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Optical and wireless network convergence in 5G systems – an experimental approach

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***Abstract*—This paper provides a description of key results stemming from experiments conducted at the wireless/optical boundary. The main aim is to show the advantages of a converged optical/wireless network deployment, which uses very recent technologies like SDN, Virtualization, fog and cloud computing, and Radio-over fiber. The results are mainly taken out of an international collaborative research project called FUTEBOL (Federated Union of Telecommunications Research Facilities for an EU Brazil Open Laboratory).**

Keywords— Experiments; Wireless/optical convergence; Control framework; 5G systems.

I. Introduction

Telecommunications networks remain largely segregated in the two domains of optical networks and wireless systems, and rarely do even researchers cross the boundary between the two, so to provide a comprehensive and holistic view of a telecommunication facility. We argue that the evolutionary path [1] and the needs of future telecommunication systems, be it for high data rate applications, for the Internet of Things (IoT) paradigm, or for aggressive backhaul requirements stemming out of cell densification, require the co-design of wireless access and optical backhaul and backbone. In this context, the EU-Brazil co-funded project FUTEBOL (Federated Union of Telecommunications Research Facilities for an EU-Brazil Open Laboratory) [2] aims at developing a converged control framework for experimentation on wireless and optical networks and to deploy this framework in federated research facilities, which will be made openly available to the whole research community.

The proliferation of small cells deployments increases frequency reuse and is one of the main means that allow for gains in mobile network capacity. On the optical network side, network function virtualization (NFV) and software-defined networks (SDN) are revolutionizing the way that network resources are managed. We view virtualization on the optical side and densification and capacity increase on the wireless access as major game changers in future networks that will deliver the best benefits when co-designed and experimented together. Therefore, we propose in this work a research infrastructure tailored to the needs of experimenters throughout the world, interested in issues that cross the boundary between wireless and optical networks.

Fig. 1 illustrates the layered nature of the proposed approach: the few key identified use cases leverage on the development of an underlying converged control framework, which, targeting some experiments focusing on selected aspects of wireless-optical converge, in turn requires the composition of federated research infrastructure, currently being enhanced by the FUTEBOL partners.

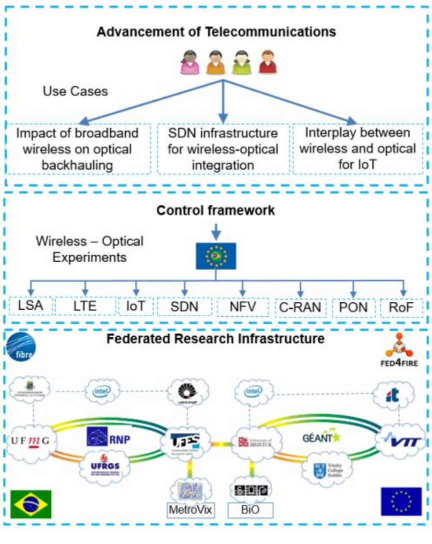

Fig. 1 Wireless-optical convergence: the FUTEBOL approach [2].

This paper provides an update of the main FUTEBOL experiments on the convergence of optical and wireless networks, initially presented in [3]. They encompass some of the main driving research areas towards 5G networks.

The paper is organized as follows: Section II describes how SDN and virtualization can be used at the wireless-optical boundary, Section III describes a Wireless-Optical SDN-Enabled Infrastructure capable of steering a robot in a controlled environment, Section IV proposes an adaptive cloud and fog environment for IoT experimentations, Section V shows a Radio-Over-Fiber monitoring system for IoT and finally section VI concludes the paper and hints at future work.

II. Heterogeneous wireless-optical network management with SDN and virtualization

The objective of this experiment is to show the dynamic adaptation of integrated optical wireless networks, considering three parts: wireless access, optical access, and metro/core. In the wireless part, virtual machines (VM) are set up to perform processing in the backhaul and fronthaul using Software Defined Radio (SDR) technology. The optical access is implemented using a Passive Optical Network (PON), including the use of logical connections. In the metro and core network parts, SDN and virtualization mechanisms are aimed at establishing wavelength paths. This experiment is comprised of two main optical-and-wireless integration elements.

A. *Flexible-rate mobile fronthaul in PON*

The concept of Cloud Radio Access Network (C-RAN) in 5G network separates the locus of Baseband Units (BBUs) and Remote Radio Heads (RRHs), and integrates multiple BBUs in centralized BBU pools, in order to manage the utilization of processing resources in a more flexible and energy-efficient way. The optical network between BBUs and RRHs is named mobile fronthaul.

We have developed a C-RAN testbed in Trinity College Dublin (TCD). We have implemented the BBU pool for LTE networks on a cloud-based testbed by open-source SDR software srsLTE [7], and developed RRHs by USRP X310s. Furthermore, we have implemented the mobile fronthaul by separating the location of BBU pool and RRH and connecting them with PON. To control and manage the PON bandwidth, we have proposed a flexible-rate fronthaul scheme with a testbed prototype shown in Fig. 2.

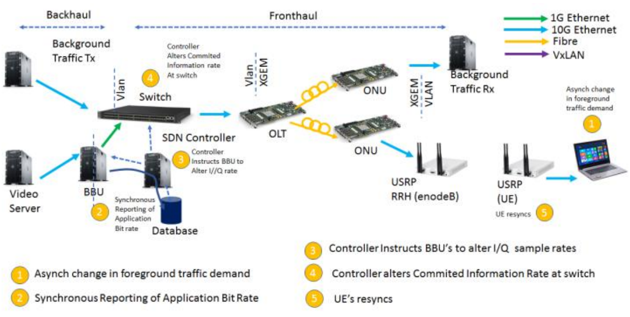

Fig. 2 Flexible-rate fronthaul system developed in the TCD testbed [4].

Wired broadband services (a.k.a., background traffic) and mobile fronthaul services (a.k.a. foreground traffic) share the same PON in the testbed. The fronthaul bandwidth for transmitting the wireless I/Q samples is adapted to foreground traffic load, by changing the LTE sampling rate on the RRH. We have also implemented an SDN controller based on RYU [4] to control the integration of background traffic and foreground traffic, using an event-triggered scheme shown in Fig. 2.

B. *End-to-end inter-testbed Optical and Wireless Integration using the FUTEBOL Control Framework*

We have developed an application-based network orchestration (ABNO) platform for control and orchestration between experiments and multiple testbeds. ABNO can integrate and orchestrate multiple SDN controllers across wireless, Ethernet (i.e., packet), and optical domains.

To test our proposed ABNO platform we interconnect the C-RAN fronthaul of TCD testbed with the convergent core WDM-optical network and edge Ethernet packet network of the University of Bristol testbed. Fig. 3 shows part of the ABNO graphical user interface, capable of controlling parameters and sending data to the TCD Cloud-RAN fronthaul.

ABNO sends control messages inside and between testbeds to establish end-to-end (E2E) connectivity across domains. The control messages can increase or decrease the bandwidth and/or the quality-of-services in the C-RAN fronthaul, and can orchestrate wavelengths, bandwidth, and ports in optical and packet backhaul.

As a result, experimenters will be able to use, integrate, and orchestrate resources across domains and FUTEBOL testbeds.

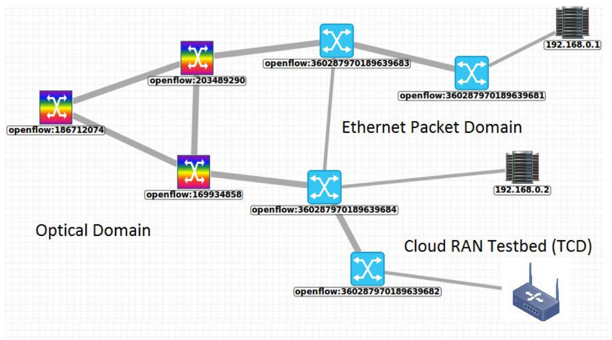

Fig. 3 University of Bristol testbed with the connection to TCD

III. Real-Time Remote Control of Robots Over a Wireless-Optical SDN-Enabled Infrastructure

The main objective of this experiment is to evaluate the impact of SDN and cloud computing technologies in systems running real-time applications with low E2E latency and high bandwidth requirements. We will demonstrate how communication infrastructure, including optical-wireless integration and datacenter networking, need to evolve to support future robotics as a service (e.g., rehabilitation therapies, robot localization and navigation, assistive robotics). Innovative solutions to reduce overall latency employing SDN to achieve complex coordinated architectures with dynamically controlled bitrates will be tested using the FUTEBOL testbed.

This experiment involves three basic groups of resources: an intelligent space, an edge datacenter, and remote datacenters, as shown in

Fig. 4 [5]. The intelligent space contains cameras, which transmit data to edge and/or remote datacenters, a remotely controlled robot, and a set of wireless devices. The cloud (represented by edge and remote datacenters) is responsible for processing data, determining the robot localization based on camera images, and, in turn, generating control commands back to the robot. The mobile robotic platform contains only the necessary components for wireless communication and execution of control commands.

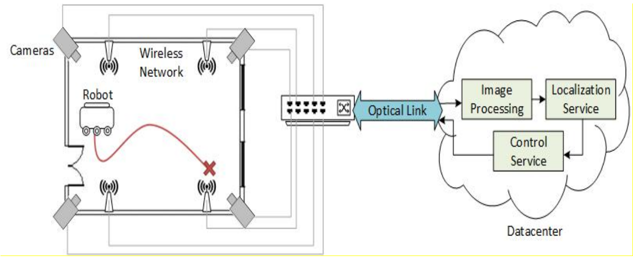

Fig. 4 Real-time robot control using SDN – Abstract architecture of the experiment [5].

The mobile robotic platform contains only the necessary components for wireless communication and execution of control commands. The cameras gather images from the intelligent space and send them to image processing and localization services in the cloud. Robot's localization is then compared against the desired trajectory and a control service, also in the cloud, produces the control command, which is transmitted using wired and wireless networks to the robot in the intelligent space.

To achieve ultra-reliable low latency communication in wireless networks to support robot mobility, we propose and implement a splitting of the WiFi architecture functionalities in a much more efficient way [6]. This software-defined wireless architecture provides multi-connectivity and redundant communication, offering seamless mobility and failover resilience. The main idea is to create a mobile Access Point (AP) to which multiple non-mobile station (STA) are associated and serve as a bridge to cloud services. Fig. 5 shows the wireless architecture and the interaction between the controller elements with the network elements.

In this way, the SDN controller can implement fast handover process and handle failovers only through updates of the OpenFlow rules in the backhaul switch, by forwarding the traffic through the corresponding port, while the robot moves in the intelligent space. The results of our solution for a more efficient handovers show that during this process, the robot does not lose communication with the cloud, and the throughput degradation is very small if compared to the handover processes in classic WiFi networks, as shown in Fig. 6 [6]. When a failure happens, the degradation of the throughput is a little greater than in the failover case because the failure procedure is made of reactive processes where the controller does not execute any action until the event happens. Even so, the results show that the architecture presents a good performance in the recovery to failures, being able of guaranteeing communication at any time.

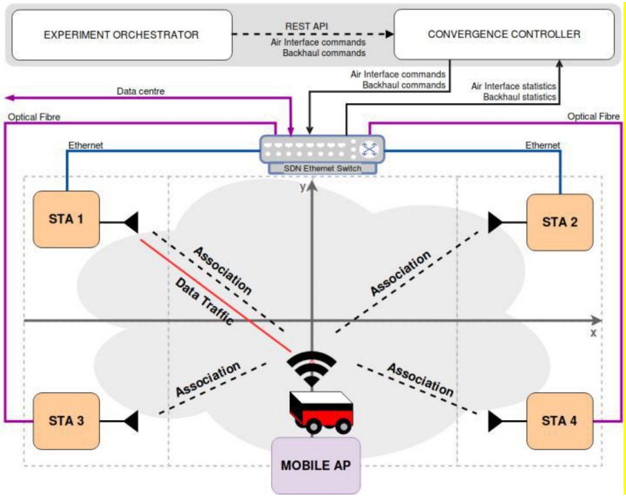

Fig. 5 Wireless mobility implementation.

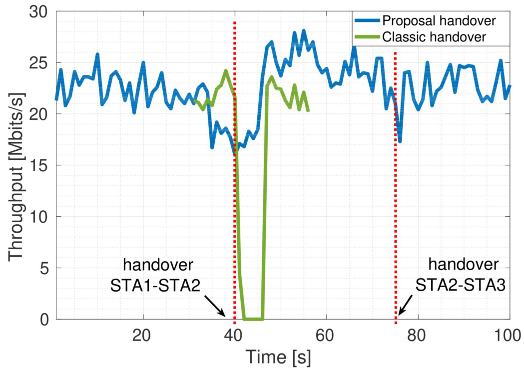

Fig. 6 Throughput during handover process [6]

IV. Adaptive Cloud/Fog for IoT according to Network Capacity and Service Latency Requirements

The main objective of this experiment is to use the FUTEBOL federation to set up a flexible optical-wireless network to interconnect smart objects and explore the interplay between Fog and Cloud, so to enhance the performance of an IoT application in a converged optical wireless network. This optical-wireless integration will create a tradeoff between Fog and Cloud when applied to IoT environments, while considering different conditions of optical and wireless links.

For this experiment showcase, we have built a smart lighting system in which a person can control the lights through either voice or sign language commands. The lights can be controlled in three ways: turn on/off, increase/decrease brightness, and change color. This system spans a wireless and an optical network and is divided into two segments. In the first segment, the command (voice or sign language) is captured. In the second segment, which operates across the optical network, the captured command is processed. In this case, processing can occur on a local server, in a gateway, or in the Cloud (i.e., Local, Fog, or Cloud tiers).

The COPA (Container Orchestration Platform Architecture), which is an integrated tool of the FUTEBOL control framework capable of monitoring the network and migrating the processing, is used to measure in real time the E2E latency in optical and wireless segments. The measurement starts from the moment that a command is captured and processed, until the moment when the light bulb reacts (i.e., changes its color or brightness intensity). Through this monitoring, it is possible to identify problems in the processing of the IoT service at different tiers and migrate such processing to the most appropriate location.

The experiment set-up architecture is presented in Fig. 7.

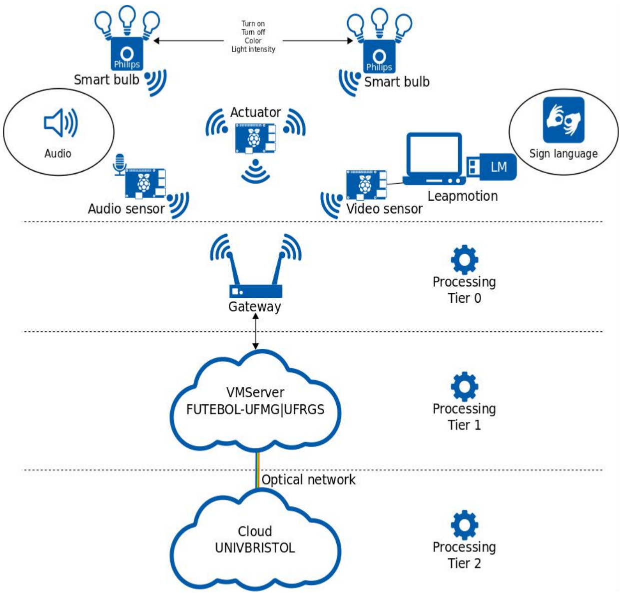

Fig. 7 Setup for adaptive Cloud/Fog experimentation.

Tier 0 is "Local", tier 1 is "Fog" and tier 2 is "Cloud". Each tier has a VM, in which the container service is available. In tier 0, we have the IoT application. Tier 1 contains a data center that can process video and sound on demand, so to send the results to both Smart Objects (i.e., voice sensor and smart bulb) and the Cloud. Tier 2 represents the cloud, which is linked to the optical infrastructure where VMs process the voice or sign language commands.

To allocate in different locations the three tiers and integrate testbeds network, we use JFed, a Java-based framework for testbed federation [8]. To perform the monitoring of the network to gather and further evaluate key performance indicators (KPI) of the experiment and to support and provide migration of the containerized application to orchestrate the processing application between Fog and Cloud, COPA is used. Through the interface offered by COPA, any user can access the data of the servers in the slice in real time and has the possibility to migrate network resources in any easy way. Besides, it is possible to set the automatic orchestration threshold algorithm that can provide the best performance to the application, based on several key parameters, like latency and CPU load. If the mean CPU load or mean tier latency is, respectively, over 90% or 100 ms for the last ten measurements, the processing is migrated to a less loaded server. We measured the latency and identified its impact on the response time to the voice and signal commands. In Fig. 8 the response time measured for voice commands in each processing tier is depicted. For different voice commands the response time is always longer when the voice recognition processing is performed in the Cloud, as compared to either VMServer or Local VM. For more complicated commands, the response time increases, mainly for the Cloud. In the worst case, 1190 ms are needed to perform the "light two on color blue" control.

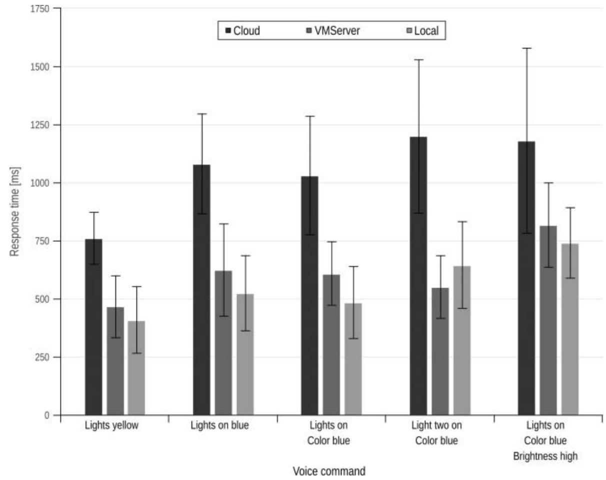

Fig. 8 Response time for voice commands.

V. Radio-Over-Fiber for IoT Environment Monitoring

This experiment aims to implement a robust and efficient RoF (Radio-over-Fiber) environmental monitoring system at the University of Campinas – Brazil (UNICAMP) campus. In this experiment, several indoor/outdoor IoT sensor devices communicate over an RoF system, which employs optical fibre already deployed in the campus. Moreover, an indoor RoF-based infrastructure deployment is available at the Federal University of Rio Grande do Sul - Brazil (UFRGS) to offer a configurable, distributed RoF-based IoT testbed.

In this experiment we aim to demonstrate the suitability of RoF transmission (RoF and Digitalized RoF systems (D-RoF)) for IoT applications. A comparison of wireless, RoF and D-RoF is provided, describing their advantages and drawbacks for IoT applications in terms of system performance degradation, latency and node energy consumption. Moreover, since the IoT devices can use technologies such as ZigBee to transmit data, an efficient data reporting is also aimed at, by providing multi-hop protocols. Furthermore, to enable an easy reconfiguration for each application according to specific needs, remote real-time configuration capabilities is provided. Finally, data reported by each IoT device, according to specific profiles, is stored in a database for further analysis.

A preliminary result obtained with the infrastructure deployed for this experiment was the assessment of the impact of RoF systems on IEEE 802.15-4-based IoT applications in terms of the packet success ratio. Two instances of the experiment were performed separately, one using XBEE-Pro S1 (IEEE 802.15.4) RF modules at UNICAMP and the other one using NI-USRP-2901 devices at UFRGS. The XBEE modules offer a limited set of transmit power levels ({-3, 2, 8, 10} dBm), whereas the USRPs allow for a fine control of the transmit power level up to 20 dBm by adjusting their normalized power gain between 0 and 1. In both instances, there is a device acting as a source and another as a sink. The source transmits

1000 messages with a 10 ms time interval. Each setup was executed 20 times with each transmit power level.

At UNICAMP, in a first setup, called *non-RoF*, the source node and a 9dBi antenna (connected to the sink node) are 20 m away from each other. The nodes communicate via wireless crossing an ordinary brick wall. In a second setup, called *RX-RoF*, source and sink nodes communicate via a hybrid wireless/optical RoF infrastructure, in which the 9 dBi antenna is connected to the RF-in port of an OZ810 RoF device from OpticalZonu. This RoF device is connected by a 300 m fiber to another RoF device to which the sink is connected (i.e., an uplink scenario).

At UFRGS, the source and sink nodes are separated about 6 m with a brick wall in the middle and three different setups were implemented. The first two setups are similar to the ones described previously, with the difference that the distance between source and sink in the *RX-RoF* scenario is also 6 m. In a third setup, called *Tx-RoF*, the source is directly connected to the RoF infrastructure, while the sink node received the data through a 9 dBi antenna (i.e., a downlink scenario).

The packet success ratio increases as the transmit power increases in both instances (Fig. 9 (a) and (b)). The packet success ratio values for higher transmit power levels (8 dBm and 10 dBm or after gain of 0.85) are quite similar for all scenarios, whereas the values given by the RoF scenarios for lower transmit power levels (-3 dBm and 3 dBm or gain less than 0.85) are lower than those given by the non-RoF scenario. Moreover, the RoF scenarios yields a higher variance, particularly, for low transmit power levels (Fig. 9 (a)).

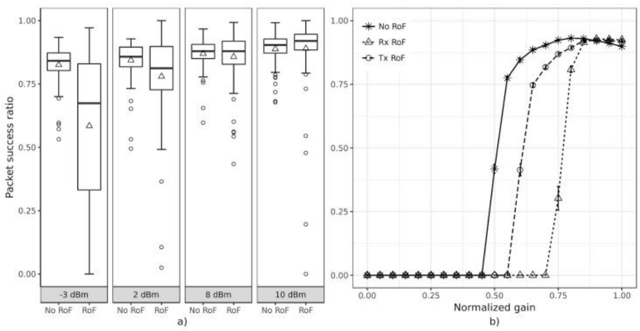

Fig. 9 Impact of RoF on IEEE 802.15.4-based technologies; a) XBEE-based results; b) USRP-based results.

These results show that the impact of the RoF system may be partially or completely compensated by increasing the transmit power, depending on channel condition and the maximum transmit power. Note that, although the packet success ratio can decrease in RoF scenarios, the distance between the two end-side devices can be much larger than that of the non-RoF scenario. Moreover, the RoF system can be shared with other technologies such as WiFi or cellular networks. These results demonstrate the suitability and feasibility of the RoF technology for IoT data transmission.

VI. Conclusions and Future Work

This paper shows some interesting experimentations that make use of advanced experimental testbed already available in both Europe and Brazil, enhancing and extending their capabilities, for research and education purposes across the wireless and optical domains.

Future work will go in the direction of enhancing the facility provided by the FUTEBOL project, especially in targeting some key advancements stemming from the first 5G system deployments.

Acknowledgment

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