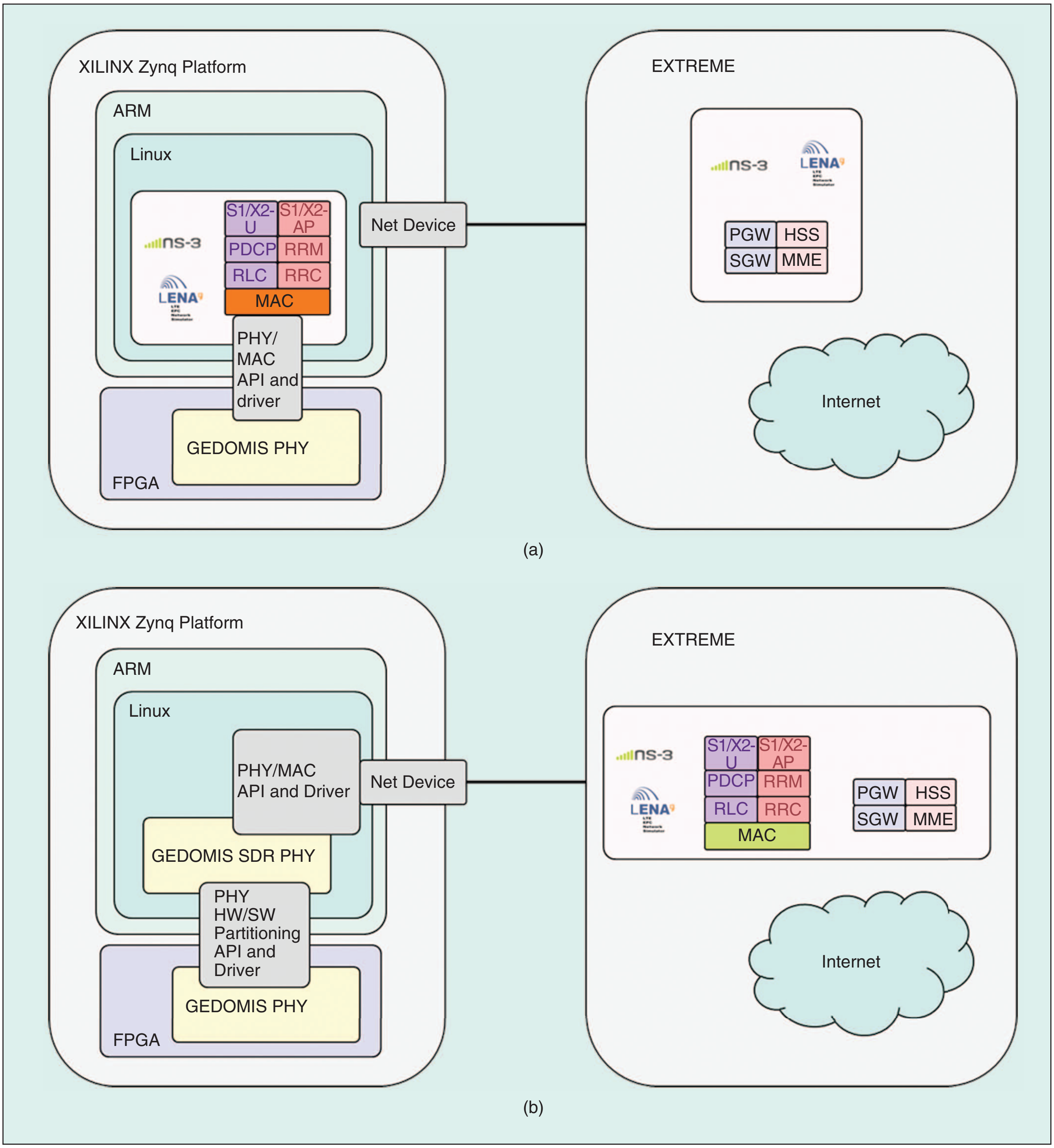

FIGURE 10 (a) The intelligence to the edge and (b) the cloud stack with dynamic HW/SW PHY partitioning.

The development and testing of analog front ends capable of interfacing with the digital baseband output from GEDOMIS and CASTLE test beds and introducing the necessary operating frequency translation and efficient amplification and filtering of the underlying signals into reconfigurable antenna arrays with beam-forming capabilities is of particular interest as it ultimately permits the real-world testing of 5G systems, and, more importantly, it enables the joint optimization of the baseband circuitry and analog front end, which is not always possible when utilizing commercially available solutions. Similarly, the ability to implement and integrate different energy harvesters with the analog front end enables one to explore different circuit architectures and materials and low-cost and mechanically conformal designs, which can be jointly optimized and tailored to efficiently power wireless sensor circuits.

Conclusions

Conducting real-life demonstrations of an E2E 5G scenario, including both IoT and mobile broadband services, requiring the integration of heterogeneous wireless access and optical transport networks, distributed cloud computing, wireless sensor, and actuators networks, is a very challenging task. CTTC has been working on the development of the first E2E 5G platform capable of reproducing such an ambitious scenario. This article has described the existing and planned integration, supported functionalities, use cases, and preliminary results among the different experimental facilities available at CTTC.

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