The CTTC 5G end-to-end experimental platform integrating IoT, SDN, and distributed cloud

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***Abstract*—The Internet of Things (IoT) poses at least three key challenges to future communications networks, namely: *i)* the need for interoperability, *ii)* the management of a wide variety of sometimes opposite requirements defined by various applications (e.g., ultra-low latency, high reliability for mission-critical applications, or highly dynamic bandwidth allocation for mobile broadband), and *iii)* scalability. In this context, Software Defined Networking (SDN) emerges as a key enabler for the IoT to face these three unique characteristics of the IoT. SDN enables a global orchestration of the cloud, network, and IoT resources in a scenario where multiple network domains integrating all network segments (radio access/backhaul, aggregation and core transport) with heterogeneous wireless and optical technologies interconnect wireless sensor and actuator networks with distributed computing nodes, edge, and core data centers. Conducting real-life demonstrations of such a complex system is not easy. This paper describes the first-known 5G end-to-end experimental platform for the IoT developed by CTTC. This platform integrates various experimental facilities already available at CTTC. In addition, the roadmap for future integration, supported functionalities, and use cases between the different experimental facilities is also described in this paper.**

Keywords*— Internet of Things (IoT), Software Defined Networking (SDN), Cloud computing, Fog computing, Big data, radio access/backhaul network, metro aggregation and core transport network.

I. INTRODUCTION

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, elderly assistance, or home automation, among others. Communication networks of the future must deal with at least three of the key challenges posed by the IoT; need for interoperability, management of a wide variety of sometimes opposite requirements defined by various applications, and scalability.

Interoperability; to date, multiple heterogeneous connectivity technologies for smart objects or “things” have been developed in parallel for the purposes of IoT. Unfortunately, the majority of them cannot interoperate with each other. Moreover, most of the “smart” applications which use these technologies are vertically integrated and technology dependent, thus creating non-interoperable "Intranets of Things", as coined within the IoT-A project. This lack of interoperability could be overcome by adopting a common architecture that enables different applications to access to different physical resources (sensors, actuators, tags) independently of the communication technology used in each network.

Wide variety of requirements; the heterogeneity of the applications sets different requirements in terms of networking resources, ranging from ultra-low latency and high reliability for mission-critical applications to highly dynamic bandwidth allocation for video surveillance.

Scalability; the IoT paradigm is about connecting billions of heterogeneous smart devices with the capacity of interacting with the environment to the Internet. Therefore, the proposed solutions from an IoT networking perspective should take into account the scalability of the IoT nodes as well as the operational cost of deploying the networking infrastructure. The vast amount of connected devices will generate an aggregated huge volume of data which poses a tremendous challenge both from the transport and processing of information points of view.

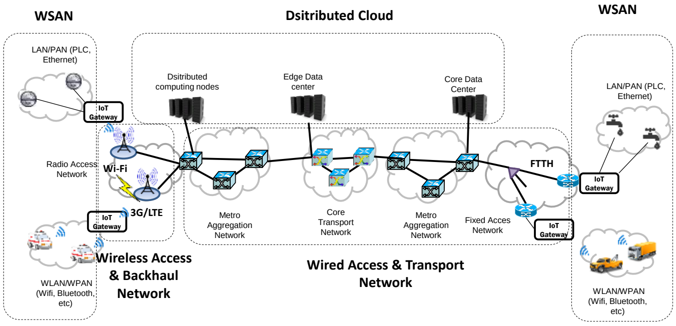


Fig. 1. End-to-end IoT scenario integrating distributed cloud and heterogeneous networks.

At the processing level, it is worth mentioning that there are different needs in terms of data processing depending on the application at hand. Some applications require a fast processing whereas others require a long term processing. This motivates the use of fog and cloud computing respectively, and as a consequence, the integration of the IoT with such technologies is of paramount importance. Fog and Cloud computing help to process the data coming from billions of smart things and the IoT gateways. Originally, cloud computing services have been offered in centralized Data Centers (DCs). However, there is a general trend to spread the DCs to the edge of the network in order to reduce services' latency to the end user. The extension of cloud computing and services to the edge of the network is known as fog computing. Fog computing covers the need to ingest data which requires a faster response, in terms of latency or processing time. For instance, the control of traffic lights in smart cities.

At the transport level, it requires to integrate all network segments (radio access/backhaul, aggregation and core transport) with heterogeneous wireless and optical technologies (5G, mmWave, LTE/LTE-A, Wi-Fi, Zigbee, Ethernet, MPLS, WDM, software-defined optical transmission, etc.) in order to interconnect wireless sensor and actuator networks (WSAN) with distributed computing nodes, edge, and core DCs.

Software Define Networking (SDN) [1] can be considered as a key enabler for the next generation of networks, the so-called 5G, which will need to integrate both IoT services together with traditional human-based services. In this context, SDN enables a global orchestration of distributed cloud, heterogeneous network and IoT resources required in order to; i) transport the huge amount of data generated at the terminals, sensors, machines, nodes, etc., to any distributed computing node, edge, or core data center; ii) allocate computing and storage resources in distributed data centers, and iii) process the collected data (Big Data) and make the proper decisions (cognition).

Conducting real-life demonstrations of such a complex system is not easy. However, for the last three years, the CTTC has been working on the development of the first-known end-to-end (E2E) 5G platform capable of reproducing such an ambitious scenario. This paper introduces in Section II the advantages of SDN and it provides a description of the CTTC 5G E2E experimental platform for the IoT that includes the integration of heterogeneous networks, distributed cloud, and IoT. Section III describes the integration between the wireless and optical transport networks for end-to-end transport services. Section. IV is addressing the integration of IoT with optical metro aggregation networks with distributed cloud computing. Section V is dealing with the integration of IoT with wireless access and backhaul networks. Section VI presents energy harvesting devices for IoT and finally Section VII concludes the paper.

II. CTTC 5G E2E EXPERIMENTAL PLATFORM FOR IOT LEVERAGING ON SDN TECHNOLOGY

SDN emerges as a key enabler for the IoT to face the three unique characteristics of the IoT described in Section I. SDN is a new networking paradigm which aims at overcoming the limitations of traditional IP networks, reducing complexity and making their management easier in terms of network configuration and reconfiguration in case of faults or changes. The idea is to separate the control plane from the data plane, thus moving the control logic from routers and switches to a centralized network controller. This is the reason why SDN can be viewed as a network operating system which interacts with the data plane and the network applications by means of Application Programming Interfaces (APIs). One of the main benefits of this architecture resides on the ability to perform unified control and management tasks of different wireless and wired network forwarding technologies (e.g., packet/flow switching or optical circuit switching) to provide end-to-end transport services.

CTTC is deploying a 5G end-to-end top-bottom converged experimental platform leveraging on SDN for testing and developing advanced end-to-end IoT services by integrating various existing experimental facilities at CTTC. To be more precise, three experimental facilities are involved, namely: i) the ADRENALINE Testbed® for wired fronthaul/backhaul (SDN-enabled packet aggregation and optical core network, distributed cloud and NFV services in core and metro data-centers);ii) the EXTREME Testbed® for wireless fronthaul/backhaul (SDN-enabled wireless HetNet and backhaul, edge datacenter and distributed computing nodes for cloud and NFV services); and finally; iii) the IoTWorld Testbed (sensors, actuators and wireless/wired gateways) combined with energy harvesting devices.

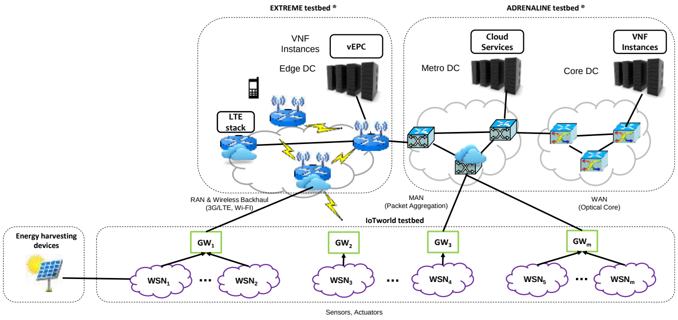


Fig. 2. CTTC 5G end-to-end experimental platform for the IoT.

III. INTEGRATING WIRELESS AND OPTICAL TRANSPORT NETWORKS FOR 5G MOBILE NETWORKS

Future 5G networks will have to be highly flexible to serve multiple services. The most stringent requirements for these services include low latency, ultra-high bandwidth and virtualized infrastructure in order to deliver end-to-end services. These requirements can be met by efficiently integrating heterogeneous wireless and optical network segments (radio access/backhaul, aggregation and core) and massive computing and storage services, delivered by means of Cloud/Fog computing [2]. It is in this context where hierarchical SDN Orchestration has been proposed as a feasible solution to handle the heterogeneity of different network domains, technologies, and vendors. It focuses on network control and abstraction through several control domains, whilst using standard protocols and modules. The need of hierarchical SDN orchestration has been previously justified with two purposes: Scaling and Security.

Fig. 3 shows the proposed hierarchical SDN architecture for the integration of wireless and optical transport networks. In the wireless segment, implemented over the EXTREME Testbed [3], 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 Testbed [4], we propose an SDN-enabled MPLS-TP aggregation network, while a core network might use an Active Stateful PCE (AS-PCE) on top of a GMPLS-controlled optical network.

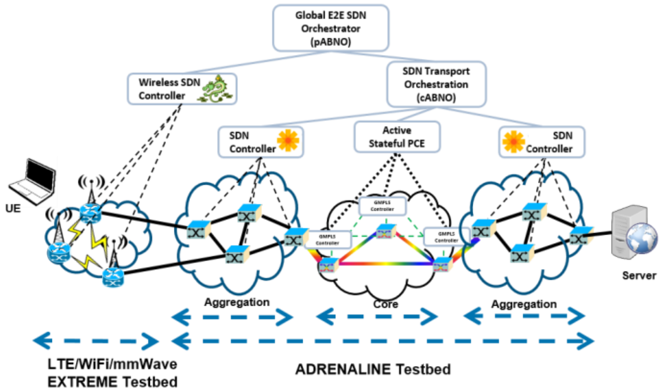


Fig. 3. Integration of ADRENALINE and EXTREME testbeds.

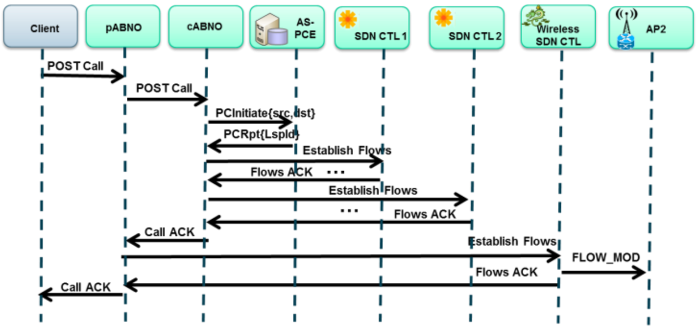
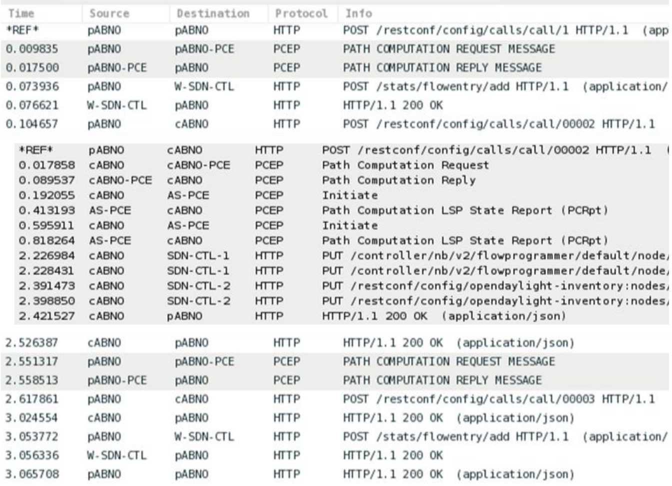


Fig. 4. Message exchange diagram of E2E provisioning services between ADRENALINE and EXTREME Testbeds.

In the proposed architecture, we introduce a Global E2E SDN Orchestrator, which is responsible for the provisioning of E2E connections through different network segments. It has been implemented using the parent ABNO (pABNO) in [5]. 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). ABNO is an IETF RFC which describes the internals of an SDN Controller.

Fig. 4 shows the proposed message exchange between a pABNO and wireless SDN controller/cABNO. 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, as presented in [6].

Fig. 5 shows the PCEP and HTTP messages captured at the pABNO. Once a connection is requested, the pABNO requests to its internal PCE the path between the underlying SDN Controllers. The requested connections are provisioned through a REST interface. A bidirectional E2E connection between the EXTREME and ADRENALINE testbeds is provisioned in our setup in 3.06s.



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Time       Source      Destination  Protocol  Info
*REF*      pABNO       pABNO        HTTP      POST /restconf/config/calls/call/1 HTTP/1.1  (app
0.009835   pABNO       pABNO-PCE    PCEP      PATH COMPUTATION REQUEST MESSAGE
0.017500   pABNO-PCE   pABNO        PCEP      PATH COMPUTATION REPLY MESSAGE
0.073936   pABNO       W-SDN-CTL    HTTP      POST /stats/flowentry/add HTTP/1.1  (application/
0.076621   W-SDN-CTL   pABNO        HTTP      HTTP/1.1 200 OK
0.104657   pABNO       cABNO        HTTP      POST /restconf/config/calls/call/00002 HTTP/1.1

  *REF*     pABNO      cABNO      HTTP   POST /restconf/config/calls/call/00002 HTTP/1.1  (
  0.017858  cABNO      cABNO-PCE  PCEP   Path Computation Request
  0.089537  cABNO-PCE  cABNO      PCEP   Path Computation Reply
  0.192055  cABNO      AS-PCE     PCEP   Initiate
  0.413193  AS-PCE     cABNO      PCEP   Path Computation LSP State Report (PCRpt)
  0.595911  cABNO      AS-PCE     PCEP   Initiate
  0.818264  AS-PCE     cABNO      PCEP   Path Computation LSP State Report (PCRpt)
  2.226984  cABNO      SDN-CTL-1  HTTP   PUT /controller/nb/v2/flowprogrammer/default/node/
  2.228431  cABNO      SDN-CTL-1  HTTP   PUT /controller/nb/v2/flowprogrammer/default/node/
  2.391473  cABNO      SDN-CTL-2  HTTP   PUT /restconf/config/opendaylight-inventory:nodes/
  2.398850  cABNO      SDN-CTL-2  HTTP   PUT /restconf/config/opendaylight-inventory:nodes/
  2.421527  cABNO      pABNO      HTTP   HTTP/1.1 200 OK  (application/json)

2.526387   cABNO       pABNO        HTTP      HTTP/1.1 200 OK  (application/json)
2.551317   pABNO       pABNO-PCE    PCEP      PATH COMPUTATION REQUEST MESSAGE
2.558513   pABNO-PCE   pABNO        PCEP      PATH COMPUTATION REPLY MESSAGE
2.617861   pABNO       cABNO        HTTP      POST /restconf/config/calls/call/00003 HTTP/1.1
3.024554   cABNO       pABNO        HTTP      HTTP/1.1 200 OK  (application/json)
3.053772   pABNO       W-SDN-CTL    HTTP      POST /stats/flowentry/add HTTP/1.1  (application/
3.056336   W-SDN-CTL   pABNO        HTTP      HTTP/1.1 200 OK
3.065708   pABNO       pABNO        HTTP      HTTP/1.1 200 OK  (application/json)
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Fig. 5. Wireshark capture of E2E provisioning (taken at pABNO/cABNO).

IV. INTEGRATING IOT AND OPTICAL METRO AGGREGATION NETWORKS WITH DISTRIBUTED CLOUD COMPUTING.

SDN is a key enabler technology to address all the technical challenges posed by the IoT. SDN aims to overcome the limitations of traditional IP networks, which are complex and hard to manage in terms of network configuration and reconfiguration due to faults and changes. SDN can be viewed as a network operating system which interacts with the data plane and the network applications by means of APIs. In this regard, also the different needs in networking resources such as bandwidth and delay can be managed more easily thanks to the software programmability approach facilitated by SDN in the network control. Another important benefit of 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 SDN, the data flows of information between IoT nodes and fog or cloud computing can be easily managed, which opens the door for collaborative analytics between geo-distributed smart things.

Integrating 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. Moreover, IoT applications where the data is transmitted from the sensors periodically in specific time frames, the requested bandwidth on the paths, can be easily scheduled, by using SDN, to be available only during the duty cycle. These dynamic reconfigurations of the forwarding devices it is only possible by centralized applications which orchestrate IoT collected information and network resources information jointly. SDN security can also be applied to IoT gateways in order to enforce security at the network edges.

We propose an SDN/NFV-enabled Edge Node for IoT Services by means of E2E SDN Orchestration of integrated Cloud/Fog and network resources. E2E SDN orchestration will provide network connectivity between IoT gateways and deployed virtual machines (VMs) which might be allocated in the proposed edge node or in a DC located in the core network.

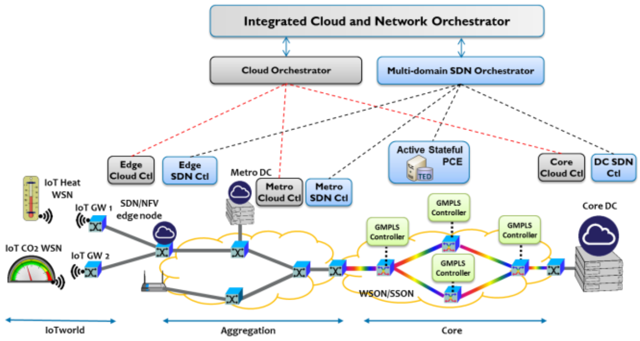

Fig. 6. End-to-End SDN Orchestration of SDN/NFV-enabled Edge Node for IoT Services.

Fig. 6 shows the considered system architecture. On top, the Integrated Cloud/Fog and Network Orchestrator is responsible for handling Virtual Machine (VM) and network connectivity requests, which are processed through the Cloud and SDN orchestrators.

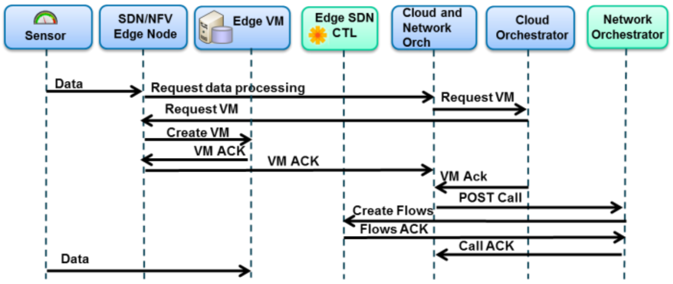

Fig. 7. E2E provisioning of IT resources and network connectivity through IoT World and ADRENALINE Testbeds.

The orchestration process consists of two different steps: the VM creation and network connectivity provisioning (Fig. 7). The integrated Cloud/Fog and Network Orchestrator requests the creation of virtual instances (VMs) 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 VMs creation is finished, the Cloud Orchestrator replies the VM's networking details to the integrated Cloud/Fog and network orchestrator (MAC address, IP address and physical computing node location). The SDN orchestrator is the responsible to provision E2E network services. The SDN orchestrator will provide the E2E connectivity between the requested IoT gateway and the deployed VM. Finally, data from IoT gateway will flow to the processing resources located in the proposed SDN/NFV-enabled edge node.

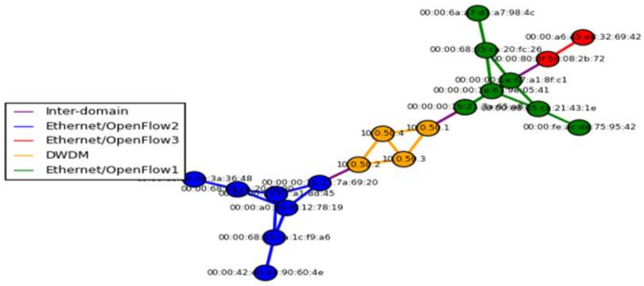

Fig. 8. Message exchange diagram of E2E provisioning services.

Fig. 8 shows the network topology as seen by the SDN orchestrator. Each network domain (network elements controlled by a single SDN controller) is depicted with a different color. It can be observed that the SDN/NFV-enabled edge node is depicted in red, and interconnected towards the metro network.

V. INTEGRATING IOT WITH WIRELESS ACCESS AND BACKHAUL NETWORKS

Experimenting with cellular networks, including the wireless backhaul, and the IoT is not an easy task. A powerful alternative for research purposes would consist in using Software Define Radios (SDR) to deploy an IoT network which is LTE-enabled, i.e. every single IoT device has an SDR LTE radio, and connect it to an SDR-based eNodeB. Then the various eNodeBs could be interconnected using another SDR-based solution. Unfortunately, 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.

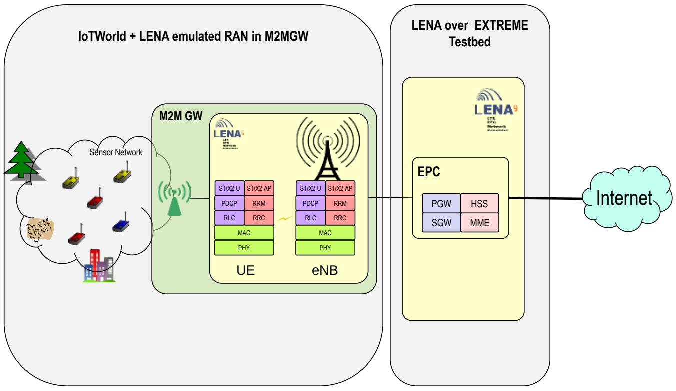

Fig. 9. M2M Gateway connected to UE Stack of LENA running inside a single LENA process that includes the eNodeB and the Core Network.

As an alternative, the solution presented in the E2E Testbed of CTTC consists in connecting real IoT devices to EXTREME in various ways. Towards this end, it is first necessary to integrate the category-0 UE in the LENA modules. Such integration would then enable the following levels of connection between the IoTWorld and EXTREME:

1) First option would consist in running LENA in the gateways, e.g. Raspberry-Pi modules of IoTWorld. LENA could operate in emulation mode with an instance of a 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 9.

2) The main limitation of the first option is that it would only be possible to run a single gateway connected to a single eNodeB, thus limiting the capability of the joint testbed to emulate a realistic IoT Network where more than one M2M Gateway is expected to be deployed at the same time to run an IoT application. In order to overcome this limitation, the second option would consist in setting up a central server where LENA runs with various instances of UEs. Then, the

data traffic actually received by each gateway 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 gateways simultaneously connected to a common eNodeB and the EPC. This approach is shown in Figure 10.

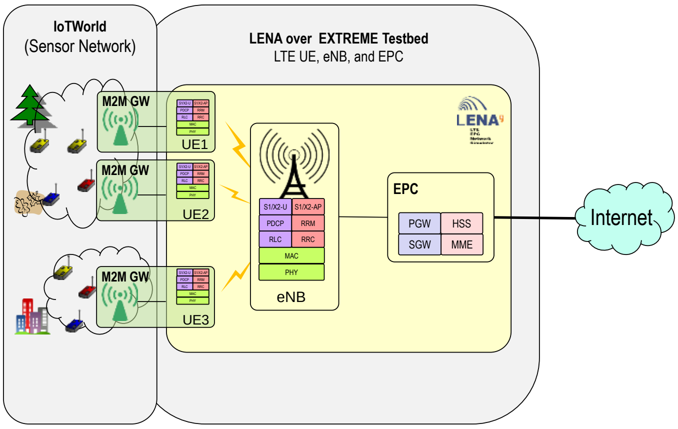

Fig. 10. Various M2M Gateways, each connected to a different UE running inside a single LENA process.

With any of the above two approaches, the IoTWorld testbed could also benefit from the existing connections between EXTREME and ADRENALINE, thus enabling for 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 heterogeneous multi-domain transport layer. Such a unique and complete E2E integration is illustrated in Figure 11.

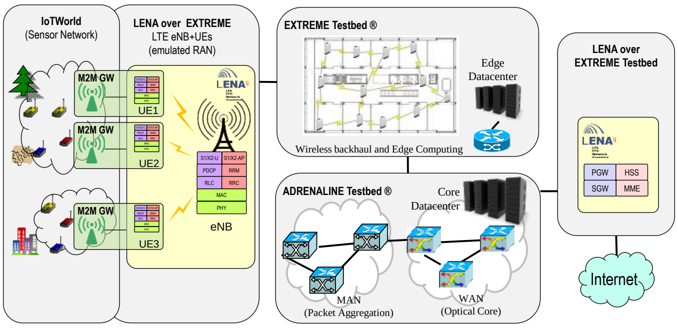

Fig. 11. End-to-End MTC Testbed with emulated RAN and EPC with wireless and optical backhaul.

VI. Energy Harvesting Devices for IoT

In addition to the challenges related to the connectivity itself, which can be explored by the triplet IoTWorld-EXTREME-ADRENALINE described before, there is a key issue that remains unsolved: how to power the IoT devices.

Like any electronic device, sensors and actuators need energy to operate. Until now, this has largely been solved by hooking them up to the grid or using batteries. Unfortunately, these two approaches have considerable drawbacks. Grid-connected sensors need cables, limiting where they can be used, and contribute to electricity consumption and CO2 emissions, while battery-powered ones only last as long as their battery life. Alternatively, by equipping sensors and actuators with energy harvesting devices, they could harvest energy directly from their environment – from the sun, from ambient heat, from radio waves or vibrations. As a consequence, energy harvesting sensors and sensor networks can be set up anywhere with ease and in theory would operate perpetually with little or no maintenance or environmental impact.

Bearing these reasons in mind, the E2E IoT Tesbed of CTTC is capable of testing and integrating novel technologies that enable sensors of the testbed to use solar and thermal energy as well as radio waves and vibrations to power themselves. This means not only using off-the-shelf energy-harvesters, but also studying, testing and deploying novel, more efficient energy harvesting devices and integrating multiple harvesting and sensing circuits into individual devices.

Thanks to this integration of energy harvesting capabilities, the E2E IoT testbed leverages research actions based on understanding the sharp differences in the design and operation of networks which support energy-harvesting. Note that these networks are very different from that of standard battery-powered networks because the goal is no longer to minimize energy draw, but rather to smartly manage the available energy taking into consideration QoS requirements and harvesting capabilities in order to keep all the devices connected for, ideally, infinite time.

VII. Conclusions

Conducting real-life demonstrations of an end-to-end ecosystem for IoT requiring the integration of heterogeneous wireless access and optical transport networks, distributed cloud computing, and wireless sensor networks is very challenging. For the last three years, the CTTC has been working on the development of the first-known end-to-end 5G platform capable of reproducing such an ambitious scenario. This paper has described the planned integration, supported functionalities, use cases, and preliminary results between the different experimental facilities.

VIII. ACKNOWLEDGEMENTS

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References

[1] "SDN architecture 1.0," Open Networking Foundation (ONF), https://www.opennetworking.org/images/stories/downloads/sdnresources/technical-reports/TR SDN ARCH 1.0 06062014.pdf, 2014.

[2] R. Muñoz, *et al.*, Towards an SDN/NFV-based multi-tenant network and cloud testbed for end-to-end 5G services, WWRF 34, 2015

[3] "EXTREME Testbed," http://networks.cttc.es/mobilenetworks/extreme testbed/ .

[4] ADRENALINE Testbed," http://networks.cttc.es/ons/adrenaline/

[5] R. Vilalta *et al.*, Hierarchical SDN Orchestration for Multi-technology Multi-domain Networks with Hierarchical ABNO, ECOC 2015.

[6] A. Mayoral, *et al.*, Experimental Seamless Virtual Machine Migration Using an Integrated SDN IT and Network Orchestrator, OFC 2015.