# Enhancing LTE with Cloud-RAN and Load-Controlled Parasitic Antenna Arrays

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***Abstract* — Cloud radio access network (C-RAN) systems consisting of remote radio heads (RRHs) densely distributed in a coverage area and connected by optical fibers to a cloud infrastructure with large computational capabilities, have the potential to meet the ambitious objectives of next generation mobile networks. Actual implementations of C-RANs tackle fundamental technical and economic challenges. In this article, we present an end-to-end (E2E) solution for practically implementable C-RANs by providing innovative solutions to key issues such as the design of cost-effective hardware and power-effective signals for RRHs, efficient design and distribution of data and control traffic for coordinated communications and conception of a flexible and elastic architecture supporting dynamic allocation of both the densely distributed RRHs and the centralized processing resources in the cloud to create virtual base-stations (BSs). More specifically, we propose a novel antenna array architecture called load-controlled parasitic antenna array (LCPAA) where multiple antennas are fed by a single RF chain. Energy and spectral-efficient modulation as well as signaling schemes that are easy to implement are also provided. Additionally, the design presented for the fronthaul (FH) enables flexibility and elasticity in resource allocation to support BS virtualization. A layered-design of information control for the proposed E2E solution is presented. The feasibility and effectiveness of such LCPAA-enabled C-RAN system setup has been validated through an over-the-air (OTA) demonstration.**

**Keywords—C-RAN, Load Controlled Parasitic Antenna Arrays, Ethernet Fronthaul**

## I. INTRODUCTION

Mobile data traffic is expected to continuously rise in the future [1]. In view of the radio spectrum's scarcity, it is necessary to incorporate in the long term evolution (LTE) standard technologies and techniques that have the potential to enhance the capacity of next-generation LTE-based systems.

We present a solution based on the synergy of universal frequency reuse, cell densification and coordinated multi-point (CoMP) to improve spectral efficiency (SE), increase system capacity and mitigate inter-cell interference (ICI). Albeit promising, these techniques present implementation challenges: the current network architecture struggles to meet the stringent inter-cell communication throughput and latency requirements of the various CoMP "flavors", thus reducing the effectiveness. Moreover, while it is well known that typically the multi-user spatial multiplexing (MU-SM) and interference management capabilities of CoMP benefit from more antennas installed at the base station (BS), in practice conventional antenna arrays make use of a limited number of elements. This is because of cost and power constraints due to the standard practice of feeding each antenna by a separate radio frequency (RF) module. Additionally, this is also because of the reduction of the radiation efficiency observed when the antennas are too closely spaced, due to the resulting strong electromagnetic coupling. This limits the performance gains of CoMP techniques.

The system described in this work brings together two elements that address the aforementioned issues: cloud radio access network (C-RAN) architecture [1] and load-controlled parasitic antenna arrays (LCPAA). The former envisages that the baseband units (BBU) of the BSs are centralized, virtualized via cloud technology and connected to the remote radio heads (RRH) - located at the cell sites - through an optical aggregation network called fronthaul (FH). C-RAN ensures the timely communication between cooperating cells and accommodates the heavy data/control traffic load related with CoMP [1]. It provides flexibility and allows for cost-effective deployment of dense networks due to the reduced number and energy needs of the cell site facilities. Additionally, C-RAN results in efficient utilization of the available resources, because of the dynamic allocation of BBUs and RRHs to "virtual BSs," according to the traffic and radio coverage demands. LCPAAs, on the other hand, use fewer RF chains than antenna elements and exploit the mutual coupling among the antennas to shape the radiation pattern. This provides a high number of antenna array degrees-of-freedom (DoF), thus boosting the performance of the system, while reducing the hardware cost, complexity, energy consumption and footprint.

We have to note that while the C-RAN paradigm has been extensively studied in the past few years as a CoMP- and (network) densification-enabler, the proposed setup, which considers RRHs equipped with LCPAAs, presents clear advantages over conventional configurations. That is, the use of LCPAAs leads to an additional beamforming (BF) gain for a given number of RF chains or a cost reduction for a target BF gain.

Since its introduction in 2010, C-RAN has received a tremendous interest from academia and industry and there are multiple works addressing topics of optimal resource allocation, RRH and virtual BBUs clustering, fronthaul optimization and enhancing C-RAN with SDN as well as presenting test beds and prototypes. Reconfigurable solutions based on C-RAN to improve resource utilization are proposed in [2] and references therein.

The FH evolution has received considerable attention recently, that will lead to different functional splits for different deployment scenarios, most likely resulting in a packet-based transport network. To enable this, the following standardization activities are in place:

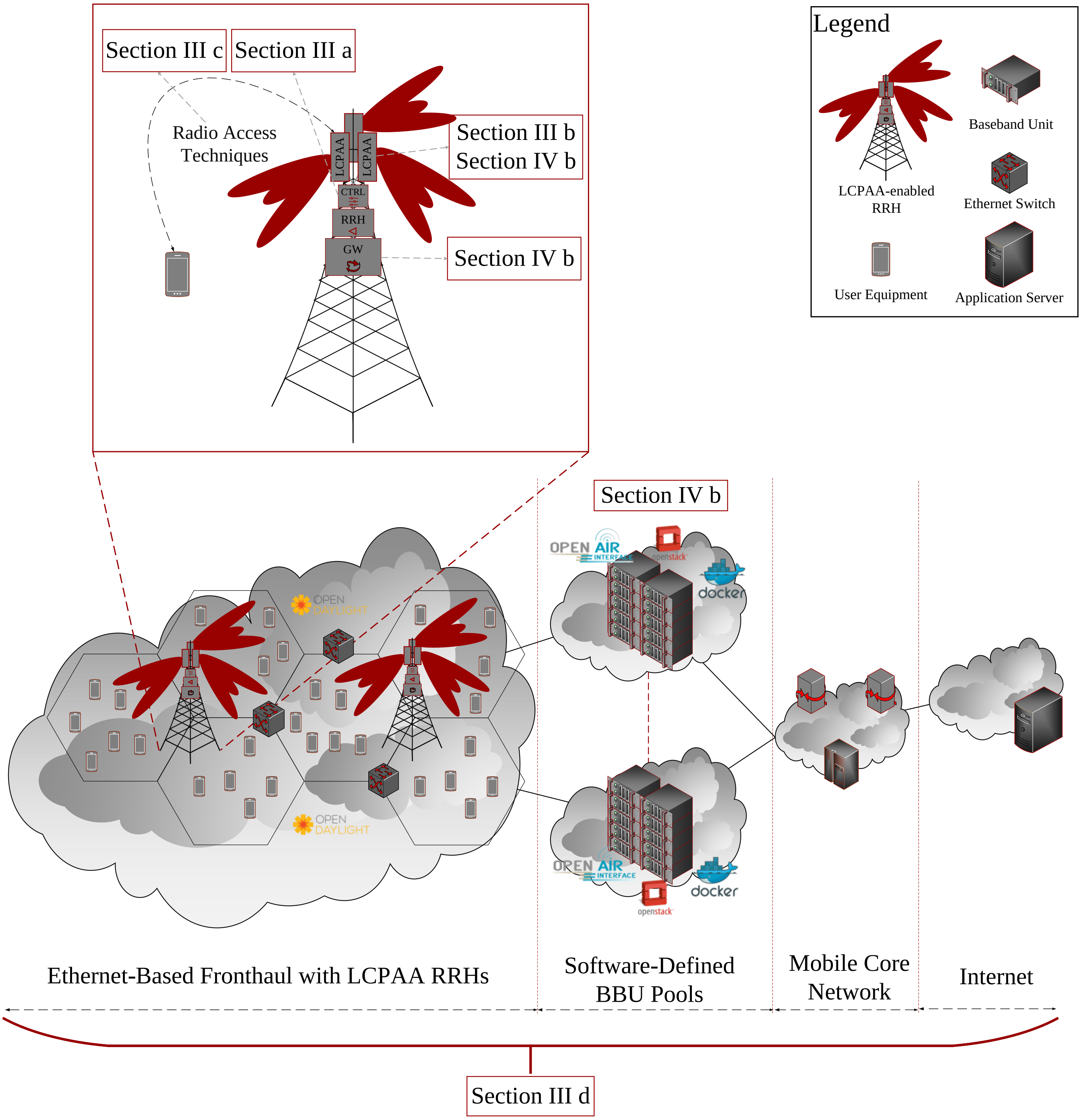


Fig. 1 Proposed Architecture for LTE Evolution

- IEEE 1904.3 *"Standard for Radio over Ethernet Encapsulations and Mappings"* that aims to define the encapsulation of FH data, independently of the functional split, to Ethernet frames.
- IEEE 1914 "Next Generation Fronthaul Interface" aims at defining architectures for fronthaul transport, requirements and definitions for the fronthaul network as well as possible functional split schemes.
- IEEE 802.1Qbv *"Bridges and Bridged Networks—Amendment: Enhancements for Scheduled Traffic"* standardizes source scheduling in order to reduce jitter of FH streams in Ethernet switches by ensuring that, at specific times, only one traffic stream has access to the network.
- IEEE 802.1Qbu *"Bridges and Bridged Networks—Amendment: Frame Preemption"* standardizes preemption which can suspend the transmission of the lower priority traffic when FH traffic needs to be transmitted.
- IEEE 802.1CM *"Time-Sensitive Networking for Fronthaul"* is a profile that selects features, options, configurations, defaults, protocols and procedures – defined in the IEEE 802 standard – for switches and stations for the FH use case.

Moreover, the EU project iCirrus – among others[1] – also investigates using Ethernet for FH networks. [3] identifies benefits and challenges of Ethernet-based FH (EFH).

The novelty of this work lies in combining LCPAA with software-defined C-RAN and with EFH, as well as presenting an E2E prototype. Thus, cost and performance benefits of C-RAN can be further enhanced by usage of LCPAA:

1) Cost and energy savings due to the utilization of reduced number of RF chains for given antenna array DoFs in comparison with conventional antenna systems,

2) Reduced complexity and simpler control circuits for performing beam shaping/steering, in contrast to phased antenna arrays,

3) Lighter weight and more compact size, due to the closer vicinity of antenna elements, leading to arrays that fit into the RRH's limited volume.

as well as EFH:

1) optimal support of decreased fronthaul data rate: variable bit rate data from the new functional split can be transported in packets,

2) flexibility in deployments and operation: traffic aggregation and switching is supported allowing optimal resource allocation and maximization of multiplexing gain

3) cost optimization: EFH networks could utilize widely-deployed existing Ethernet deployments so that I/Q (In-phase/Quadrature) data shares resources with other types of traffic.

Our contributions on the EFH are aligned with aforementioned standardization efforts. The considered solution does not consist of simply using diverse technological components and transmission methods, but it also introduces enhancements of the employed CoMP techniques, network protocols and technologies (Figure 1). Moreover, it defines design and implementation guidelines that span every aspect of the system architecture, from the air interface to the EFH network and from virtualization to E2E network design. The considered solution is complementary to the existing state-of-the-art of C-RAN. The aim of this article is to present the system architecture, describe the aforementioned advances, study the fundamental performance limits for the related techniques under this setup and propose an E2E system prototype.

## II. System Architecture

The evolution of LTE requires a rethink of the network E2E and of the synergies between the different components. This ensures a harmonious integration of advancements in different research areas. Figure 1 depicts the proposed integrated vision for future mobile communication networks.

Starting from the antennas used at the RRHs, we present a new design and control in the family of LCPAA, based on the concept of load-modulated array (LMA) that ensures high flexibility as it contains elements tunable at the symbol level (Section III a).

Introducing this element raises the issue of understanding its fundamental characteristics, especially as compared with other variations of LCPAA systems, such as electrically steerable passive array radiators (ESPARs). Our results on the fundamental limits of both cases, point out that for the case of ESPAR, signal preprocessing at the transmitter can ensure significant improvements, while in the case of LMA, fixing the sum power of the antennas is beneficial (Section III b).

As the network is equipped with this advanced control and antenna system, it allows the consideration for advanced MIMO radio access (RA) schemes at the radio interface. However, the volume of data and control to be processed increases dramatically and poses serious challenges in terms of efficient and timely processing of the signal. We therefore designed a novel RA scheme that capitalizes on the synegies between ESPAR antennas and C-RAN. Addittionally, we explored also the general properties of distributed RRH systems to emulate and approximate centralized joint processing under practical constraints. (Section III c)

Finally, to ensure that this advanced processing can take place, the entire FH connecting the RRHs to the BBU pool has to be designed, keeping in mind the requirements of the aforementioned RA techniques and at the same time ensuring flexibility and elasticity. To tackle this problem, an EFH has been considered, together with a complete virtualization of the BBU functionalities in the pool. This clearly ensures the flexibility and the elasticity required in future communications system, so that advanced CoMP techniques can be implemented and a multiplexing gain can be exploited. However, it introduces challenges such as synchronization of traffic, dimensioning and the impact of the network design on the

1 Related projects in the area are 5G-Crosshaul (http://5g-crosshaul.eu/ accessed 16.08.2016) and 5G-xhaul (https://5g-ppp.eu/5g-xhaul/ accessed 16.08.2016)

applications used by the user equipment (UE). We thus contribute to address these challenges in the overall design of the system by taking a holistic view of the system (Section III d).

## III. PROPOSED ENHANCEMENTS FOR FUTURE C-RAN NETWORKS

### *A. Novel Antenna Design*

We consider two types of LCPAAs: ESPARs and LMAs. In ESPARs, the parasitic antenna elements are not directly connected to the single power amplifier, but fed by current induced by the active antenna element. LMAs are the novel single-RF multiple-antenna transmitters introduced in [5]. In contrast to ESPARs, in LMAs, all the antenna elements are fed by a central power amplifier via transmission lines.

A block diagram of an LMA transmitter is presented in Figure 2. In LMAs, the source is a simple oscillator. Each antenna element $m$ is connected to a load modulator LM$_m$ tunable at symbol rate. The variations of the load are steered via a level shifter from digital baseband and modulate the signal onto the amplified carrier. Each load modulator contains some passive and some tunable elements. Since the load modulators are steered directly from digital baseband, there is neither need for mixers nor for Digital to Analog Converters (DACs). The signal on each antenna is set by changing the state of the tunable elements in the respective load modulator. In LMAs, the signal at the input of the central power amplifier is a constant envelop sinusoid signal. Thus, the central power amplifier may be non-linear and efficient. If the number of antenna elements is large, the law of large numbers ensures that the aggregate load seen by the power amplifier hardly varies, little power is reflected into the circulator, and the overall architecture operates at high power efficiency. For 100 antenna elements, a power efficiency of 70% at Error Vector Magnitude (EVM) of -40dB is reported in [4].

A load modulator is a linear two-port network, e.g., Π or T network, containing some tunable elements, e.g., variable capacitors or switched capacitor banks. A load modulator can be implemented either using softly tunable elements, e.g., varactor diodes or using hard RF-switches, e.g., pin diodes. All digital processes (e.g., mapping, coding, precoding) occur in the digital baseband block. The latter one also computes the appropriate bias states for all diodes at all symbol times. The bias voltages of the diodes are generated by level shifter blocks which execute commands by the digital baseband block every symbol clock cycle.

### *B. Fundamental limits*

Here we discuss limits and flexibility of multi-antenna architectures fed by single RF modules (ESPAR and LMA) in efficiently using frequency spectrum and energy.

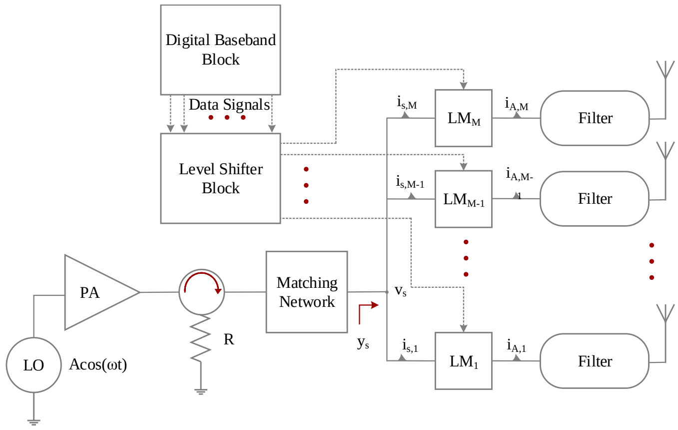


Fig. 2. Architecture of an LMA Transmitter

#### 1) ESPAR

In the ESPAR antenna (EA) configuration, for some signals transmission, the input resistance becomes negative leading to oscillatory/unstable behaviour. We showed that instead of these actual signals, one can transmit approximate signals and we derived a simple closed-form expression that enables an easy generation of the approximate signals at the transmitter [5]. The EA utilizing this novel closed-form expressions are denoted as EA with preprocessing (EA-P). According to simulation results, conducted for various communication scenarios, the EA-P transmitter provides significant improvement over the performance of the EA without preprocessing and performs nearly the same as the standard multi-antenna system (SMA).

Addittionally, in [6] we have studied the impact in terms of energy efficiency (EE) of using EAs in the RRHs of a C-RAN, for both single- and multi-UE systems. The closed-form expressions were derived to obtain the EAs' configurations to maximize the EE. We have shown that such EA-equipped system provides better EE performances while providing similar Symbol Error Rate (SER) performances as compared to a SMA.

#### 2) *LMAs*

In LMA, the sum power of all the antennas is generated by a central amplifier which necessitates peak and average power constraints. The capacity of the MIMO channel under these constraints is investigated in [7] where it was found that the support of the capacity-achieving distribution is a finite set of hyper-spheres for the identity channel matrix. Interestingly, when the average power constraint is relaxed, if the number of antennas is large enough, the capacity has a closed form solution and it is achieved by constant amplitude signaling at the peak power. Several upper and lower bounds for the capacity of the non-identity channel matrix are proposed.

In order to make the central power amplifier efficient, we have proposed to fix the sum power of all the antennas for all channel uses in [8]. We name this new type of modulation Phase Modulation on the Hypersphere (PMH). PMH is suitable for UEs with few antenna elements. Figure 3 shows the mutual information of uniform PMH in an uplink multiple-access channel. It is assumed that the number of antenna elements at the BS and the aggregated number of antenna elements at the

UEs are equal and go to infinity. It is observed that with only few antennas at the UEs, the mutual information becomes very close to the mutual information which results from Gaussian input. This shows that fixing the sum power does not cause significant rate loss, while it makes the power amplifier in LMA efficient.

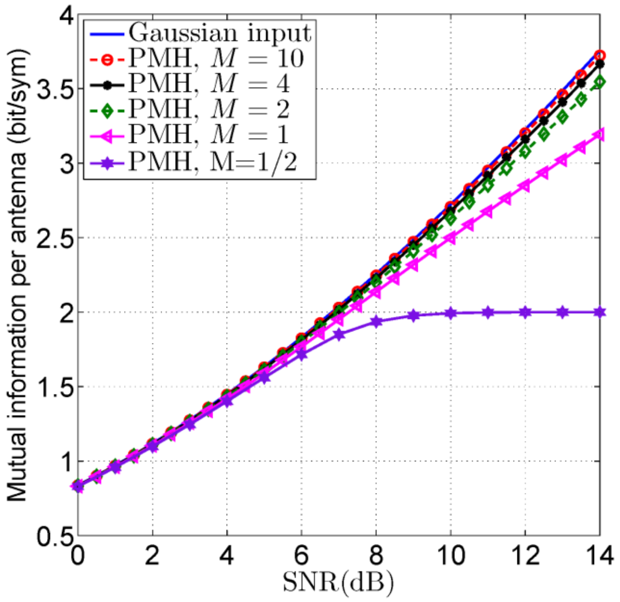


Fig. 3. The mutual information of PMH in a multiple-access iid Gaussian channel for different number of antenna elements at the UEs [9].

### C. *Transmission Techniques*

1) *Arbitrary Channel-dependent Precoding Utilizing Single-RF ESPAR Antennas*

In order to perform closed-loop MIMO transmission using single-RF ESPAR antennas, we map the precoded symbols on the antenna currents [9]. Unfortunately, for some input signal constellations the required loading values may lead to circuit instability. We can overcome the aforementioned issue and perform arbitrary channel-dependent precoding by splitting the problem in two parts:

- *Beamforming:* a radiation beam pattern is shaped using any valid method.
- *Precoding:* precoding-based transmission is performed over the employed beam.

An example of this solution is depicted in Figure 4. We assume a C-RAN setup with two RRHs connected to a BBU pool and two single-antenna UEs. Each RRH is equipped with a 5-element single-RF ESPAR that is able to generate four predetermined beams. Hence, there are $4^2 = 16$ possible beam combinations.

The system operates in three phases:

1. *Learning:* The UEs estimate the gains of the cross and direct links corresponding to each beam combination and report these estimates back to their BSs.
2. *Selection:* The $2 \times 2$ channel matrix for each beam combination is compiled at the BBU pool for the RRHs from these estimates. Then, based on that channel state information (CSI) knowledge, the best pair of beams is jointly selected for transmission.
3. *Transmission:* A Joint Transmission (JT) scheme is chosen for the precoding: We opt for zero-forcing beamforming (ZFBF), which is applied on top of the selected beams, to null the resulting inter-user interference (IUI) at each single-antenna receiver.

Figure 5 (left) illustrates the attained average sum-rate throughput, as calculated via numerical simulations for signal-to-noise-ratio (SNR) values in the range [-20,30] dB (red). For comparison, three more scenarios are simulated:

- An equivalent single-RF scenario where each RRH is equipped with a conventional omni-directional antenna and joint ZFBF transmission takes place (blue).
- A non-precoded transmission scenario, where the best beam pair is selected based on signal to interference plus noise ratio (SINR) feedback information but no precoding takes place. In this case, there is no need for the UEs to send back the channel gains of the selected beam pair (purple).
- A limited feedback scenario, where the system operates according to the aforementioned phases, but the UEs report to the BSs their SINR that is used for the selection of the best beam pair (green).

Based on the simulation results on the left side of Figure 5 we can point out:

- In schemes where precoding is used, the sum-rate curves do not floor since the joint ZFBF transmission nulls IUI, in contrast to the non-precoded transmission schemes.

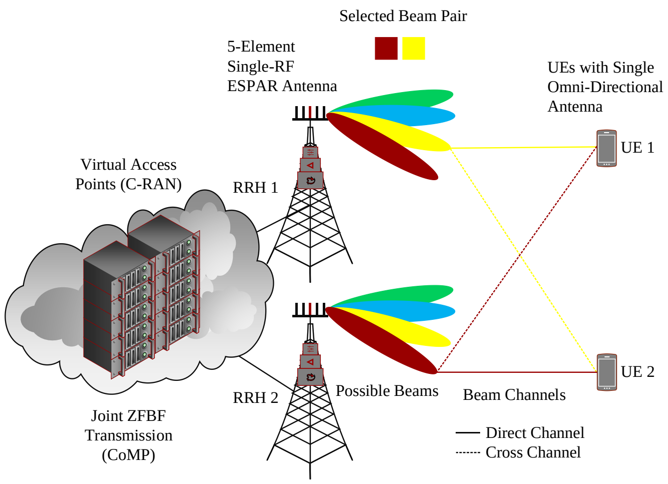


Fig. 4. System setup for the given example.

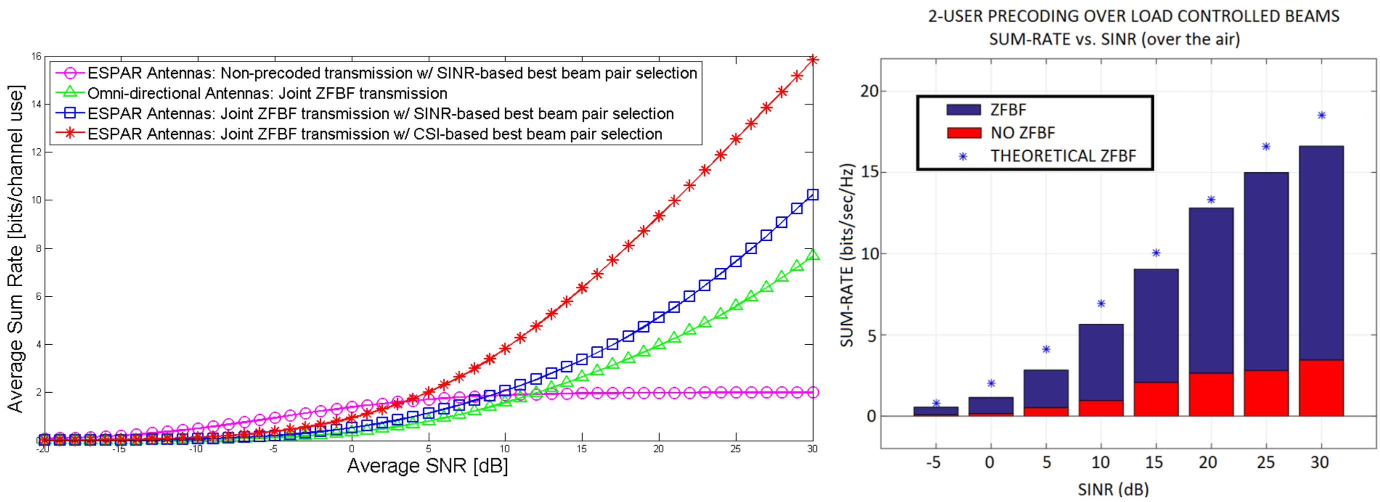


Fig. 5. Left: Numerical simulation results. Right: Over the air measured sum rates with / without precoding using the LCPAAs.

- The ESPAR-enabled precoding-based setup outperforms the omni-directional setup over the entire SNR range due to the power gain related with the application of transmit beamforming.
- CSI-based transmission outperforms significantly SINR-based transmission, since in the former case the beam pair selection process is ZFBF-driven, while in the latter case the procedures of beam pair selection and ZFBF precoding design are decoupled.

Additionally, Figure 5 on the right shows the over the air (OTA) sum rates measured with and without precoding using the LCPAAs. The testbed setup was configured for two active users transmitting concurrently while having their arrays placed within a distance of few meters. We connected two directional LCPAAs at each transmitter port and sent two independent spatial streams of data at the same time and in the same frequency band and used two Omni-directional monopole antennas at the receiver ports to disentangle the received data symbols. With zero-forcing precoding we achieved to quadruple the capacity.

2) *Statistical MIMO Processing for Distributed RRHs*

The processing of MIMO signals in a network with many distributed ESPAR-enabled RRHs hinges on the large volume of data to be processed. This poses problems related to computing complexity and signaling overhead as both channel state and I/Q samples have to be conveyed from the RRHs to the BBU pool. As a countermeasure, algorithms allowing for a partitioning of the signal processing across the various levels of the network can lift the signaling and complexity burden, thus making them very desirable. As such, ESPAR antennas can offer local beamforming capabilities at the individual RRH level, while keeping the number of active RF branches low. Another strategy relies on antenna dimension reduction via so-called layered precoding or decoding. The layered approach consists in exploiting an inner antenna combiner that is based on channel statistics alone, followed by an outer (reduced-dimension) combiner which is designed based on instantaneous CSI. The statistical combiner exploits the intrinsic spatial structure in the UE's channel vectors revealed by their covariance matrices. In particular, the existence of the low-rank of the covariance matrix can enable interference mitigation without requiring instantaneous CSI. In [10], this property is evidenced for massive antenna array channels, be they linear arrays or distributed arrays such as RRHs.

3) *MIMO System with Imperfect CSIT*

In MU-MIMO networks, the knowledge of CSI at the transmitter (CSIT) is crucial for interference mitigation and beamforming purposes. However, in practice, CSIT may be imperfect due to channel estimation error and/or feedback latency. CSIT inaccuracy results in MU interference that is the primary bottleneck of MIMO wireless networks as highlighted e.g. in LTE-A CoMP studies. In ESPAR and LMA-based networks, the knowledge of CSIT also plays a crucial role as for conventional arrays. A complete characterization of general MIMO networks with perfect, delayed or unknown CSIT is an open problem. In [11], we provide some answers toward this goal for a K-user multi-user MIMO downlink. An outer bound for the Degrees of Freedom (DoF) region is derived based on the marginal probabilities of CSIT availability of each UE. A set of inequalities is proposed that captures not only the marginals, but also the joint CSIT distribution. This shows that in general, marginal probabilities are not sufficient for characterizing the DoF region. Said otherwise, any two CSIT patterns with the same marginals but different joint statistics can have different DoF regions and some CSIT patterns are much more suitable than others. This provides new perspective on how to design novel and efficient CSI feedback mechanisms in LTE-A.

*D. Network and Protocols Design*

1) *Cooperative signal processing in C-RAN*

C-RAN enables CoMP at the physical layer (PHY) by allowing low-latency communication between BBUs serving neighboring cells. In uplink, cell-edge UEs' signal can be affected by severe interference from co-channel UEs in congested scenarios where the same frequency is used by UEs on the edge of two adjacent cells. Since ICI signals are received by both of the two neighboring cells, thanks to centralization this interference can be exploited. We use multi-cell joint scheduling for interfering UEs, so they transmit on the same frequency resource and their signals can be detected in the BBU-pool with conventional MIMO detection on the signals received by two (or more) RRHs. By slightly increasing transmit power, the same error rate as in the interference-free case is reached by using two times less resources [12].

#### 2) *Multiplexing Gain*

BBU centralization enables also cost savings due to statistical multiplexing gain (MG). However, they can be compromised because of the large capacity required in the FH when a "traditional" functional split based on the Common Public Radio Interface (CPRI) is used [1]. Deployment decisions thus benefit from our results focused on calculating MGs achieved in the BBU pool and on the FH with various functional splits. For a CPRI-based FH, the MG on traffic-dependent BBU resources is 1.2-1.6 and tops for 30% office and 70% residential BSs. [1] further examines MGs for BBU as well as FH links for the "traditional" CPRI-based split, the user/cell split and the packet-data convergence protocol (PDCP)/radio link control (RLC) split.

#### 3) *Synchronization*

Existing Ethernet networks can be reused for C-RAN FH to leverage their wide deployment, cost efficiency and switching possibility. With the new aforementioned user/cell functional split we expect variable bit rate data streams on the FH, therefore a packet-based transport will optimize resource utilization in the network. The main challenges in using EFH are assuring low delay and clock recovery. We built a demo of SDN-controlled EFH carrying 2.5 Gbps I/Q data streams where the delay to pass one switch was within 3 μs [1]. Moreover, we studied factors influencing synchronization in an architecture employing the IEEE 1588 protocol between a master clock in the BBU pool and a slave node in the RRH or in the common public radio interface CPRI-to-Ethernet Gateway (GW).

#### 4) *Application-Layer Performances*

Dimensioning of the EFH should reflect the maximum latency requirements of the communication protocols used. A too-large FH latency triggers the retransmission timers in the hybrid retransmission request (HARQ) that leads to a waste of network capacity with a chain effect that propagates to the higher layers, thus seriously affecting the performances of the applications running in the UEs. We used network and protocol simulations to estimate how FH latency affects the page response time of typical web browsing traffic [13]. Simulation results show that up to 0.6 ms of latency can be tolerated, however, optimal results are obtained with 0.1-0.2 ms of latency, that ensure a page response time of ~3.6 s for the 80$^{th}$ percentile of the UEs.

#### 5) *Transport Control Protocol Optimization*

The natural following optimization for C-RAN has been focused on the transmission control protocol (TCP), due to its central role in providing a reliable E2E communication link for many applications in the UEs. The aforementioned network model has been integrated with offline PHY processing and BBU signal processing delay estimations from OpenAirInterface (OAI). Simulation results for typical UEs' operating systems are compared and an optimized TCP configuration is presented based on the implementations present in Google's Android and Apple's iOS, to ensure fewer TCP retransmissions and a better response time for web browsing than the initial ones [14].

## IV. Demonstrator for LTE Evolution Technologies

### A. *Overview*

A selection of the enhancements listed above has been integrated in a prototype demonstrator. The system concept has been validated in a setup based on LCPAA and C-RAN. The diagram of the system is shown in Figure 6, while the key elements of the demonstrator are briefly presented in the following. Two laptops are used as UEs, one connected with an LTE dongle, the other with a USRP B200 software-defined radio (SDR) card. An overall E2E prototype has been presented in [15], albeit without precoding. The prototype for this portion of the system has been presented above, alongside test results in Figure 5.

### B. *Key Demonstrator Elements*

#### 1) *LCPAA*

Beam steering for the LCPAAs is controlled from the BBU with each antenna making use of four parasitic elements and tuned at 2.6 GHz that can create four distinct predetermined beams with a width of 40° each. At each symbol time, the receiver feeds back to the transmitter the channel quality indicator (CQI) for each beam pair combination and the best pair is selected. In low-mobility or static scenario, the selection normally take place once and for all during an initial training phase.

#### 2) *RRH*

The RRH used in the demonstration is a NG3 Nokia unit configured in 10 MHZ bandwidth with single-input and single-output (SISO) interface to the antenna system and connected to the CPRI-to-Ethernet GW via a rate 3 CPRI link.

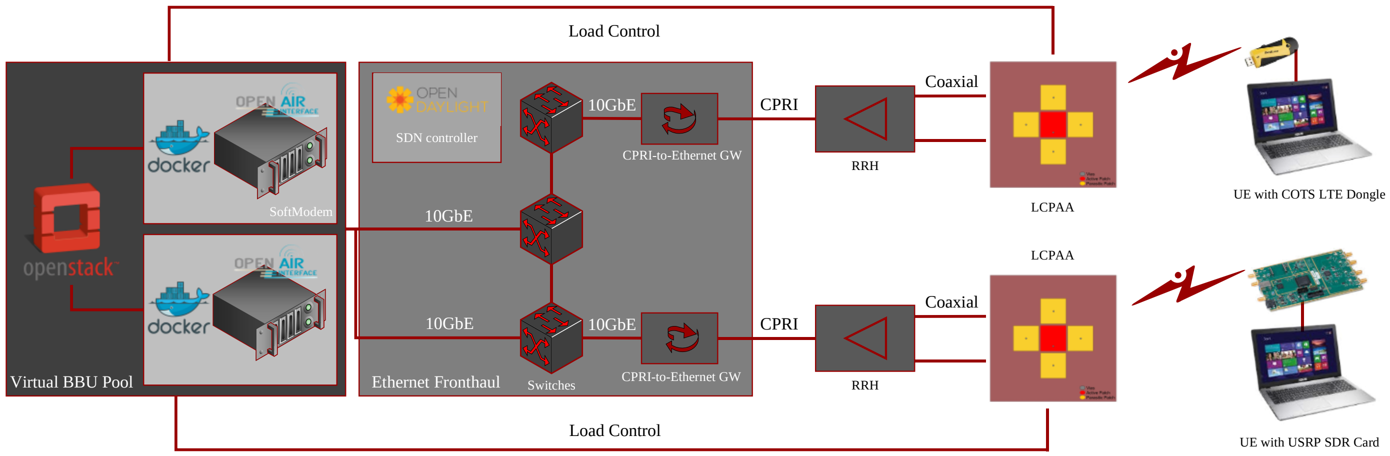


Fig. 6 Demonstrator Setup Diagram

3) *CPRI-to-Ethernet GW*

Nokia's CPRI-to-Ethernet GW converts I/Q data from CPRI to 10 Gigabit Ethernet (10GbE) and vice versa. Commercial RRHs typically support CPRI so the GW is necessary to connect them to a EFH. The GW is based on the Zynq board from Xilinx, a System on Chip (SOC) embedding field programmable gate array (FPGA) and a dual core ARM processor. The FPGA carries the I/Q from Ethernet to CPRI with minimum delay and the ARM processor is used for configuration and monitoring as well as configuration and management functions (C&M). C&M messages from the CPRI links and non-I/Q packets from the 10GbE links are routed to the ARM processor. 2 GWs are used, each with one 10GbE link to the EFH network and one rate 3 CPRI link to the RRH port.

4) *EFH*

The EFH is built using 3 Nokia enterprise OmniSwitch 6900, ensuring 10Gbps latency in the order of sub-microseconds. They also support the OpenFlow (OF) protocol, thus the EFH is controlled by an SDN controller. This allows routing and dynamic mapping of flows between the GW and the virtualized BBUs, depending on network conditions and load in each BBU. Ethernet packets are sent from the BBU through the switches to the GW; here they are re-encapsulated to CPRI towards a legacy RRH and vice versa.

5) *Virtualised BBU Pool*

OpenStack is used for the virtualized BBU pool with OAI virtual eNodeBs within Docker containers. Docker is a virtualization technology for deploying applications and processes inside Linux containers. This ensures higher efficiency as compared to virtual machines. The virtual eNodeB is converted into a Docker image together with its dependencies and stored in the Docker registry – a repository for virtual images. The virtualized BBU pool is controlled by the OpenStack cloud controller: it can deploy virtual BBUs by instantiating eNodeB Docker containers from the Docker registry and configure the E2E network in less than 60s.

## V. Conclusions

We presented an E2E system, from antenna design and CoMP to FH optimization, BBU pool virtualization and protocol design to enhance LTE networks while reducing capital and operational expenditures. The proposal is based on a C-RAN wherein the RRHs are equipped with LCPAAs. It enables dense deployments with CoMP, it mitigates ICI thanks to increased DoFs that increase SE and system capacity and does so while ensuring cost reductions. Finally, our results provide an indication of the benefits associated with the implementation of the proposed system and can inspire further developments.

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