Software-Defined Hyper-Cellular Architecture for Green and Elastic Wireless Access

Sheng Zhou, Tao Zhao, Zhisheng Niu, and Shidong Zhou

To meet the surging demand of increasing mobile Internet traffic from diverse applications while maintaining moderate energy cost, the radio access network of cellular systems needs to take a green path into the future, and the key lies in providing elastic service to dynamic traffic demands. To achieve this, it is time to rethink RAN architectures and expect breakthroughs.

ABSTRACT

To meet the surging demand of increasing mobile Internet traffic from diverse applications while maintaining moderate energy cost, the radio access network of cellular systems needs to take a green path into the future, and the key lies in providing elastic service to dynamic traffic demands. To achieve this, it is time to rethink RAN architectures and expect breakthroughs. In this article, we review the state-of-the-art literature, which aims to renovate RANs from the perspectives of control-traffic decoupled air interface, cloud-based RANs, and software-defined RANs. We then propose a software-defined hyper-cellular architecture (SDHCA) that identifies a feasible way to integrate the above three trends to enable green and elastic wireless access. We further present key enabling technologies to realize SDHCA, including separation of the air interface, green base station operations, and base station functions virtualization, followed by our hardware testbed for SDHCA. In addition, we summarize several future research issues worth investigating.

INTRODUCTION

Since their birth, cellular systems have evolved from the first generation analog systems with very low data rate to today's fourth generation (4G) systems with more than 100 Mb/s capacity to end users. However, the radio access network (RAN) architecture has not experienced many changes: base stations (BSs) are generally deployed and operated in a distributed fashion, and their hardware and software are tightly coupled. Facing the exponential growth of mobile Internet traffic on one hand, and the significant energy consumption of mobile networks on the other hand, breakthroughs are strongly expected in RAN architecture design and corresponding systematic control methods. In the conventional RAN architecture, even though there is little traffic requirement, the BSs cannot be switched off in order to maintain the basic coverage. This requires substantial static power to keep the BS active and to transmit the required signaling, thus causing energy waste. To meet the urgent need for green and elastic wireless access, it is envisioned that next-generation RANs should become increasingly software-defined, and the layout of their physical resources should break away from the fully distributed model.

Along with the above paradigm shift, emerging RAN architectures have been developed from three perspectives. The first is the new air interface architecture of cellular networks that features signaling and data separation, aimed at flexible and efficient control of small cells for throughput boosting and BS sleeping-based energy saving [1, 2]. To make cell coverage more adaptive to traffic dynamics, some control signaling functions should be decoupled from the data functions so that the data traffic service is provided on demand, while the control plane is always "on" to guarantee basic coverage. The second is renovating cellular networks into massive BSs with centralized baseband processing and remote radio heads (RRHs), which further evolves to have a cloud-based baseband processing pool [3] and BS functions virtualization. The third is inspired by software-defined networking (SDN) from wired networks, which separates the control and data planes to enable centralized optimization of data forwarding.

We believe that successfully delivering green and elastic mobile access relies on the deep convergence of the above three perspectives, of which the rationale is as follows. First, to realize the control-traffic decoupled air interface, flexible and efficient signal processing is required to reconstruct the frame components from the control and traffic layers of the air interface. The load of control signaling can also vary over time and space for current mobile networks, which requires the control coverage to be reconfigurable with adaptive power and spectrum resources in order to match the signaling load variations. To tackle these challenges, cloud-based RAN architectures can offer help by providing programmable BS functions and reconfigurability of radio elements. Furthermore, the fronthaul network in cloud-based RAN architectures can be aided by SDN to enable efficient data forwarding and flexible function splitting. Meanwhile, the control-data separation in SDN can be extended to wireless access by the control-traffic decoupled air interface. Naturally, the air interface separation should converge with cloud-based baseband processing under software-defined provisioning, exploiting its high flexibility and reconfigurability. In fact, recent studies have begun to investigate the integration of these perspectives [5, 10]. However, the problems of how to combine the

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Trend	Literature	Features	Benefits
Decoupled air interface	• HCN [1] • Phantom Cell [2]	• Separation of control and data coverage • CBSs gather network control information	• Energy saving • Global optimization of network resources
Cloud-based RAN	• WNC [7] • C-RAN [3]	• BBU RRH separation • BBU consolidation • Virtual base stations	• Cost reduction • Improved flexibility
Software-defined RAN	• SoftRAN [8]	• Control data separation • Logically centralized controller • Control APIs	• Global utility optimization • Simplified network management
Integrated architectures	• OpenRAN [4] • CONCERT [5] • SDF [9] • Zaidi *et al.* [10]	• Integration of SDRAN and cloud computing • Integration of SDRAN and decoupled air interface	• Combined benefits • Realization acceleration

Table 1. Summary of new RAN architectures.

three perspectives into a converged architecture and how to realize the architecture in practice remain unclear.

To this end, in this article we propose a new software-defined hyper-cellular architecture (SDHCA) that realizes the separation of the air interface via a software-defined approach in a cloud-based infrastructure. We begin with reviewing the recent research on RAN architecture innovations from the aforementioned three perspectives. Then we present the overall design of SDHCA, which integrates air interface separation, cloud RAN, and SDN, emphasizing the major technical contributions of SDHCA that bring elastic and green mobile service. In the next section, our initial research efforts toward the key enabling technologies of SDHCA are presented, followed by the testbed implementation showing the feasibility of SDHCA. Finally, we outline future research directions that can ultimately facilitate SDHCA in practical RANs.

Recent RAN Architecture Developments

People have witnessed a rising interest in novel RAN architectures in the recent literature. We categorize them into three independent trends, and summarize their main features and benefits in Table 1. The first trend is signaling-data separation at the air interface. Among them the hyper-cellular architecture (HCA) [1] and the Phantom Cell concept [2] are typical examples. Under such architectures, the network coverage is divided into two layers: control coverage and traffic coverage. For instance, in HCA, BSs are classified into two types: control base stations (CBSs) and traffic base stations (TBSs). Specifically, CBSs take care of control coverage, which provides network access, system information broadcast, and so on. On the other hand, TBSs are meant for data traffic services to mobile users. With the decoupled air interface, TBSs can be switched on/off for significant energy savings without generating coverage holes. Besides, CBSs can gather network control information and globally optimize the on/off states of TBSs and the radio resource allocation. The idea of decoupled air interface has made its way into the cellular standard known as “dual connectivity” in Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) Release 12 [6].

Industry and academia are also investigating integrating cloud computing technologies into RANs. Among the most representative are wireless network cloud [7] and Cloud RAN (C-RAN) [3]. They share the same idea of consolidating baseband units (BBUs) of BSs to a centralized computing cloud, while only leaving remote radio heads (RRHs) in the front-end. Cloud-based architecture can reduce energy consumption, as well as the RAN deployment and operational costs [3]. Besides, with virtualization, virtual base stations (VBSs) can be realized, opening up the RAN for flexible system configurations and operations.

Third, SDN has brought a rethinking of packet switching and routing in the Internet, and there have been emerging studies to bring SDN concepts such as control-data separation, centralized control, and software application programming interfaces (APIs) to RANs. SoftRAN [8] aims to enable software-defined RANs (SDRANs). It introduces the concept of the big BS, including a logically centralized controller and distributed radio elements. With the centralized controller, SDRAN optimizes the global utility over a local geographic area, and simplifies network management by software programming.

The recent literature has started to explore the integration of the above trends for future RANs. OpenRAN [5] is proposed to utilize a cloud computing resource pool and virtualization to implement the SDRAN architecture. CONCERT [5] builds a converged cloud and cellular system based on control-data decoupling. Arslan *et al.* [9] propose the concept of software-defined fronthaul (SDF) based on SDN and C-RAN. Zaidi *et al.* propose an integrated architecture that combines SDN concepts from SoftRAN and signaling-data separation [10]. These research works motivate us to explore the integration of the above three perspectives in order to take a further step in enabling green and elastic wireless access in future cellular systems.

Software-Defined Hyper-Cellular Architecture

As shown in Fig. 1, the SDHCA design is based on the deep integration of air interface separation, cloud RAN, and SDN. It exploits the cloud infrastructure, which can be divided into three subsystems: the RRH network, the front-haul network, and the virtual BS (VBS) cloud. The radio elements (RRHs) can merely deal with

The advantage of dual connectivity is that it requires minimum changes to the overall RAN architecture in LTE, and one can expect standard terminals to gradually support it. However, minimum changes also limit the degree of freedom in separation, which implies the separation scheme can be suboptimal.

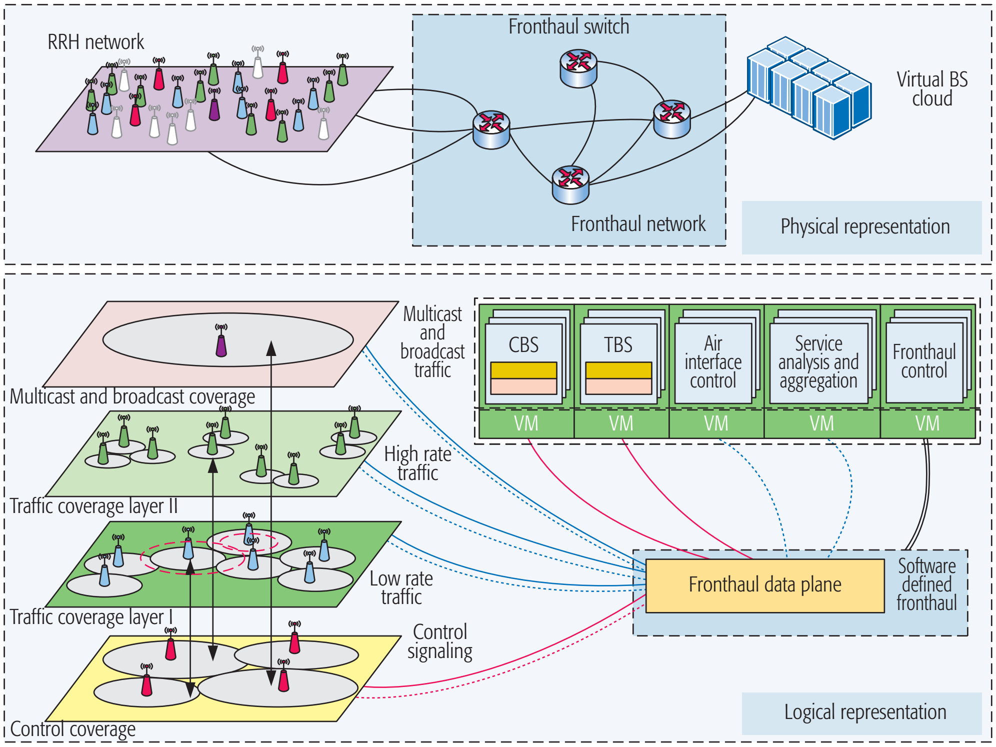

Figure 1. Software-defined hyper-cellular architecture.

RF transmission/reception, or have some baseband processing functions, and their roles can be dynamically configured as CBS or TBS, or put into sleep mode, according to the network status and hardware capabilities of the RRHs. The deployment of the RRHs can be done via conventional network planning mechanisms, satisfying the peak hour traffic of the network. From the perspective of logical functions, the proposed SDHCA provides one control coverage layer and multiple conceptual layers for different user traffic types. In this way, the cell coverage is "softer" and smarter to deliver greener wireless access. RRHs are connected to the VBS cloud via the fronthaul network, which is also software defined. In the cloud, the functions of CBS and TBS are realized as VBS applications in virtual machines (VMs).

The key features of SDHCA are summarized as follows.

Control Data Separation. The separation lies in three aspects. First, in the air interface, CBSs are in charge of control coverage, while TBSs are responsible for traffic coverage. Second, on the infrastructure level, the software in charge of the network functions is separated from the hardware that forwards or transmits the data. In particular, one RRH can be dynamically configured to act as a CBS or a TBS or even both (i.e., handling some traffic while acting as a CBS). Last but not least, the control and data planes of the SDF network are also decoupled.

CBS as the RAN Controller. CBSs take care of mobile users and TBSs underlying their coverage. Besides, CBSs also control the fronthaul network. In this way, the CBS has a global view of the RAN in a local geographic area, and optimizes the on-demand configuration and activation of TBSs so that the network resources, including spectrum resources and energy resources, can well match the dynamic traffic in an elastic way. When the traffic load changes, a CBS can also control the cell zooming behavior of active TBSs to balance the load, as shown in the red dashed circles on traffic layer 1 in Fig. 1.

Software-Defined Network Functions via Virtualization. The network functions, including air interface control, service analysis and aggregation, baseband sample generation, the fronthaul control plane, and so on, are realized by software applications running in VMs. The functions are thus easily programmed and updated, allowing for flexible and efficient network operations, potentially reducing the computing energy consumption.

Thanks to the above tightly integrated features, SDHCA provides flexible services to users exploiting spatial-temporal variations of the traffic demand, so the energy efficiency of the whole network can be greatly improved:

- The decoupled air interface produces flexible sleeping opportunities for TBSs. As shown in Fig. 1, the access control and other coverage-related signaling of different traffic layers are handled by CBSs, and the vertical arrows in Fig. 1 indicate that cells in the traffic layers are covered by a CBS in the control layer based on their positions. Therefore, the RRHs can be configured to TBSs on any traffic layer shown in Fig. 1, and they can be switched off without having coverage holes, leading to significant energy saving. Regarding active TBSs, the energy consumption related to control signaling can also be saved.
- The required compute resources in the BBU pool can adapt to the number of active RRHs,

and so do the virtualized fronthauling functions needed to support these active RRHs. For instance, the VMs that run the CBS and TBS realizations can be constructed or released on demand based on the active/sleeping status of the associated CBSs and TBSs, saving the energy of the computing cloud.

• Unlike conventional cost-inefficient solutions that rely on dark fibers to connect RRHs to the VBS cloud, the SDF enables flexible mapping between BBUs and RRHs [9], and efficient baseband function splitting [11] for equivalent baseband signal compression, so the high bandwidth requirement of the fronthaul is guaranteed at low cost.

In short, the proposed SDHCA is a viable solution to offer green and elastic mobile access.

Enabling Technologies

The enabling technologies of SDHCA are described in detail in this section. We first compare existing air interface separation solutions and discuss future separation-oriented air interface design. Then our initial research efforts to realize green BS operations with BS dispatching and BS sleeping are presented. Finally, possible solutions of BS functions virtualization in SDHCA are discussed.

Separation of the Air Interface

For possible air interface separation schemes, we observe that the naive "extreme separation" scheme is in fact unsuitable. Here, extreme separation means that only the transmission of user perceived data is handled by the TBS, while all other parts are processed at the CBS. The reason extreme separation fails is that modern cellular systems rely on pilot symbols to estimate the wireless channel to aid the decoding of user data bits. With pilots transmitted by the CBS and data bits transmitted from the TBS, this extreme separation approach will lead to inaccurate channel estimation and thus incorrect decoding of the data.

One possible method suggested in the literature is functionality separation [12], where functionality is defined as the essential sets of functions provided by the network to mobile users. It can be divided into five classes: synchronization, broadcast of system information, paging, multicast (for low-rate data transmissions, e.g., voice), and unicast (for high-rate data transmissions). Through functionality separation, the CBS is responsible for the former four classes, and the TBS for synchronization and high-rate data transmission. Careful analysis was conducted to ensure that the user equipment (UE) state transitions continue to work after the separation, although specific to the LTE standard. Based on functionality separation, an alternative separation scheme was proposed in HyCell [14], which is discussed in detail in the next section.

Besides, the separation of the air interface has also undergone discussion in 3GPP, called dual connectivity [6]. In dual connectivity, CBS and TBS are called PeNB and SeNB. respectively, and the separation scheme is specified in the aspects of the control plane (C-Plane) and user plane (U-Plane). In the C-Plane, only a CBS sends out radio resource control (RRC) messages to the user after coordination with the TBS. Two options are available for the U-Plane:

1. Independent Packet Data Convergence Protocol (PDCP) layers are used at the CBS and the TBS, and each node carries one bearer.
2. A slave bearer is split between the PDCP and radio link control (RLC) layers so that CBS processes the PDCP layer, and TBS processes the RLC and lower layers.

The advantage of dual connectivity is that it requires minimum changes to the overall RAN architecture in LTE, and one can expect standard terminals to gradually support it. However, minimum changes also limit the degree of freedom in separation, which implies the separation scheme can be suboptimal.

For future cellular systems, a new separation-oriented air interface design is preferable if one is allowed to break backward compatibility with earlier cellular standards, guided by the principle of separating control from traffic. It is expected to reduce redundancy and keep the protocol simple. It can also improve network efficiency through independent optimization of the air interface at the CBS and TBS according to their different characteristics. Besides, the air interface should be made easily programmable and upgradable via software, thus improving flexibility. The discussion of the aforementioned separation schemes is summarized in Table 2.

Green Base Station Operations

As mentioned earlier, SDHCA can improve network energy efficiency by allowing flexible TBS sleeping and reducing the signaling related energy consumption on TBSs. We conduct a simulation study to evaluate the energy saving gain. We use a system-level simulator in accordance with 3GPP simulation requirements, and the BS power model is from the EARTH project [13]. The layout of 19 CBSs follows a standard hexagonal topology, while the distribution of TBSs follows a homogeneous Poisson point process with a total of 38 TBSs on average. Users, each with an FTP downloading source of the same volume, are randomly and uniformly dropped in the 19-hexagonal area, and we vary the number of users according to a daily traffic profile provided by EARTH [13], resulting in the average total number of users in each hour shown in Fig. 2a. In Fig. 2b, three schemes are compared. "HCA w/o sleep" corresponds to the case when TBSs are not allowed to sleep, while in "HCA w/ sleep" TBSs can dynamically go to sleep according to a simple load-threshold-based policy. "HetNet" corresponds to a conventional heterogeneous network, where we turn CBSs into macro BSs and TBSs into micro BSs from HCA w/o sleep. The time-frequency resource blocks (RBs) are fully used in all BSs in HetNet, while on CBSs, only those for control signaling are used, and the RBs for control signaling are muted on TBSs. The energy reduction from HetNet to HCA w/o sleep is due to the muted control-signaling-related RBs, while the energy saving from HCA w/o sleep to HCA w/ sleep is due to the dynamic TBS sleeping. Note that the separated air interface guarantees this flexible TBS sleeping. One of the

BS functions virtualization is part of network functions virtualization (NFV) in cellular systems. Proposed and standardized by ETSI, NFV aims to virtualize the network node functions and build virtual networks. With BS functions virtualization, BSs become VBSs, and their functions are software defined and can provide various APIs to network operators.

Scheme	Advantages	Drawbacks
Extreme separation: • TBS: user data • CBS: all others (including pilot)	–	Unsuitable
Functionality separation [12]: • CBS: synchronization, broadcast of system information, paging, multicast • TBS: synchronization, unicast	Analytic feasibility validation	LTE-specific
HyCell [14] • Joint functionality and logical channel separation • Synchronization only at CBS	• Generic to multiple standards • Testbed evaluation	Evaluation only on GSM/GPRS
Dual connectivity [6]: • C-Plane: CBS sends out RRC • U-Plane: –Option 1: independent PDCP –Option 2: slave bearer PDCP at CBS, RLC and lower at TBS	• Standard • Minimal change	Suboptimal
Separation-oriented air interface: • Separation in design phase • Independent optimization • Software defined	• Simple and efficient • Programmable	Backward compatibility breakage

Table 2. Comparison of air interface separation schemes.

fundamental issues in SDHCA or any air interface separation scheme is the channel condition acquisition, which is particularly important for BS dispatching and sleeping. When a new user arrives, the network should dispatch the best RRH to act as its serving TBS, which possibly requires waking up a sleeping RRH. However, getting to know the channel conditions of the sleeping RRH to the user is very challenging.

We thus propose a novel method based on machine learning to see the unobservable channel conditions of sleeping RRHs. The main idea is to build a mapping function from the user's observable channel conditions of active CBSs and TBSs to the unobservable channel conditions of sleeping RRHs. A neural network (NN)-based algorithm for RRH selection learning in SDHCA is designed, which combines the standard approaches in NN with crafted processing procedures including discrete Fourier transform (DFT), quantization by logarithmic treatment, and Lloyd's algorithm to form input features. We consider a single CBS with 80 antennas and 5 candidate single-antenna RRHs in sleep. The objective is to select a RRH from the five candidates with the best channel gain to a user, given that the user only has the instantaneous channel condition to the CBS, and historical channel conditions to the CBS and RRHs recorded by other users. The prediction accuracy is defined as the percentage of correct selection. Another performance metric is relative selection error between the predicted RRH's channel gain and the actual best channel gain. We compare our algorithm with other algorithms, and the results are shown in Table 3. The random selection (RS) method provides the baseline accuracy, which is 20 percent for all scatterer configurations. The simple K-nearest-neighbor (KNN) algorithm, which outputs the dominant choice among the K nearest neighbors in the channel space, increases the accuracy to about 55 percent. In comparison, the accuracy of the proposed NN-based channel learning algorithm with channel response as input (NN-CR) is around 70 percent. Moreover, there is an 8 percent gap between the accuracies of NN-CR and an NN-based algorithm using genuine user location as input (NN-LO). But note that in practical systems, location information sufficiently accurate for channel estimation is generally hard to obtain.

Base Station Functions Virtualization

BS functions virtualization is part of network functions virtualization (NFV) in cellular systems. Proposed and standardized by ETSI, NFV aims to virtualize the network node functions and build virtual networks. With BS functions virtualization, BSs become VBSs, and their functions are software defined and can provide various APIs to network operators.

Currently there are several proof-of-concept implementations of VBSs in cellular networks, typically implemented on hypervisor-based virtualization platforms, such as KVM and VMWare ESX, and one major challenge is providing real-time performance [3]. Modern cellular systems have stringent real-time requirements. For example, the LTE standard specifies that one subframe must be acknowledged after three subframes upon reception in frequency-division duplex (FDD) mode. It leaves a total of 3 ms budget for decoding and subframe generation. To fulfill the task, software optimization and hardware accelerators are employed in current implementations. In the software domain, real-time optimization of the whole software stack, including the host and guest operating system (OS, typically Linux) kernel, the hypervisor, and the guest applications, is necessary to power up modern cellular standards on general-purpose processor (GPP) platforms, which makes BS functions virtualization a daunting task.

Container virtualization has the potential to provide a lightweight but effective way to virtualize the BS functions and realize SDHCA. Compared to hypervisor-based virtualization, container virtualization eliminates the need for a guest OS. By reducing the intermediate virtualization layers, container virtualization provides better performance than hypervisor-based virtualization. Therefore, when using container virtualization to build VBSs, the need for real-time optimization can be relaxed.

Another issue of realizing BS functions on virtualization is inter-VM communication. Virtualization typically provides isolation across VMs for fault tolerance, but it also makes inter-application interactions difficult, because the network communication across VMs can degrade system performance dramatically. However, coordinated multipoint (CoMP) communication and CBS-TBS signaling rely on efficient inter-VBS communications. To tackle this issue, new mechanisms are needed to share resources such as disk, memory, or CPU cache to facilitate inter-VBS communications. Instruction set architecture enhancements can also be exploited as a complementary approach to improve the performance of VM communications.

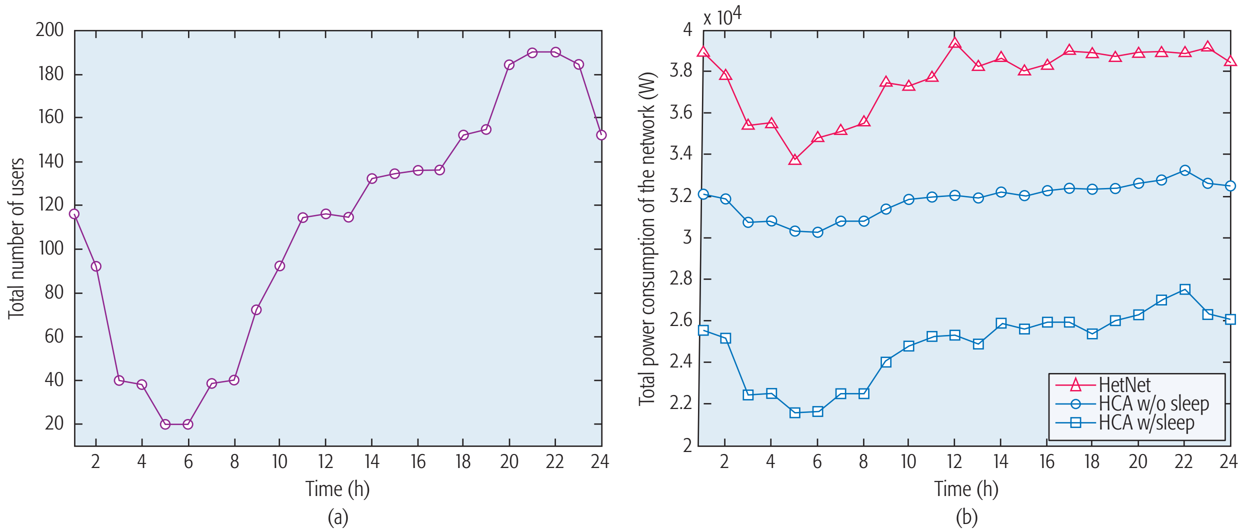

Figure 2. Simulation comparison of the network power consumption: a) average total number of users in the network for each hour; b) average total network power consumption for each hour.

No. of scatterers	10	15	20	25	30	35
RS	0.2/0.4062	0.2/0.3815	0.2/0.3665	0.2/0.3562	0.2/0.3488	0.2/0.3395
KNN ($K = 5$)	0.5601/0.1741	0.5532/0.1622	0.5420/0.1606	0.5306/0.1601	0.5188/0.1593	0.5029/0.1563
NN-CR	0.7483/0.0662	0.7249/0.0703	0.7140/0.0662	0.6871/0.0744	0.6700/0.0791	0.6528/0.0855
NN-LO	0.8268/0.0317	0.7972/0.0376	0.7845/0.0392	0.7788/0.0398	0.7584/0.0429	0.7443/0.0476

Table 3. Prediction accuracy/relative prediction error of different algorithms.

Hardware Testbed

We are prototyping a hardware testbed for systematic evaluation of SDHCA, which is realized via programmable software on GPP platforms. Figure 3 shows our current testbed called HyCell [14], which is based on OpenBTS,[1] an open source Global System for Mobile Communications (GSM)/general packet radio service (GPRS) BS application, and the USRP[2] hardware platform. The overall system structure including hardware interconnection and major software modules are shown in the left part of Fig. 3. In the testbed, the association between the BS servers and the USRP devices is static due to hardware limitations. The static assignment makes it relatively simple and easy to implement our testbed, while it cannot fully reveal SDHCA's potential adaptiveness to traffic dynamics.

Our testbed work presents an alternative separation scheme by jointly considering the functionality and logical channels of current standards. In this design, synchronization only resides at the CBS side, and the TBS is only in charge of high-rate data transmission. As a result, synchronization between the TBS and the UE is guaranteed by CBS-UE synchronization over the air. One major advantage of this synchronization scheme is that no user side modification is needed, so existing mobile terminals can seamlessly access the renovated cellular network. The scheme has been evaluated on our GSM/GPRS based testbed implementation, and is generic to multiple standards. Currently we are investigating its implementation over the LTE standard based on an open source platform OpenAirInterface.[3]

Besides, our testbed is able to demonstrate green BS operations including BS dispatching and BS sleeping. BS sleeping is utilized when the network load is light, and some TBSs can be switched off for energy saving, while load-balancing BS dispatching is beneficial for highly loaded networks or when some TBSs are in sleep mode and the remaining "active" network has high load. In the testbed, we also evaluate the delay overhead of the air interface separation and BS sleeping scheme, which are important factors to guarantee quality of service (QoS) while enjoying the energy saving benefits. In the performance measurements of Fig. 3, we have shown the delay overhead of signaling interaction between the CBS and the TBS when processing the channel request from a user terminal, of which the mean is about 0.36 ms and the standard variance is about 0.1 ms . The small values indicate the feasibility of the air interface separation in SDHCA. As for BS sleeping, we measure the close-down time of turning off a TBS, and its mean is about 52 ms. On the other hand, the setup time of waking up a TBS is several seconds; its optimization needs future study.

Regarding BS functions virtualization, we are prototyping a VBS pool on a commodity x86 server based on Docker[4] containers in

[1] http://openbts.org/

[2] http://www.ettus.com/

[3] http://www.openairinterface.org/

[4] https://www.docker.com/

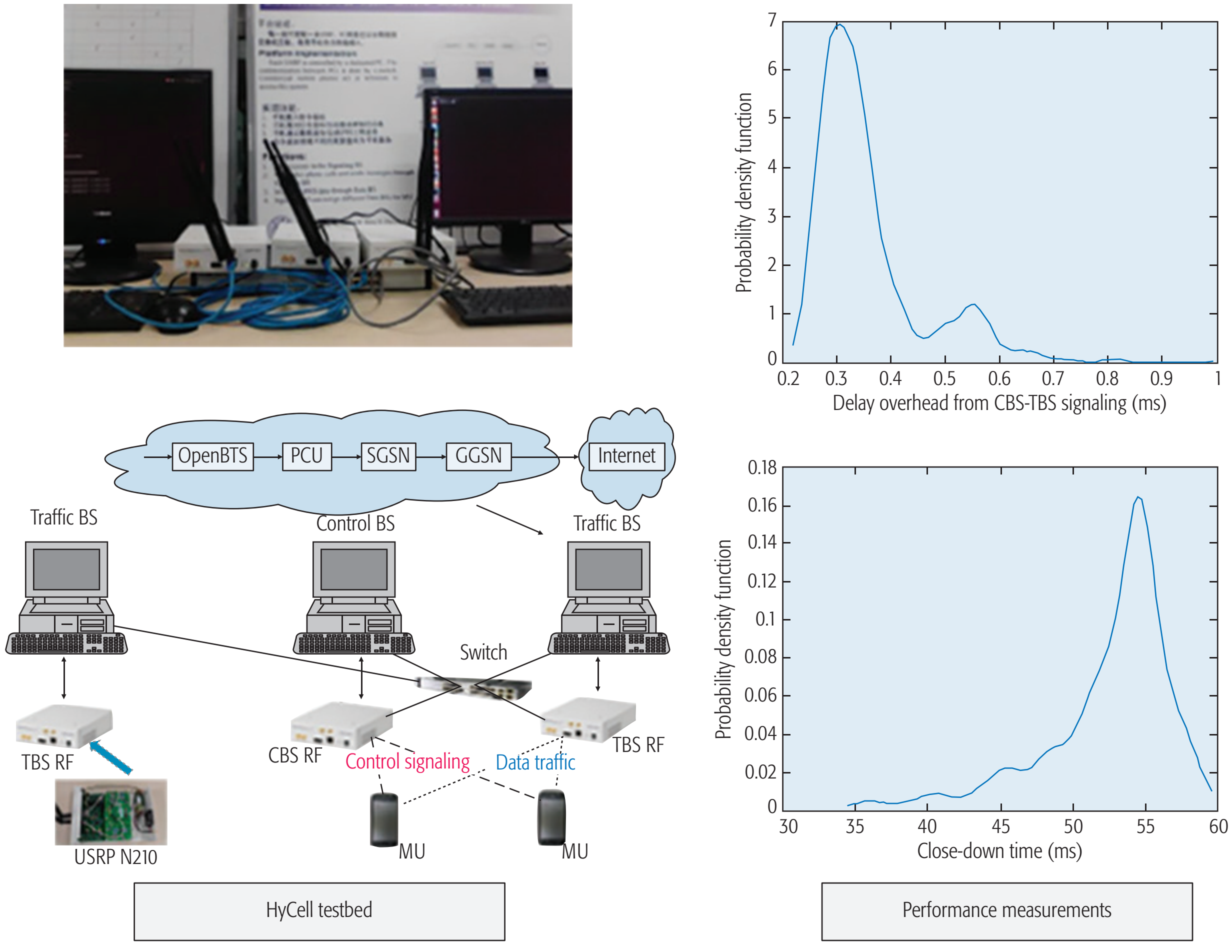

Figure 3. The HyCell testbed.

order to implement dynamic resource allocation algorithms for multiple VBSs and design the API for software-defined network control and management, including more sophisticated BS dispatching and sleeping algorithms. We envision a complete SDHCA testbed to demonstrate its concepts, compare different algorithms, and evaluate system performance as well as inspire new research directions.

The Way Forward

Synchronization is a big challenge in realizing SDHCA. Fine synchronization between different network elements is required to enable green BS operations. Current implementations typically make heavy use of GPS receivers. However, it incurs additional cost, and might not work well in indoor and underground environments. Alternative solutions such as fronthaul-based synchronization or radio-based synchronization should be investigated to tackle this challenge.

Inherited from the cloud-based RAN, SDHCA also faces the challenge of designing high-bandwidth fronthaul. Moreover, future fronthaul networks can have heterogeneous physical realizations, including wireless, fiber, high-speed Ethernet, and so on. As a promising solution for the next generation fronthaul, software-defined packet switching should be evaluated, and the question of how to realize it needs to be answered [15].

From the perspective of better satisfying mobile users' needs, SDHCA should be programmed to provide user-centric services by making the network aware of mobile users' states and allocating network resources to deliver their request contents. How to capture users' state and how to schedule users accordingly have yet to be addressed; for example, interference-aware RRH selection in SDHCA is a valuable but challenging issue.

By building virtual network functions on a software-defined platform, the same physical infrastructure can be shared by multiple network operators, including virtual operators. Dynamic RAN sharing relies on high-level abstraction of the RAN as a controllable entity. Technical problems lie ahead including RAN resource slicing and isolation, as well as RAN provisioning and orchestration. Besides, novel business models between multiple operators call for investigation, possibly via a game theoretic approach.

SDHCA enables green and elastic wireless access, and can further serve as a platform for RAN innovations. In this work we focuses on the RAN part of cellular systems. There are quite a few works trying to bring SDN and NFV concepts to the core network part. How to combine the RAN innovations with core network advances is an exciting research direction.

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SDHCA enables green and elastic wireless access, and can further serve as a platform for RAN innovations. In this work we focuses on the RAN part of cellular systems. There are quite a few works trying to bring SDN and NFV concepts to the core network part. How to combine the RAN innovations with core network advances is an exciting research direction.