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Dynamically Delivering Radio Signals by the Active Routing Optical Access Network

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Abstract—In this paper, we present a dynamic distributed antenna system based on a reconfigurable optical access network. Radio signals from the central office are delivered to the remote antenna units by means of optical channels where dynamic radio sub-carrier assignment to the antenna units is performed by reconfiguring optical channels. The bidirectional transmission experiment demonstrates that a switching time of 450 ns can be used to allocate an additional radio channel to antenna units. The impact to existing radio signals is negligible. The error vector magnitude penalty is only 0.5% and 1% for the downlink and uplink radio signals, respectively.

Index Terms—Reconfigurable Optical Access Networks, Distributed Antenna System, Cellular Land Mobile Radio.

I. INTRODUCTION

Radio cellular mobile networks are reducing cell sizes to increase overall network capacity through the frequency reuse. In densely populated areas, the cell size may decrease to tens of meters [1]. The distributed antenna system (DAS) was proposed to cost-effectively implement such extremely small cells [2, 3]. A bank of base stations is located in the central office (CO) and radio signals are delivered to remote antenna units (RAU) by means of optical channels.

Furthermore, a new technique to reduce call blocking in cellular mobile networks is to employ dynamic RF sub-carrier assignment in which sub-carrier allocation of radio cells is adapted to match instantaneous traffic demands [4, 5]. Congested cells are provided additional RF sub-carriers, which are reallocated from light load cells. To conventionally implement this scheme, a redundant capacity, e.g., hardware and backhaul resource, is added to every base station and activated and deactivated accordingly. Apart from the electronic implementation, an alternative is to use the dynamic DAS (DDAS) in which RF sub-carrier assignment is handled by reconfigurability in the optical domain. The electronic base stations are replaced by RAUs that dynamically share a common bank of base stations centralized in the CO. This approach decouples dynamic RF capacity allocation from the RF domain to allow transparency in terms of radio standards. Hence, it facilitates multi-standard operations and future upgrades.

The DDAS can be implemented either by RF or by optical switching. In the first option, the DDAS employs an RF switch matrix at the CO to dynamically map RF sub-carriers to statically routed wavelengths. However, the design of a large RF switch matrix is very challenging in terms of insertion loss, reflection, and cross-talk. Additionally, the RF switching matrix usually operates on a certain frequency range, which reduces the transparency of DDAS. In this paper, we study the second option to realize DDAS by the active routing optical access network (ARON) in which an array of semiconductor optical amplifiers (SOAs) at the remote node (RN) performs downstream (DS) and upstream (US) wavelengths routing [6]. An optical wavelength couples with one or more pre-assigned RF carriers to allow RF reconfiguration to be carried out in the optical domain. As a proof-of-concept experiment, we demonstrate that the time required to allocate new RF channels, a pair of downlink and uplink sub-carriers, is 450ns and the impact on existing RF channels is negligible. The error vector magnitude (EVM) degradation contributed by DDAS optical channels is only 0.5% and 1% for the downlink and uplink radio signal, respectively.

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II. DDAS OVER ARON ARCHITECTURE

The ARON architecture is shown in Fig. 1 where the RN is able to route one or more wavelengths arriving from the optical line terminal (OLT) to an output port. Each RN output port connects to an optical network unit/remote antenna unit (ONU/RAU). The OLT located at the CO transmits two wavelength bands: modulated DS wavelengths and unmodulated continuous-wave (CW) US wavelengths (Fig. 2.c). Each DS wavelength is modulated by a downlink RF signal. A DS wavelength couples with a US wavelength where the spectral distance is one free spectral range of the cyclic arrayed waveguide grating (AWG) in the RN (Fig. 2.a). As a result, each pair of wavelengths is output from the same AWG port towards a SOA gating module. The state (ON/OFF) of SOAs in the gating module determines the RN output port the wavelength pair will be routed to.

At the ONU/RAU, a DS-US waveband splitter directs the DS wavelength(s) to one port and the US wavelength(s) to the other. The US CW(s) is modulated by the uplink radio signal(s) using a reflective-type modulator such as a reflective semiconductor optical amplifier (RSOA) or a reflective electro-absorption modulator (REAM). The modulated US wavelength(s) is reflected back and propagates towards the OLT. The US wavelengths originating from an ONU/RAU carry the same RF signals which allow the receiver module in the OLT to be simplified since a RF receiver can be coupled with an opto-electronic converter (O/E) by a bandpass filter in between to select the desired RF subcarriers. When a radio cell needs more capacity, the corresponding ONU/RAU will be allocated an additional RF channel by routing one more DS/US wavelength pair to it.

Although the O/E receives multiple wavelengths at the same time, there is negligible interference because the carried RF channels are centered in different frequencies. The optical beat noise is also avoided since the beat noise spectrum is centered at a frequency that is equal to the difference of the optical wavelengths [7]. In the worst case, the difference of two dense WDM wavelengths is 100 GHz, which is very far from RF sub-carriers (well below 10 GHz). The ONU/RAU is wavelength-agnostic, and thus emits all the microwave signals carried by the received wavelength signals. Besides the electrical bandpass filter which has to select the desired microwave frequency, the ONU/RAU is also fairly frequency independent. Therefore, this approach has a radio-standard agnostic outside plant, which can ease future upgrades. In order to control and manage the RN, a common signaling channel is established between the RN and the OLT. The signaling channel is physically embedded in the first wavelength pair by subcarrier multiplexing.

III. EXPERIMENTAL SETUP AND RESULTS

The experimental setup shown in Fig. 3 focuses on investigating dynamic characteristics of DDAS over ARON. The OLT transmits four wavelengths, two for DS and two CWs for remote modulation at the ONU/RAU. The wavelengths are compliant to ITU-T 100-GHz spaced C-band wavelength grid and selected only because of their availability in our lab. Two DS wavelengths modulated by RF1 signal centered at 2 GHz and RF2 signal centered at 2.04 GHz, respectively. The ONU/RAU uses an RSOA for modulating US CW by the RF3 signal of 1.93 GHz and the RF4 signal of 1.97 GHz. All RF signals are 20 MHz wide carrying 20 Msymbol/s in 16-QAM format. To emulate the cyclic property of the proposed AWG in the RN, wavelengths in the same pair are combined again after the AWG. A similar configuration with the AWG in the ONU/RAU is used to emulate a waveband splitter. Using variable optical attenuators placed in front of each SOA, the loss for a splitting ratio of 1:64 is emulated.

RF1 associates with RF3 and RF2 associates with RF4 to form two pairs of downlink and uplink channels. The wavelength pair ($\lambda_{d1}, \lambda_{d2}$) carrying the RF pair (RF2, RF4) is constantly allocated to the ONU/RAU and the wavelength pair ($\lambda_{d1}, \lambda_{d2}$) carrying the RF pair (RF1, RF3) is allocated to the ONU/RAU for 150 $\mu$s and unallocated for 50 $\mu$s in a 200 $\mu$s cycle. With the symbol period of 50 ns, a single 200 $\mu$s cycle contains 4000 symbols. This experiment emulates the case where the radio cell served by the ONU/RAU requires more channels to increase the cell capacity.

To evaluate the quality of the received radio signals, the time traces of the error vector magnitude (EVM) of received symbol constellations is shown in Fig. 4. The traces consist of two repeated 200 $\mu$s cycles, where SOA1 is gated OFF for 50 $\mu$s from the 1001$^{th}$ to the 2000$^{th}$ symbol in the first cycle and from the 501$^{th}$ to 6000$^{th}$ symbol in the second cycle. As observed in Fig. 4, after 9 symbols (450ns) from the moment...
that the ON signal is applied to SOA1, the RF1 EVM falls below 10%. In principle, this turn on period can be lower because the control signal and SOA rise time is 1n and 5ns, respectively. Due to the imperfect impedance matching between the control circuit and the SOA, a longer turn on time is experienced. This matching may improve when the control circuit and SOAs are integrated on a single chip. The impedance mismatch effect still can be observed after EVM reducing below 10% as the EVM is higher than normal. This noise also impacts existing RF signals, which can be observed in the RF2 EVM trace shown in Fig. 4.b. However, the EVM rises below 1% for only 250 symbols (12.5 μs).

The uplink RF3, on the other hand, needs only 6 symbols to get below 10% because RF3 bypasses the SOA in the US direction and only its seeding wavelength goes through the SOA. Therefore, downlink RF1 determines the allocation time, which is 450ns. The new allocation has no impact on uplink RF4 performance as observed in Fig. 4.b.

Average EVMs of RF1 and RF3 as a function of received optical power are shown in Fig. 5. The average EVM is calculated for 50 cycles. In each cycle, the calculation excludes 50μs unallocated period from 101th symbol to 2000th symbol and 450ns guard time from 2001th symbol to 2009th symbol. In each direction, there are three cases, including SOA back-to-back (BtB), in which 20km and 5km fibers before and after the RN are removed. The proximity between SOA BtB DS curve and DS curve reveals that the SOA is the dominant source for RF1 signal impairment, not the transmission distance. In the upstream direction, the SOA BtB US almost coincides with the optical BtB plot, showing that the SOA is no longer the source for the RF3 signal impairment but the transmission distance. The reason is RF3 bypasses the SOA in the upstream direction but suffers backscattering and reflections from the seeding CW wavelength. At the received optical power of -25dBm, The EVM performances for both DS and US are 3.5% and 5.2% and the degradations to optical BtB cases are only 0.5% and 1% respectively. The optical upstream (RF uplink) performs worse than downstream because RF3 centered at 1.93 GHz is almost close to the RSOA electrical bandwidth limit. Alternatively, the RF signal can be down converted to remain within the RSOA bandwidth, which requires an extra local oscillator and may increase ONU/RAU complexity. To modulate higher frequencies, a REAM is recommended instead of the RSOA. REAMs can be used for frequencies up to 60 GHz [8], but exhibits high insertion loss. Recent developments in devices combining REAM with SOA could mitigate these losses.

In the experiment, discrete optical components are used in the RN. However, integration of these components is expected to drive down costs and power consumption [9]. To address the heat generated by SOAs when active, which is an inherent issue of highly integrated photonic circuits, we adopted the RN configuration that has a minimal number of SOAs that are simultaneously active. By photonic integration, the proposed architecture can be cost-effectively implemented.

### IV. CONCLUSIONS

In this letter, we present a new concept of DDAS based on a reconfigurable optical access network. DDAS is a promising solution for implementing dynamic frequency planning in cellular networks. The concept also can be used in a small scale to realize “moveable” cells to provide high-speed connections to users in a bullet train. A proof-of-concept demonstration was presented with bidirectional transmission. The physical performance was shown to have very low EVM penalty for both upstream and downstream transmissions.

### REFERENCES


