Experimental Demonstration of Elastic RF-Optical Networking (ERON) for 5G mm-wave Systems

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Abstract This paper experimentally demonstrates an elastic RF-Optical C-RAN based on mm-wave MIMO systems. An RF-Optical SBVT in the CO generates 1-GBd signals which are elastically assigned (in time and frequency) by the C-RAN controller to multiple remote antenna units.

Introduction
The exponential growths in the Internet traffic have continued impressively from one TB/month in 1990 to ten million TB/month in 2014 and is projected to exceed one hundred million TB/month by the year 2020 [1, 2]. The Internet applications have evolved from fixed desktop environments to cloud environments that emphasize ubiquity, mobility, and bandwidth. Future Internet applications are expected to demand even more ubiquity, mobility, and bandwidth through diverse platforms. Today’s wireless networks are typically limited to 1~100 Mb/s connectivity. While fiber optic networks provide 1~100 Tb/s capacity on each single-mode-fiber over thousands of kilometer distances, they are limited to wide area and metro networks, not readily accessible by mobile users. On the other hand, the new elastic optical networking (EON) [3] with coherent optical communications and sliceable bandwidth variable transponders (SBVT) [4] is emerging as a viable platform also for future metro and access networks. EON could then pave the way for next-generation 5G systems with a seamless interface between EON and mmWave MIMO technologies.

This paper proposes a new elastic RF-photonic communication and networking (ERON) (Fig. 1) architecture that harnesses symbiotic relationships of RF and photonics to bring mobility and high capacity to networks. ERON makes use of three main technologies: (a) RF-optical sliceable bandwidth variable transponders (RFO-SBVT) located at the central offices (COs) generating radio-over-fiber (RoF) signals with variable baud-rate and modulation formats for elastic utilization of wireless and optical networking resources in space-time-frequency domains; (b) mm-wave remote antenna units (RAUs) with optical beam forming capabilities; and (c) spatial division multiplexing multi-input-multi-output (SDM-MIMO). This architecture assumes to use a functional split eight approach [5] where all the processing is performed at the CO. Under this assumption, the centralized processing and RFO-SBVTs at the CO, together with RAUs with RF-optical processing units (RF-OPUs [6]), can implement a photonic hybrid precoding architecture for mm-wave SDM-MIMO systems [7]. Fig. 1 shows how the RFO-SBVT generates WDM RoF signals (each RoF signal is composed of a baseband optical signal plus an
unmodulated carrier) for the different RAUs. Different RAUs can get elastically assigned a different number of RoF signals depending on the number of beams each RAU needs to generate. This can be determined by the C-RAN controller [8] based on certain traffic monitoring information received from the COs.

**Testbed Experiment**

Fig. 2(a) shows the ERON testbed experiment. *Control and Management Plane:* The C-RAN controller is mainly composed of a workflow manager (orchestrator), a topology manager, and a monitoring database [8]. We implemented the C-RAN controller in C++. Regarding the control plane, we implemented an SDN architecture based on OpenFlow (OF). For the controller, we used the Ryu SDN framework. For the OF switches (agents), we deployed one Open vSwitches (OVS) for each element to be controlled (i.e., SBVTs, routers, WSSs). It is worth mentioning that we extended OF to control optical equipment.

*Data plane:* A 25 GHz optical frequency comb acts as WDM laser source for the RFO-SBVT. A wavelength selective switch (WSS) deinterleaves the comb lines producing two 50 GHz OFCs. One OFC is demultiplexed using a 50 GHz spacing arrayed waveguide grating (AWG). The first AWG output is modulated with the OOK modulation format by a Mach-Zehnder (MZ) modulator and pulse pattern generator (PPG). The second, third and fourth AWG outputs are coupled together (only one modulator was available at the time of the experiment) and modulated with QPSK or 16QAM modulation formats by an I/Q modulator driven by an electrical arbitrary waveform generator. The modulator outputs are then combined with the second 50GHz OFC from the second WSS port. This is necessary to provide for each optical signal carrying the data a reference optical carrier (with an offset equal to the RF frequency required at the antennas; i.e. 25 GHz in this paper) that will beat at the photodetectors (PDs) and provide direct optical-to-RF conversion. After amplification by means of an erbium doped fiber amplifier (EDFA), the WDM RoF signal is then distributed to the RAUs using a flex-grid WSS (Fig. 3, step 2). The OOK signal together with its reference goes to RAU3 with a single horn antenna (no MIMO). A photoreceiver with 40 GHz bandwidth performs optical-to-RF conversion at 25 GHz center frequency. Another horn antenna placed at a 1 m distance receives the signal which is then downconverted to baseband through a mixer. A real-time scope captures the down converted OOK signals for BER calculation. The other three signals modulated with QPSK or 16QAM, together with their respective reference optical
carriers, are then elastically assigned to RAU1 and RAU2. After optical-to-RF conversion, we measured the 25GHz RF signals using a real-time scope. The offline DSP digitally down-converted the RF signals to baseband and performed CMA and frequency offset estimation for signal recovery. According to the flow shown in Fig. 3(a), we emulated a high load at RAU1. CO#1 detected the threshold violation and reported the problem to the C-RAN controller.

Fig. 3. (a) Proposed workflow. (b) Messages exchange at the C-RAN controller.

The C-RAN controller decided that the best solution is to elastically update the already established LSPs (Fig. 3, step 3). On the data plane, this corresponds to wavelength domain switching of the number of RoF signals going to RAU1 and RAU2 (Fig. 3, step 4; Fig. 2 (d)). Under the assumption of hybrid precoding scheme and beamforming [6, 7], the elasticity in wavelength domain would map then in elasticity in the RF space domain by changing the number of beams. We also demonstrated elasticity in time and modulation format domains by varying the baud-rate of the OOK signal for RAU1 while changing the modulation format for the signals going to RAU1 and RAU2 (Fig. 3, step 5). Fig. 2(b) shows the measured OOK signal eye diagram, achieving BER < 10^{-7}. The C-RAN controller configures the switching of signal speed from 1 Gbits/s to 2 Gbits/s (Fig. 3, step 5). The received power after horn antenna was -24 dBm. The power of local oscillator was 12 dBm, and the down-converted OOK signal power was around -35 dBm. A real-time scope captured 12.5M symbols, achieving an error-free condition in both 1Gb/s and 2Gb/s cases. Fig. 2(b) shows the BER curves before/after switching for the signals going to RAU1,2. The second link first is transmitted at 4Gb/s 16QAM signal along with a 25GHz reference tone. To optimize power budget and spectrum utilization, the C-RAN controller switched the 16QAM signal to a QPSK (Fig. 3, step 5). At the same time, the WSS received an OF message from the SDN controller and reallocated a second 2Gb/s QPSK channel from the light-loaded third link to the second link (Fig. 3, step 4). In this way, the C-RAN controller maintains the link capacity, and improve the power budget by load-balancing different links’ channel allocation. The original channel was located at 1551.74 nm. After switching, a new channel was assigned at 1551.47 nm. Fig. 2(b) shows the BER curves before/after switching for the signals going to RAU1,2. The second link first is transmitted at 1Gb/s and 2Gb/s cases. The 16QAM signal requires 16 dB OSNR to achieve BER < 10^{-3}, while QPSK signal only requires 9 dB OSNR.

Conclusions

This paper proposes and experimentally demonstrates for the first time to our knowledge, an elastic RF-optical C-RAN architecture for mm-wave SDM-MIMO RAUs. A C-RAN controller orchestrates the generation and elastic assignments of 1GBd RoF signals to multiple mm-wave RAUs based on the traffic load information reported by the COs.

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References