Software Defined Mobile Networks: Concept, Survey and Research Directions

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Abstract

This article provides a brief overview on the current development of software-defined mobile networks (SDMN). Software defined networking (SDN) is seen as a promising technology to manage the complexity in communication networks. The need for SDMN comes from the complexity of the network management in 5G mobile networks and beyond, driven by increasing mobile traffic demand, heterogeneous wireless environments and diverse service requirements. Needs are strong to introduce new radio network architecture, by taking advantage of software oriented design, the separation of the data and control plane, and network virtualization, to manage complexity and offer flexibility in 5G networks. Clearly, the software oriented design in mobile networks will be fundamentally different from SDN for Internet, for mobile networks deal with the wireless access problem in complex radio environments while Internet mainly addresses the packet forwarding problem. Specific requirements in mobile networks shape the development of SDMN. In this article we present the needs and requirements of SDMN, with the particular focus on the software-defined design for radio access networks (RAN). We analyze in RAN the fundamental problems which call for the SDN design and present a SDMN concept. We give a brief overview on current solutions for SDMN and standardization activities. We argue that though the SDN design is currently focusing on mobile core networks, extending SDN to RAN would be naturally the next step. We identify several research directions on SDN for RAN and expect more fundamental studies to release full potential of software-defined 5G networks.

I. Introduction

After three decades of evolution, mobile networks are moving into the 5th generation (5G) [1]. In Europe, 5G infrastructure public private partnership (PPP) defined the following ambitious performance goals for 5G networks: 10 to 100 times higher typical user data rate, 10 to 100 times more connected devices, 10 times lower network energy consumption, less than 1ms end-to-end latency, and 1000 times higher mobile data traffic per geographical area. To satisfy these new requirements, we will witness more disruptive changes in mobile networks.

One prominent feature would be the full embrace of the software-defined networking (SDN) design in mobile networks. Indeed, the software-defined design of mobile networks could effectively tackle the most difficult problems in current cellular and other wireless access networks, to manage heterogeneity, complexity and consistency in the network and further catalyze fundamental changes in the mobile ecosystem.

While the definition of software-defined mobile networks (SDMN) remains open, SDN for Internet is widely used as the reference model for the SDMN design. The essential ideas from SDN for Internet are the decoupling of the data plane and control plane, and the use of the logical centralized control to manage the forwarding problem in large scale networks. Clearly SDMN will not be a simple extension of the SDN concept for Internet, because the radio access in mobile networks is different from the routing in Internet. Software-defined features in SDMN shall satisfy specific needs from mobile networks.

The evolution history of computer systems may give some hints on the design of SDMN. Nowadays computer systems have been advanced to such a level that the performance of a smart phone easily surpasses that of the supercomputer decades ago. This evolution is firmly backed by advances in the development of the operation system (OS) and programming languages. The OS successfully decouples high layer programs from the low layer hardware implementation. The function abstraction and the modular design of the computer system, along with the paradigm shift towards the object-oriented programming, establish design principles to master the complexity in computer systems. The computer science was born to build the theoretic foundation, which further guarantees the innovation and continuous evolution of computer systems.

The same trend fits the development of mobile communications. Interactions and complexity in current heterogeneous mobile networks (HMN) are very similar to the early stage in the history of computer systems. We need to rethink the design of mobile networks. Referred to the SDN design for Internet, a simplified SDMN architecture is illustrated in Fig. 1.

This article provides an overview on the current development of SDMN. As for mobile networks there is a clear division between radio access networks (RAN) and mobile core networks (CN), we focus the discussion on the RAN side. We start by listing the driving force and enabling technologies for SDMN. Following that, we examine fundamental problems in SDMN, propose a SDMN concept, and briefly analyze the business impact of SDMN. The current SDMN research is briefly surveyed. Finally we identify several important research directions in SDMN.

II. DRIVING FORCES TOWARDS SDMN

The development of 5G networks and the new trend in the spectrum regulation become the strong driving forces to make mobile networks software-oriented.

A. Requirements of 5G networks

5G networks aim to provide the native support for a variety of services with major differences on quality of service (QoS). In additional to applying advance physical layer technologies and using new spectrum, 5G networks needs an orchestrated service platform to effectively and efficiently coordinate network resources. The increasing complexity in 5G network calls for the new network design for flexibility and cost efficiency. It requests the similar design principles driving the evolution of computer systems.

B. Flexible spectrum management

In 5G the spectrum availability is one of key challenges to fulfil the enormous mobile traffic demand. The access to new bands and flexible spectrum sharing become very necessary in 5G networks. The most promising approaches for sharing are the spectrum access system (SAS) and licensed shared access (LSA), where the licensed shared spectrum are allowed to be available to mobile operators. To improve the spectrum reuse, mobile networks need to be aware of the spectrum usage, traffic load and network conditions. The software-defined approach allows spectrum to be managed more efficiently, since the logical centralized control can be aware of the spectrum usage in the network, and allow proper spectrum mobility and effective implementation of spectrum sharing strategies in SDMN.

III. KEY ENABLERS OF SDMN

Technical advances in SDN, Network Functions Virtualization (NFV), cloud computing and fog computing provide technical enablers for SDMN.

A. SDN

The origin of the SDN concept can be traced back to 90's. However, the SDN concept received the global attention after the introduction of the OpenFlow concept in 2006. SDN technologies are promoted and standardized by Open Network Foundation (ONF). By far it has over 150 member companies. SDN enabled network devices are commercially available.

The success of SDN comes from the systematic abstraction of complex networking problems in Internet, which turns previous distributed networking problems into a logical centralized problem, where the rich theories and optimization tools well developed by computer science can be applied. The separation of data and control plane, open control interfaces for network devices of different vendors, and programmable control make a disruptive paradigm shift in the networking business.

The same level of complexity exists in HMNs, but has not been systematically studied. SDN gives a fundamental new thinking on the design of mobile networks. The key question is how to extract the simplicity from complex radio access problems and build principles to guide the mobile network design.

B. NFV

NFV is the recent initiative from the telecom industry to achieve more flexible and cost efficient network architecture [2]. The key idea of NFV is to virtualize the network functions, like NAT, firewall and load balancers, and implement them in industry standard high volume servers, instead of the proprietary hardware. The virtualized network function (VNF) can be run cross different software and processes through virtualization techniques. The focus of NFV is currently on infrastructure networks. It will be an important technology to redesign the cellular CN. The combination of NFV and SDN bring the new architecture design to mobile networks.

C. Cloud computing and fog computing

The development of SDN is tightly connected to the cloud computing, since the cloud computing makes feasible large scale logical centralized control solutions. The cloud computing allows centralized data storage, process and online access to computer resources through remotely deployed server farms and software networks [3]. It aims to maximize the effectiveness of resource sharing. Cloud computing is one enabler of NFV. The resource sharing nature in cloud computing is suitable for the joint signal process and control among RANs. Indeed, the cloud RAN (C-RAN) concept promoted by China Mobile and other major telecom companies is one concrete example of applying cloud computing in mobile networks.

However, the traditional cloud computing architecture may have the problem to meet strict latency requirements for fine timescale control functions in SDMN. It is reasonable to move the logical centralized control close to the edge in mobile networks. Fog computing could fill this gap for the better architecture design of SDMN. Fog computing is a variant of the cloud computing concept [4], which uses the computer resources and storage at the edge of network for substantial amount of communication, storage, control and configuration. In mobile networks, fog computing can be utilized for the control and joint signal process at the RAN level, to serve densely deployed cells, while cloud computing can be used for the control in CN, for packet process and forwarding. The integration of fog computing and cloud computing may lead to an end to end (E2E) SDN solution for mobile networks.

IV. SDMN CONCEPT AND BUSINESS IMPACT

A. Technique aspects

The design of SDMN for RAN needs to address three fundamental problems. In this section we first examine these problems and explain why software-defined approaches will provide a good solution. Then we will present the SDMN concept and briefly analyze the business impact.

The first problem concerns distributed network states in HMNs, in which each network and even each base station (BS) make their own resource allocation decision with limited state information from others. The spectrum reuse in mobile networks calls for optimization and control cross cell borders. However, current mobile networks have the limited support on the network level coordination. It is beneficial to use the network view, as in SDN for Internet, for optimal control and coordination in mobile networks. Considering even in a single BS hundreds parameters need to be tuned, the information presented in the high level network view need to be simplified. The design principles from OS may provide the answer to this problem: the abstraction of system functions and behaviors to shield the details of the low layer implementation. Network views at the high control layer are built upon the proper abstraction of low layers, through defined open control interfaces and primitives. It turns distributed control problems in mobile networks to a centralized coordination problem, allowing more fine-grained optimization. Fig. 2 shows the preliminary simulation study on the performance of the abstracted network view applied on small cell networks. It illustrates the potential of the logical centralized control in small cells networks.

The second problem addresses the network configuration among multiple network entities. In future mobile networks, the performance of network entities is more likely to be coupled due to the spectrum reuse, mobility and traffic offloading. There is an increasing demand to configure network entities in RANs coherently, similar to those in SDN for Internet. The network configuration needs to be done among coupled network entities, by control algorithms based on the logic centralized control framework. To make it scalable, this high level configuration should not go into details of the low layer implementation. This means the network configuration only defines the preferred behaviors of low layers. The behaviors are mapped to the configuration of low layers through middleware. The new network configuration approach needs the deep understanding of network behaviors, especially cooperative behaviors in, e.g., coordinated multipoint transmission (CoMP) and inter-cell interference coordination (ICIC).

The third problem handles the fine-grained cooperation among different entities in the network, for instance, CoMP and enhanced ICIC in long term evolution (LTE) networks. ICIC may require the joint resource allocation and signal process among involved entities. Currently this kind of cooperation is mainly addressed by self-organizing network (SON) features implemented by a bottom-up approach targeting the specific problem. As the fine-grained cooperation becomes a common feature in mobile networks, the top-down approach is needed to incorporate the cooperation in the native system design. With this in mind, we should define open control interfaces, programmable SON features, and proper network abstraction to implement and control different kind of network cooperation in a software manner. It will provide flexibility and reduce the cost to implement new network features in mobile networks.

We believe the software-defined design will expand in mobile networks through two dimensions, as illustrated in Fig. 3. The vertical dimension handles the coarse level network coordination among cells and networks. The horizontal dimension targets the fine-grained network cooperation among network entities. In the vertical direction, the common control requirements and functions need to be extracted from different mobile network. The systematic abstraction and modularity of network functions will enable hierarchical control architecture, in which the high control layer controls low layers through defining behaviors, without the need to know their specific implementation. It will allow the programmable control to coordinate HMNs. In the horizontal direction, cooperative behaviors among network entities will be abstracted. Following that, common control protocols and open interfaces will be developed to support different cooperative behaviors under same software-defined architecture. It will facilitate the implementation of cooperative functions and enable the programmable SON for the fine-grained low layer cooperation in the network.

Different from the software-defined design in CN, software-defined features at the RAN side are focused on the joint resource allocation, spectrum management, mobility and cooperative functions among HMNs. The benefits of SDMN are highlighted in Table I.

B. Business aspects

SDMN will enable an open network architecture which allows the vertical and horizontal control flexibility in mobile networks. It breaks the boundary of a single RAN and provides the extendibility and programmability for control and coordination in HMNs. The development of SDMN will have profound business impact on the value chain of mobile industry.

Operators will be able to reduce the capital expenditure (CAPEX) and time to deploy services, because new open control interfaces and the software-defined control will reduce time and cost to reconfigure and optimize RANs, and to introduce new network features. By the software-defined control architecture, it will allow more efficient use of spectrum, energy resource, as well as the network infrastructure so as to reduce the operational expenditure (OPEX).

For network equipment vendors, because of open control interfaces, they will have more flexibility to implement network functions, making their equipment easily integrated into operators' networks. It will reduce the time of their product to the market, and allow open innovation by embracing competition.

For content providers, SDMN could provide interfaces to allow over-the-top (OTT) services being better served. RAN can be tuned for OTT services according to the software-defined control. It provides content providers and mobile network operators (MNO) a cooperation framework to benefit their business.

For end users, the improved coordination among different mobile networks will provide smooth network experience. SDMN is able to provide customized control to satisfy certain subscriber groups, and to deploy new services in shorter time. It will bring operators more value-added services for the business growth.

The benefits of SDMN to different business players is summarized in Table II.

V. Current research

The ongoing research on SDMN is briefly summarized in this section. The survey is by no mean complete but aims to identify important research directions. We divide the research into three main directions: ideas derived from SDN for Internet, centralized solutions similar to C-RAN, and approaches applied at the mobile edge. Note that a solution can be the combination of these three categories.

A. SDN oriented approaches

The majority of the SDMN research derives from the original SDN concept. The common features are the decoupling of the control and data plane, and the use of the logical centralized control.

OpenRoad is the very early study on this topic [5]. It is mobile version of SDN, which use OpenFlow for control, FlowVisor for network slicing, and NOX as the network operation system to support the programmable control in WiFi and WiMAX networks. OpenRoad allows different control algorithms concurrently running in one network, and thus realizes network slicing, one of the key features in SDN. Network slicing is extended to cellular networks in [6], where the network virtualization substrate and CellSlice are proposed to virtualize wireless resources and allow virtual mobile network operators coexist in a single physical network.

Softcell is the first effort to extend the SDN concept to the mobile CN [7]. It applies SDN principles to redesign the control plane of CN. The centralized controller and the flow concept allow the previously centralized packet processing in CN to be distributed among separated packet processing middleboxes, and thus improve scalability and flexibility. Pentikousis et al. proposed another flow-based forward model, named MobileFlow, to facilitate the deployment of new services and network features in the mobile CN [8]. An OpenFlow controller is introduced in [9], which allows the separation of control and data plane in CN of LTE networks and moves core control functions in CN to the cloud for reliability and scalability. The similar idea has been proposed in [10], where the mobile network SDN controller governs not only LTE, but also Universal Mobile Telecommunications System (UMTS), WiFi, and other wireless networks.

Further, a SDN-based plastic architecture is introduced for 5G networks [11], with the aim to support a heterogeneous set of services with flexibility. It introduces a clean-slate date plane design, and the SDN controllers at three levels, i.e. device, mobile edge, and CN, respectively. By this design, it avoids the use of tunnel protocols for mobility, and allows backward compatibility to 4G networks.

B. C-RAN oriented approaches

C-RAN oriented approaches centralize not only the control but also partial of the radio signal process in the network. Note that C-RAN, although not necessary to be implemented by the SDN approach, will definitely benefit from the SDN design.

SoftRAN is one of the early proposals under this approach [12]. It virtualizes the RAN into a single virtual BS, performing resource allocation, mobility, load balancing, and other control functions at a single place. The centralized control plane of the network takes advantage of full network knowledge for global optimization. To solve the latency problem, time-critical controls remain at the local BS.

A recent design proposed by Arslan et al. combines the centralized signal process in C-RAN and the programmable feature at the fronthaul [13]. The software-defined fronthauls (SDF) form a fronthaul network, where joint processed radio signals are forwarded to fronthauls by the centralized control. The control architecture is similar to SDN for Internet. The programmability in the fronthaul network allows practical fine timescale physical layer cooperation like CoMP. It provides potential for the fine-grained RAN optimization in extremely dense wireless networks.

C. Mobile edge oriented approaches

Mobile edge oriented approaches apply the SDN design at RAN. The need of this approach comes from the adaption of the air interface as well as the fine-grained radio function coordination in dense wireless networks. To adapt air interface behaviors to network conditions, Bianchi proposed the MAClet concept, which allows the central controller dynamically change the MAC process in air interfaces, e.g., from the contention based medium access to time-division multiple access [14]. The SDF proposed in [13] is also a mobile edge solution, which brings the programmability to the radio fronthaul. While more research is expected in this direction, we believe SDN principles will be widely applied in the radio architecture design of future wireless networks. This trend has been observed in ongoing major European 5G research projects.

In Europe the world's largest 5G research initiative, known as the Horizon 2020 5G-PPP Action, has been launched since July 2015. The purpose of this initiative is to lay the foundation of 5G mobile communication networks. Among 19 funded projects in the first phase of this initiative, the METIS-II project will focus on overall 5G RAN design, the 5G-NORMA project will dedicate to a novel radio adaptive network architecture, the COHERENT project will concentrate on the uniform control platform for heterogeneous RANs, the XHual and 5G-XHual project aim at developing adaptive and sharable 5G transport network solutions. These projects have special interests to investigate and implement the software-define mobile control in 5G RANs. We will see the SDMN design and development from them in the next three years.

VI. Standardization activities

While the standardization of SDMN is yet to come, the efforts from ONF, European Telecommunications Standards Institute (ETSI) and 3rd Generation Partnership Project (3GPP) are paving the way for the realization of SDMN.

ONF is the organization promoting and standardizing SDN and OpenFlow technologies. In 2014, ONF formed the Wireless and Mobile Working Group (WMWG) to extend ONF based SDN technologies to wireless and mobile domain. The current tasks in WMWG include defining the use cases, architectural and protocol requirements for the ONF extension to wireless backhaul networks, cellular CN, and other wireless access technologies. Three major use cases identified by WMWG are: wireless transport networks, cellular access networks, and enterprise networks.

In 2012, ETSI formed NFV industry specification group (ISG) to promote the IT virtualization technologies into the telecom industry. We have mentioned the NFV as the enabler for SDMN in Section II. Currently the NFV ISG has four working groups: infrastructure architecture, management and orchestration, software architecture, and reliability & availability; and two expert groups: security and performance & portability. NFV ISG is not a standards development organization, but it will be the main driving force for the standardization of NFV technologies.

The first discussion on 5G has been started in 3GPP since November 2014. The potential 5G study items were discussed in 3GPP Service and System Aspects (SA) technique specifications Group (TSG), in which the user perceived performance, business enabling capabilities, cost, operation and energy efficiency have been highlighted. Given the key requirements identified by 5G promotion groups and the research trend in the mobile industry, SDN is expected to receive the main attention in the radio network architecture design.

More information on standardization of SDMN can be found in [15] [10].

VII. Challenges and research directions

A. Architecture design

SDMN aims to provide programmable and unified control solutions for 5G networks. We believe network abstraction will be essential for the SDMN architecture design. For this, we need to build the theoretic foundation for network abstraction and derive control principles for SDMN. Firstly, spectrum sharing behaviors in mobile networks needs to abstracted for the high level coordination. Secondly, the abstraction should consider control operations with different time scales. This leads to the question of implementing certain control functions at local or central point. Thirdly, in the ideal case the SDN based control plane for SDMN should behave like an OS, where low layer implementations are encapsulated by abstraction and seen by the high level control plane through application programming interfaces (API). This creates a general programmable control framework cross different physical entities. Programmable control, combining with network virtualization, will enable very flexible control functions for different group of network entities or end users. It allows fast deployment of new control algorithms and services. To encapsulate the low layer implementation, the programmable SON will play an important role to handle the automation.

B. Advanced radio resource management

The decoupling of control and data plane in SDMN needs to consider different time scales in radio resource management. For instance, the frame scheduling in a BS will occur in milliseconds, while the spectrum assignment among small cells may change hourly according to busy hours. In small cell networks the control and data plane separation will certainly benefit the radio resource utilization in the network. However, radio resource management needs to carefully split at local or remote in order to match new network architecture. The first step is to model behaviors of the physical layer and the link layer so we can build an open yet accurate control framework for different RANs. For instance, for dynamic CoMP in SDMN, the high level control plane only needs to know which BSs are selected.

RAN sharing of mobile network operators adds a high requirement on radio resource management, because the network slicing to support RAN sharing does not simply mean the spectrum slicing, but the logic isolation of wireless resources. Spectrum sharing implies the spectrum access of different virtual mobile networks is coupled. The challenge is how to abstract spectrum sharing properly so that the high level of control framework is able to share radio resources among virtual networks, for guaranteed services.

C. E2E SDN solution

SDN solutions for RAN, mobile CN and Internet have different control targets. For RAN the main objective is to coordinate and control the radio resource; for mobile CN it is to orchestrate the packet processing for mobility, billing and service provisioning; for Internet the main target is for effective and efficient packet forwarding. Because of different control requirements, the integration of SDN in different network segments towards an E2E solution is extremely challenged. However, the demand is high as different services, especially time-critical services from vehicles or Internet of things, will be provisioned in the same network infrastructure. The key to enable E2E SDN solutions lies in the software oriented design. It requires a systematic, software oriented thinking to integrate different SDN solutions.

D. Network intelligence

Along with SON, network intelligence is important to support automation in SDMN. It will be embodied in multiple layers of the SDMN. In the physical and link layer, the cognitive radio may apply to improve spectrum sharing of SDMN. On the high level of the control framework, network intelligence, particularly, the deep learning and artificial intelligence, will find the place on predictive modeling, traffic prediction and dynamical configuration of network resources according to the learning from environment, traffic pattern from previously statistic traffic data, and even users' behaviors in the network access. The control framework should provide open interfaces to support network intelligence at different layers. It is also important to well evaluate the developed network intelligent methods to avoid the over-control of the networks.

VIII. Conclusion

The 5G development has been put on the schedule by the ICT industry around the world. Following the development history of previous mobile systems, in ten years we will see the deployment of 5G networks. The industry has achieved the consensus to redesign the radio network architecture for 5G. The software-defined design has been identified as the important evolution path for 5G networks. We summarized in this article the key research problems in SDMN. The current research shows open problems and the diversity of solutions. We believe SDMN will be the next big thing for the mobile industry. New thinking and more fundamental research are expected to consolidate the SDMN design and development.

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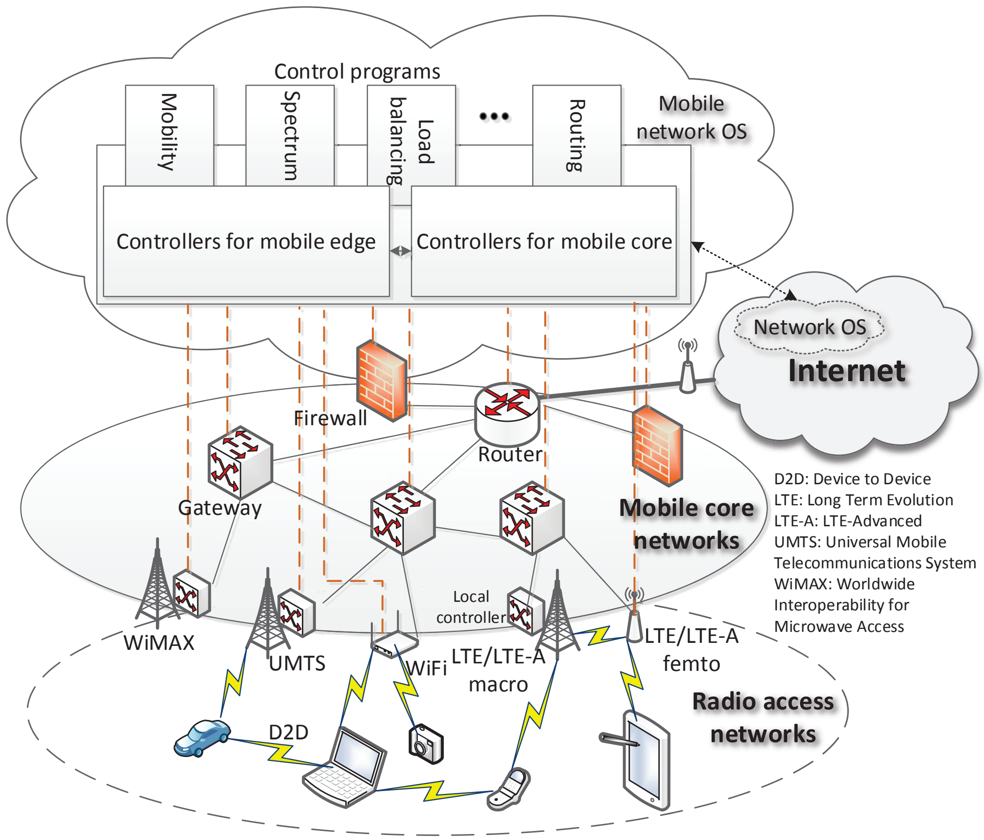
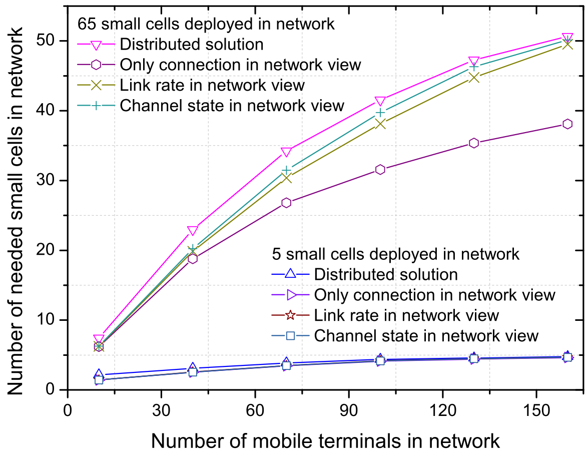


Fig. 1. Illustration of software-defined mobile network.



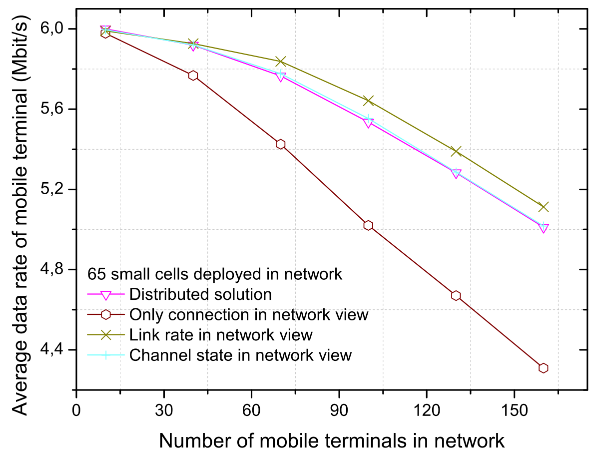


Fig. 2. Performance of network view for small cell network energy saving. In the network small cell BS and mobile terminals (MT) are ad-hoc deployed. MT has the date rate requirement. The objective is to find the smallest number of BSs to support MTs while other BSs go to sleep. In the distributed solution MT connects to nearest BS. In the network view approach three network views are evaluated: in the Connection Only case the network view only knows if a MT can connect to a BS; in the Link Rate case the interference-free link rate is known in the network view; in the Channel State case the average channel state of links is known in the network view.

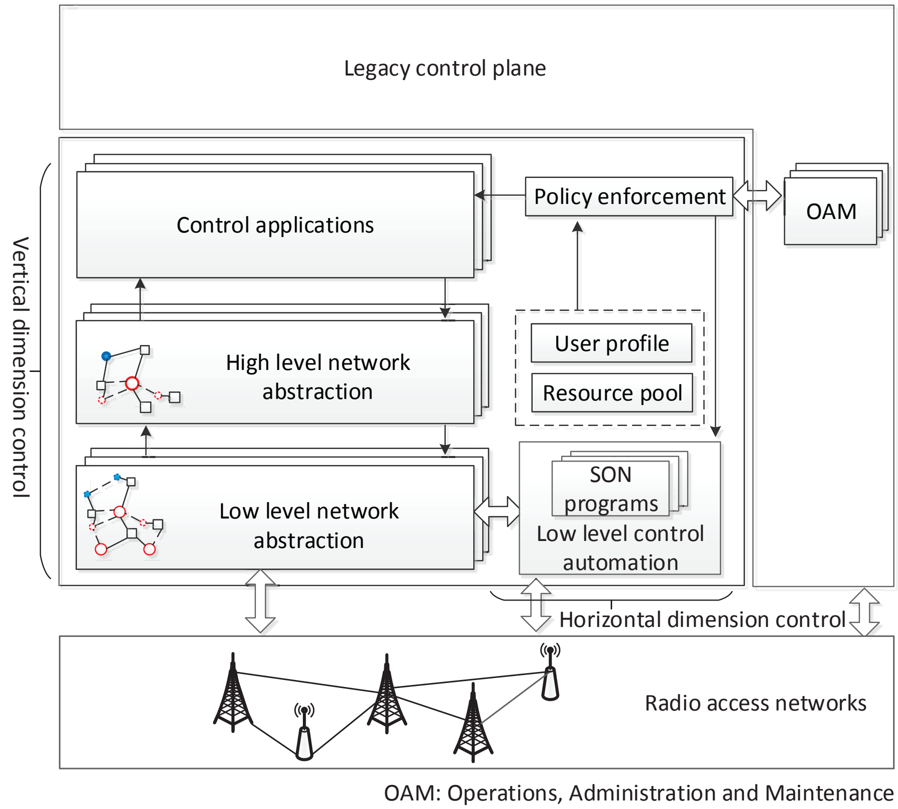


Fig. 3. Example of software-defined control architecture for mobile networks.

TABLE I
BENEFITS OF SDMN FOR SERVICE SUPPORT AND NETWORK FUNCTION IMPLEMENTATION.

	Software-defined design at RAN	**Software-defined design at CN**
E2E services	Network awareness to improve QoS, support services with network reality	Traffic steering, QoS support
Heterogeneous network integration	Open control interfaces, network awareness, joint network configuration	Traffic steering to improve network resource utilization
Spectrum management	High level spectrum provision, network awareness, facilitate SAS and LSA	Traffic load awareness for spectrum allocation
Mobility	Network awareness, resource reservation, mobility prediction	Logic centralized control, reduce mobility overhead
RAN cooperation	Programmable SON, open cooperation interface	Traffic steering to better support CoMP and other cooperative techniques

TABLE II
BUSINESS BENEFITS OF SDMN

Role	Cost structure related benefits	Revenue structure related benefits.
MNOs	Decreased CAPEX through easier RAN configuration and optimization; decreased OPEX through more efficient use of spectrum, energy and infrastructure	New connectivity and content services; context information (big data, user profile) services; Business to Business (B2B) commerce services related to sharing
Equipment vendors	Easier and faster integration of technologies and services	Flexibility to add new functionality/services
Content providers	OTT cooperation framework	Opportunities for providing network as a service locally
B2B end users	Customized control features	Easier and faster adoption and integration of new services
Business to consumer (B2C) end users	Seamless and smooth network experience, new services	Easier and faster adoption and integration of new services