Received July 1, 2014, accepted July 14, 2014, published August 22, 2014, date of current version September 19, 2014.

Digital Object Identifier 10.1109/ACCESS.2014.2351411

Recent Progress on C-RAN Centralization and Cloudification

CHIH-LIN I[1], JINRI HUANG[1], RAN DUAN[1], CHUNFENG CUI[1], JESSE (XIAOGEN) JIANG[2], AND LEI LI[3]

[1]Green Communication Research Center, China Mobile Research Institute, Beijing 100053, China
[2]Alcatel-Lucent Shanghai Bell Company, Ltd., Shanghai 200233, China
[3]Ericsson (China) Communications Company, Ltd., Beijing 100102, China

Corresponding author: J. Huang (huangjinri@chinamobile.com)

This work was supported by the National High-Tech Research and Development Program of China under Grant 2014AA01A703 and Grant 2014AA01A704.

ABSTRACT This paper presents the latest progress on cloud RAN (C-RAN) in the areas of centralization and virtualization. A C-RAN system centralizes the baseband processing resources into a pool and virtualizes soft base-band units on demand. The major challenges for C-RAN including front-haul and virtualization are analyzed with potential solutions proposed. Extensive field trials verify the viability of various front-haul solutions, including common public radio interface compression, single fiber bidirection and wavelength-division multiplexing. In addition, C-RANs facilitation of coordinated multipoint (CoMP) implementation is demonstrated with 50%–100% uplink CoMP gain observed in field trials. Finally, a test bed is established based on general purpose platform with assisted accelerators. It is demonstrated that this test bed can support multi-RAT, i.e., Time-Division Duplexing Long Term Evolution, Frequency-Division Duplexing Long Term Evolution, and Global System for Mobile Communications efficiently and presents similar performance to traditional systems.

INDEX TERMS C-RAN, CoMP, virtualization, cloud, front-haul.

I. INTRODUCTION

The telecom industry has been witnessing a traffic explosion in recent years. It has been estimated that consumer Internet traffic is expected to increase over 1000 times by the year 2020 with over 50% of the traffic volume in file sharing. Unfortunately, operators will not see a proportionate increase in revenue. Instead, in order to accommodate such a data explosion, traditional operators have to invest in more infrastructure, significantly increasing total costs. This not only increases total cost of ownership (TCO) but also complicates maintenance with several networks such as 2G, 3G and 4G co-existing with each other. In addition, system upgrades will become far more challenging when new technologies such as 5G are introduced into the multi-network environment [1].

Traditional radio access network architecture is facing various challenges in the 4G era and beyond. First, traditional network deployment usually requires a separate room per site with supporting facilities such as air-conditioning to accommodate the base station (BS) or base-band unit (BBU). This form of deployment is becoming increasingly difficult since available real estate is becoming scarcer and rental costs are increasing. Furthermore, it could be foreseen that this issue would become more severe when heterogeneous networks with a high density of small cells begin to prosper.

Second, interference problems in current LTE networks are much more severe than in 2G and 3G networks due to a larger number of small-cells in order to facilitate higher data capacity. In order to mitigate this interference, collaborative radio techniques such as Coordinated Multi-Point (CoMP) [2] have been proposed. However, efficient CoMP algorithms such as Joint Transmission (JT) cannot achieve maximum performance gain with traditional X2 interface LTE architecture due to high latency and low bandwidth [3], [4]. Last but not least, power consumption is another concern for operators as both the carbon footprint and energy costs of the network increase. It is pointed out in [6] that a large percentage of power consumption in mobile networks comes from radio access networks (RAN). As a result, saving energy in the network's RAN directly lowers the OPEX of the network.

C-RAN, which is proposed by the China Mobile Research Institute and stands for Centralized, Collaborative, Cloud and Clean RAN [5], [7], is a new type of RAN architecture to help operators address the aforementioned challenges. A C-RAN system centralizes different baseband processing resources to form a single resource pool such that the resource can be managed and dynamically allocated on demand. C-RAN has several advantages over traditional base-station architecture, such as increased resource utilization, lower energy consumption and decreased interference (better support for CoMP implementation).

The C-RAN architecture was first proposed in 2009 with further investigations and subsequent trials by joint operators and academic consortia. In South Korea, SK Telecom and Korea Telecom, the two biggest carriers, adopted the C-RAN centralization method to deploy commercial LTE networks. In Japan, DoCoMo has announced their plan of C-RAN implementation in deploying their LTE-A networks. At the same time, several C-RAN projects have been initiated in many organizations such as Next Generation Mobile Networks (NGMN), European Commission's Seventh Framework Programme (EU 7FP), etc. For example, in NGMN a dedicated C-RAN project P-CRAN was founded in 2010 [8]. Led by China Mobile and received extensive supports from both operators and vendors including KT, SKT, Orange, Intel, ZTE, Huawei and Alcatel-Lucent, this project aimed at promoting the concept of C-RAN, collecting requirements from operators and helping build the ecosystem. The project was closed at the end of 2012, releasing four deliverables to the industry. Through the deliverables, the advantages of C-RAN in saving TCO cost and speeding up site construction are well understood. In 2013 NGMN extended the study on C-RAN in a C-RAN work stream under the project of RAN Evolution. On the basis of previous C-RAN projects, this work stream aims at further detailed study on key technologies critical to C-RAN implementation, including BBU pooling, RAN sharing, function split between the BBU and the RRU, and C-RAN virtualization. In addition, there are several C-RAN related projects under EU FP7. For example, the iJOIN project deals with the interworking and joint design of an open access and backhaul network architecture for small cells on cloud networks [9]. Another project, Mobile Cloud Networking (MCN) aims at exploiting Cloud Computing as infrastructure for future mobile network deployment, operation and innovative value-added services [10].

C-RAN is not only applicable for existing wireless networks but also an essential element for future 5G systems [1]. C-RAN is supposed to be able to accommodate and facilitate several 5G technologies such as Large Scale Antenna Systems (LSAS), full duplex, ultra-dense networks and so on, mainly thanks to its inherent centralization nature as well as the flexibility and scalability of a cloud-based implementation [6].

This paper discusses and presents recent C-RAN development and deployment endeavors within China Mobile (CMCC). In Section II, the C-RAN concept and its features will be described in more detail. Critical challenges to a successful C-RAN realization are covered in Section III. Section IV presents field trial results and a GPP-based C-RAN test bed is introduced in Section V, followed by the conclusion in Section VI.

II. C-RAN BASICS

This section gives a basic introduction of the C-RAN concept, features and advantages.

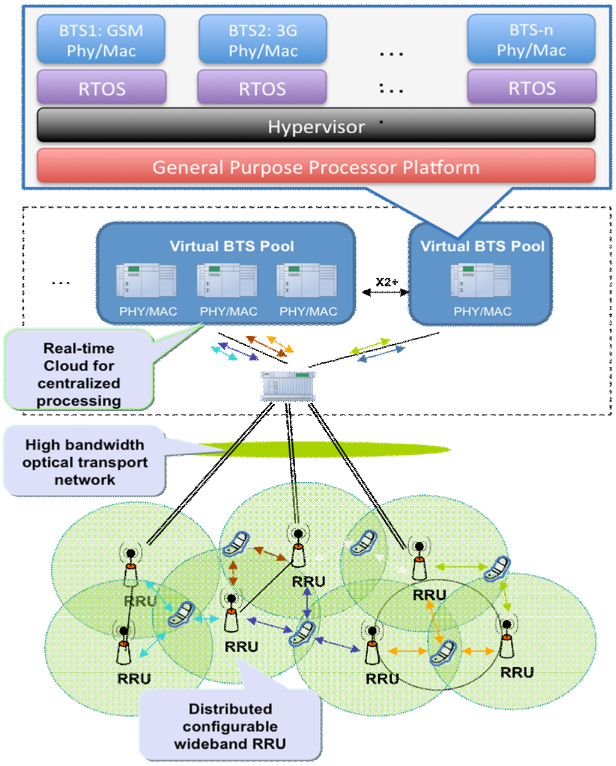

FIGURE 1. Illustrative C-RAN architecture.

A. THE CONCEPT OF C-RAN

With distributed BSs as the basic component, a C-RAN system centralizes different baseband processing resources together to form a pool so that resources could be managed and dynamically allocated on demand on a pool level. Fig. 1 shows the C-RAN architecture, which consists of three parts.

- Base-band Unit (BBU) pool: A BBU pool is located at a centralized site and consists of time-varying sets of "soft" BBU nodes. A soft BBU is a BBU instance in a traditional network where processing resources and capabilities are dynamically allocated and reconfigured based on real-time conditions (e.g. traffic status).
- Remote Radio Unit (RRU) networks: RRUs will be the same as in traditional systems to provide basic wireless signal coverage.
- Transport networks. A transport network provides a connection between a BBU instance in a pool and the RRU. It could be of different forms depending on the scenario. Some examples include direct fiber connection via dark fiber, microwave transmission and fiber transport networks.

B. FEATURES AND ADVANTAGES OF C-RAN

Although C-RAN appears to nothing more than the centralization of BBUs, centralization is just the first step toward a complete C-RAN:

- BBU Centralization: This is the most basic feature of C-RAN.
- Advanced Technology Facilitation: A prerequisite for a pool in C-RAN is an inter-connection switching network of high bandwidth and low latency. This switching mechanism realizes interconnections of different computation nodes and enables efficient information exchanges among them. As a result, many technologies that are difficult to implement in traditional architectures, especially joint processing and cooperative radio, will become viable in a C-RAN context. In this way, the system performance can be improved greatly. In Section IV, we will demonstrate notable CoMP gain under C-RAN architecture through both simulation and field trials.
- Resource Virtualization/Cloudification: Unlike traditional RAN systems in which computation resources are limited within one BBU and therefore cannot be shared with other nodes, in C-RAN these resources are aggregated on a pool level and can be flexibly allocated on demand. This feature, similar to the cloud and virtualization concept in data centers, is called resource "cloudification". It will improve not only resource utilization efficiency but also power consumption.
- "Soft" BBU: Traditional wireless equipment are developed based on proprietary platforms and possess only "hard" fixed capabilities designed for carrying peak traffic. While in C-RAN BBU pool, through resource cloudification, a BBU is of soft form, which means that the capability of a soft BBU could be dynamically reconfigured and adjusted. In this way, resource utilization efficiency can be greatly increased.
- Facilitation of service deployment on the edge: a C-RAN network covers a larger area and serves more users than traditional single base station. Making use of this, it is possible to move services to or directly deploy new services on the RAN side. In this way, the user experience could be improved and backhaul pressure could be relieved.

III. CHALLENGES AND POTENTIAL SOLUTIONS FOR C-RAN

C-RAN is designed to not only address deployment issues but also improve spectral efficiency (e.g. via collaborative radio or joint processing techniques) as well as energy efficiency (e.g., via resource cloudification). Some features such as centralization are relatively easy to realize while other features such as resource cloudification require long-term development. This section analyzes the major challenges for C-RAN implementation and realization and proposes potential solutions.

A. FIBER RESOURCE CHALLENGE BY CENTRALIZATION

For simplicity, front-haul is defined in the paper as the link between BBUs and RRUs. Typical examples of front-haul protocol include Common Public Radio Interface (CPRI) [11] and Open Base Station Architecture Initiative (OBSAI).

Centralization is the critical first step required in order to realize all the other features of C-RAN. Centralization aggregates different BBUs (typically several dozens or several hundred carriers) into one central office with shared facilities. The key challenge for centralization is that it requires a large number of fiber resources if using a dark fiber solution, i.e. direct fiber connection. The issue can be illustrated by the following example. In a TD-LTE system with 20MHz bandwidth and RRUs equipped with 8 antennas (most common scenario in the CMCC network), the CPRI data rate between one BBU and one RRU for one TD-LTE carrier transmission is as high as 9.8Gbps. When considering both UL and DL, 4 fiber connections would be required with 6Gbps optical modules. Since usually one site consists of three sectors with each supporting at least one carrier, the number of fiber connections for one site is as high as 12, which is difficult to achieve for most operators due to limited fiber resources.

In order to overcome the fiber disadvantage in a centralization implementation, various solutions have been proposed. Some are mature enough while others are still in the early stage of development.

Compression techniques are the first steps taken to reduce fiber consumption. There are various kinds of compression techniques such as non-linear quantization and IQ data compression with a lossless 2:1 compression ratio [12]. Another solution is Single Fiber Bi-direction (SFBD) which allows simultaneous transmission of UL and DL on the same fiber. SFBD could further reduce the usage of fiber by another 50%. As a result, when combining SFBD with compression, fiber resources can be reduced 4-fold with lossless performance.

Another method to reduce fiber consumption is to introduce new transport nodes for front-haul transmission. This includes wavelength-division multiplexing (WDM) and microwave transmission. WDM can carry dozens of carriers on a single fiber but may introduce additional delay and noise jitter, requiring careful design and implementation. In addition, microwave transmission may come to play a role as the last 100 meter front-haul solution for the scenarios where it is too expensive or even impossible to deploy fiber.

B. APPLICATION OF CLOUD COMPUTING AND VIRTUALIZATION

C-RAN's core feature is resource cloudification in which processing resources can be dynamically allocated to form a soft BBU entity. Given current vendors' proprietary and closed platforms, it is advantageous to develop a new BBU platform based on virtualization technology found in modern data centers. One suitable method of network virtualization is to use network function virtualization (NFV) which "consolidate{s} many network equipment types onto industry

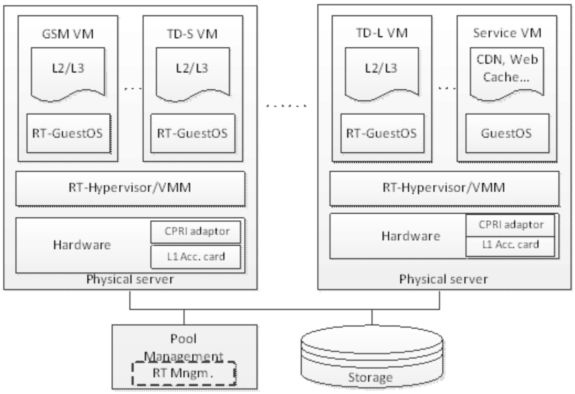

FIGURE 2. RAN virtualization.

standard high volume servers, switches and storage, which could be located in Data centers, network nodes and in the end user premises'' [13].

A new reference system architecture that uses concepts from data center virtualization technologies is proposed in order to realize base station virtualization. As shown in Fig. 2, the baseband resource pools are deployed on multiple standard IT servers. On each physical server there is an additional dedicated hardware accelerator for the computation-intensive physical layer function processes. The additional hardware accelerator design is required to meet the strict real-time requirements for wireless signal processing. The L2/L3 functionalities are implemented via Virtual Machine (VM) in a virtualization environment. Additional user applications such as Web Cache can be also deployed on the open virtualized platform.

Despite the conceptual simplicity of virtualization, the actual implementation is more difficult. Wireless communication is distinct from IT data centers in that wireless communication has extremely strict requirements for real-time processing. For example, for Time-Division Duplexing Long Term Evolution (TDD-LTE) systems it is required that an ACK/NACK must be produced and sent back to the UE/eNB within 3ms after a frame is received. Traditional data center virtualization technology cannot meet this requirement. Therefore, applying virtualization to the base station requires careful design and special optimization on key function blocks. In particular, some challenges are identified as below.

- Optimization of operating systems and the hypervisor in order to meet the requirements of real-time mobile signal processing, i.e. real-time operating system (RT-OS) and real-time Hypervisor with minimal and stable latency and jitter as well as optimum virtualization overhead.
- Optimization of virtualization management functions to fulfill the real-time constrains, e.g. VM live migration and dynamic resource orchestration with real-time signal processing.
- I/O virtualization to improve the VM's I/O performance and its compatibility with live migration.
- Design on virtualization granularity, taking into account various factors such as the correspondence between the VM and carrier and the requirements on carrier cooperation.

The readers can refer to [6] for a more detailed description of the challenges on virtualization implementation.

In the following sections, we will present our latest activities and progress in addressing the challenges in centralization and virtualization.

IV. FIELD TRIALS ON C-RAN CENTRALIZATION

The first step toward C-RAN is BBU centralization which is relatively easy to implement and can be tested with existing 2G, 3G and 4G systems. In the past few years extensive field trials have been carried out in more than 10 cities in China using commercial 2G, 3G and pre-commercial TD-LTE networks with different centralization scale. The main objective of C-RAN deployment in 2G and 3G is to demonstrate the deployment benefits of centralization, including speed-up of site construction and power consumption reduction. One example of the trial is in the city of Changchun where 506 2G BSs in five counties were upgraded to a C-RAN-type architecture, i.e. centralized into several central sites. In the largest central site, 21 BSs were aggregated to support 101 RRUs with total of 312 carriers. It was observed that power consumption is reduced by 41% due to shared air-conditioning. In addition system performance in terms of call drop rate as well as downlink data rate was enhanced using multiple-RRU-co-cell technologies. For the results and benefits by centralization in 2G and 3G trials, readers could be referred to [5], [7].

In this section, we will present the field trials in TD-LTE C-RAN from 2013 to very recently. These field trials mainly focused on validation of various front-haul solutions, including CPRI compression, SFBD and WDM, as well as the CoMP gain in C-RAN systems.

A. FIELD TRIALS ON CENTRALIZATION TO VERIFY CPRI COMPRESSION AND SFBD

The trials were carried out in three cities with similar configurations to each other as shown in Table 1. In this trial, commercial eNBs and EPCs are used together with test UEs.

TABLE 1. System configuration of TD-LTE C-RAN field trial.

Frequency	2.85GHz
Bandwidth	20MHz
Frame structure	• UL/DL configuration type 1 • Normal CP • Special Subframe configuration type7 （DwPTS:GP:UpPTS=10:2:2） • DwPTS for data transmission
CPRI	2:1 compression
Optic module	Single Fiber Bi-direction
UL	SIMO
DL	Adaptive MIMO
QCI	9
Scheduler	PF

Taking one field trial in the city of Chengdu as an example: in the trial, 12 sites, i.e. 36 TD-LTE carriers are centralized.

TABLE 2. Throughput comparison b/w with and without compression plus SFB.

	RSRP	SINR (dB)	DL (Mbps)		UL (Mbps)	
			w/	w/o	w/	w/o
Near point	(-75,-85)	>22	50.57	48. 71	18.38	18. 06
Middle point	(-90,-100)	(10,15)	21.01	24. 09	18.02	17. 93
Edge point	<-105	<5	12.66	10. 18	7.92	6. 24

TABLE 3. Coverage comparison (unit: meter).

DL coverage		UL coverage	
w/	w/o	w/	w/o
600	607	598	607

If using a dark fiber solution, one carrier requires 4 fiber cores with 6Gbps optical modules as the CPRI data rate is as high as 9.8Gbps. As the result, the total number of fiber cores needed is 36*4 = 144. In this trial, we adopted CPRI compression with 2:1 compression ratio and SFBD, with which only one fiber core is needed for one carrier. Thus, altogether 36 fiber cores are needed. It can be seen that compared with dark fiber, the saving on fiber resource is fourfold.

To evaluate the potential impact on radio performance by CPRI compression, extensive test cases, including handover, throughput, user-plane latency, control-plane latency and so on were performed to compare the system performance with and without the two technologies. Two examples of test cases are shown in Table 2 and 3, in which coverage as well as throughput are compared It can be seen the performance difference is almost negligible There is little degradation due to compression.

B. FIELD TRIALS TO VERIFY WDM FRONT-HAUL SOLUTION

In order to verify the CPRI over WDM front-haul solution and the uplink CoMP performance in a real network, we set up another C-RAN network in China Mobile's TD-LTE commercial networks. A dense urban area was selected for this trial. The system configuration is similar to the one in the previous subsection except that the RRUs in this trial are the 2-antenna type. Therefore, the CPRI data rate is 2.5Gbps. As shown in Figure 2, there are totally 7 sites centralized. To save fiber resources, WDM equipments are introduced. The 7 sites, i.e. 21 carriers are connected in two WDM rings, as shown in Fig. 3. It should be pointed out that from a capacity perspective, the WDM equipments in the trial can support up to 12 10Gbps or 2.5Gbps wavelengths. In other words, one such WDM ring can support 12 LTE carriers. The total length of the two WDM rings is 20 kilometers. Fig. 4 is the picture of the centralized baseband and WDM equipment in the C-RAN central office. The benefits and potential impact on system performance by WDM are carefully examined with the following results.

With the WDM solution in this trial, one pair of fiber cores is needed for each ring, resulting in 4 fiber cores consumed

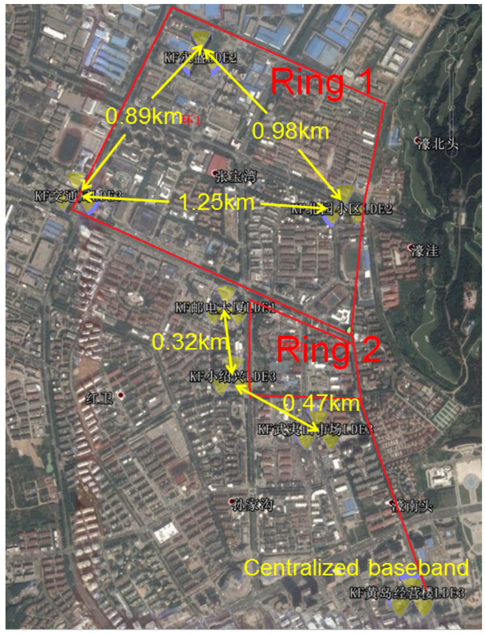

FIGURE 3. C-RAN field trial area.

FIGURE 4. The centralized baseband and WDM equipment.

in total. Compared with a dark fiber solution which requires 42 fiber cores (21 carriers, UL and DL), WDM reduces fiber consumption significantly.

The processing delay of the WDM nodes is an important metric of WDM performance. If it is too large, it may impact CPRI transmission. In this trial the processing delay is tested to find that the latency is less than 1us, which is small enough to have no impact on CPRI transmission.

Another key feature of the WDM solution is the protection switch capability. The operators' requirement in this is less

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TABLE 4. **User plan ping delay with and without WDM front-haul.**

Ping delay 32 Byte (ms)		Good Point	Middle Point	Weak Point
Without WDM front-haul	Max.	24	29	33
	Min.	16	16	16
	Ave.	18	19	20
With WDM front-haul	Max.	22	27	37
	Min.	15	15	17
	Ave.	18	19	20

TABLE 5. **Handover signaling latency with and without WDM front-haul (unit: second).**

	Min.	Max.	Ave.
Without WDM front-haul	0.017	0.02	0.018
With WDM front-haul	0.014	0.022	0.018

TABLE 6. **Handover success rate with and without WDM front-haul.**

	# of HO	# of success	# of failure	HO success rate (%)
w/ WDM	24	24	0	100
w/o WDM	60	60	0	100

than 50ms. In this field trial the fiber is pulled out to simulate the link failure and to trigger the automatic link switch. It is found that the switch time is less than 30ms, meeting operators' requirement.

In addition to the performance of the WDM network itself, we further tested the whole wireless system performance in terms of throughput, coverage, end to end latency, handover success rate and so on, the same as in previous field trial for compression and SFBD. The key finding is that all the performance metrics are almost the same with or without WDM. The trial results show no impact on radio performance with WDM front-haul. For example, Fig. 5 compares downlink and uplink throughput CDF with and without WDM front-haul. The results show very similar throughput performance. Table 4 shows the comparison of user plane ping delay with 32 Byte packages with and without WDM front-haul. The results also indicate similar user plane delay performance. We also tested the handover success rate and the handover latency with the results shown in Table 5 and Table 6. It can be seen that the handover signaling latency is almost the same for both with and without the WDM case. In addition, the handover rate is also the same.

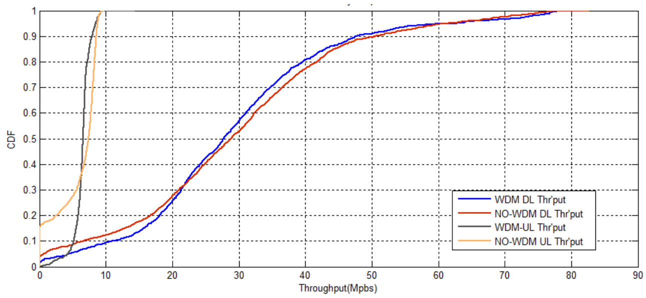


FIGURE 5. **Throughput comparison with and without WDM front-haul.**

Finally, it is worth pointing out that the network has been working well for 3 months as a commercial network with no critical failures.

C. FIELD TRIALS TO VERIFY UL COMP IN C-RAN

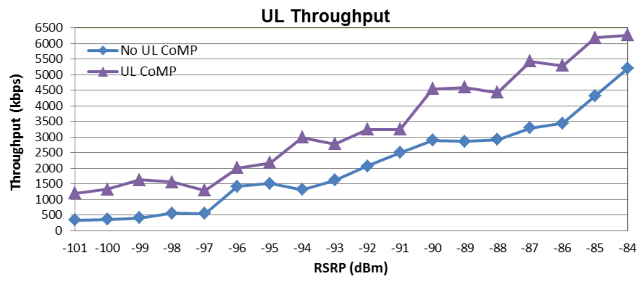
LTE networks suffer from severe interference issues. Uplink CoMP has the potential to improve uplink capacity and reduce inter-cell interference by jointly processing the received signals from more antennas of the adjacent nodes.

Uplink CoMP needs real-time operation with a great amount of data exchange among cells and requires centralized data processing. Intra-site CoMP is the easiest to deploy in contemporary networks and there is no need to update radio network architecture with sufficient coordination between cells of the same eNodeB. Inter-site CoMP and heterogeneous deployment require ideal backhaul support (fiber) to guarantee low delay, low jitter and high capacity CPRI transport from the RRUs to the centralized baseband. Therefore inter-site CoMP and CoMP in heterogeneous networks highly depend on the C-RAN architecture.

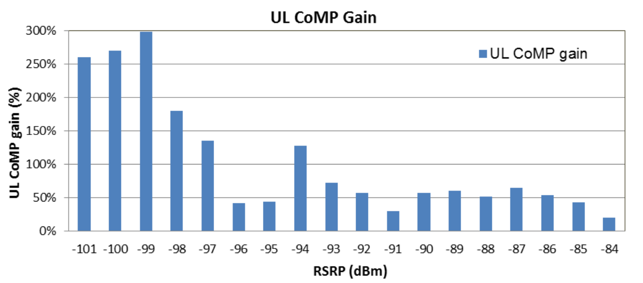
Based on the same C-RAN network with WDM as described in previous section, we further demonstrated the inter-site UL CoMP gain that C-RAN can help to achieve. We tested UL CoMP in the Ring 1 coverage area (Fig. 3), where the inter-site distance is around 1 kilometer. 6 cells are selected as one collaborative cluster out of which two cells can be dynamically chosen to perform intra- or inter-site UL CoMP. In order to emulate real network scenarios, we allocated 5 interfering users in the surrounding cells with full buffer 50% RB (Resource Block) UL traffic. After we turned on all the interfering users, the IoT (Interference over Thermal) in the test area increased 13$\sim$16dB.

During the test, one test user walked around the test area with full buffer uplink traffic. Uplink throughput, serving cell RSRP as well as supporting cell RSRP are captured.

Fig. 6 shows the uplink CoMP trial results. Fig. 6 (a) is the absolute uplink throughput comparison and Fig. 6 (b) is the uplink CoMP throughput gain. The results indicate that uplink CoMP has good potential to strengthen the uplink signal and suppress interference. It shows that uplink CoMP gain can reach 40$\sim$100% in the weak coverage area (that is the area where RSRP is lower than -95dBm), and in some areas the gain can exceed 100%. Because of the interference,



(a)



(b)

FIGURE 6. **Uplink CoMP trial results. (a) Uplink throughput. (b) Uplink CoMP gain.**

the uplink throughput cannot reach its peak in high coverage areas (e.g. where RSRP higher than −90dBm) when there is no uplink CoMP. Uplink CoMP can bring a 1∼2 Mbps throughput boost and results in a 20∼50% throughput gain at this area.

V. ACCELERATOR- AND GPP-BASED PROTOTYPE DEVELOPMENT OF VIRTUALIZED C-RAN

As pointed out in Section II, the core feature for C-RAN is resource cloudification. One solution to realize this to adopt virtualization technologies. Since the technology of virtualization is mostly deployed on a general purpose platform (GPP) such as Intel x86 architecture, it is natural to introduce GPPs as a viable C-RAN deployment platform.

To validate C-RAN technical and business feasibility, we set up a Global System for Mobile Communications (GSM)/TD-LTE/Frequency-Division Duplexing Long Term Evolution (FDD-LTE) converged C-RAN Proof of Concept (PoC) test bed in the lab. The test bed was developed based on standard IT servers of x86 architecture.

Fig. 7 shows the end-to-end architecture of the test bed. From the figure it can be seen that three Radio Access Technologies, i.e. TD-LTE, FDD-LTE and GSAM can be supported simultaneously. For TD-LTE, a dedicated hardware accelerator called the basebandassisted element (BAE) is used to process partial physical layer functions including FFT, channel coding and decoding. The remaining L1 functions as well as L2 and L3 of TD-LTE are all implemented as virtual machines in the IT servers. As for GSM and FDD-LTE, they are implemented with traditional DSP solutions with

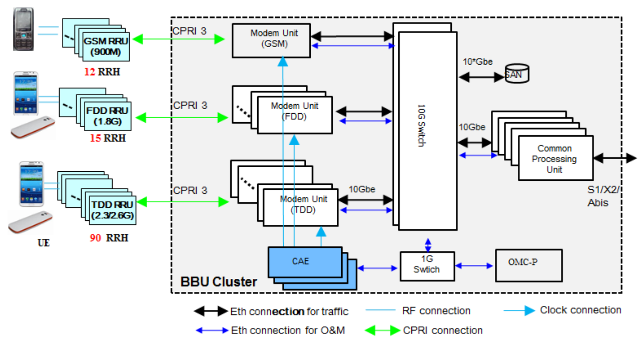


FIGURE 7. **GPP-based C-RAN large-scale PoC platform.**

baseband cards connected with the platform via Ethernet interfaces.

The common processing units as shown in Fig. 7 are standard IT servers. The servers process L3 function for TD-LTE and O&M functions for TD-L, FDD-LTE and GSM. In the common processing units all the functions such as the TD-LTE L3 are implemented all in forms of virtual machines. In the modem units, as shown in Fig. 7, IT servers are also used to process partial TD-LTE L1 and the whole TD-LTE L2 protocols in the form of VMs. In addition, CPRI PCIe plug-in cards are equipped for TD-LTE CPRI link termination. It is worth pointing out that in our demo, the realization of all the other functional blocks in TD-LTE with the exception of the accelerator is based on commercial protocol stacks. Some more detailed configuration of the test bed is as follows.

- Basic configuration:
  - 90 TD-LTE cells, one carrier per cell, 20MHz bandwidth 2.6GHz frequency spectrum with 2 antennas, 3GPP R8 compatible
  - 15 LTE FDD cells, one carrier per cell, 20MHz bandwidth 19GHz frequency spectrum with 2 antennas, 3GPP R8 compatible
  - 72 GSM TRX,1800MHz frequency spectrum with 6/6/6 per BTS
- BBU platform: IT Server (Xeon 2.G, 2 CPUs, 8 cores per CPU) + BAE, commercial TD-LTE L1/L2/L3 protocol stack, no IPSec
- Virtualization implementing environment: Real-time Linux, real-time KVM hypervisor with special optimization and oVirt-based management systems;
- Others: Test UE, RRH 2 × 20W, commercial EPC

Since the baseband implementations of GSM and FDD-LTE are realized in traditional way, we then mainly focus our tests on the TD-LTE systems, which are implemented with virtualization on IT servers. We have performed extensive tests from different perspectives.

The prototype is first tested from functional perspective. A GSM call is made between two commercial GSM UEs while at the same time several LTE terminals, including TDD-LTE and TD-LTE terminals, are accessing the LTE VM and downloading files. The services run well for at least 1 hour.

TABLE 7. Benchmark for physical functions processing (unit: microsecond).

Uplink Processing		20MHz	
		2 Ant. (us)	8Ant. (us)
PUSCH (Single UE with UL 100PRB)	7.5K shift+FFT	105.9	189.9
	Channel evaluation (IRC)	147.7	524
	PUSCH Frequency Domain Processing	52	218
	MIMO/EQU	179.8	384
	IDFT	34.6	34.6
	Demodulation	71.9	71.9
	HARQ Merge	59.7	59.7
	Turbo Decode	113	113
	CRC	9.6	9.6

PUSCH	PUCCH format 1 per UE	2.3	4.1
	PUCCH format 2 per UE	9.7	17.2

Downlink Processing		20MHz	
		2 Ant.	8 Ant.
PDSCH (Single UE, 200PRB, TM3/TM8, peak throughput)	CRC	13.8	13.8
	Turbo Encode	70	70
	Scrambling	14.9	14.9
	Mod.	36.4	36.4
	Power control, precode, BF	21	190
	iFFT	32	116

To evaluate the capability of GPP in terms of the processing of wireless stacks, we then evaluated the processing benchmark for TD-LTE L1 functions and show the results in Table 7. The figures for the 2-antenna case are tested based on the platform while those for the 8-antenna case are estimated with the same configuration.

From Table 7, it can be seen that the processing time for some module functions such as modulation and HARQ Merge are irrelevant to the number of antennas while some are not. IRC and MIMO are the two components which consume the most CPU resources with the high processing time. With the configuration and the evaluation results in the Table, it can be further calculated that on average around 2.5 CPU cores are required for one 8-antenna cell to meet the commercial capacity requirement.

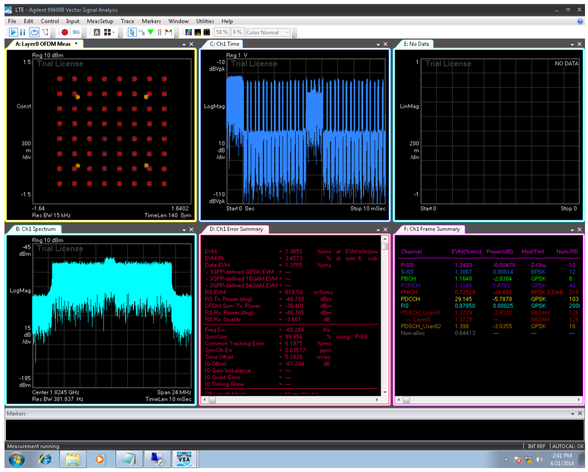


FIGURE 8. LTE TDD 64 QAM Constellation Diagram.

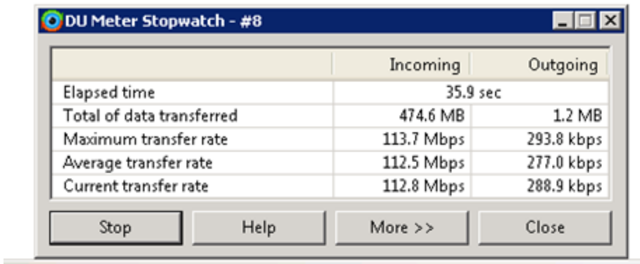


FIGURE 9. Peak throughput for TD-LTE with virtualization implemented.

We also tested the air interface KPI by using and Agilent 89600 VSA analyzer to catch the air interface signal. As shown in Fig. 8 64 QAM Constellation Diagram for TD-LTE, each physical channel is decoded successfully, which demonstrated that the PoC stack is fully 3GPP R8 compliant.

Peak user throughput is also tested with the results shown in Fig. 9. For TD-LTE with virtualization implemented based on GPPs, the peak throughput is as high as 112.5Mbps on average. It is worth pointing out that even with commercial TD-LTE products the peak throughput is around 120Mbps. The difference is very small, which is mainly due to considerable optimization of every key component, including the operating system, hypervisor and so on.

VI. CONCLUSION

From simple BBU stacking to resource cloudification, C-RAN can benefit both operators and customers by reducing energy consumption and improving spectral efficiency. On the road towards complete C-RAN realization, there lie major two challenges: efficient front-haul solutions to centralization and virtualization implementation to realize resource cloudification.

In this paper we first presented our latest field trials of C-RAN centralization. It is successfully verified that combining CPRI compression with a 2:1 compression ratio and Single Fiber Bi-direction technologies, the fiber consumption can be reduced fourfold compared to a dark fiber solution. In addition, theCPRI over WDM front-haul transport solution shows ideal performance in the C-RAN field trial with no impact on radio performance. WDM would be one of the dominant solutions for future large-scale C-RAN deployment.

We also demonstrated the UL CoMP gain was achieved with a C-RAN architecture through the field trials. The results indicate that uplink CoMP can effectively suppress the interference of neighboring cells and efficiently enhance the uplink signal strength. The uplink CoMP gain is 20∼50% at good coverage areas and can reach 50∼100% at cell edge areas.

To verify the feasibility of the use of GPPs and the NFV implementation, a prototype is developed with the ability to support as many as 90 TD-LTE carriers, 15 FDD-LTE carriers and 72 GSM carriers. This GPP based C-RAN test bed with L1 accelerators demonstrated a similar level of performance to the traditional DSP/FPGA based systems, which gives a positive indication for BBU evolution towards standard IT platforms.

ACKNOWLEDGMENT

The authors would like to thank Alcatel-Lucent for development of the GPP-based C-RAN prototype, Datang Mobile and Ericsson for the joint C-RAN field trials. The authors would also like to thank all C-RAN team members in China Mobile for helpful discussion and valuable comments.

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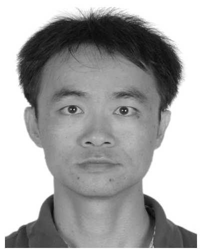
CHIH-LIN I is currently the China Mobile Chief Scientist of Wireless Technologies and in charge of advanced wireless communication research and development effort with the China Mobile Research Institute (CMRI), Beijing, China. She established the Green Communications Research Center of China Mobile at CMRI, and spearheaded major initiatives, including 5G Key Technologies research and development; high-energy-efficiency system architecture, technologies, and devices; green energy; and Cloud-RAN and soft base station.

She received the Ph.D. degree in electrical engineering from Stanford University, Stanford, CA, USA, and has almost 30 years of experience in wireless communication. She has worked in various world-class companies and research institutes, including the Department of Wireless Communication Fundamental Research at AT&T Bell Labs, Murray Hill, NJ, USA; AT&T Headquarter, Dallas, TX, USA, as the Director of Wireless Communications Infrastructure and Access Technology; the Industrial Technology Research Institute, Hsinchu, Taiwan, as the Director of Wireless Communication Technology; and the Hong Kong Applied Science and Technology Research Institute, Hong Kong, as the Vice President and Founding GD of Communications Technology Domain.

Dr. I was a recipient of the Trans. COM Stephen Rice Best Paper Award, and is a winner of the CCCP National 1000 Talent program. She was an elected Board Member of the IEEE Communications Society (ComSoc), the Chair of ComSoc Meeting and Conference Board, and the Founding Chair of the IEEE Wireless Communications and Networking Conference Steering Committee. She is currently the Chair of FuTURE Forum 5G SIG, an Executive Board Member of GreenTouch, and a Network Operator Council Member of ETSI NFV.



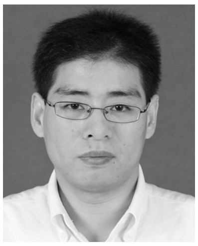
JINRI HUANG was born in Xiamen, China, in 1979. He received the B.S. degree from Xiamen University in Electronic Engineering, Xiamen, in 2001, and the M.S. and Ph.D. degrees in wireless communication from Tsinghua University, Beijing, China, in 2004 and 2008, respectively.

He was a Project Manager with the Network Institute of Technology, SK telecom, Seoul, Korea, from 2008 to 2011. Since 2011, he has been a Project Manager with the China Mobile Research Institute, Beijing. He has been actively involved in various SDOs, including Next Generation Mobile Networks, Frankfurt am Main, Germany; ITU-T, Geneva, Switzerland; and the European Telecommunications Standards Institute, Sophia Antipolis, France. His main interests include next-generation RAN evolution, wireless resource management, next-generation optical transportation technology, fiber-wireless convergence, network functions virtualization, and green communication.

RAN DUAN was born in Beijing, China, in 1980. He received the B.S. degree in electronic engineering and the M.S. degree in wireless communication system from Beijing University Post and Telecommunication, Beijing, in 2003 and 2006, respectively.

He was a Development Project Manager with 3G BBU Design and Development, ZTE telecom, Shanghai, China, from 2006 to 2011. Since 2011, he has been a Project Manager of the China Mobile Research Institute, Beijing. He has been actively involved in cloud-RAN prototype design, CPRI over Ethernet analysis, centralization deployment, and edge service.

CHUNFENG CUI is currently the Director of the Green Communications Research Center, China Mobile Research Institute, Beijing, China. He received the Ph.D. degree from the Beijing University of Posts and Communications, Beijing, in 2003, and then joined the China Mobile Research and Development Center. His work focuses on standardization of wireless communications and research on advanced wireless communications. He has been active in 3GPP, IEEE, CCSA, the IMT-Advanced Promotion Group, and Future Forum, and was the Chair of the Requirement Group of Future Forum, and the Vice Chair of CCSA TC5 WG6 and the Requirement group of IMT-Advanced Promotion Group. His current research interests focus on 5G, cloud-RAN, and wireless green communication technologies. He has authored over 20 papers, and has co-authored two books.



JESSE (XIAOGEN) JIANG is currently the Product Marketing Senior Manager with Alcatel-Lucent Shanghai Bell Company, Ltd., Shanghai, China. As the Champion of Alcatel-Lucent C-RAN Project, he led the team for a successful C-RAN prototype delivery in Q1 2014 to the customer supporting up to 100 LTE carriers pooling. He has over 17-year work experience in the mobile wireless industry in building and leading functional organizations on field customer service, research and development engineering, and product line management. Before joining Alcatel-Lucent in 2009, he spent around 12 years, respectively, with Motorola, Alcatel, and Huawei.

As a Senior Wireless Employee, he has a deep understanding of mobile wireless business, market, and technology evolution trend. He received the master's degree from Hangzhou Dianzi University, Hangzhou, China, in 1996. He is currently pursuing the M.B.A. degree with Shanghai Jiao Tong University, Shanghai.

LEI LI received the Ph.D. degree from the Department of Electronic Engineering, Tsinghua University, Beijing, China. She is currently the Technical Manager with Ericsson (China) Communications Company, Ltd., Beijing. Her study focuses include LTE/LTE-A, radio resource management, heterogeneous networks, and wireless network evolutions.