COSMOS: Optical Architecture and Prototyping

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Abstract: The COSMOS testbed provides an open-access and programmable multi-layer beyond 5G wireless platform built on an advanced optical x-haul network supporting mobile edge cloud base band processing and applications.

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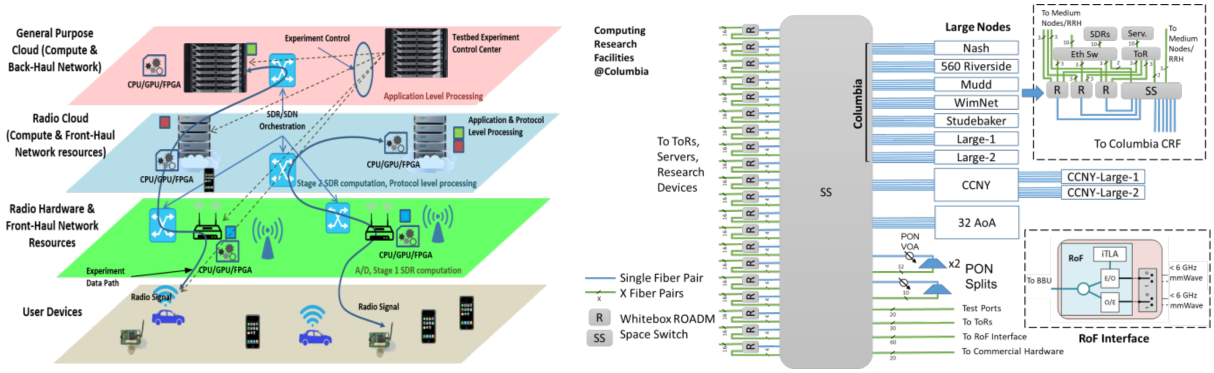
1. Introduction

5G and beyond mobile network development is being driven by rapidly growing wireless traffic supporting a large diversity of services and applications, such as the Internet of Things (IoT), 3D sensing, and virtual reality, which are calling for multi-Gb/s access rates at ultra-low latencies. New radio access network (RAN) architectures make use of raw IQ radio data transport that further drives up the bandwidth demands on the underlying optical networks [1]. In order to meet these advanced 5G requirements, researchers in both academia and industry are investigating new high-bandwidth, low latency, and resource-efficient network architectures that blend optical, wireless, and computing technologies to achieve necessary advances in scalability and performance. Driven by the application requirements, there is growing recognition that these new technologies and architectures need to be investigated together with the applications in field deployed situations. Technologies such as millimeter wave (mmWave) wireless and free space optics are sensitive to line of sight obstacles and weather conditions. Delivering high data rates and ultra-low latency requires levels of technological integration, including wireless, optical, and computing, that have not been previously encountered. It remains an open question how new applications will perform in this environment while being orchestrated with new multi-layer software-defined networking (SDN) control planes. In addition, applications will need to be developed with awareness of the underlying network performance constraints.

The global effort to address these challenges in 5G and beyond networks has led to the development of multi-technology testbeds, often in field deployed environments centered around smart city and advanced wireless applications. Bristol Is Open is a city deployed testbed that provides a research environment for edge computing, and optical and wireless networking managed through a novel network operating system [2]. Other testbeds including ADRENALINE in Spain [3] and RISE/JGN-X in Japan [4], allow for experimentation on optical-wireless 5G architectures converged with SDN and network function virtualization (NFV), edge cloud, or user-end services.



(a) (b)

Fig.1. COSMOS architecture. (a) COSMOS multi-layer computing systems. (b) COSMOS optical architecture.

The Cloud Enhanced Open Software Defined Mobile Wireless Testbed for City-Scale Deployment (COSMOS) platform is a programmable city-scale shared multiuser advanced wireless testbed that is being deployed in New York City [5]. Open APIs and programmability across all the technology components and protocol layers in COSMOS enable researchers to explore 5G technologies in a real world environment. A key feature of COSMOS is its dark fiber based optical x-haul network that enables both highly flexible, user defined network topologies as well as experimentation directly in the optical physical layer. In this paper, we briefly introduce the software-defined radio (SDR) and mobile edge cloud wireless network architecture of COSMOS, and its integration with the optical x-haul network with SDN control. Remote processing of digitized radio-over-fiber signals from a custom full-duplex (FD) radio and on-demand optical switching of video streams from different servers are used to prototype cloud radio access network (C-RAN) functionality across dark fiber infrastructure deployed in upper Manhattan.

2. COSMOS Architecture

Massive MIMO and high capacity SDR mmWave (28 and/or 60 GHz bands) access points in COSMOS will need substantial baseband computing resources in the RAN. This situation motivates the development of front and mid-haul (or x-haul) C-RAN capabilities for investigating different approaches to offloading a node's workload to an infrastructure-based, more powerful edge computing cluster. The same edge cloud on top of the optical x-haul transport system can also be used for network- and application-layer processing, especially in scenarios requiring low end-to-end latency. The COSMOS architecture (Fig. 1(a)) provides four technology layers for experimentation: user device layer, radio hardware and front-haul network resources, radio cloud, and general purpose cloud. An RF thin client can flexibly partition signal processing and NFV between a local SDR (with FPGA assist) and a C-RAN with distributed x-haul processing scalable to massive CPU/GPU and FPGA assist. Further, these two computing layers are backed up by a third layer of general purpose cloud computing useful for network and application level functions associated with an experiment.

3. Optical Architecture in COSMOS

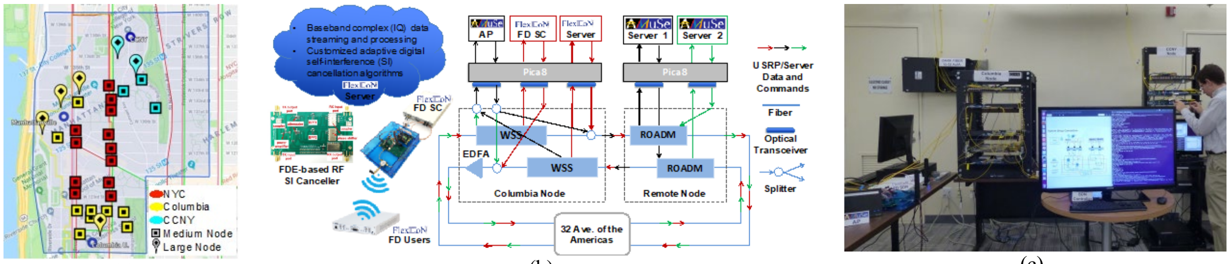
The COSMOS optical network design makes use of wavelength division multiplexing and optical switching to provide two important capabilities: 1) flexible experimentation and network topology reconfiguration of large numbers of radio and computing connections, and 2) multi-layer optical networking for experimentation on novel optical devices, systems, SDN/NFV optical control planes, and optical architectures. Fig. 1(b) shows a schematic of the planned core network connecting the large radio nodes shown in the top inset. A Calient S320 320×320 space switch forms the core of the network in the main computing research facilities (CRF) at Columbia University. Dark fiber pairs connect this switch with similar smaller space switches at each of the large nodes. These space switches allow for remote and automated re-fibering of connections and devices throughout the testbed. Wavelength division multiplexing (WDM) is provided by whitebox reconfigurable optical add drop multiplexing (ROADM) units connected to the space switches. Other devices such as splitters for passive optical networks (PON), test equipment, and other experimental hardware are also attached to the central space switch. Using these capabilities, each of the six fiber pairs between any two large nodes can be configured for combinations of point to point, PON, and ROADM/WDM networks. WDM can also provide basic capacity expansion to the links, supporting up to 96 channels for a maximum link capacity of 96×6 = 576 separate signals. These channels are fully transparent and flex-grid configurable to support 10 Gb/s and 100 Gb/s wavelengths planned for the testbed as well as custom user-supplied signals. As shown in the lower inset of Fig. 1(b), many radio nodes will be equipped with analog radio over fiber (RoF) capabilities in addition to the digital RoF used throughout.

The Columbia CRF optical space switch is planned to have 48 fiber pairs connecting 9 large radio nodes in different locations including several Columbia University buildings (tentative locations appear in the Fig. 1(b)), City College of New York (CCNY) buildings, and city locations. Another six fiber pairs are used to connect to the data center at 32 Avenue of the Americas (32 AoA). The fully equipped testbed will include 20 programmable ROADM units connected to the space switch via 20×4 wavelength filtered add/drop fiber pairs and another 20×16 add/drop pairs for connecting to computing resources or research devices. The 20 line side fiber pairs connect to the space switch for WDM transport over the dark fiber pairs to other nodes. These ROADMs can be reconfigured to support various requirements from connected servers and research devices through top-layer user applications orchestrated by a COSMOS SDN controller. The three PON splitters are connected via 3×11 fiber pairs, two with 1×10 splits and the other with 1×32 splits. In addition, there are 60 fiber pairs for medium node direct connections, 20 pairs for commercial hardware, 20 pairs for test connections, and 3 spare pairs.

Large radio nodes are constructed with a 16×16-port space switch with 3×1 fiber pairs for 3 ROADMs, 6 pairs for direct Columbia CRF connections, 2 pairs for Ethernet switches, 2 pairs for Top of Rack (ToR) switches, and 3 pairs for medium nodes/remote radio heads (RRHs). For medium nodes, currently there are two different configurations. One will use 6 fiber pairs to carry 1550 nm sub-6 GHz radio and spectral monitoring signals, and mmWave/RoF signals. The other configuration is implemented with only 2 fiber pairs. One pair will use a fixed 8-channel mux/demux to support carrying all of these signals on one fiber and the other fibers are left for WDM expansion and mmWave/RoF signals. All node control information is carried on a dedicated 1300 nm signal introduced through a red/blue filter or using a 1300 nm port on the device, added and dropped prior to the ROADM units. A combination of short reach and long reach pluggable transceivers at 10 and 100 Gb/s will be used throughout the testbed. Long reach pluggables include full band tunability for dense WDM operation. For multi-hop amplifier transmission, Menara IPG pluggables with built in OTN wavewrapper, include forward error correction.

4. Prototype Demonstration

Fig. 2(a) shows the planned main dark fiber deployment area for COSMOS. Dark fiber already connects Columbia University to a large co-location data center at 32 AoA (7 miles south of the deployment area). Fig. 2(b) shows overall system design and diagram of the COSMOS x-haul network prototype. In particular, a wideband FD transceiver prototype based on National Instruments (NI) USRP SDRs with custom-designed RF self-interference cancellation circuitry serves as a small cell (SC) node in Columbia University [6, 7]. The SC node communicating with user-end wireless devices sends complex IQ data through the dark fiber network for remote processing at the edge-cloud server using NI LabVIEW. On the x-haul side, real-time USRP-server communication is realized over a metro optical network using dark fiber provided by New York City and ZenFi Networks. In addition, the Adaptive Multicast Services (AMuSe) application [8] simultaneously operates on the x-haul network where the wireless access point (AP) receives video streams from different servers through on-demand optical switching managed by a Ryu based SDN controller [9] (black path to server 1 or green path across 32 AoA to server 2).



(a) (b) (c)

Fig. 2. COSMOS x-haul network: (a) deployment area and dark fiber network map, (b) system design and diagram, and (c) the optical-wireless testbed protytype demonstration at Columbia University.

In our prototype testbed node as shown in Fig. 2(c), the x-haul optical system is composed of two custom-designed optical nodes, including two 90-channel 1×4 WSSs and an EDFA and two Lumentum whitebox ROADM units. All optical switches and amplifiers are reconfigurable by a Ryu SDN controller. A Pica8 whitebox Ethernet switch with Menara Networks tunable OTN SFP+ DWDM transceivers is used to convert Ethernet packets (e.g., to/from the USRP/server) to optical signals. In this method, rather than placing all the computational functionalities at the radio node, having a reconfigurable and dynamic optical layer C-RAN capability allows for offloading the node's functionality based on application requirements (e.g., baseband IQ data streams or multicast video) to a remote compute cluster as illustrated in Fig. 1(a) and Fig. 2. Due to its high capacity (10s of Gb/s) and low latency (less than 1 ms), such an x-haul optical system can support high-performance computing tasks, and flexible network topologies for next-generation wireless devices. With different application requests, the SDN controlled x-haul optical system automatically switches the optical path either to the 32 AoA dark fiber network or to the Pica8 switch, enabling an optically switched bi-directional communication link between the AMuSe AP and the servers. Error free operation of the amplified dark fiber network was demonstrated along with switching of the AMuSe video server between near and far locations. Following the success of the prototype demonstration, the COSMOS testbed will be deployed in upper Manhattan and Harlem areas shown in Fig. 2(a).

5. Acknowledgement

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