Received August 15, 2014, accepted September 9, 2014, date of publication October 1, 2014, date of current version October 21, 2014.
Digital Object Identifier 10.1109/ACCESS.2014.2361259

Cloud-RAN Architecture for Indoor DAS

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This work was supported by Aalto-yliopisto, Espoo, Finland, through the Aalto ELEC Doctoral School Scholarship.

ABSTRACT A cloud radio access network (Cloud-RAN) is a new cellular technology that brings baseband processing units for a set of base stations into a central server retaining only the radio front-ends at the cell sites. This new architecture opens up opportunities for algorithms that require centralized processing. However, efficient implementation of the algorithms presents a number of challenges the most critical being latency, fronthaul capacity, and resource control. In this paper, we propose a software-defined radio-based architecture that addresses these problems and can be implemented on a cloud of general purpose computing platforms. We also present the practical implementation of Cloud-RAN running on an off-the-shelf server to validate the flexibility of the architecture. The implementation is able to realize various cellular networks, including heterogeneous networks, distribute-antenna systems, and transmission schemes, such as transmit antenna selection and open-loop transmit diversity.

INDEX TERMS Cloud RAN, distributed-antenna systems, software-defined radio.

I. INTRODUCTION

The practical realisation of newly introduced technologies in cellular standards has always required significant effort in overcoming implementation challenges. Every now and then come around technologies that remove many practical limitations and force us to rethink the whole network structure. One recent example of such disruption is Cloud radio access network (Cloud-RAN) that allows concentration of baseband processing of multiple base stations (BSs) into one cloud server. Cloud-RAN enables many algorithms that require centralized processing. However, the practical limitations of the Cloud-RAN are still to be identified.

In current cellular systems BS constitutes both baseband processing and radio front-end. Recent advances in software-defined radios enable efficient and scalable implementation of RAN functionalities on programmable platforms. This makes feasible to split the BS into radio front-end and software implementation of baseband processing. A pool of software-defined radio engines, baseband units (BBUs), running on a cloud computing platform can provide baseband processing services to radio front-ends, remote radio heads (RRHs), which are deployed in the cell cite. Though this idea is an attractive low cost solution for highly coordinated cellular networks, practical realization of software-defined radio-based RAN have to take into consideration the need for high-capacity and low-latency fronthaul link, as well as, heavy real-time signal processing.

Since its first introduction by China mobile [1], Cloud-RAN implementations are being reported. Especially, software-based Cloud-RAN implementation has got interest from industry [2], [3] and academia [4], [5]. It has been shown that general purpose computing platforms can be used to realize radio access technologies such as LTE [6] and WiMAX [7]. The authors in [5] argued that centralized control management abstracted big BS (with a number of BSs) that can make better decisions in terms of load balancing and interference management.

A Cloud-RAN architecture removes some of the obstacles that occur due to distributed algorithms. However, the centralized architecture also introduces new practical limitations that impact the radio network development. Early academic studies considered only a general Cloud-RAN network structure and new business possibilities it could provide [8], [9]. However, they did not anticipate potential practical limitations. Moreover, very optimistic business structures proposed in those papers might not be feasible in practice. The first Cloud-RAN testbeds have already identified some of limitations we address in this paper, these limitations are summarized below.

- The Cloud-RAN configuration requires high speed link between BBU and RRH.
- The existing RAN components need architectural changes that can accommodate flexible and complex signal processing and radio resource management (RRM) functions.

- There has to be a virtualized interface in order to have unified interaction among heterogeneous networks.

The Cloud-RAN concept emerged on the cross-section of multiple trends. It brings together new approaches in software-defined radios, cloud computing and radio interface design. Lately all of those areas have been a focus of academic research. However, how to combine them in practice is still not clear. We have implemented an indoor distribute-antenna system (DAS) by using a Cloud-RAN platform. We provide a succinct description on our Cloud-RAN platform implementation, present architectural solutions we used and provide insight on the impact of our architecture on radio throughput. The focus of our experimental study is on three particular areas, namely: how to control the communication between BBU and RRH; how to control the BS resources in the server platform; and what kind of impact it has on the design of radio interface algorithms.

By combining multiple BSs into server, we increase demand for resource control. The control has multiple levels: control of BSs in different virtual machines, or control of the resources within one BS [10]. Here we are considering a set of BSs and resources within each. A natural way for Cloud-RAN is to use the software platforms developed for cloud computing [11]. Unfortunately traditional cloud computing resource sharing platforms are developed for different workloads and do not meet the stringent timing requirements of a cellular BS [12]. The Cloud-RAN control layer has to be aware that it manages cellular BBUs. Tests of one such control layer are reported in [13]. The radio transmission stack reported in [13] does not follow stringent frame structure of cellular standards and therefore it is not clear how well the system can mange BBU that has few millisecond time constraints. A server structure that can provide sub-millisecond response times is described in [14]. The analysis in [14] describes not only the server architecture but also dissects the signaling needs in RRH to BBU fronthaul interface. The analysis in [14] is rather general and provides only broad implementation guidelines. We extend this research and describe an implementation of resource control layer. The implemented control layer manages multiple RRHs for BBU that produces TD-LTE radio frames.

Cloud-RAN has to cope not only with processing latency in servers but also with latency and throughput on fronthaul interface. A fronthaul link, an interface between RRH and BBU, is a new element that does not exist in traditional BS. The fronhaul connection is usually served by Common Public Radio Interface (CPRI) [15] or Open Base Station Architecture Initiative (OBSAI) protocol [16]. For wide bandwidth multi-antenna LTE system the CPRI protocol provides 6144 Mbps data rate. Such high data rate can be supported on dedicated fiber links [17]. The latency and throughput constraints of fronthaul link have ignited research in data compression [18]–[20] and power saving [21] on that interface. However, these studies do not consider the fact that by changing radio interface algorithms we can reduce load of a fronthaul link. The Cloud-RAN allows to modify the radio interface protocol in a way that was not reasonable in old architectures [22]. Different RRHs could use synchronization signals to inform users about system state or they can share broadcast signals creatively [22]. Clearly Cloud-RAN opens up a new design criteria of a system. Here we look at the simple trade-off in a Cloud-RAN DAS system: whether to use MIMO diversity schemes or to be satisfied only with simple antenna selection.

In this paper we propose a light-weight and fully flexible architecture for Cloud-RAN. We also present a prototype implementation of Cloud-RAN based on software-defined radio architecture. This is to demonstrate practical realization of central (cloud-based) RAN connected to a number of RRHs through a fiber network. We are looking at an indoor system where the RRHs are served over TCP/IP local are network (LAN). In the designed indoor Cloud-RAN, we compare DAS algorithms with transmit antenna diversity (TxD) versus transmit antenna selection (TAS). Antenna diversity provided by linear algorithms, like the Alamouti scheme [23], is efficient way to combat channel fading. The open loop diversity schemes have been extensively studied and they have firm position in LTE specifications [24]. However, it has been argued that the TAS provides better system capacity than open loop diversity schemes [25]. The problem with TAS is lack of sufficient feedback signaling. We implement TAS in TD-LTE system in the case where the channel state is known due to the reciprocity of the channel. By selecting a single antenna the TAS reduces the need for frouthaul capacity.

II. PROPOSED ARCHITECTURE

We consider Cloud-RAN that serves indoor front-ends. The BBU server can be installed inside the building that is covered with multiple RRH. Here we are dealing with DAS system that will be served by Cloud-RAN. The question is how to select suitable implementation and how the selected implementation impacts performance of the radio interface.

In Cloud-RAN, the RAN functionalities of a BS are partially or fully implemented in software. In hybrid systems intensive baseband processing is accelerated by hardware while the software handles configuration of parameters and realizing higher layer functions. In order to adapt to various transmission parameters, RRHs will have to be re-configurable radio front-ends which can be controlled by the Cloud-RAN engines.

The proposed Cloud-RAN architectures is shown in Fig. 1. The system is divided into four layers: (i) Cloud-RAN which is a pool of software-defined RAN engines running in the cloud (ii) Radio Interface (RI) that abstracts hardware specific settings and exposes re-configurable interface for assigning arbitrary number of RRHs to RAN engines (iii) Radio-over-Fiber (RoF) which transports baseband signal between distant RRHs and the RI through high-speed optical link (iv) RRHs deployed in cell sites. One of the advantages of this architecture is that it is generic and can be scaled to any arbitrary

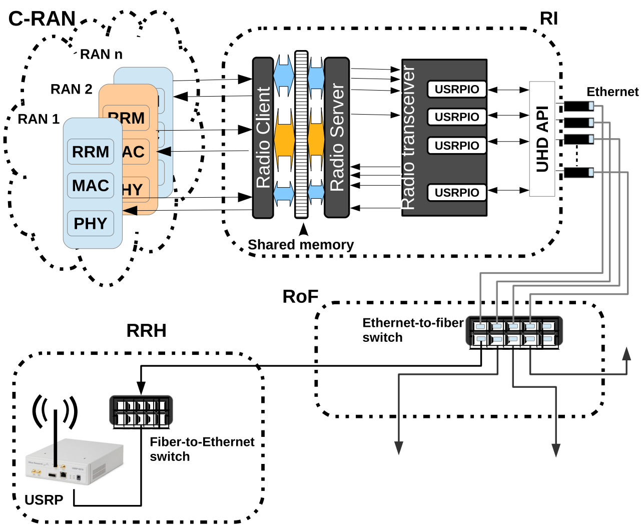

FIGURE 1. **Cloud-RAN Architecture.**

size of RRHs and cells/networks as a plug-and-play fashion. In practice, there can be more than one distinct RAN engines each of which acting as, for example, a macro-cell. In a given macro-cell there can be many small-cells served by individual RRHs. By associating a RAN engine with RRHs in the macro-cell, a DAS can be realized.

We validate our architecture by implementing it with Universal Software Radio Peripheral (USRP) [26] and Intel Xeon class server. The signals to the USRPs are distributed over local area network. In software side we have implemented Cloud-RAN control layer that handles TD-LTE BS frames. We report simple physical layer measurements that require only subset of the TD-LTE software stack functionality. The reported measurements do not push the limits of the platform. Description of the implemented software pipeline requires paper of its own and is left out from the scope of this paper.

A. RRH

We consider a structure where BBU sends baseband samples to RRH. RRHs contain antennas and RF circuitry for translation of signals to baseband and passband frequencies. In our practical implementation the RRH are synchronized by Global Positioning System (GPS) clock. In indoor settings it is reasonable to assume that the fronthaul signal are carried over LAN network.

In our practical implementation we use USRP as RRH. USRP is an open-source software-defined radio platform with RF up/down converters. It is fully programmable and parameters such as carrier frequency, bandwidth and transmit power can be changed on the fly. The network series device NI USRP-2932 from National Instruments [27] is able to stream baseband samples with a rate of upto 25 MS/s full duplex via a Gigabit Ethernet (GigE) interface. The USRP supports a range of Radio Frequency (RF) *daughterboards* that cover carrier frequencies up to 6 GHz.

B. RoF

One of the main features of Cloud-RAN is the decoupling of radio front-ends and the baseband processing. To gain the most out of the limited radio spectrum, a centralized joint processing is required. In order to enable joint processing, baseband signals from RRHs need to be transported to the cloud of computing engines. RoF is responsible for handling this task with lowest possible latency. Optical fiber is an ideal solution to connect geographically distributed RRHs as it enables reliable and high bandwidth communication over a long distance.

In our demonstration platform we use a fiber-to-Ethernet switch to connect USRP to the fiber network by using Juniper EX3300 Ethernet switches [28]. The switches can accept copper and fiber connections. The copper GigE connections are used towards USRP and BBU server. The fiber connection is used for covering long distance between the switches. The copper cables simplify installation of RRH units. Towards server we used copper GigE connection just because it was a readily available cheap solution. In practice such interface will be provided by dedicated fiber connection.

By routing baseband signals over LAN network we have cheap solution that allows use of off-the-shelf commodity technology. We have to recognize that this has its own limitations though. In 20 MHz LTE bandwidth a cheap GigE connection is able to serve only few antennas. In our practical implementation, the USRP hardware was limited to 1x1 antenna system operating with 10 MHz bandwidth. The LAN introduces packet transmission jitter and the system has to cope with random delays in fronthaul network. In [29] the authors report on approach that overcomes the impact of jitters.

C. RI

The RI is a control function that interfaces baseband signals and multiple RRH. It helps to select which signal is sent to which RRH and it informs BBU about the number of available RRHs. In Fig. 1 two sides of RI are illustrated. Towards software-defined RAN engines the RI handles mapping between BBU and RRH, and towards RRH the RI has output buffers. In a generic Cloud-RAN implementation, RAN engines may run as a process inside one computer or there can be physically separated servers one for each RAN engine. RI provides this flexibility through a client-server architecture. The server, called *Radio server*, exposes MIMO streams of the *Radio transceiver*. On the other hand, a client, called *Radio client*, gets resource (data streams) from the server and assigns them to one or more RAN engines. Depending on how many resources (RRHs) the *Radio client* assigns to each RAN engine, different network architectures can be realized. For instance, in single-cell a RAN is connected to multiple RRHs, while in multi-cell there is a set of RAN engines each with its own RRH.

In demonstration platform we noticed that moving data from one memory location to another can consume lot of CPU cycles. This becomes serious problem in Cloud-RAN with many RRHs. RI minimizes this overhead by letting the *Radio server* and *Radio client* to share a common memory space. Hence data from RRHs is copied only once before reaching the respective RAN engine. In practice this means that traditional client server architecture might not be a very attractive option for Cloud-RAN.

On one side, RI provides fully flexible interface between a set of RRHs and one or more RAN engines. On the other side, it abstracts communication to RRH. The usage of Ethernet is done over a driver that hides the communication routines. In our demonstration the USRP units use Universal Hardware Driver (UHD) [30]. UHD is the most commonly used open-source interface for the USRP devices. It allows applications running on non real-time operating systems to talk to real-time hardware. However, the UHD does not compensate for any synchronization error that occurs due to signal processing delay and packet losses before reaching the RRH. For this reason we have implemented a USRP input-output wrapper called *USRPIO*. Each RRH is associated with an instance of *USRPIO* which handles the following functions:

- Transmit and receive data in a timely fashion.
- Detect late or lost packets and correct logical timers accordingly.
- Synchronize to external timing reference, for example GPS, and align uplink and downlink data streams.

All *USRPIO* instances are attached to a common multiple data stream transceiver, called *Radio transceiver*. The *Radio transceiver* combines individual data streams from each *USRPIO* and forms a multiple-input-multiple-output (MIMO) interface. In practical Cloud-RAN these functions should be part of the RRH driver.

III. RADIO NETWORK DESIGN WITH CLOUD-RAN

The described Cloud-RAN test platform is a flexible tool that allows us to compare different network configurations. We illustrate this by measuring radio interface performance in multi-cell and distributed antenna settings.

The platform has two points of control: the number of RAN engines and number of RRHs. The RAN engines are software routines that implement functionalities of a base station. They are flexible enough to accommodate various number of RRHs. In general, RRHs can be co-located (as in traditional MIMO), distributed (DAS) or indoor and outdoor with different transmit powers (heterogeneous). Hence, there can be different flavors of RAN engines for various network configurations.

In this work we analyze indoor radio network. Indoor is a complex radio environment that is difficult to model in distributed transmission settings. Each building has slightly different propagation characteristics, the antennas might observe correlated fading and so on. We avoid radio environment modeling by simply setting up required radio network configuration and measuring the network performance.

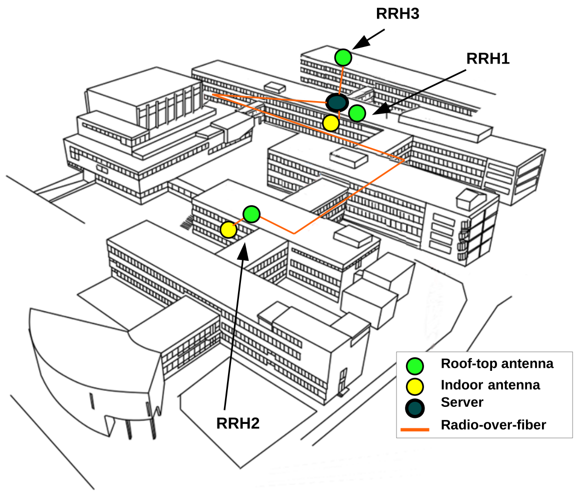

FIGURE 2. Cloud-RAN network configuration.

A. HETEROGENEOUS NETWORK

In heterogeneous networks we insert low power pico and femto-cells into coverage area of a macro-cell. Intention of this configuration is to create small-cell hot-spots that serve low mobility users located in its vicinity.

As the small-cells are deployed inside the coverage area of a macro-cell, they will cause interference. The question in heterogeneous networks is whether to use same frequency in all the cells or to split the frequency and use orthogonal frequencies in all the cells. It is not obvious which approach provides better capacity. We contribute to answering this question by setting up an heterogeneous network with one outside macro-cell and two indoor femto-cells Fig. 2. The measured results are reported in the subsection IV-B.

B. DAS

In DAS setting a single RAN engine simultaneously operates multiple RRHs. This is similar to classical MIMO system except that geographically distributed RRHs give additional degree of freedom, usually referred to as *macro diversity* [31]. In DAS setting we are interested whether to use linear diversity pre-coding or a simple transmit antenna selection (TAS). A linear pre-coding [23] is a fashionable way to tap into diversity. However, in DAS the antennas are located far away from each other. User has significant path loss difference towards different antennas and it is preferable to direct all the transmission power to strongest RRH only. As a natural extension of TAS, we also consider space-division-multiplexing (SDM) where as many users as RRHs are simultaneously scheduled. In SDM, each RRH serves one user.

While in theory TAS provides higher radio interface capacity than transmit diversity, it has been avoided because of practical limitations. It needs information about signal strength at each antenna, and in traditional BS architecture it takes some time to switch signal from one antenna to other. In Cloud-RAN with TD-LTE radio interface those limitations do not hold anymore. In TD-LTE system the signal strength information is readily available due to the channel reciprocity. The uplink received signal provides information about downlink signal strength (and vice versa). In Cloud-RAN the antenna switching speed does not limit us since it is implemented as simple copy of data in RI (described above). Additional benefit with TAS is that the signal has to be sent to one RRH only and as such it reduces pressure on fronthaul link capacity.

In the DAS settings we configure one BBU unit with three RRH (see Fig. 2). We measure radio interface performance with TxD and TAS. In TAS case we analyze how the performance is degraded when the switching is delayed.

IV. MEASUREMENT SETUP

In our measurements we use Cloud-RAN configured with one Intel Xeon-based server and three RRH (USRP) front-ends. All the RRH are clock and frame synchronized. The clock synchronization is achieved by GPS. The frames are synchronized over the air as explained in [29].

The BBU contains RI and TD-LTE radio stack. The radio stack implements TD-LTE physical layer signal format in software. In physical layer we do measurements with orthogonal or overlapping signal. The orthogonal signals are created when RRHs transmit in different TD-LTE subframes. Correspondingly, the overlapping signal occurs when different RRHs are transmitting in the same subframe. The measurements were carried out on 630 MHz. The TD-LTE bandwidth was 5 MHz.

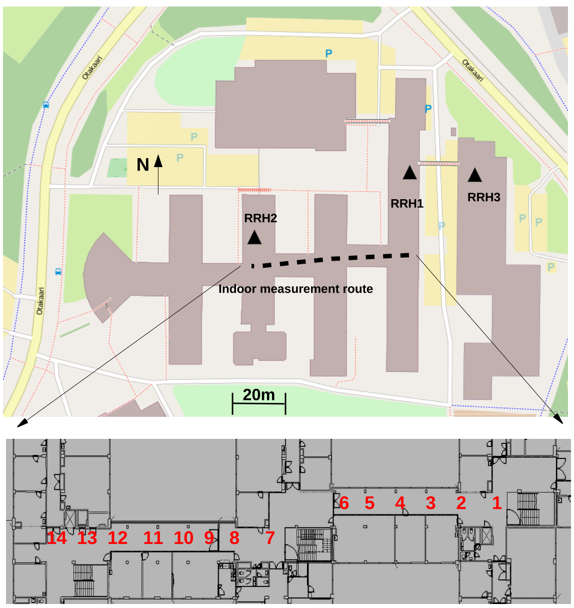

FIGURE 3. Measurement points (indoor 3^{rd} floor).

All the measurement were made indoor on the route described in Fig. 3. The distance between measurement points was 10 m (where applicable). At each measurement point, signal-to-interference-plus-noise ratio (SINR) and Bit Error Rate (BER) of 1000 LTE frames were recorded from each base station. For ease of measurement run, RANs were configured to broadcast dummy data over LTE frames without feedback loop in uplink. The SINR is computed from the Error Vector Magnitude (EVM) of the received signal.

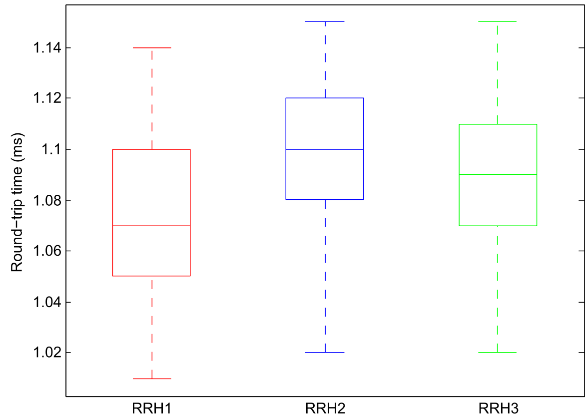

FIGURE 4. Distribution of RTT for RRHs.

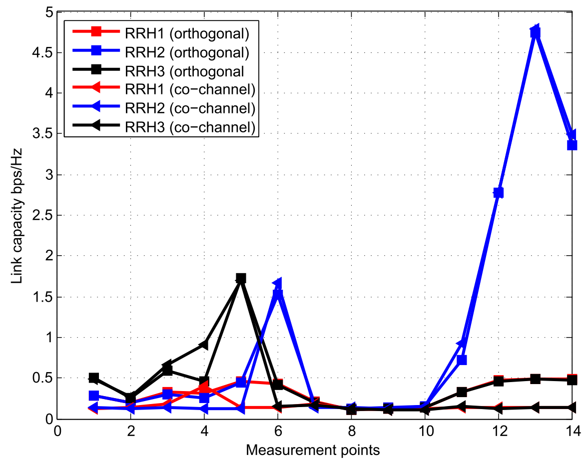

FIGURE 5. Link capacity for heterogeneous network configuration with co-channel and orthogonal transmissions.

A. PLATFORM MEASUREMENTS

One of the practical limitations of Cloud-RAN is the overall fronthaul link latency. This calls for efficient transport of baseband data between BBU and RRH. For example, in LTE the latency between uplink and downlink subframes should be in the order of few milliseconds. We measured the round-trip time (RTT) for Ethernet packets that are sent to the RRHs and received back. Fig. 4 shows box-plots of RTT measurements for 1000 packets, and the RTT is seen to be about a millisecond. It reasonable to assume that one-way delay is in order of half a millisecond.

B. HETEROGENEOUS SYSTEM MEASUREMENTS

We compared co-channel and orthogonal channel transmissions in heterogeneous network. The network is configured to have one rooftop RRH (RRH3) as a macro-cell and two indoor RRHs as pico-cells in four-storey campus buildings shown in Fig. 2. RRH1 is located at the fourth floor while RRH2 is located at the third floor.

The heterogeneous network measurements correspond to downlink-donwlink configuration, that is, interfering signals are from other downlink type subframes. Fig. 5 shows link capacity. At the measurement points considered, it can be

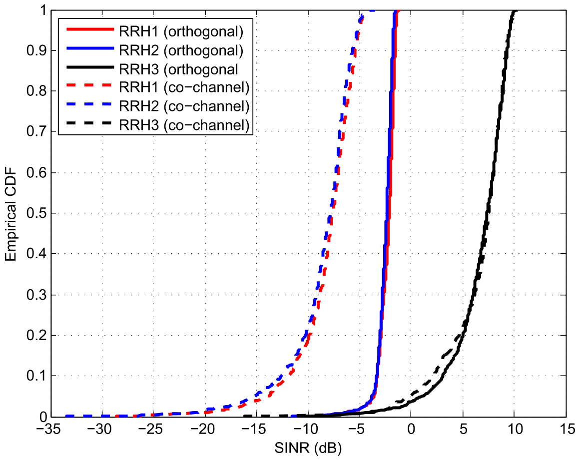

FIGURE 6. **Empirical CDF of received SINR at user location 5 for heterogeneous network configuration with co-channel and orthogonal transmissions.**

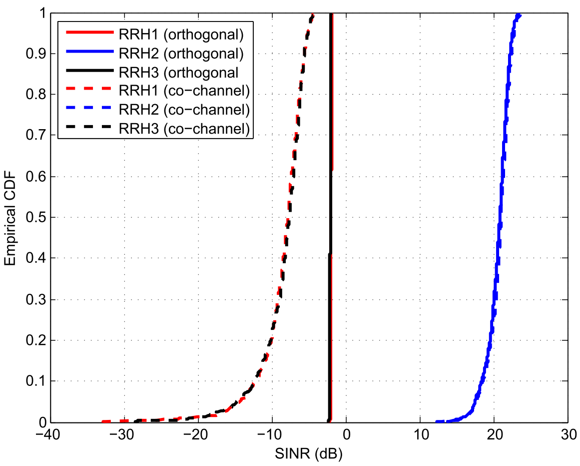

FIGURE 7. **Empirical CDF of received SINR at user location 13 for heterogeneous network configuration with co-channel and orthogonal transmissions.**

seen that the gap between performances of orthogonal and co-channel transmissions is surprisingly small. This confirms that link capacity loss due to downlink-to-downlink interference in single frequency network is negligible. For example, users at locations 5 & 13 can be served simultaneously by the macro-cell and the pico-cell (RRH2) respectively without interfering each other. The empirical cumulative distribution function (CDF) of received SINR at these locations is shown in Fig. 6 and 7 respectively.

C. DAS MEASUREMENTS

In DAS settings, we change all three RRH to be rooftop antennas (see Fig 2). We compare three transmission schemes: SDM, open-loop TxD and TAS. In SDM, one user is scheduled per RRH. Hence, RRHs simultaneously transmit to their respective users. In open-loop setting, the RAN engine serves single user by transmitting the same signal through all RRHs with equal power allocation. The TAS scheme selects the RRH with the best instantaneous channel quality for transmission. In the later two schemes, only one user is served

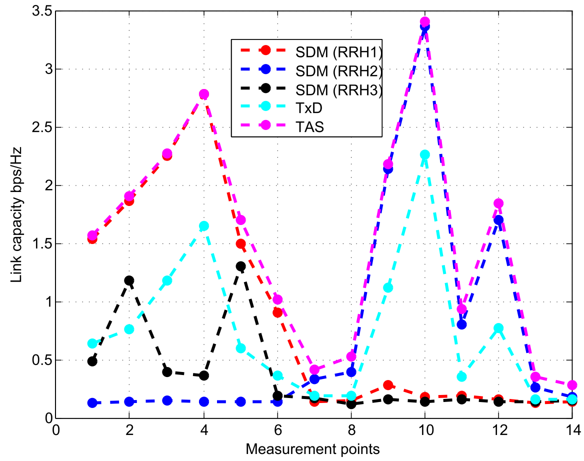

FIGURE 8. **Link capacity for DAS configuration.**

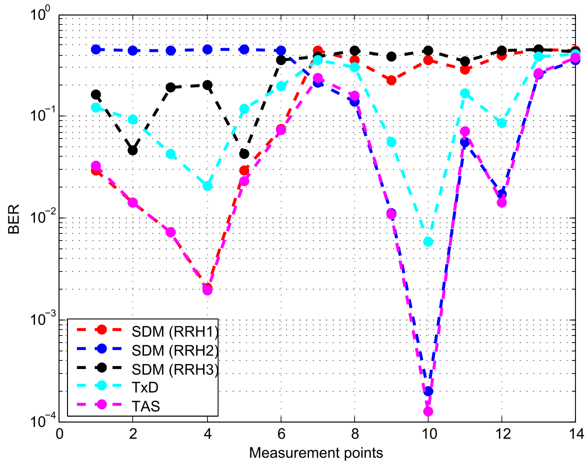

FIGURE 9. **Average BER for DAS configuration.**

at a time while SDM supports as many users as RRHs. The schemes considered here are for demonstration purpose only. Link capacity and average BER measurements are shown in Fig. 8 and 9 respectively.

As expected, the antenna selection scheme offers the best link quality. This is due to the fact that the best RRH is selected instantaneously and there is no interference unlike SDM. On the other hand, TxD has moderate performance. Fig. 8 also shows an interesting result where capacity of one of the SDM links closely follows that of antenna selection scheme. Therefore, SDM gives higher capacity than other schemes since more users are served simultaneously. For example, three users at locations 4, 5 and 10 can be served simultaneously by RRH1, RRH3 and RRH2 respectively in SDM. The total capacity of these links is $2.78 + 1.30 + 3.37 = 7.45$ bps/Hz while the maximum link capacity of antenna selection scheme is 3.4 bps/Hz observed at location 10.

V. CONCLUSION

This paper proposes software-defined radio-based architecture for Cloud-RAN. The architecture has control function that maps BBU to RRH without using complex signaling.

It is a flexible approach that allows realization of various kinds of network configurations. It has primarily been shown using our testbed platform that Cloud-RAN can be implemented on general purpose processor and an off-the shelf software-defined radio front-end connected over commodity LAN network. The testbed is installed in indoor environment. It acts as a platform for validation of radio network designs in real environment. We demonstrated this potential by configuring the Cloud-RAN to operate as heterogeneous network (macro and femto-cell) and as DAS with single BBU.

We used the testbed for comparing different competing radio network configurations. In heterogeneous configuration, we tested co-channel and orthogonal resource allocation. Surprisingly, when using the resources simultaneously by all cell, the link capacity loss compared to orthogonal usage is negligible. In DAS configuration, TAS scheme offers substantial gain over open-loop TxD scheme.

Though measurements gave some insights about possible network configurations, they are not very extensive. The intention here has been to illustrate how Cloud-RAN can be used for supporting and optimizing radio interface design. In addition to link level performances, studies on higher layer algorithms are needed to have broad understanding of Cloud-RAN implications. Future research could be oriented towards these aspects of Cloud-RAN.

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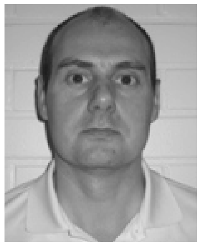

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