A Super Base Station Architecture for Future Ultra-Dense Cellular Networks: Toward Low Latency and High Energy Efficiency

Mingjin Gao, Jun Li, Dushantha Nalin K. Jayakody, He Chen, Yonghui Li, and Jinglin Shi

Abstract

To meet the explosive growth of mobile data traffic, ultra-dense networks have emerged to enhance spatial and spectral efficiency. Densely deployed small cell architecture faces several major challenges, including low infrastructure utilization ratio, severe inter-cell interference, and so on. In this article, we aim to develop a novel super base station (SupBS) network architecture to tackle these issues. The proposed SupBS architecture consists of two layers, namely, an infrastructure layer and a virtualized network layer. In the infrastructure layer, there are three key physical components: the hybrid heterogeneous radio unit pool, line interface switch unit, and computing resources pool. In the virtualized network layer, there are two logical modules designed on top of the three physical components, namely, the virtualized base station and virtualized software defined core network. The two logical modules are designed to facilitate the use of the underlying three physical components by reducing the energy consumption and processing delay. We present the functionalities of the two virtualized modules and explain how they are utilized to create virtual networks. Moreover, we demonstrate a recently developed SupBS prototype, and provide an application scenario for this prototype in an Internet information broadcast-storage system to show the advantages of our architecture.

Introduction

To accommodate the dramatically increased demand on extremely high service data rate in wireless communications, one promising and effective solution is to densely deploy a large number of small cells in radio access networks (RANs) to achieve high frequency reuse, namely, ultra-dense networks (UDNs) [1]. However, the dense deployment of small cells also brings new problems, including low infrastructure utilization, severe inter-cell interference, and so on. To address these issues, cloud-RAN (C-RAN) becomes a vital solution for achieving high energy efficiency and effective interference management [2] in UDN architectures.

C-RAN architecture was proposed by China Mobile in 2009 [3]. Since then, it has attracted much attention from both academia and industry. Following C-RAN, IBM and Alcatel-Lucent have proposed the wireless network cloud (WNC) and Light Radio, respectively [4, 5], as possible solutions for future centralized wireless networks. The key idea of these architectures is to decouple the RF heads and baseband processing resources, which are usually co-located in traditional base stations (BSs). The decoupling process places remote radio heads (RRHs) at cell sites to provide wireless signal coverage, while congregating the baseband units (BBU) to form a BBU pool. This BBU pool can be shared among a large number of cells to achieve much more efficient utilization of processing resources and interference management.

In China, extensive field trials of BS centralization have been carried out using commercial second generation (2G), 3G and pre-commercial time-division Long Term Evolution (TD-LTE) networks at different scales. Reports indicated that with centralized deployment, the operating expenditure (OPEX) and capital expenditure (CAPEX) can be reduced by up to 53 and 30 percent, respectively [3]. However, the aforementioned work has mainly focused on solving existing problems in current RANs with extremely high OPEX and CAPEX. How to meet other important requirements for UDN in the centralized architecture, such as supporting ultra dense deployment of RRHs, extreme low latency, low power consumption [6], and seamless coverage for a variety of topologies [7], has become a critical challenge.

To tackle these new challenges, in this article, we develop a novel network architecture for future UDNs, namely, super BS (SupBS). SupBS exploits the joint design of the RAN and core network by considering a two-layer framework: an infrastructure layer at the bottom to implement physical functions, and a virtualized network layer on top of it to fulfill logical functions. For the infrastructure layer, the SupBS takes the computing resource pool (CRP) as its core component, supplemented by the hybrid heterogeneous radio unit pool (HHRUP) and line

To meet the explosive growth of mobile data traffic, ultra-dense networks have emerged to enhance spatial and spectral efficiency. Densely deployed small cell architecture faces several major challenges, including low infrastructure utilization ratio, severe inter-cell interference, and so on. The authors aim to develop a novel super base station (SupBS) network architecture to tackle these issues.

The work of Mingjin Gao was supported in part by the key project of the National Natural Science Foundation of China under Grant 61431001, by Beijing Municipal Science & Technology Commission Project under Grant D161100001016002. The work of Jun Li was supported in part by the National Key R&D Program under grant number 2018YFB1004802, and by the key project National Natural Science Foundation of China under Grant 61727802, 61501238, by the Jiangsu Provincial Science Foundation under Project BK20150786, by the Specially Appointed Professor Program in Jiangsu Province, 2015, by the Fundamental Research Funds for the Central Universities under Grant 30916011205, and by the Open Research Fund of National Mobile Communications Research Laboratory, Southeast University, under Grant 2017D04. The work of Yonghui Li was supported by ARC under Grant DP150104019 and NSFC under Grants 61531006 and 61671183.

Mingjin Gao is with the Institute of Computing Technology, Chinese Academy of Sciences, and also with the University of Sydney; Jun Li is with Nanjing University of Science and Technology and Southeast University; Dushantha Nalin K. Jayakody is with National Research Tomsk Polytechnic University; He Chen and Yonghui Li are with the University of Sydney; Jinglin Shi is with the Institute of Computing Technology, Chinese Academy of Sciences, and also with the Beijing Key Laboratory of Mobile Computing and Pervasive Devices.

Digital Object Identifier: 10.1109/MCOM.2018.1700414

 0163-6804/18/$25.00 © 2018 IEEE

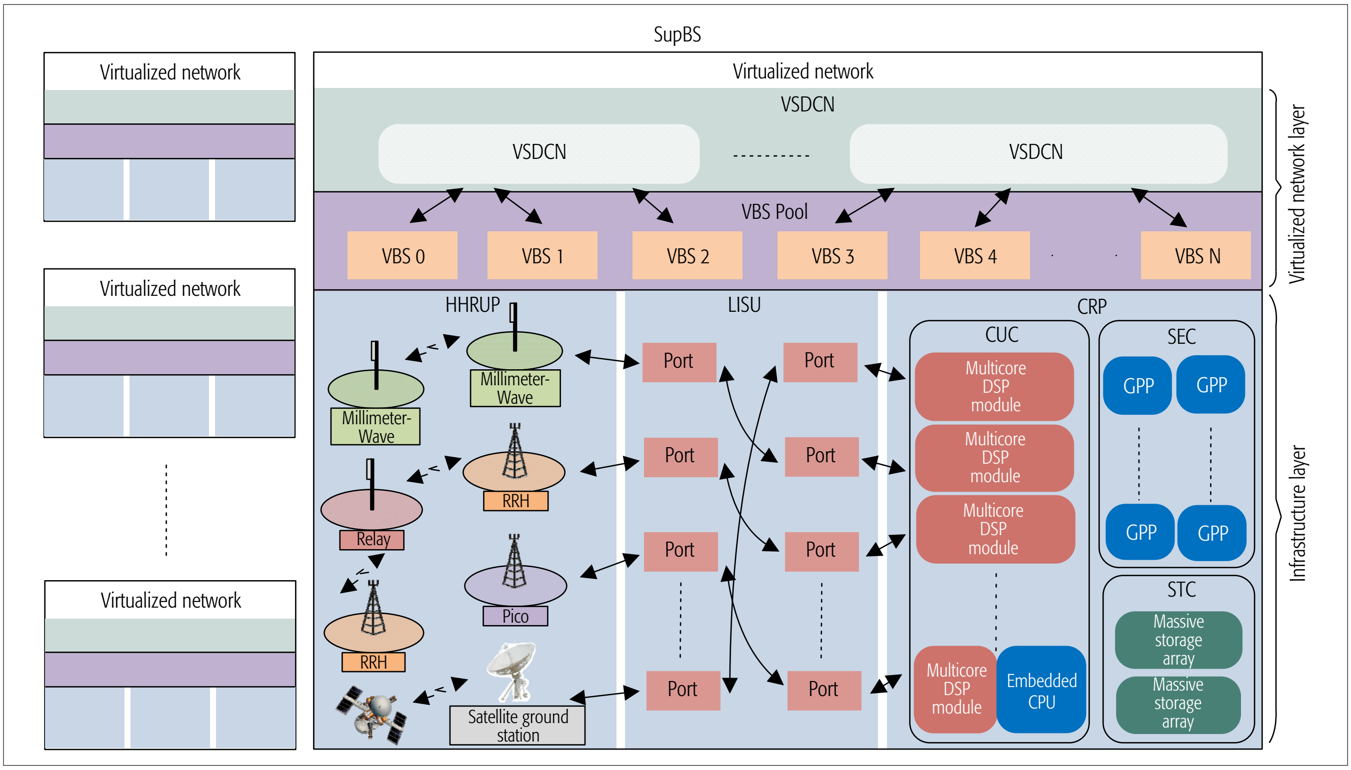

Figure 1. The architecture of the proposed SupBS.

interface switch unit (LISU). Logically, a virtualized network layer is developed for the SupBS on top of the infrastructure layer, with two key modules named virtualized BS (VBS) and virtualized software defined core network (VSDCN). Through dynamic resource sharing and intelligent control, wide area distributed cooperative multi-point transmission, and seamless coverage over a variety of topologies, the SupBS architecture is expected to be superior to traditional cellular architectures.

The challenges faced by the SupBS architecture include how to fully explore the efficient usage of the resource pool, effectively reduce the bandwidth requirements caused by extensive interconnections within the pool, address the low processing and energy efficiency for the pool to be commercialized, jointly design the core network with lower power consumption, and mitigate the transmission latency for guaranteeing quality of service (QoS).

The main contributions of our work are in designing the key components in the two layers. First, for the infrastructure layer of the SupBS, our contributions include:

1. We propose a novel design of LISU by constructing a data switching network between the BBUs and RRHs so as to tremendously reduce bandwidth requirements of interconnection inside the BBU pool. Furthermore, with the LISU, our SupBS provides not only terrestrial radio access interfaces, but also additional interfaces (e.g., the satellite interface) for supporting more applications.

2. We design a heterogeneous CRP by integrating digital signal processors (DSPs) and general-purpose processors (GPPs) to enhance processing and energy efficiency. The advantage of integrating DSP is obvious, since one LTE subcarrier (20 MHz bandwidth, 2-antenna configuration) consumes around 50 W power using GPP, but only roughly 4 W with DSP [8, 9].

From the virtualized network layer perspective, our contributions include:

•To reduce the power consumption in the core network, we jointly design the RAN and core network in the SupBS, and propose a VSDCN logical architecture. In the VSDCN, the core network becomes software-defined entities running on a common hardware platform (e.g., GPPs) together with the VBS, constituting virtualized networks. An individual SupBS can contain multiple virtualized networks that can be shared by multiple virtualized operators. This architecture may open up new business models and increase the revenue of the infrastructure owner and network operators [10].

•To reduce the transmission delay, we develop a parallel middle layer software (PMLS) to accelerate protocol processing. The proposed PMLS exploits parallel processing to take full advantage and achieve high utilization of the resource pool. It is proved that the proposed parallel processing architecture can reduce the processing time by up to 80 percent for the LTE physical layer.

Additionally, we develop an application, namely, a SupBS-based Internet information broadcast-storage (IIBS) system, to demonstrate how our SupBS reduces transmission latency. The proposed SupBS-based IIBS system takes advantage of satellite broadcasting, information storage, and application acceleration function to deliver information to end users directly, thereby significantly reducing the delay relative to conventional cellular networks [11].

The remainder of this article is organized as follows. We first introduce the infrastructure layer and its three components. Then we present the concept of the virtualized network layer, along with its two key modules. Following that, we design a specific application, IIBS, based on the SupBS architecture to illustrate its advantages. Finally, we draw our conclusions.

Infrastructure Layer

In this section, we introduce the architecture of the SupBS. As shown in Fig. 1, the SupBS is composed of multiple virtualized networks. Each virtualized network can be further divided into an infrastructure layer and a virtualized network layer. The infrastructure layer has three key components, HHRUP, LISU, and CRP, which are presented in this section. Afterward, a SupBS prototype is demonstrated to verify the design.

The HHRUP provides pooled heterogeneous terrestrial radio heads and satellite. The LISU decouples RRHs and BBUs through constructing real-time mapping between the HHRUP and CRP, which greatly reduces the data transmission burden within the CRP. The CRP incorporates both DSP and GPP computing resources, which are shared by the VBS, VSDCN, and user application acceleration platform so as to achieve efficient infrastructure utilization.

HHRUP

HHRUP is the radio front-end of the SupBS. Unlike traditional BS and C-RAN architectures, the HHRUP contains hybrid and heterogeneous radio heads. The term "hybrid" means that the HHRUP includes both terrestrial radio access and satellite access heads, which is a distinctive and important characteristic of the SupBS. The term "heterogeneous" means that the HHRUP includes radio heads for different radio access modes, including 2/3/4G radio heads, WiFi radio heads, and so on. By incorporating satellite, WiFi, and so on, the SupBS provides seamless coverage for the surface of land and sea, or even in the air, which extends the coverage from two-dimensional space to three-dimensional space compared to traditional cellular networks. Since all radio heads are located at the same SupBS, advanced interference control strategies can be realized and implemented in practice.

LISU

In the SupBS architecture, the LISU is a switching network between CRP and HHRUP. The data from HHRUP can be switched to any computing unit (CU, analogous to BBU in C-RAN) of CRP by the LISU. In traditional wireless networks, one radio head is usually dedicated to one BS. This static connection makes load balancing among different BSs difficult. In the C-RAN architecture, the RRHs are connected with a BBU pool using optical fiber, and resource sharing can be achieved inside the BBU pool. However, the disadvantage is that high data transmission bandwidth is needed between BBUs for data exchange; for example, a TD-LTE configuration with 20 MHz bandwidth and 8 antennas needs 10 Gb/s rate.

Note that the LISU is deliberately designed to reduce the bandwidth requirements caused by the interconnections of the BBUs inside the pool. The structure of LISU is shown in Fig. 1. It provides

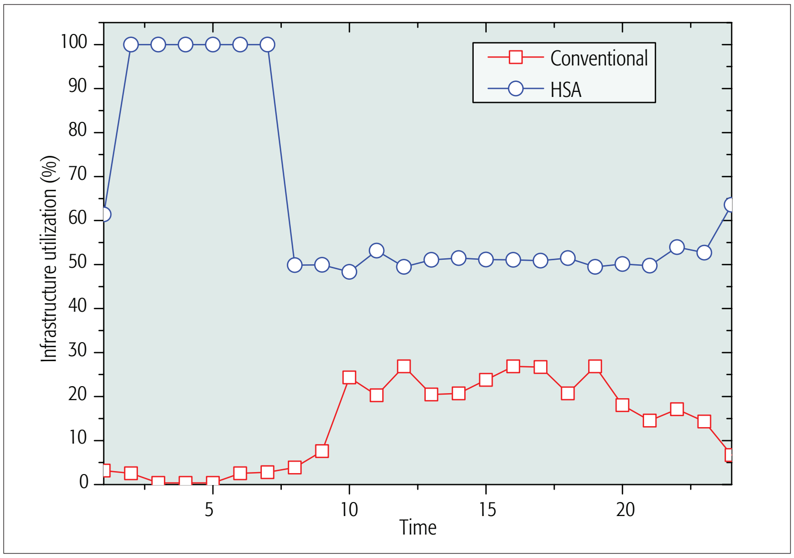

Figure 2. Infrastructure utilization of SupBS.

an "all-in-one" RRH interface solution. Each port is a replaceable interface module. It supports multiple kinds of interface modules, including common public radio interface (CPRI), Open Base Station Architecture Initiative (OBSAI), intermediate frequency (IF) interface, and so on. For the uplink, signals are passed from HHRUP to CRP, and vice versa for the downlink. With the help of the front-end switching network, data exchange requirements inside the CRP is greatly reduced. As such, the LISU enables integration of interfaces in the SupBS for the new communication system without introducing additional data transfer burden to the BBU pool. By providing satellite ground station interface, the LISU can incorporate the terrestrial and satellite telecommunication systems into one.

The typical switching latency caused by the LISU mainly depends on its switching chips. For instance, the switching latency of 80HCPS1848 is 100 ns. Thus, the total latency caused by the LISU is approximately equal to the signal delay in an optical fiber of 30 m length. Usually, the optical fiber between the RRH and LISU can be several kilometers long. In this sense, the latency produced by the LISU would not cause a notable performance degradation.

For the design of LISU, there are several challenges. One is the design of an efficient routing algorithm. Not only do different transmission scenarios need to be included (i.e., one-to-one, one-to-many, and many-to-one transmissions), but also the time and frequency synchronization mechanisms need to be jointly considered in the routing algorithm due to the requirements of strict latency control and data sampling. Another challenge is the design of the control and management layer. Besides the self-management of the LISU, the real-time response to the SupBS needs to be particularly processed.

CRP

The CRP is the main part of our SupBS. Physically, the CRP includes the computing unit cluster (CUC), server cluster (SEC), and storage cluster (STC). The reason for dividing the CRP into clusters is that when the number of CUs gets very

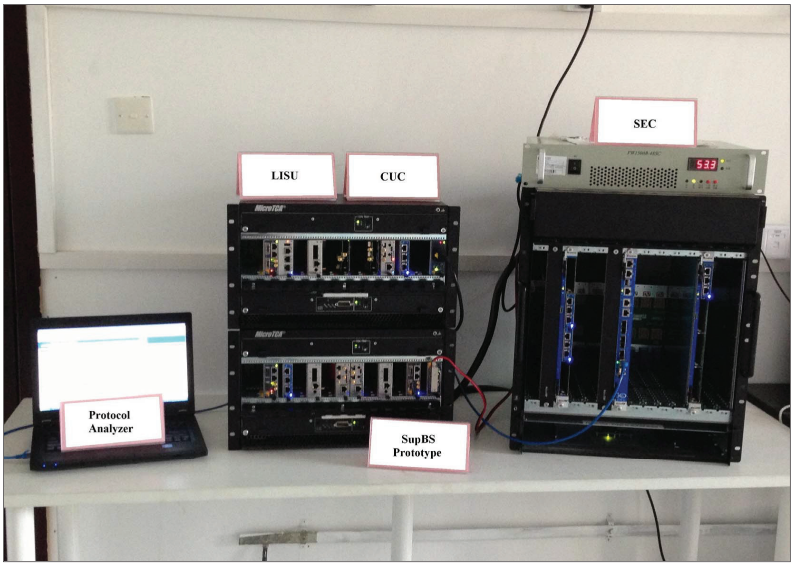

Figure 3. The prototype of SupBS.

large, it is very hard to make all CUs fully connected due to the great challenge of fully interconnecting hardware networks and stringent delay constraints.

Different from the conventional C-RAN architecture, where the BBU pool is composed of GPPs [3], the CUC consists of massive DSP arrays and embeded processors. The DSPs are mainly used to process tasks that have intensive digital signal processing demands, such as physical layer (PHY) processing and the higher-layer protocol processing in LTE systems. It is shown that to support the signal processing of an 8-antenna LTE cell, 2.5 Xeron CPU cores are required, and each core consumes about 25 W power [8]. For the same processing, using DSP only needs four DSP cores, and each core only consumes less than 1 W of power [9].

One BBU cabinet using a commercial Xeron CPU server (with 2 Xeron CPUs, each with 8 cores) consumes around 500 W power and supports around 7 LTE carriers. In contrast, one BBU cabinet of our prototype system consumes around 700 W power while supporting 20 LTE carriers. Therefore, for each LTE carrier, on average, our prototype consumes 35 W power, compared to around 70 W using a commercial Xeron CPU server.

It is obvious that DSP has great advantages in both performance and power consumption for conducting digital signal processing. Compared to the GPP-only structure, integrating DSPs and GPPs in the CRP can achieve significantly more advantages and is promising in commercialization. In the CUC, embedded processors are dedicated for lightweight protocol stack processing [12]. To reduce transmission delay, they are close to the DSP arrays in physical location or even within the same chip.

The SupBS strategically incorporates SEC and STC as part of the BS, where the SEC mainly consists of GPPs, while the STC is composed of storage arrays. This can be regarded as an extension of the C-RAN architecture, where only GPPs are included in the BBU pool. In CRP, SEC and STC are used to support three main functionalities, the high layer software in the VBS, VSDCN, and user application acceleration platform. VBS's high-layer software includes higher-layer protocol stack software (e.g., L3 of an LTE system) and VBS's management software. VSDCN is scalable software running on SEC and is introduced later.

The user application acceleration platform is also a highlighted functionality enabled by SEC and STC. It provides acceleration for various Internet-based applications by moving the application server to the BS (i.e., the edge of network), which dramatically shortens the distance between users and servers. It also builds a platform in which third parties can implement innovative applications with high-throughput low-latency services. This new structure is very similar to integrating a content delivery network (CDN) within the BS, which brings new revenue for operators. These three functionalities share the hardware of SEC, and all of them are scalable for various traffic or business needs.

In the centralized BS architecture, the infrastructures of different functionalities are simply gathered together. In contrast, in our SupBS, all these functionalities (e.g., VBS, VSDCN, and user application acceleration platform) share the same hardware platform, which enhances the utilization to a large extent. Figure 2 shows the utilization comparison of using a heuristic simulated annealing (HSA) resource allocation scheme within SupBS and a simple put-on-together (conventional) scheme. It can be observed that the HSA scheme achieves significant higher infrastructure utilization compared to the conventional scheme.

A SupBS Prototype

Based on the proposed SupBS architecture, we have built a SupBS prototype as shown in Fig. 3. In this prototype, the HHRUP includes traditional 2G and 4G remote radio heads. The LISU is implemented to support both CPRI and intermediate frequency (IF) interfaces. The CRP is constructed by both CUC and SEC. All the devices are controlled by a central controller, which performs overall configuration. The SupBS prototype was tested with the TD-LTE systems. The protocol processing is executed in CUC, where L1 is implemented on DSP, and L2/L3 is on embedded processors. The test data shows that the LISU can support up to 40 Gb/s data transmission rate. IQ data from HHRUP can be efficiently transferred to any processing unit in CUC, which helps verify the proposed CUC resource sharing scheme.

It is shown that there is no system performance degradation compared to a traditional BS, where the resource is occupied exclusively. This initial prototype has demonstrated that the proposed SupBS architecture is effective and efficient. We are currently working on the implementation of virtualized network functions introduced in the following subsection.

Virtualized Network Layer

The virtualized network layer is implemented on top of the infrastructure, which consists of two key elements: VBS and VSDCN. Each VBS is allocated with a slice of the infrastructure resource (HHRUP, LISU, CRP) and constructed from this slice of resource. The VSDCN is constructed within the CRP. Both VBS and VSDCN occupy the infrastructure resources in a dynamic manner.

Thus, a SupBS with flexible capacity and high utilization efficiency can be achieved.

Setting up a virtualized network consists of several stages as detailed below. First, the SupBS allocates a slice resource of the infrastructure layer for the virtualized network. After the infrastructure resource is allocated, a number of VBSs and VSDCNs are then created using this resource. Each virtualized network is in charge of at least one VSDCN and a number of VBSs. During the operating period, the resource occupied by the VBSs and VSDCNs changes dynamically according to the traffic needs. At the end, when the virtualized network is no longer in use, the VBSs and VSDCNs are dismissed, and the resources are recycled back into the infrastructure layer.

In this virtualized architecture, all these virtualized entities (e.g., VBS, VSDCN) share the same infrastructure platform, which increases the utilization to a large extent. Thus, the unoccupied infrastructure can be kept in a low-power mode or even shut down. Therefore, this architecture can help bring down the power consumption. Through the realization of a virtualized network, our SupBS will be able to support a mobile virtual network operator, enrich wireless network business models, enable diverse resource sharing strategies, and create new revenue sources.

Virtualized Base Station

Physical layer software, usually termed L1 software, is mainly composed of intensive signal processing units, which are generally executed serially and thus time-consuming. In order to satisfy the strict time constraint (e.g., LTE requires about 15 ms round-trip latencies and 1 ms subframe interval [6]), software engineers have been struggling with the program optimization. In many cases, they even need to employ low-level primitive language (e.g., assembly language), which makes the design work more difficult and complex. It can be seen that this design methodology can hardly meet the challenge and requirements of 5G. In 5G networks, round-trip latency of around 1 ms will be satisfied, roughly an order of magnitude faster than LTE.

To address this issue, in the SupBS architecture, we propose a common platform to support the operations of all VBSs, namely, PMLS. This platform provides a unified programming interface for the VBS, and makes efficient use of parallel computing to achieve high performance while increasing the infrastructure utilization. The PMLS is dedicated to dealing with the signal processing and supporting the realization of both physical layer and upper layer protocol stack software.

The main task of the PMLS is to reduce processing time through parallel computing, increase the infrastructure utilization, and provide a unified program interface for signal processing software engineers. Through the PMLS, the resources can be dynamically added or removed according to the processing or traffic needs, which means that the VBSs can be reconfigured easily without interrupting the service. Meanwhile, with the PMLS, the hardware becomes scalable. Specifically, when processing cards are inserted or extracted, the PMLS can dynamically add or remove these cards from the parallel processing resource pool, thereby achieving a flexible, programmable, runtime reconfigurable SupBS.

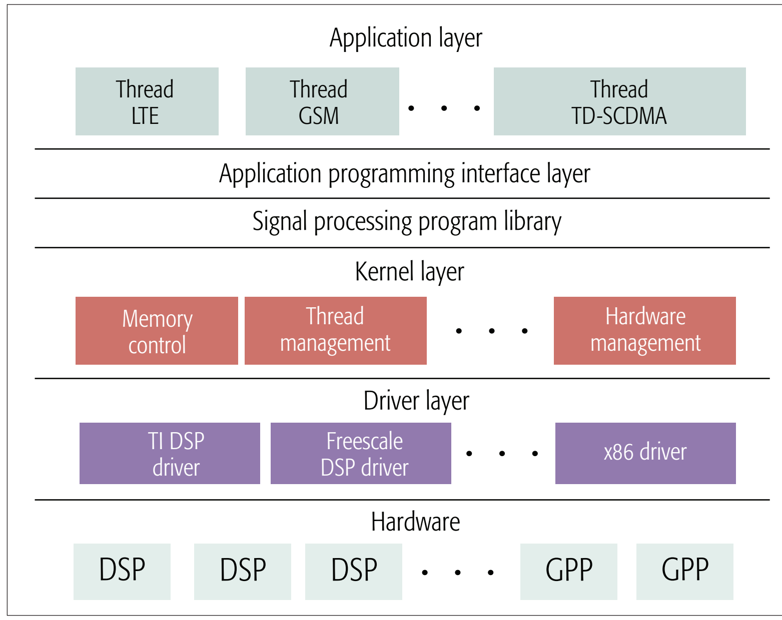

Figure 4. The hierarchy and programming models of PMLS.

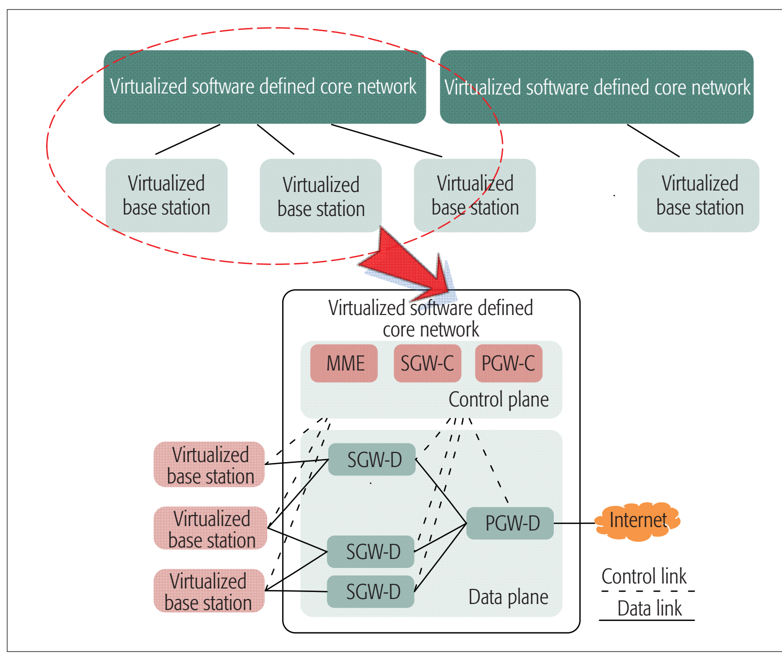

Figure 5. Implementation of VSDCN.

The hierarchy of the PMLS is shown in Fig. 4, which can be further divided into five layers. The top one is the application layer. The software for each VBS on this layer can be regarded as an application, and VBSs with heterogeneous modes — for example, LTE mode and time-division synchronous code-division multiple access (TD-SCDMA) mode — can coexist and run in parallel.

The layer below the application layer is the signal processing program library layer. It provides all pre-verified functions for constructing a VBS, including PHY module and L2/3 protocol module, including turbo coding/decoding, fast Fourier transform (FFT)/inverse FFT (IFFT), LTE radio link control (RLC) function, LTE PDCP function, and so on. All these functions are optimized, and the parallel programming technology is used for further performance improvement. Take LTE PDCP

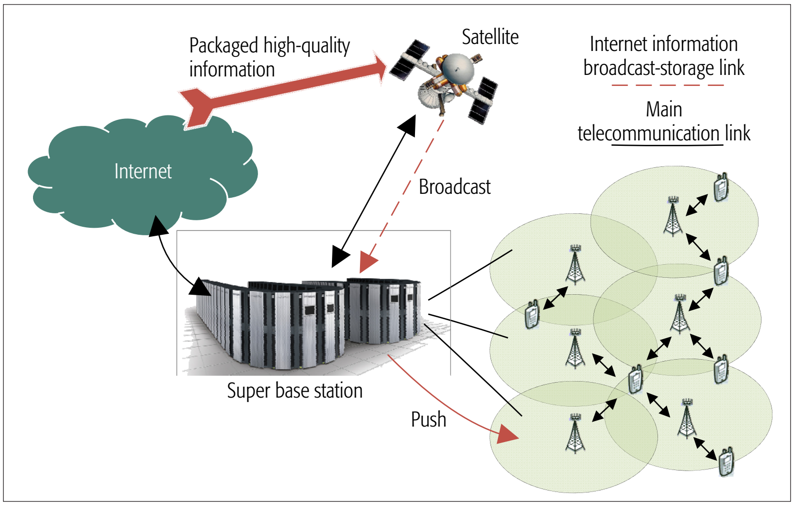

Figure 6. The architecture of SupBS-based IIBS.

function as an example. The PDCP is responsible for IP header compression and ciphering, which is independent for each packet. Thus, in the realization of the PDCP function, the processing procedure can be divided into multiple tasks and performed by CUs in parallel.

To implement a VBS, the programmer can either directly call a VBS initiation function or integrate some predefined modules to build on their own. We thus claim that the designed signal processing program library layer can simplify the BS software design by breaking the static binding between software and hardware, which enables the programmer to assign the hardware resource for a VBS.

The next layer is the kernel layer, which is the core of PMLS. It has a memory control unit, hardware management unit etc. The key component of kernel layer is its process management unit, which is dedicated for run-time parallel task scheduling. While the VBS is running, the process management unit dynamically provides task scheduling and constructs the mapping between the tasks and hardware.

The lowest layer is the hardware management layer. It integrates drivers for various hardware (e.g., DSPs from different vendors). This enables the isolation of hardware from upper layers and increases the PMLS platform's compatibility.

It is worth pointing out that there are a number of challenges to realize the PMLS. For example, to dynamically map the tasks onto the hardware, several factors need to be considered, such as the synchronization control between tasks while deploying dynamic mapping, the trade-off between performance and energy consumption, and load balancing of the CUs. For the program library design, it is also challenging to efficiently increase the performance of the algorithm by using a parallel computing technique.

Virtualized Software-Defined Core Network

In traditional wireless networks, the core network usually has a number of entities. For example, LTE Evolved Packet Core (EPC) architecture includes the mobility management entity (MME), serving gateway (SGW), packet data network gateway (PGW), and home subscriber server (HSS) as the main functionalities. The telecommunications equipment manufacturers normally realize these entities in the form of different kinds of hardware equipment.

Specifically, Huawei has the product USN9810 for MME and UGW9811 for SGW and PGW. Due to the fixed scale and limited capacity of single equipment, the EPC may not be efficient to tackle various emerging challenges in networks, such as the "tidal effect" (i.e., the traffic load varies with time [3, 5]) or network load imbalance. To guarantee the service quality, the service provider has to increase the capacity of the core network according to peak service requirements. This may lead to low utilization as peak service only occurs at low probabilities, and more than 70 percent of hardware resources are not actually used in off-peak periods during daily operation.

Motivated by the aforementioned problems, in the SupBS architecture, we propose the VSDCN and evolutionarily incorporate the core network as part of the SupBS. The VSDCN is an application that provides services to users who are interconnected by the RAN. It implements all the functionalities in the traditional core network in software and runs on the common platform.

As shown in Fig. 5, in each VSDCN realization, there are two main planes: the control plane and data plane. The control plane integrates all control entities (i.e., MME, SGW-C, PGW-C, etc.), where the SGW-C and PGW-C stand for the control function of SGW and PGW, respectively. The data plane includes SGW-D and PGW-D and so on, where the SGW-D and PGW-D represent the data link of SGW and PGW.

To tackle dynamic traffic needs, the control plane may create new data links or release data links without modification of the control plane and assign the data links according to the sessions' quality of service (QoS) requirements. Different from traditional core network equipment, which have specific hardware, all the VSDCN functions are software-based and realized on SEC. This indicates that the scale of each VSDCN realization is no longer bounded by the hardware and can rapidly expand or shrink.

Moreover, in our SupBS, the VSDCN shares the same hardware server platform with application acceleration functionalities. In this case, when the hardware resource is not occupied by the VSDCN, it can be allocated to application acceleration functionalities or kept in a low-power mode to achieve optimal utilization. Furthermore, several VSDCN entities can be created and coexist in the same hardware, which means that the VSDCN can be shared by different operators. This can also bring new income for the operators. Since all VSDCN realizations are within SupBS, the VSDCN has a global view of the whole network. Thus, the control entity is enabled to implement global load balance, even among different operators, which dramatically improves the network utilization efficiency.

Case Study: A SupBS-Based IIBS System

With the built-in virtualized network and user application acceleration platform, SupBS is well suited for a wide variety of services. Here we present a SupBS-based IIBS system to demonstrate the merits of SupBS.

According to the Statistical Report on Internet Development in China, the Internet penetration rate in China is still not high; it was only 46.9 percent by the end of 2014. The low Internet penetration rate results in an information barrier, especially in remote areas. Meanwhile, the continuous increase of Internet users brings a heavy burden on the backbone network. The bandwidth growth of the network cannot catch up with the growing demand.

In [11], an IIBS system was proposed to tackle the aforementioned issues. In IIBS, the aggregated and selected information is first sent to the satellite periodically, then broadcast to distributed servers by the satellite, and finally pushed to end users by servers.

The proposed SupBS can be used to implement the IIBS system, where the SupBS can serve as the center that temporarily stores the information received from the satellite, as shown in Fig. 6. This is a natural implementation since the SupBS integrates the functionalities of satellite ground station and Internet server. In this SupBS-based IIBS system, the SupBS can receive the aggregated information from the satellite in off-peak time (e.g., at night), and pushes this information to the subscribers who have ordered them. For example, in the morning, the subscribers can receive newspapers and magazines. Thus, the SupBS-based IIBS system delivers the information to wireless end users directly. This implementation scheme can dramatically extend the coverage of the IIBS system.

Furthermore, with the SupBS, the routers between the information source and users can be reduced to less than three. This means that the SupBS-based IIBS system can effectively reduce the stress of the backbone network, cut the delay, and enhance the information security.

The proposed SupBS can be used to implement the IIBS system, where the SupBS can serve as the center that temporarily stores the information received from the satellite, as shown in Fig. 6. This is a natural implementation since the SupBS integrates the functionalities of satellite ground station and Internet server.

Conclusion

In this article, we propose SupBS as a new network architecture toward UDNs. The concept of the SupBS is introduced, along with its main differences from traditional BSs and C-RAN. Then we explain the key physical components, HHRUP, LISU, and CRP, in the SupBS architecture, and present a SupBS prototype to verify the architecture design. From the perspective of logical composition, we introduce VBS, VSDCN, and network virtualization within the SupBS. Finally, we present one representative application, the SupBS-based IIBS system, to illustrate the advantages of the SupBS architecture.

Acknowledgments

References

[1] H. Zhang *et al.*, "Energy Efficient User Association and Power Allocation in Millimeter Wave Based Ultra Dense Networks with Energy Harvesting Base Stations," *IEEE JSAC*, vol. 35, no. 9, Sep. 2017, pp. 1936–47.

[2] H. Zhang *et al.*, "Fronthauling for 5G LTE-U Ultra Dense Cloud Small Cell Networks," *IEEE Wireless Commun.*, vol. 23, no. 6, Dec. 2016, pp. 48–53.

[3] C. M. R. Institute, "C-RAN: The Road Towards Green RAN," 2013; http://labs.chinamobile.com/cran, accessed Apr. 20, 2017.

[4] Y. Lin *et al.*, "Wireless Network Cloud: Architecture and System Requirements," *IBM J. Research and Development*, vol. 54, no. 1, Jan. 2010, pp. 4:1–4:12.

[5] Alcatel-Lucent, "LightRadio White Paper: Technical Overview," 2013; http://www.alcatel-lucent.com/, accessed Mar. 15, 2017.

[6] J. G. Andrews *et al.*, "What Will 5G Be?," *IEEE JSAC*, vol. 32, no. 6, June 2014, pp. 1065–82.

[7] J. P. Choi and C. Joo, "Challenges for Efficient and Seamless Space-Terrestrial Heterogeneous Networks," *IEEE Commun. Mag.*, vol. 53, no. 5, May 2015, pp. 156–62.

[8] C. L. I *et al.*, "Recent Progress on C-RAN Centralization and Cloudification," *IEEE Access*, vol. 2, Aug. 2014, pp. 1030–39.

[9] Texas Instruments; http://www.ti.com/product/TCI6638K2K/description#features, accessed May 15, 2017.

[10] C. Liang and F. R. Yu, "Wireless Virtualization for Next Generation Mobile Cellular Networks," *IEEE Wireless Commun.*, vol. 22, no. 1, Feb. 2015, pp. 61–69.

[11] W. En-hai and L. You-ping, "Study on Internet Information Broadcast-Storage System Based on Scale-Free Network," *ACTA Electron. Sin.*, vol. 39, no. 4, Apr. 2011, pp. 737–41.

[12] C. Rowell *et al.*, "Toward Green and Soft: A 5G Perspective," *IEEE Commun. Mag.*, vol. 52, no. 2, Feb. 2014, pp. 66–73.

Biographies

Mingjin Gao (gaomingjin@ict.ac.cn) received his Ph.D. degree from the Institute of Computing Technology, Chinese Academy of Sciences, Beijing, China, in 2017. His research interests include parallel signal processing, computing resource allocation, and centralized cellular network architecture.

Jun Li (jun.li@njust.edu.cn) received his Ph.D. degree in electronic engineering from Shanghai Jiao Tong University, P. R. China, in 2009. From June 2015 to now, he has been a professor at the School of Electronic and Optical Engineering, Nanjing University of Science and Technology, China. His research interests include network information theory, channel coding theory, wireless network coding, and resource allocation in cellular networks.

Dushantha Nalin K. Jayakody (nalin.jayakody@ieee.org) received his Ph. D. degree in electronics and communications engineering in 2014 from University College Dublin, Ireland. Since 2016, he has been a professor in the Department of Control System Optimization, Institute of Cybernetics, National Research Tomsk Polytechnic University, Russia.

He (Henry) Chen (he.chen@sydney.edu.au) received his Ph.D. degree in electrical engineering (telecommunications) from the University of Sydney, Australia, in 2015. He is currently a postdoctoral research fellow at the School of Electrical and Information Engineering, University of Sydney. His current research interests include ultra-reliable low latency communications, millimeter-wave wireless communications, and wireless energy harvesting and transfer.

Yonghui Li (yonghui.li@sydney.edu.au) received his Ph.D. degree in November 2002 from Beijing University of Aeronautics and Astronautics. He is now a professor at the School of Electrical and Information Engineering, University of Sydney. He is the recipient of the Australian Queen Elizabeth II Fellowship in 2008 and the Australian Future Fellowship in 2012. His current research interests are in the area of wireless communications, with a particular focus on MIMO, cooperative communications, and coding techniques.

Jinglin Shi (sjl@ict.ac.cn)received his Ph.D. degree in signal and information processing from Beijing Institute of Technology in 1999. He is currently a professor of the Institute of Computing Technology (ICT), Chinese Academy of Science. He is also the director of the Wireless Communication Technology Research Center of ICT. His research interests include intelligent management and control signalling systems for next generation networks, and the air interface architecture of next generation mobile communication networks.