Software defined mobile networks: Concept, survey, and research directions

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5 authors, including:

Marja Matinmikko
VTT Technical Research Centre of Finland

Xianfu Chen
VTT Technical Research Centre of Finland

Petri Ahokangas
University of Oulu

Software Defined Mobile Networks: Concept, Survey, and Research Directions

Tao Chen, Marja Matinmikko, Xianfu Chen, Xuan Zhou, and Petri Ahokangas

ABSTRACT

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

Tao Chen, Marja Matinmikko, and Xianfu Chen are with VTT Technical Research Centre of Finland.

Xuan Zhou is with Zhejiang University.

Petri Ahokangas is with Oulu Business School.

INTRODUCTION

After three decades of evolution, mobile networks are moving into the fifth generation (5G) [1]. In Europe, the 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 1 ms 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 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 (SDMNs) remains open, SDN for the Internet is widely used as the reference model for SDMN design. The essential ideas from SDN for the Internet are the decoupling of the data and control planes, and the use of logical centralized control to manage the forwarding problem in large scale networks. Clearly SDMNs will not be a simple extension of the SDN concept for the Internet, because the radio access in mobile networks is different from the routing in the Internet. Software-defined features in SDMNs shall satisfy specific needs of mobile networks.

The evolution of computer systems may give some hints on the design of SDMN. Nowadays computer systems have advanced to such a level that the performance of a smartphone 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 low-layer hardware implementation. The function abstraction and modular design of the computer system, along with the paradigm shift toward object-oriented programming, establish design principles to master the complexity in computer systems. Computer science was born to build the theoretic foundation that further guarantees the innovation and continuous evolution of computer systems.

The same trend fits the development of

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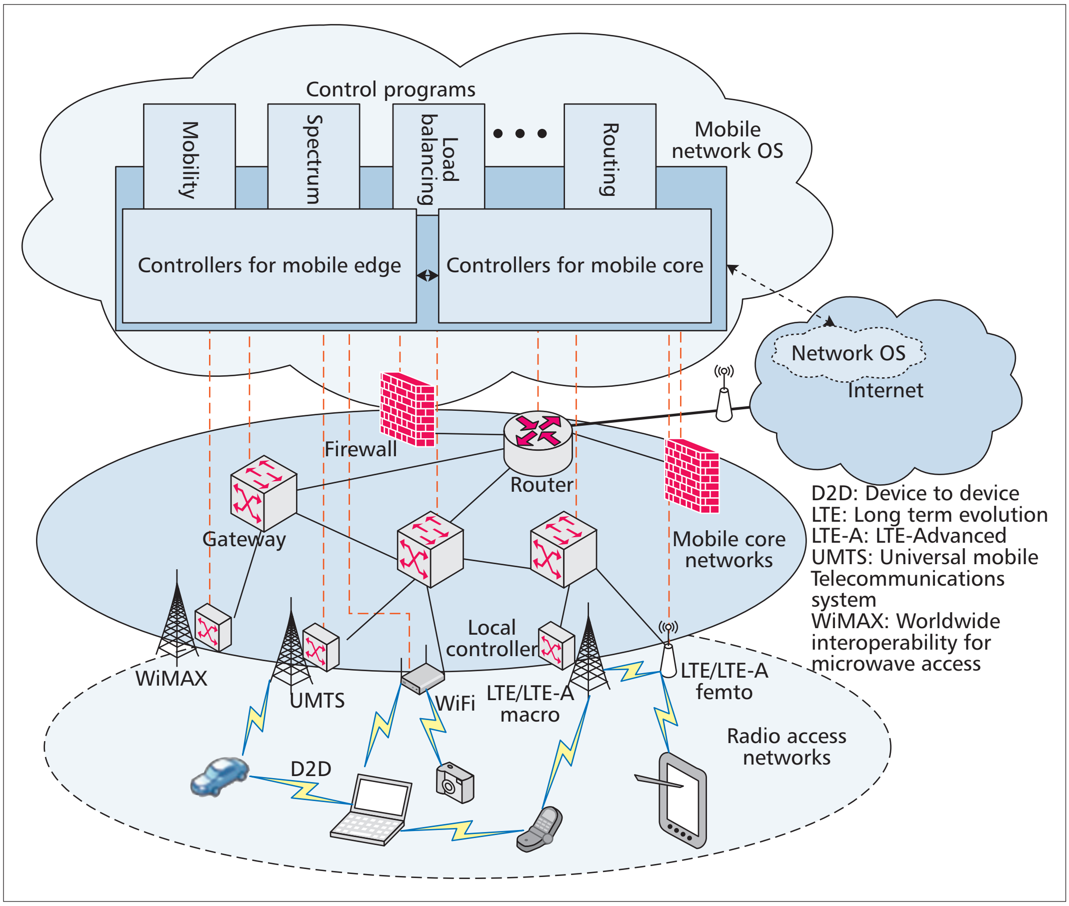

Figure 1. Illustration of software-defined mobile network.

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.

mobile communications. Interactions and complexity in current heterogeneous mobile networks (HMNs) are very similar to the early stages in the history of computer systems. We need to rethink the design of mobile networks. Referring to SDN design for the 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 (RANs) and mobile core networks (CNs), we focus the discussion on the RAN side. We start by listing the driving forces and enabling technologies for SDMNs. Following that, we examine fundamental problems in SDMNs, propose an SDMN concept, and briefly analyze the business impact of SDMNs. The current SDMN research is briefly surveyed. Finally, we identify several important research directions in SDMNs.

Driving Forces toward SDMN

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

Requirements of 5G networks

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

Flexible Spectrum Management

In 5G spectrum availability is one of the 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 is made available to mobile operators. To improve 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 SDMNs.

Key Enablers of SDMNs

Technical advances in SDN, network functions virtualization (NFV), cloud computing, and fog computing provide technical enablers for SDMN.

The origin of the SDN concept can be traced back to the 1990s. However, the SDN concept received global attention after the introduction of the OpenFlow concept in 2006. SDN technologies are promoted and standardized by the Open Network Foundation (ONF). So far it has more than 150 member companies.

SDN

The origin of the SDN concept can be traced back to the 1990s. However, the SDN concept received global attention after the introduction of the OpenFlow concept in 2006. SDN technologies are promoted and standardized by the Open Network Foundation (ONF). So far it has more than 150 member companies, and SDN enabled network devices are commercially available.

The success of SDN comes from the systematic abstraction of complex networking problems in the 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 planes, 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 rise to 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.

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 network functions (e.g., NAT, firewall, and load balancers) and implement them in industry standard high volume servers instead of proprietary hardware. A virtualized network function (VNF) can be run across 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 new architecture design to mobile networks.

Cloud Computing and Fog Computing

The development of SDN is tightly connected to cloud computing, since cloud computing makes large-scale logical centralized control solutions feasible. Cloud computing allows centralized data storage and processing, 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 of cloud computing is suitable for joint signal processing 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 a problem in meeting the strict latency requirements for fine timescale control functions in SDMNs. It is reasonable to move the logical centralized control close to the edge in mobile networks. Fog computing could fill this gap for better architecture design of SDMNs. Fog computing is a variant of the cloud computing concept [4] that uses the computer resources and storage at the edge of a network for a substantial amount of communication, storage, control, and configuration. In mobile networks, fog computing can be utilized for the control and joint signal processing at the RAN level to serve densely deployed cells, while cloud computing can be used for control in CNs for packet processing and forwarding. The integration of fog computing and cloud computing may lead to an end-to-end (E2E) SDN solution for mobile networks.

The SDMN Concept and Business Impact

Technique Aspects

The design of SDMNs for RANs 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 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) makes its own resource allocation decision with limited state information from others. The spectrum reuse in mobile networks calls for optimization and control across cell borders. However, current mobile networks have limited support for network-level coordination. It is beneficial to use the network view, as in SDN for the Internet, for optimal control and coordination in mobile networks. Considering that even in a single BS hundreds of parameters need to be tuned, the information presented in the high-level network view needs to be simplified. The design principles from OSs 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 on the proper abstraction of lower 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. Figure 2 shows a 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 cell 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 spectrum reuse, mobility, and traffic offloading. There is an increasing demand to configure network entities in RANs coherently, similar to those in SDN for the Internet. Network configuration needs to be done among coupled network entities by control algorithms based on the logical centralized control framework. To make it scalable, this high-level configuration should not go into detail on the lowwer-layer implementation. This means the network configuration only defines the preferred behaviors of lower layers. The behaviors are mapped to the configuration of lower layers through middleware. The new

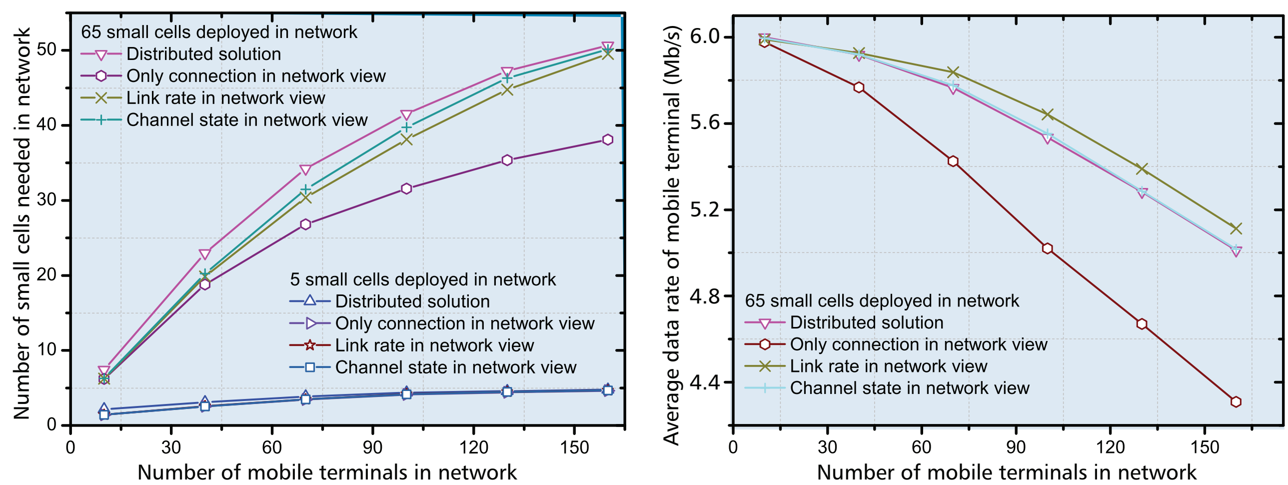

Figure 2. Performance of the network view for small cell network energy saving. In the network small cell BS and mobile terminals (MTs) are deployed ad hoc. MT has the date rate requirement. The objective is to find the smallest number of BSs to support MTs while other BSs go to sleep. In the distributed solution an MT connects to the nearest BS. In the network view approach three network views are evaluated: in the connection only case the network view only knows if an MT can connect to a BS; in the link tate 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.

network configuration approach needs deep understanding of network behaviors, especially cooperative behaviors, such as in coordinated multipoint (CoMP) transmission and inter-cell interference coordination (ICIC).

The third problem addresses fine-grained cooperation among different entities in the network, for instance, CoMP and enhanced ICIC in Long Term Evolution (LTE) networks. ICIC may require joint resource allocation and signal processing 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 fine-grained cooperation becomes a common feature in mobile networks, a 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 kinds 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 software-defined design will expand in mobile networks through two dimensions, as illustrated in Fig. 3. The vertical dimension handles coarse network coordination among cells and networks. The horizontal dimension targets fine-grained network cooperation among network entities. In the vertical direction, the common control requirements and functions need to be extracted from different mobile networks. The systematic abstraction and modularity of network functions will enable hierarchical control architecture, in which the high control layer controls lower layers through defining behaviors without the need to know their specific implementation. It will allow 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 fine-grained low-layer cooperation in the network.

Different from the software-defined design in CNs, software-defined features at the RAN side are focused on joint resource allocation, spectrum management, mobility, and cooperative functions among HMNs. The benefits of SDMN are highlighted in Table 1.

Business Aspects

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

Operators will be able to reduce capital expenditure (CAPEX) and time to deploy services, because new open control interfaces and 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 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 to market of their product and allow open innovation by embracing competition.

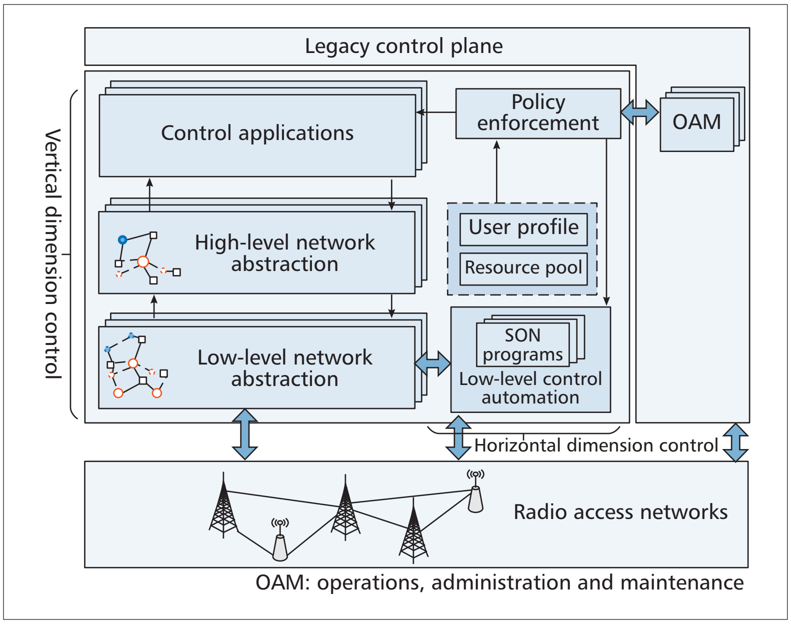

Figure 3. Example of software-defined control architecture for mobile networks.

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

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

The benefits of SDMNs for different business players is summarized in Table 2.

Current Research

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

SDN-Oriented Approaches

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

OpenRoad is a very early study on this topic [5]. It is a mobile version of SDN that uses OpenFlow for control, FlowVisor for network slicing, and NOX as the network operation system to support programmable control in WiFi and WiMAX networks. OpenRoad allows different control algorithms to concurrently run 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 MNOs to 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 the CN. The centralized controller and the flow concept allow the previously centralized packet processing in CNs 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 CNs of LTE networks and moves core control functions in CN to the cloud for reliability and scalability. A similar idea was 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.

Furthermore, an SDN-based plastic architecture was introduced for 5G networks [11], with the aim to support a heterogeneous set of services with flexibility. It introduces a clean-slate data plane design, and the SDN controllers at three levels: device, mobile edge, and CN, respectively. This design avoids the use of tunnel protocols for mobility and allows backward compatibility with 4G networks.

C-RAN-Oriented Approaches

C-RAN-oriented approaches centralize not only the control but also part of the radio signal processing in the network. Note that C-RAN, although it does not need to be implemented by the SDN approach, will definitely benefit from 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 in 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 processing in C-RAN and the programmable feature at the fronthaul [13]. Software-defined fronthauls (SDFs) form a fronthaul network, where jointly processed radio signals are forwarded to fronthauls by the centralized control. The control architecture is similar to SDN for the Internet. The programmability in the fronthaul network allows practical fine timescale physical layer cooperation like CoMP. It provides potential for fine-grained RAN optimization in extremely dense wireless networks.

Mobile-Edge-Oriented Approaches

Mobile-edge-oriented approaches apply SDN design at the RAN. The need for this approach comes from the adaptation of the air interface as

	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 1. Benefits of SDMN for service support and network function implementation.

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

Table 2. Business benefits of SDMN.

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 to dynamically change the MAC process in air interfaces (e.g., from contention-based medium access to time-division multiple access) [14]. The SDF proposed in [13] is also a mobile edge solution that brings 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 Initiative, was launched in July 2015. The purpose of this initiative is to lay the foundation for 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 be dedicated to a novel radio adaptive network architecture, the COHERENT project will concentrate on a uniform control platform for heterogeneous RANs, and the XHual and 5G-XHual projects aim to develop adaptive and sharable 5G transport network solutions. These projects have special interests to investigate and implement software-defined mobile control in 5G RANs. We will see the SDMN design and development from them over the next three years.

Standardization Activities

While the standardization of SDMN has yet to come, the efforts from the Open Networking Foundation (ONF), European Telecommunications Standards Institute (ETSI), and Third Generation Partnership Project (3GPP) are paving the way for the realization of SDMNs.

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 the wireless and mobile domain. The current tasks in WMWG include defining the use cases, and architectural and protocol requirements for the ONF extension to wireless backhaul networks, cellular CNs, 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 the NFV Industry Specification Group (ISG) to promote the IT virtualization technologies in the telecom industry. We have mentioned NFV as an enabler for

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.

SDMNs earlier. Currently, the NFV ISG has four working groups: infrastructure architecture, management and orchestration, software architecture, and reliability and availability; and two expert groups: security and performance, and portability. NFV ISG is not a standards development organization, but will be the main driving force for the standardization of NFV technologies.

The first discussion on 5G was started in 3GPP in 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 were 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 SDMNs can be found in [10, 15].

Challenges and Research Directions

Architecture Design

The 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 theoretical foundation for network abstraction and derive control principles for SDMNs. First, spectrum sharing behaviors in mobile networks need to be abstracted for high-level coordination. Second, the abstraction should consider control operations with different timescales. This leads to the question of implementing certain control functions at local or central points. Third, in the ideal case the SDN-based control plane for SDMNs 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 across different physical entities. Programmable control combined with network virtualization will enable very flexible control functions for different groups 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 in handling the automation.

Advanced Radio Resource Management

The decoupling of the control and data planes in SDMNs needs to consider different timescales 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 be split locally or remotely in order to match new network architecture. The first step is to model behaviors of the physical and link layers so that we can build an open but accurate control framework for different RANs. For instance, for dynamic CoMP in SDMNs, the high-level control plane only needs to know which BSs are selected.

RAN sharing of mobile network operators adds a huge requirement on radio resource management, because the network slicing to support RAN sharing does not simply mean spectrum slicing, but also the logical isolation of wireless resources. Spectrum sharing implies that 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 the control framework is able to share radio resources among virtual networks for guaranteed services.

E2E SDN Solution

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

Network Intelligence

Along with SONs, network intelligence is important to support automation in SDMNs. It will be embodied in multiple layers of SDMNs. In the physical and link layer, cognitive radio may apply to improve spectrum sharing of SDMNs. At 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 dynamic configuration of network resources according to learning from the environment, traffic patterns from previous traffic data statistics, and even users' behaviors in network access. The control framework should provide open interfaces to support network intelligence at different layers. It is also important to thoroughly evaluate the developed network intelligent methods to avoid over-control of networks.

Conclusion

5G development has been put on the schedule of the ICT industry around the world. Following the development history of previous mobile systems, in 10 years we will see the deployment of 5G networks. The industry has achieved consensus to redesign the radio network architecture for 5G. Software-defined design has been identified as an important evolution path for 5G networks. In this article, we summarize the key research problems in SDMNs. The current research shows open problems and the diversity of solutions. We believe SDMNs will be the next big thing for the mobile industry. New thinking and more fundamental research are expected to consolidate SDMN design and development.

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Biographies

Tao Chen [S'05, M'10, SM'13] (tao.chen@vtt.fi) received his B.E. degree from Beijing University of Posts and Telecommunications, China, in 1996, and his Ph.D. degree from the University of Trento, Italy, in 2007, both in telecommunications engineering. He is currently a senior researcher at VTT Technical Research Centre of Finland. He is the project coordinator of the EU H2020 5G-PPP COHERENT project. His current research interests include software defined networking for 5G mobile networks, dynamic spectrum access, energy efficiency and resource management in heterogeneous wireless networks, and social-aware mobile networks.

Marja Matinmikko (marja.matinmikko@vtt.fi) is a senior scientist at VTT Technical Research Centre of Finland. She received her M.Sc. degree in industrial engineering and management, and her Dr.Sc. degree in telecommunication engineering from the University of Oulu. She is the coordinator of the Finnish project consortium on Cognitive Radio Trial Environments (CORE). Her current research interests include technical, trialing, regulatory, and business aspects of spectrum sharing for mobile communications.

Xianfu Chen received his Ph.D. degree from Zhejiang University, Hangzhou, China, in 2012. He is currently a senior scientist at VTT Technical Research Centre of Finland Ltd., Oulu. His research interests cover various aspects of wireless communications and networking, with emphasis on software-defined radio access networks, green communications, centralized and decentralized resource allocation, and the application of artificial intelligence to wireless communications.

Xuan Zhou received his Ph.D. in communication and information systems from Zhejiang University. From 2009 to 2014, he worked as a system engineer in China Mobile Zhejiang Company. Since 2014, he has been a solution architect in the Service Provider Operation Lab (SPO Lab) of Huawei Technologies. His research efforts focus on innovative service scenarios in 5G and NFV/SDN.

Petri Ahokangas (petri.ahokangas@oulu.fi) received his M.Sc. (1992) and D.Sc. (1998) degrees from the University Vaasa, Finland. He is currently adjunct professor and senior research fellow at Martti Ahtisaari Institute, Oulu Business School at the University of Oulu. His research interests are in how innovation and technological change affect international business creation, transformation, and strategies in highly technology-intensive or software-intensive business domains. He has 80+ publications in scientific journals, books, conference proceedings, and other publications. He is actively working in several ICT-focused research consortia leading business-related research streams.

Following the development history of previous mobile systems, in 10 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.