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Experimental framework and evaluation of the 5G-Crosshaul control infrastructure

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ABSTRACT

The goal of 5G-Crosshaul is to integrate fronthaul and backhaul operation under the same data and control planes. This paper focuses on the latter, by experimentally showing the flexibility of the 5G-Crosshaul Control Infrastructure (XCI). In this sense, various network setups featuring heterogeneous network and computing resources and high-speed mobility were deployed over the 5G-Crosshaul testbed. More specifically, three different use cases that exploit the capabilities embedded in the XCI have been experimentally evaluated. First, "hierarchical network orchestration" demonstrates how service setup times in complex multi-technology transport networks can be decreased from current manual configuration times in the order of days down to automated setups in the order of seconds by means of a resource management application that consumes the XCI services. Second, "energy management of IT and network resources" presents an energy management application that exploits the XCI to deploy network configurations that achieve energy savings ranging from 15% to 40% by dynamically reacting to datacenter and network conditions. Finally, the XCI was also exploited by an energy management application in a high-speed train mobility scenario featuring a radio over fiber network in which savings close to 80% were achieved.

1. Introduction

The fifth generation (5G) communication system has gained a lot of traction recently, and this is for all segments including access, transport, and core. In particular, for the 5G transport segment, the convergence between backhaul and fronthaul has made a major leap towards a fusion of both into a single network commonly referred to as Crosshaul (Xhaul) [1] or AnyHaul [2]. In project 5G-Crosshaul [1], the integration between fronthaul and backhaul is achieved in two planes, namely, data plane and control plane. First, in the data plane, the integration was done through a packet-based transport protocol suite capable of carrying the backhaul traffic together with any type of fronthaul traffic. This includes legacy fronthaul (CPRI) and any new fronthaul corresponding to the new functional splits defined by standards development organizations (SDOs) and industry, such as 3GPP [3] and eCPRI [4]. Key features of this integrated data plane are: (1) the support of a wide range of latency and bandwidth requirements, (2) the support of various underlying transmission (link) technologies, and (3) the sharing of the infrastructure by multiple tenants by multiplexing a variety of traffic flows. In the control plane, the integration was done by

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means of a hierarchical orchestration and control solution based on the Software Defined Networking (SDN) and the Network Function Virtualization (NFV) paradigms. Fundamental concepts of NFV, such as virtualization and dynamic deployment of functions, and fundamental concepts of SDN, such as network programmability through clearly defined open Application Programming Interfaces (APIs), are key concepts of the 5G-Crosshaul architecture, which have been shaped to serve the requirements considered within the scenarios defined in the project.

The main contribution of this paper is the experimental validation of the flexibility of the proposed XCI (5G-Crosshaul Control Infrastructure). On the way towards this validation, this paper also presents the 5G-Crosshaul architectural framework of the European H2020 5G-Crosshaul project [1]. Furthermore, it presents and evaluates three very different use cases, showing, in a tangible manner, the flexibility of the proposed XCI architecture to adapt to diverse network scenarios. The results obtained for each of these use cases emphasize different aspects of the same control architecture and its operation with real hardware and under close-to-real working conditions, again, aiming at stressing the elasticity of the conceived architecture.

The first considered use case ("hierarchical network orchestration") shows how the resource management application exploiting the hierarchical SDN orchestration integrated in the 5G-Crosshaul architecture allows the dynamic provisioning of network resources in multi-technology domains in a scalable way. In our setup, we demonstrate that service setup time in complex multi-technology transport networks can be decreased from current manual configuration times in the order of days down to the order of seconds. The second use case ("energy management of IT and network resources") shows how 5G-Crosshaul network management applications exploit the services of the XCI, which features a management stack aligned with ETSI NFV Management and Orchestration (MANO) [8] with a northbound interface compliant with the information model specified in ETSI NFV IFA013 [5], extended to provide information about the specific tenants issuing the requests. Thanks to energy saving algorithms, the power consumption of the tested setup could be decreased by 15% to 40% by reacting to datacenter and network conditions. Finally, the "energy management of the high-speed train" scenario shows how the XCI enables controlling a Radio Over Fiber (RoF) infrastructure by means of an extension of an open source SDN controller and its available agents. In such use case, energy savings close to 80% were achieved. Overall, the heterogeneity of the considered scenarios controlled by the XCI architecture shows the wide application scope of the XCI architecture, as required by integrated fronthaul and backhaul transport in 5G networks, which was the scope of the 5G-Crosshaul project.

This paper is organized as follows. First, background and related work in relation with the considered use cases presents some previous solutions to the challenges that the 5G-Crosshaul flexible architecture solves in an integrated manner. Then, the 5G-Crosshaul architecture, as well as that of the XCI, are introduced. After that, the three use cases are discussed, including rationale, network setup, and relevant experimental results to emphasize various aspects of the architecture. Finally, the last section summarizes and concludes the paper.

2. Background and related work

Current operational networks involving a heterogeneity of technological domains (e.g., optical and wireless transport and packet-based services on top) involve substantial manual management even if such domains belong to the same company, since multiple departments may be involved. In general, this translates into ticketing systems among departments and task queues that are executed in appropriate operational windows to not disrupt (or have the minimum possible impact to) the regular operation of the network. If we add to that the heterogeneity of requirements that fronthaul and backhaul traffic have, up to now, the norm has been to deploy (and manage) two different specialized networks. Consequently, the vision of automated end-to-end network management is far from being realized [34]. Furthermore, adding computing resources to the equation makes this end-to-end management much more complex, since there are multiple options for the integration of SDN and NFV [31] and, in general, NFV MANO stacks (e.g., Open source MANO –OSM [36]) mostly focus on cloud resources and the end-to-end multi-domain perspective is still lacking. 5G-Crosshaul defines a novel architecture that integrates fronthaul and backhaul at the data and control planes [35]. Since the focus of this paper is on experimentally validating the flexibility of the 5G-Crosshaul control plane through three selected use cases, the following paragraphs describe previous work done in each of these use cases so as to exemplify the variety of requirements posed over the XCI and how they have been solved in isolation. In this way, the advantages of deploying such a control architecture offering a unified framework for tackling these diverse challenges will be more evident.

The architecture of the control plane evaluated in this paper, which is further developed in Section 4, is aligned with ETSI NFV [8,9] recommendations. This architecture has been adapted to the needs of fronthaul and backhaul transport over heterogeneous computing and network setups. In this sense, the SDN hierarchy and API presented in the first use case offers the programmability and recursion proposed by Open Networking Foundation [29] (and also discussed in [31]) as well as the ideas behind the Transport API (T-API) [30] to achieve an end-to-end (E2E) global management of network resources. As mentioned, this contrasts and advances current management schemes, where the management is done almost manually and in isolation at each domain using per-vendor/per-technology proprietary extensions, hence implying big delays to configure a new service in the transport networks (up to a few days), mainly due to operational overheads.

The idea of using a hierarchical control of SDN networks has been proposed in the context of data centers [10] and in [11] to interconnect different datacenters by means of multi-domain transport optical networks. Katsalis et al. [12] consider also the hierarchical model for the management of mobile networks. However, these approaches lack the distinguishing features of our approach, that is, the real testing and integration of heterogeneous technologies (wireless and optical) at the transport level to combine fronthaul and backhaul traffic under the same end-to-end transport network. Preliminary work in this direction is described in [13].

As API to offer programmability, our approach relies on the developed Control Orchestration Protocol (COP) [25], which pre-dates T-API and it is strictly a functional subset of the functions that T-API offers. In this sense, the T-API interface and protocol has been increasingly used in the context of transport networks as an open API to not only interconnecting heterogeneous domains, such as the fronthaul and backhaul, in the scope of research projects [14], but also as reflected in white papers covering industry interoperability events, such as [15,16]. Additionally, T-API has been selected as the interface for the SDN Controller NorthBound Interface (NBI) in the scope of ONF project Open and Disaggregated Transport Network (ODTN) Optical networks [17]. In a related activity, T-API has been listed as the potential protocol for the Orchestration-WAN Infrastructure Manager (Or-Wi) interface, as introduced in the proof-of-concept (PoC) for NFVI-PoP interconnection scenario [18].

In relation with the second use case, which integrates network management applications and MANO stacks, previous work also offered solutions with a limited scope. In fact, although energy efficiency has been widely addressed in the literature (see, e.g., [19] for a survey), few works have dealt with the development of energy-aware routing and node activation policies in SDN/NFV based systems. Examples include [19,20], which, however, do not fully address the challenges brought by the SDN and NFV paradigms. Particularly relevant to the work herein presented is [32], which seeks to optimize Virtual Network Function (VNF) placement and job scheduling in order to minimize energy consumption. Nevertheless, the algorithm presented in [32] optimizes the server utilization but neglects the energy consumed by network elements such as backhaul/fronthaul nodes, as considered in the considered second use case. It is worth mentioning that a preliminary work on Energy Management and Monitoring Application (EMMA), our energy efficient application, has appeared in the conference paper [7]. However, no integration with the XCI described in this paper was developed and only emulation results were presented. On the other hand, in our architecture, different network management applications (e.g., resource management or energy management) exploit the XCI NBI API over an infrastructure combining IT and network resources of a real testbed.

In the same way, no previous work was found that exploits control architectures equivalent to the one presented in this paper over a real high-speed train scenario served by RoF nodes. References [21,22] deal with the energy efficiency schemes for small cells, but they do not address extensions that allow tackling RoF needs. In [28], the authors investigated the ability of the SDN-based control of reconfiguring the fronthaul to maintain virtualized network function connectivity when cell and optical access turn into sleep mode for energy efficiency purposes. It was shown that upon cell and optical access turning on and off, the fronthaul reconfiguration time is limited to a few tens of milliseconds. However, it is not combined with any realistic use case and energy consumption of the transport network is roughly estimated. In [23], a RoF network manager was proposed for the network equipment on the optical fronthaul between the Central Unit (CU) and all Remote Antenna Units (RAU)s. The RoF manager follows an autonomous and generic network management framework, designed to be scalable in terms of adding new network elements (NEs). However, the RoF Manager exclusively operates in the signal control plane, and thus, it has no access to the user-specific data or flows. Though RoF is considered to be a green technology in terms of power consumption, in a high-speed train environment, a regular RoF system merely serves the trains for a few seconds, and then, it stays idle for the rest of its operations. This does not only consume unnecessary energy, but it also decreases the lifetime of each RoF node. Thus, in this paper we experimentally validate an energy efficient solution operating over the XCI which makes decisions to change the power state of connected RoF nodes only to serve the high-speed train based on its location. And this is done based on actual measurements over a real testbed, contrarily to [28].

In summary, though there have been past attempts to tackle some of the challenges that appear in each of the use cases in isolation, the aim of this paper is to show how the architecture defined in 5G-Crosshaul, and more specifically, its control architecture, is flexible enough to handle a variety of use cases (including the three ones featured in this paper) from a single unifying control framework. Its characteristics and operational results for each of the use cases are presented in the following sections.

3. The 5G-Crosshaul architecture

The 5G-Crosshaul architecture is depicted in Fig. 1 [6]. Core and Access segments and associated west/eastbound interfaces (W/EBI) are also depicted for completeness, though they are out of the scope of the project. At the heart of the architecture lay:

1. The *Crosshaul forwarding elements (XFE):* switching units that support single or multiple link technologies (e.g., mmWave, Ethernet, Fiber, microwave, copper). They support various fronthaul and backhaul traffic profiles. A key part of the XFE is a common switching layer implementing a Layer 2 common frame encapsulation for enabling a unified and harmonized transport traffic management. Non-XFE nodes may also be integrated. As for IT resources, *5G-Crosshaul Processing Units (XPU)* are in charge of hosting the various virtual network functions (VNFs) of the deployed services.
2. The *Crosshaul Control Infrastructure (XCI):* the brain controlling the overall operation of the 5G-Crosshaul network. It can be seen as a Management and Orchestration (MANO) entity which also supports the management of networking, storage and processing resources through dedicated controllers. The XCI is aligned with the ETSI NFV architecture [8,9].
3. Innovative *network applications:* network management logic to support the most diverse management functionalities, such as planning, network and service monitoring/prediction, optimization of resources, energy management, multi-tenancy, media distribution, such as content delivery networks and TV Broadcasting, etc. They are located at the top-most part of the architecture and exploit the 5G-Crosshaul resource orchestration functions. Among the previously mentioned applications, Fig. 1 shows the 5G-Crosshaul applications key for the use cases evaluated in this paper: the Resource Management Application (RMA) and the Energy Management and Monitoring Application (EMMA).

4. The 5G-Crosshaul control infrastructure (XCI)

Fig. 1 also presents a bird's-eye view of the XCI architecture. The design principle of the XCI is to support the different 5G-Crosshaul applications through open application programming interfaces (APIs), which manage not only networking but also computing and storage resources, applied to both physical and/or virtual infrastructures. In this way, the Crosshaul network functionality can be extended through an ecosystem of applications.

To provide control of the heterogeneous resources, e.g., computing, storage and networking resources, composing a Crosshaul network, the XCI is designed to integrate the SDN control principles in the ETSI/NFV MANO architecture [9]. At a high level, the XCI has two layers. The first layer, NFV management and orchestration, includes the ETSI NFV MANO components, such as the NFV orchestrator (NFVO), multiple VNF managers (VNFM), and the Virtual Infrastructure Manager (VIM). The second layer corresponds to the different controllers in charge of managing the allocation and configuration of the different types of available resources (network, computing and storage) in the NFV Infrastructure of a 5G-Crosshaul environment. This ETSI NFV/SDN unified platform allows upper layer applications to program and monitor the underlying data plane through a common set of core services and primitives. The XCI interacts with the data plane entities via a Southbound interface (SBI) in order to: (i) Control and manage the networking resources of the network, e.g., the 5G-Crosshaul Forwarding Elements (XFEs), (ii) control and manage the PHY configuration of the different link technologies (e.g., transmission power on wireless links), and (iii) control and manage the 5G-Crosshaul Processing Units (XPU) computing operations (e.g., instantiation and management of VNFs via NFV procedures).

The following sections present three representative use cases that exemplify the programmability and flexibility offered by the XCI not only from a functional perspective, but also by evaluating its performance through key 5G key performance indicators, or KPIs, (e.g., service deployment time or energy consumption). More specifically, the first use case shows how the XCI deals with heterogeneous network resources through a hierarchy of controllers. The second one shows how IT and network resources are orchestrated in an energy-related context. Finally, mobile network entities (RoF nodes) are also managed by the XCI in a high-speed train scenario to reduce energy consumption.

5. Use case 1: hierarchical multi-technology network orchestration

The flexible and fast deployment of E2E services with diverse requirements and network scenarios combining multiple transport technologies (optical and wireless) will be the rule in future 5G networks. However, the trend in current commercial networks composed of multiple domains is to perform such service deployment almost

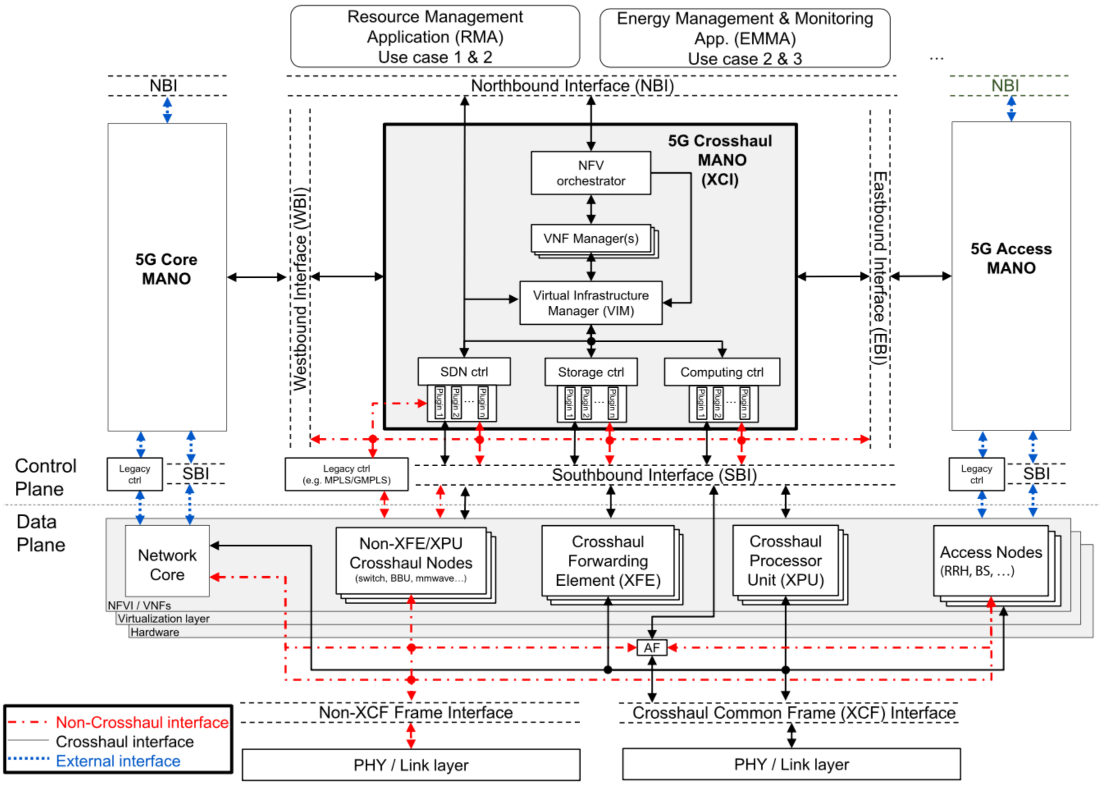

Fig. 1. 5G-Crosshaul architecture.

manually, thus, service setup times are in the order of days or weeks. Nonetheless, the 5G-Crosshaul system can cope with the previously mentioned dynamicity both from the perspective of technology heterogeneity of transport networks and from the perspective of service requirements to provide a service setup in the order of seconds or minutes, contributing to the 5G target KPI of reduced time to enable the introduction/provisioning of new network services.

In this use case, we present how the XCI enables the control of a complex multi-domain and multi-technology transport network by means of a hierarchy of SDN controllers that expose the appropriate APIs to the resource management application (RMA). These transport networks consist of heterogeneous technologies, namely wireless and optical, which need end-to-end orchestration. In the proposed hierarchical XCI deployment, child controllers deal with the specificities of each technology whilst the parent controller offers the appropriate abstraction level and an E2E view to the RMA, which exploits the XCI APIs.

5.1. *Scenario setup*

The foundations of the 5G-Crosshaul control plane architecture lay on the integration of the NFV and SDN paradigms. Integration of SDN in NFV follows what is described in [31], with the following deployment options for the scenarios presented in this paper: (1) SDN resources are physical and virtual switches; (2) SDN controller located in the NFV Infrastructure (NFVI); and (3) application in the Operations and Support System (OSS) interfacing with the SDN controller.

Fig. 2 presents the architecture of the hierarchical deployment of the XCI to provide multi-domain multi-technology network orchestration. At the top of Fig. 2, the RMA is in charge of computing optimal routes between endpoints in the multi-domain data plane relying on a graph-based abstracted view of the underlying topology, provided by the XCI. Thanks to this abstracted view, network management applications (application plane) can exploit 5G-Crosshaul resources without having to deal with the specificities of the heterogeneous technologies deployed at the underlying data plane, as explained later. More specifically, the data plane encompasses (1) IEEE 802.11ad and IEEE 802.11ac technologies at the edge packet-switched wireless transport domain/segment, and (2) wired packet-switched layer on top of an optical circuit-switched layer in the aggregation and core transport domain.

The XCI SDN controller component is hierarchical, where the *parent controller* orchestrates the different underlying *child controllers,* in charge of handling the specificities of its underlying equipment. In the setup of Fig. 2, the E2E Transport Orchestrator module (parent ABNO, or pABNO) is the parent controller of the system [24]. This module is based on the Application-Based Network Operations (ABNO) controller [19] architecture. In turn, the child controllers for each domain are the Wireless SDN controller and the Multi-layer Optical Orchestrator (cABNO). It is worth noting the capabilities of the ABNO architecture to support recursive deployments with arbitrary depth, as seen with the child ABNO (cABNO) controller. This recursion is enabled in part by a component of the ABNO architecture called the Abstraction Manager (AM). The AM is able to provide several types of abstraction levels, such as node or link abstraction of the underlying network resources. Such abstractions serve to hide unnecessary specific low-level details to control elements up in the hierarchy, hence easing its job towards more modular and scalable deployments, as depicted in Fig. 2. Another enabler of the recursion is the use of a unified application programming interface (API) providing common abstraction models simultaneously at the southbound and the northbound interface, as discussed in [29]. In order to expose this multi-domain information and to execute establishment path requests in a homogeneous manner to the RMA, the pABNO controller interacts with the child controllers via the Control

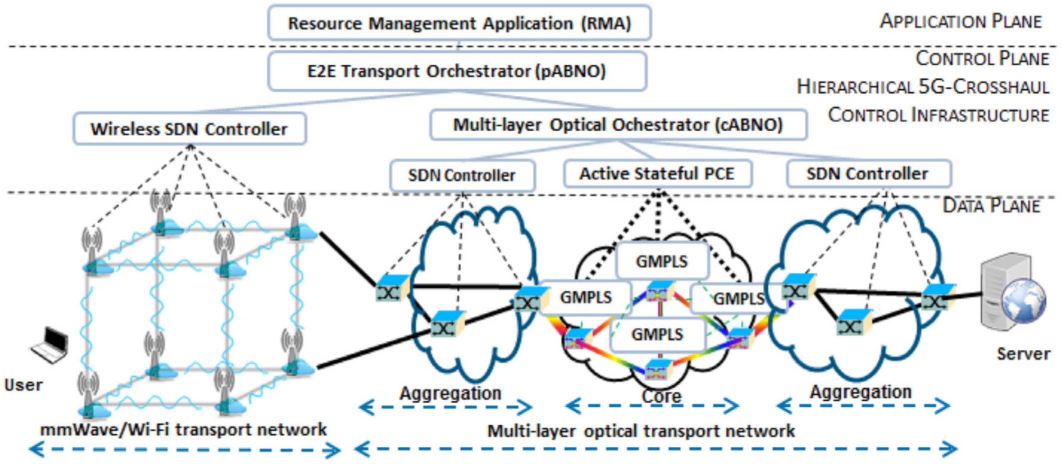

Fig. 2. Network scenario for use case 1.

Orchestration Protocol (COP) [25] API, and so does the RMA with the parent controller. As mentioned previously, the COP protocol precedes similar efforts later carried out at SDOs such as ONF T-API (Transport API) [30].

Furthermore, through this hierarchical operation and depending on the XCI configuration, the child controllers could make local decisions after a link status event at a shorter time-scale than the RMA and the parent controller, given their proximity to the network nodes. In fact, the proposed hierarchical XCI deployment also provides flexibility when facing unexpected network events, such as link failures. More specifically, the XCI can be configured to perform a distributed or a centralized recovery. In the distributed case, the closest controller in the hierarchy can take some technology-specific local decisions, hence saving processing and propagation time up in the hierarchy. In our case, and depending on the domain, there may be differences in path setup/restoration values observed at child vs. parent controller ranging from around 500 ms to one order of magnitude (up to units of seconds) [13].

5.2. Experimental evaluation results

This section focuses on the analysis of the contribution of each component and layer of the heterogeneous E2E transport network to the total setup time. Though the focus is on this quantitative analysis, other conclusions are implicit while doing this exercise. First, the fact that the E2E path is established based on a single request sent to the pABNO experimentally validates that the hierarchy of controllers, with each layer having different abstraction levels, is indeed enabled by the unified COP-based API. Furthermore, it is shown how service setup is automated, as opposed to the remarkable manual intervention required in current operational networks. And second, by observing the values obtained for the total E2E service setup time, we show have the XCI enables to substantially reduce one of the key 5G KPIs (i.e., service setup time).

To eventually understand the E2E behavior related with the service setup, we have evaluated the contribution to E2E service setup time of each network segment (wireless and optical), each plane (application and control planes), and each layer of the hierarchy inside the XCI. In the scenario under study, the main components of the path setup delay are: (a) RMA processing, (b) RMA-to-parent ABNO latency (about 60 ms of RTT) for each message exchange, (c) bidirectional multilayer connection setup in the optical network (around 2.5 s), and (d) wireless domain connection setup (tens of ms) assuming a wireless control channel. Fig. 3 shows the cumulative distributed function and the histogram of the elapsed time at the parent ABNO to establish each of the 10,000 E2E path requests from the RMA application. The experimental results obtained show an average of 3.349 s of E2E path setup delay as seen from the parent controller, which resulted in an average of 3.971 s as seen from the RMA. It is worth mentioning that in the case of a network service requesting multiple E2E connections, the setup of the optical lightpath is only done for the first connection. The remaining flows required by the network service reuse this same optical path, and so, there is less setup delay for the following connections.

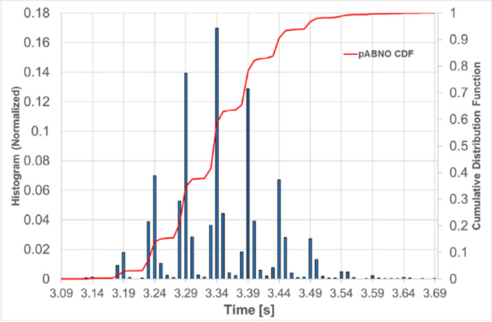

Fig. 3. Cumulative distribution function of the E2E setup delay as seen from the parent controller.

6. Use case 2: energy management of IT and network resources

The second use case focuses on a different aspect of the XCI, that is, (1) the services offered by the MANO stack integrated in the XCI and exposed through its northbound interface, and (2) the joint orchestration of IT and network resources. In this specific use case, these services are exploited by our energy management application (EMMA) through the northbound API of the XCI. In this sense, the XCI enables high degrees of dynamicity in managing and programming the 5G-Crosshaul infrastructure, based on services and traffic demands. This feature can be exploited to reduce the global power consumption of the physical data plane through the automated activation and de-activation of IT and network nodes, based on the virtual resources allocated to satisfy the service requests.

The Energy Monitoring and Management Application (EMMA) applied to VNFs and virtual infrastructures orchestration combines two major concepts. First, there is a resource management and allocation algorithm that jointly selects VNFs placement and network paths with the objective function of minimizing the total power consumption of the physical Crosshaul resources. And second, there is a set of procedures integrated into the XCI's NFV Orchestrator (NFVO) and SDN controller to adjust the power states of XPUs and 5G-Crosshaul Packet Forwarding Elements (XPFEs) (i.e., switching on and off IT and network nodes) during the instantiation of the virtual services, based on the resource allocation solution elaborated by the algorithm. The performance of the resource allocation algorithm and its comparison with the "always on" approach have been analyzed using emulated Mininet-based network environments, as reported in [7].

6.1. Scenario setup

The EMMA application interacts with the XCI software prototype, which integrates an OpenDaylight[2] SDN controller and the developed ETSI NFV MANO stack, both with extensions that can be exploited by EMMA. OpenDaylight is extended with applications for multi-tenant path provisioning through a resource management application, monitoring of power metrics and configuration of power states in XPFEs. The NFV Orchestrator (NFVO) at the MANO stack implements mechanisms for multi-tenant provisioning of Network Services and configuration of underlying transport network via an SDN controller and it integrates the EMMA algorithms and mechanisms for dynamic activation and de-activation of XPFEs and XPUs.

The reference testbed is composed of three XPUs managed through an extended OpenStack[3]-based Virtual Infrastructure Manager (VIM). The XPUs are interconnected through a network composed of six XPFEs running OpenFlow virtual switches based on Lagopus[4] software, as depicted in Fig. 4. In this paper, we experimentally analyze the performance of our solution when running in a real testbed, also evaluating how much the power state adjustment impacts the service provisioning time.

6.2. Experimental evaluation results

The first round of tests focuses on network path provisioning and XPFE power consumption monitoring. The EMMA application interacts with the OpenDaylight SDN Controller through a REST API to perform power consumption monitoring. Then, the SDN controller retrieves power consumption data directly from the XPFEs, using the Simple Network Management Protocol (SNMP) with SBI protocol used within the SDN controller to retrieve power consumption data directly from the XPFEs is the Simple Network Management Protocol (SNMP), using the EMAN MIB [26]. A specific SNMP Agent for providing power consumption data and changing power states is implemented is implemented within each XPFE.

Measurements show that the power consumption of a node can be decomposed into a constant baseline component and a traffic load dependent component. For the system under evaluation, the constant component is around 23 W in sleeping mode and 35 W in active mode, while the variable component due to the traffic load is very low, in the order of hundreds of mW (e.g., around 500 mW for 1 Gbps traffic for the devices under test).

The on-demand provisioning of energy-efficient network connections over the XPFE domain triggers the automated regulation of device´s power states (i.e., sleeping mode, active mode for low traffic and active mode for high traffic). Results show consistent energy savings especially under low traffic conditions. For instance, Fig. 5 shows that a power saving of 40% (from 210 W to 126 W) is possible in the reference XPFE topology and without connections, when comparing our approach with the "always on" approach. Increasing the number of paths interconnecting the XPUs, the power saving decreases to 28 W (power saving around 13%) for a full mesh interconnection with the three paths shown in Fig. 6.

One key aspect to consider is the network path provisioning time, including the switching between different energy management states when needed. For the scenario under evaluation, connection setup time for network paths crossing three nodes is in the order of 3 s when an XPFE power state change is required, while it is in the order of few hundreds of milliseconds otherwise, as shown in Fig. 7. It is worth mentioning that power state changes in the network are determined by the EMMA application as a result of current network state and the needs of the request. For instance, in a larger network, if the traffic is not too high, the EMMA routing algorithms will decide to concentrate the traffic on a limited number of XPFEs so that a large percentage of the nodes can remain in sleeping mode.

Additional tests cover IT resources and automatic activation of XPUs where VNFs are deployed. In this case, the average provisioning time is nearly 130 s for a virtual Evolved Packet Core (vEPC) network service consisting of four VNFs based on the Open Air Interface (OAI) software [27].

The most consuming steps are the VNFs virtual machines (VMs) creation and configuration (around 65 s), while the activation time for both XPUs and XPFEs remains in the order of a few seconds. These measurements in a real environment demonstrate how network function virtualization and smart resource orchestration can effectively reduce the delivery time up to just few minutes, even for complex end-to-end services, while guaranteeing an energy-efficient sharing of the infrastructure. The scalability of the proposed solution has been studied in [33] where a network with around 100 nodes has been emulated. Results show that the designed algorithm performs very close to the optimum, mainly thanks to its ability to account for all the main sources of energy consumption that characterize 5G systems.

7. Use case 3: energy management of high-speed train

The third use case also demonstrates the ability of the XCI to expose information on the operation of the network so that the EMMA application can take energy-efficient network configuration decisions. However, this time the network managed by EMMA is a RoF-based mobile network, which is substantially different from the network in use case 2 (consisting of IT and transport network resources). Furthermore, train mobility is also taken into account in this use case. Despite these heterogeneity, the XCI is still capable of providing a global view of the entire network along with the programmability of the connected nodes to dynamically provision and allocate the required resources. Moreover, with the support of the SNMP plug-in, the XCI enables reducing the power consumption of the RoF nodes deployed along the railway track. In the high-speed train, the EMMA application exploits the NBI API of the XCI, which is responsible to enforce EMMA decisions. EMMA applied to RoF nodes combines two major concepts, namely (1) adjusting the power state of the RoF nodes based on the mobility of the train, and (2) exposing a power consumption-monitoring interface to the network managers. In this case, train mobility is tracked by making the equipment on the train to periodically transmit the physical cell ID (PCI) to which it is attached. The goal is to minimize the energy footprint of the deployed RoF nodes while being able to serve ground-to-train communication. The performance of the algorithm is compared with an always on approach where RoF nodes are on all the time to serve the high-speed train, which is the common practice.

7.1. Scenario setup

EMMA was evaluated in a real-world high-speed train scenario operating on a 10 Km railway track including two tunnels, as illustrated in Fig. 8. In the high-speed train setup, the experiment demonstrates the reduction in energy consumption of the RoF nodes deployed along the track. In this testbed, nine RoF nodes are deployed, especially in the two tunnels, where they provide better coverage to the passengers of the train, as shown in Fig. 8, where the highlighted circles represent

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[2] https://www.opendaylight.org/

[3] https://www.openstack.org/

[4] http://www.lagopus.org/

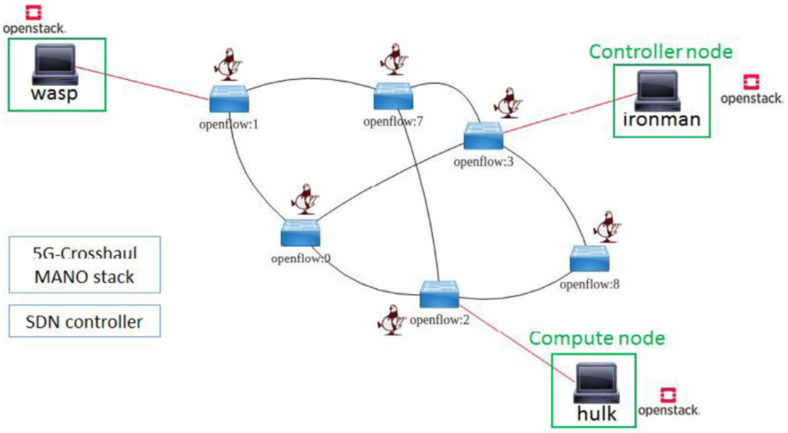

Fig. 4. Testbed topology for use case 2.

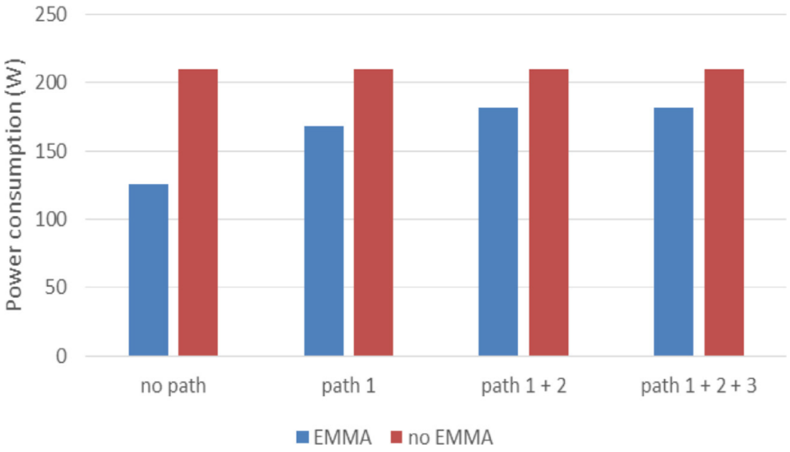

Fig. 5. Power consumption saving.

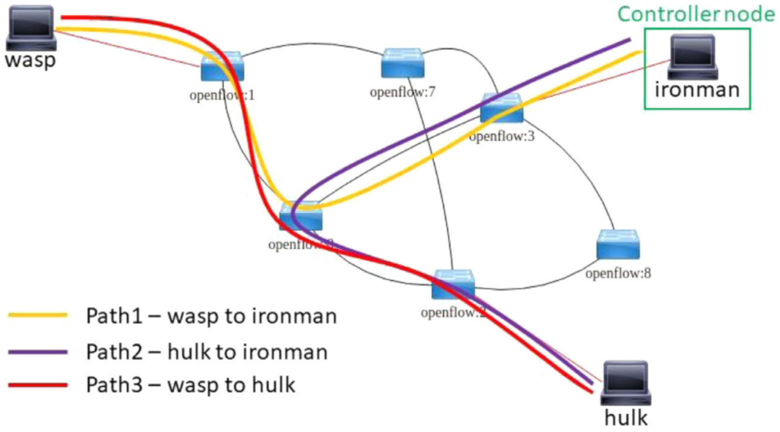

Fig. 6. Network connections in energy management test.

different cells. The scenario was composed of the following components: (1) EMMA to reduce the energy consumption of the connected RoF nodes, (2) Extended OpenDayLight (ODL)-based SDN controller with modifications to the SNMP agent, (3) nine RoF nodes, (4) Cubie board attached to the RoF node to carry out the management functions, (5) Customer Premises Equipment (CPE) to access logs of the roadside eNBs, (6) Industrial Personal Computer (IPC), a computer connected to CPE control interface to save and process logs from the CPE. After processing the logs, it pushes the extracted information to the database, and (7) High-Speed Train.

7.2. Experimental evaluation results

A field trial was conducted to collect the results. The experiment

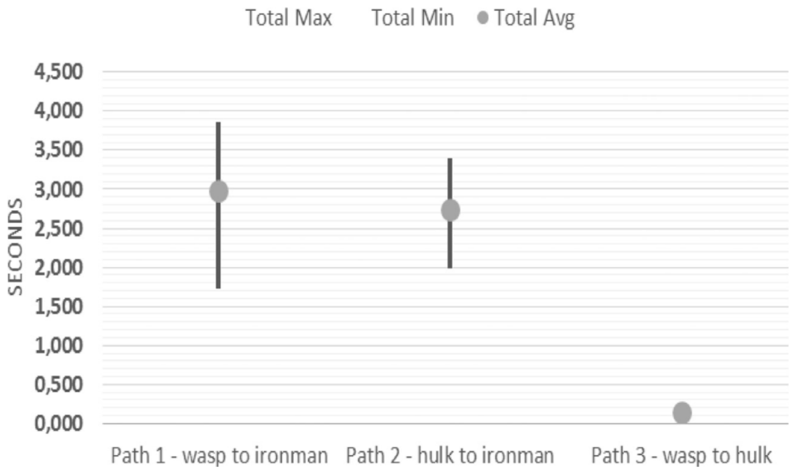

Fig. 7. Total network path provisioning time: average (dots), max and min values (line edges).

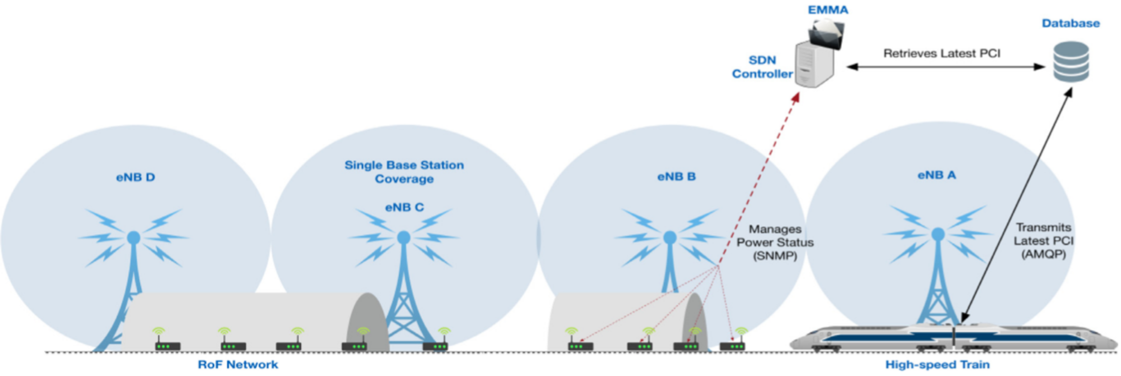

Fig. 8. EMMA integrated in High-Speed Train scenario.

Table 1
Power values of different components used.

Component	Power consumption (Watt)
RoF 2×2 MIMO (P_r)	19.8
Cubie board (P_c)	1.375

evaluates the performance of the EMMA application in terms of reduction in RoF nodes energy consumption. EMMA onboard components (i.e., CPE and IPC) were deployed in the train, and then, the experiments were performed repeatedly to quantify the obtained results. In the calculation of energy consumption of the experiments, the power consumption of the RoF node and the supporting Cubie Board are considered. The Cubie Board is a single-board computer that runs an agent for the connected RoF node. Table 1 shows the power consumption values for a single RoF node and the Cubie board.

In this experiment, we show the reduction in energy of the RoF node without switching off the Cubie Board, which acts as an SNMP client and manages the RoF nodes based on the received signals. The Cubie Board is always on in our field trials and always consumes energy. In its regular setup, the high-speed train operates daily from 7 AM to 11 PM and RoF nodes are always switched on, regardless of operational time of the train. Fig. 9 illustrates the comparison of energy consumption of RoF nodes with and without EMMA only in the operational time of the train. The *X*-axis and *Y*-axis represent, respectively, the time of day in one-hour increments and the energy consumption per hour with and without EMMA. With EMMA, RoF nodes are switched on only to serve the high-speed train when it is approaching, saving a significant amount of energy. In the field trial, the sojourn time of a train in a given RoF node is approximately 130 s. Based on the measurements in Table 1, a single node consumes 21.175 W. Considering that there are nine RoF nodes along the railway and the above sojourn time, these results in an energy consumption of 24.8 kJ for a single train trip. The obtained results demonstrate that EMMA reduces energy consumption by 78.6%, which is equivalent to energy savings of 17,257 kJ per day (considering all the train trips per hour), as illustrated in Fig. 9.

8. Summary and conclusions

This paper experimentally validates the operation of the 5G-Crosshaul Control infrastructure (XCI), the control plane of the 5G-Crosshaul integrated fronthaul and backhaul. For that purpose, three widely different use cases are deployed in the testbed. They feature different technologies (optical, wireless, and mobile networks or computing resources) and have scopes (efficient energy and path management) that allow showing how the openness and automation capabilities of the XCI provide the required flexibility to handle such diversity of scenarios. This assessment shows that the services offered by the XCI through its northbound interface enable network management applications to decrease service deployment times from months (due to current substantial manual configuration) to minutes, or even seconds, depending on the specific service. In the same way, energy reductions of up to 80% can be achieved depending on the scenario while maintaining the required level of service. Such features of the XCI contribute to reach some of the ambitious goals initially set for 5G, like reduction of service deployment time or network energy footprint.

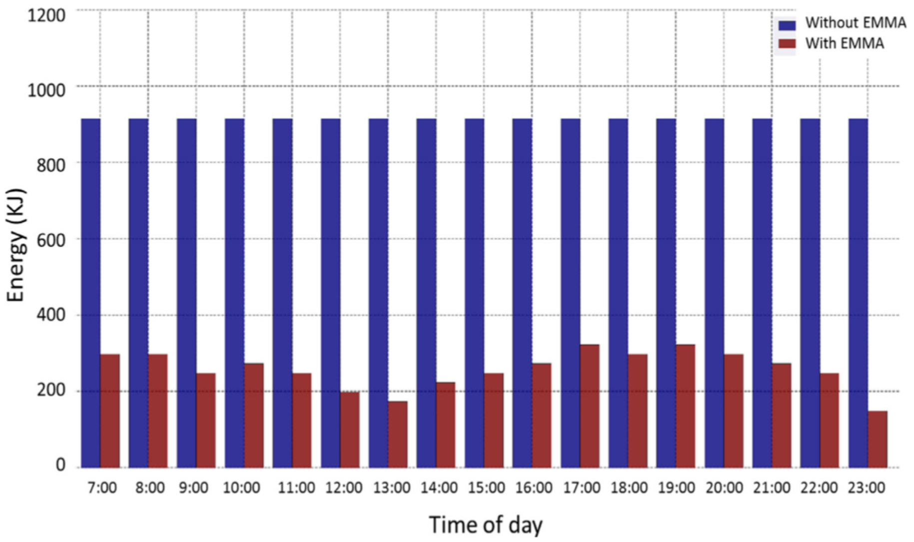

Fig. 9. Energy consumption comparison with and without EMMA.

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