Challenges to Support Edge-as-a-Service

Steven Davy, Waterford Institute of Technology
Jeroen Famaey, Ghent University — iMinds
Joan Serrat and Juan Luis Gorricho, Universitat Politecnica de Catalunyna
Avi Miron, Technion
Manos Dramitinos, Athens University of Economics and Business Research Center
Pedro Miguel Neves, Portugal Telecom Inovacao SA
Steven Latré, University of Antwerp — iMinds
Ezer Goshen, BandWD

ABSTRACT

A new era in telecommunications is emerging. Virtualized networking functions and resources will offer network operators a way to shift the balance of expenditure from capital to operational, opening up networks to new and innovative services. This article introduces the concept of edge as a service (EaaS), a means of harnessing the flexibility of virtualized network functions and resources to enable network operators to break the tightly coupled relationship they have with their infrastructure and enable more effective ways of generating revenue. To achieve this vision, we envisage a virtualized service access interface that can be used to programmatically alter access network functions and resources available to service providers in an elastic fashion. EaaS has many technically and economically difficult challenges that must be addressed before it can become a reality; the main challenges are summarized in this article.

INTRODUCTION

The current networking landscape locks network operators into a traditional business model wherein deployment of a dedicated access network is a prerequisite. This has resulted in staggering costs and stagnation of the traditional telecommunications business; as a consequence, much of the innovation is happening "over the top." The increasing demand for higher-capacity broadband networks is urging the rapid deployment of multiple types of access networks across the world, often consisting of completely new technology solutions. Network operators are beginning to modernize their infrastructure but need to be able to effectively keep capital expenditure (CAPEX) and operational expenditure (OPEX) under control, in particular when faced with falling average revenues per user (ARPU). This is proving to be a difficult challenge, primarily due to current competition models for network operators. They offer extensive standalone infrastructures in an effort to keep up with the demand, but with little or no incentive to differentiate their services. Current structures also lock them down in a race-to-the-bottom competition, offering ever more bandwidth for lower returns on investment and with few options to drastically lower CAPEX and OPEX.

There is an opportunity for network operators to "open up" secure and limited access to their networks through the use of network function virtualization [1, 2] and network resource virtualization [3, 4]. Network virtualization is the process of multiplexing physical network resources to appear as dedicated networks with particular dynamic properties such as on-demand growth in capacity and size, flexible provisioning of new routes, new endpoints, and new address schemes. When coupled with network programmability [5, 6], new network functions and services can be deployed into the virtual networks to support more adaptive delivery of services to network users.

The concept of leveraging network virtualization to facilitate the flexible usage of access network resources is called "edge as a service." This term has connotations with infrastructure as a service and platform as a service. Effectively, it involves applying concepts of cloud computing directly into access networks. Access network resources, such as base stations, radio network controllers, digital subscriber line access multiplexers (DSLAMs), and even wireless access points, are the points in the network in closest attachment to the network end users. EaaS enables the flexible sharing of these resources among interested service providers, where they can make use of network programmability to distribute service enabling functionality (content caching, multiplexing, or other data plane processing), and whereby they can make use of network virtualization to request or relinquish resources based on service demand.

There are a number of difficult challenges related to the full realization of the EaaS concept, and we present a detailed analysis of these challenges in this article. The challenges can be classified as technical, including the large-scale virtualization of heterogeneous access network resources and functions; and economical, including how best to predict service demand and proactively adapt service price and quality. We present the current state of the telecommunications sectors and outline some of the current practices in use today to alleviate escalating network costs. We propose that a new type of network interface can be used to offer a solution to network providers. A scenario is outlined. We present a series of technical and socio-economic challenges that must be researched to aid in realizing EaaS, and these are discussed with respect to the state of the art. Finally, conclusions are presented later.

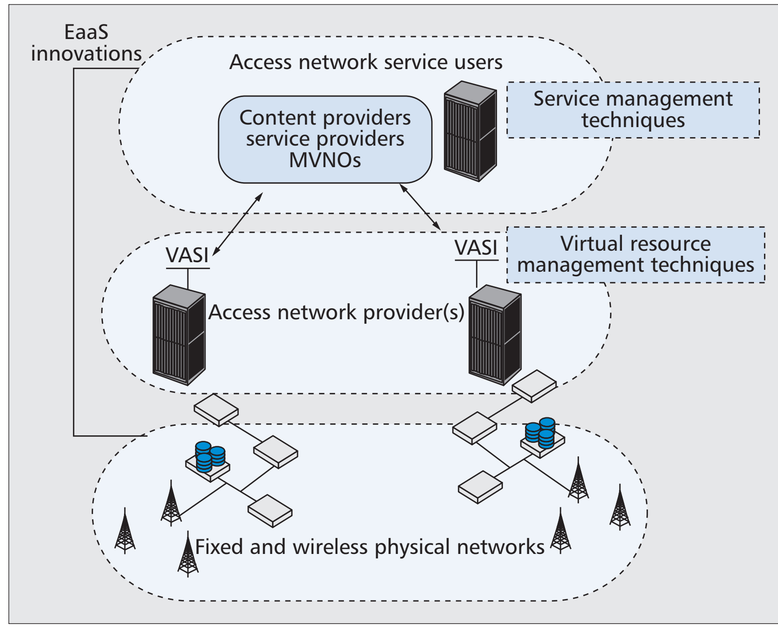

Figure 1. *The Virtual Access Service Interface (VASI) can be used by content / service providers to request customization of resources deep in network providers access networks. It is supported by advanced usage of network virtualization and network programmability.*

TELECOMMUNICATIONS STATE OF PLAY

The access network is the most expensive part of an operator's network and often comprises many different types of network equipment. This may include equipment to support cable modems, DSL broadband, third and fourth generation (3G and 4G) mobile broadband, WiFi, and increasingly, optical network equipment to support fiber to the home. Crucially, network operators that seek to offer mixed infrastructure, need to deploy multiple types of access network technologies, which is very costly and promotes inefficiency.

It is widely accepted that improving national and international Internet infrastructure will have a profoundly positive socio-economic impact.[1] The costs associated to these infrastructures are massive, and regulators are looking for ways to bring some stability to the situation. Specifically in Europe, recommendations on open access to next generation access networks[2] are promoting the concepts of network sharing, and is encouraging incumbent network operators to open up their networks for new entrants. However, there is currently no leading technical solution to these recommendations.

A recent study[3] highlights that there are several short-term fixes that can help network operators control the cost of new network deployments, these include data offloading to WiFi from Long Term Evolution (LTE), introducing more constrained data download capacities on users, more comprehensive traffic shaping through the use of deep packet inspection (DPI) and introducing caching of content at the edge of networks. However, these short-term fixes are not sustainable into the future, and only innovation at the business level will allow network operators to maintain sustainable revenues. The EaaS concept not only supports the short-term fixes, but introduces a new and innovative approach to reverse the trend of increasing CAPEX and OPEX. This is through the opening up and sharing of access network resources in a secure, intelligent, and targeted way.

Current network sharing practices, such as those adopted by mobile virtual network operators (MVNOs) are based on long-term and rigid contractual agreements, which are both inflexible and time consuming to arrange. The MVNO model is beneficial for incumbent network operators as it promotes an increase in network revenue and a reduction in network costs.

We firmly believe that the EaaS concept can bring significant stability and innovation to the telecommunications market. We also see that the current MVNO models are too restrictive, based primarily on resale of network minutes and data. With EaaS, one can develop new ways for third parties to leverage the resources of large network operators and ultimately provide higher value to the end users.

A NEW NETWORK INTERFACE

To realize the concept of EaaS, network operators need to be able to offer customized portions of their networks to services providers, and also a way to enable the further customization of the network as new services are deployed and demand changes. This new network interface will be used by service providers to request limited access to a virtualized network segment that can support advanced per-node customization. For example, a video on demand service provider may request a virtualized network connecting to its customers, and can deploy custom logic to enable content caching right in the access network nodes, it can support the provisioning of multicast trees close to customers, it can also support the proactive triggering of network access handover for its customers. The virtualized network slice provisioned to the service provider can also react to service demand, accumulating more resources in the access network should the service become more popular.

The new network interface, if supported by

[1] *A Study on Socio-Economic Impact of Bandwidth, http://ec.europa.eu/digital-agenda/en/news/study-socio-economic-impact-bandwidth-smart-20100033, 2013.*

[2] *Commission Recommendation of 20 September 2010 on regulated access to Next Generation Access Networks (NGA)*

[3] *Wireless Technology: Breaking the Limits of the TCO Reduction in Mobile Networks, Frost & Sullivan, 2011.*

A pay-as-you-use billing model towards the ANSU can be very suitable to Big Events. There is a low overhead involved in setting up the service, and so, it can prove to encourage innovation in the delivery of these types of services in the future.

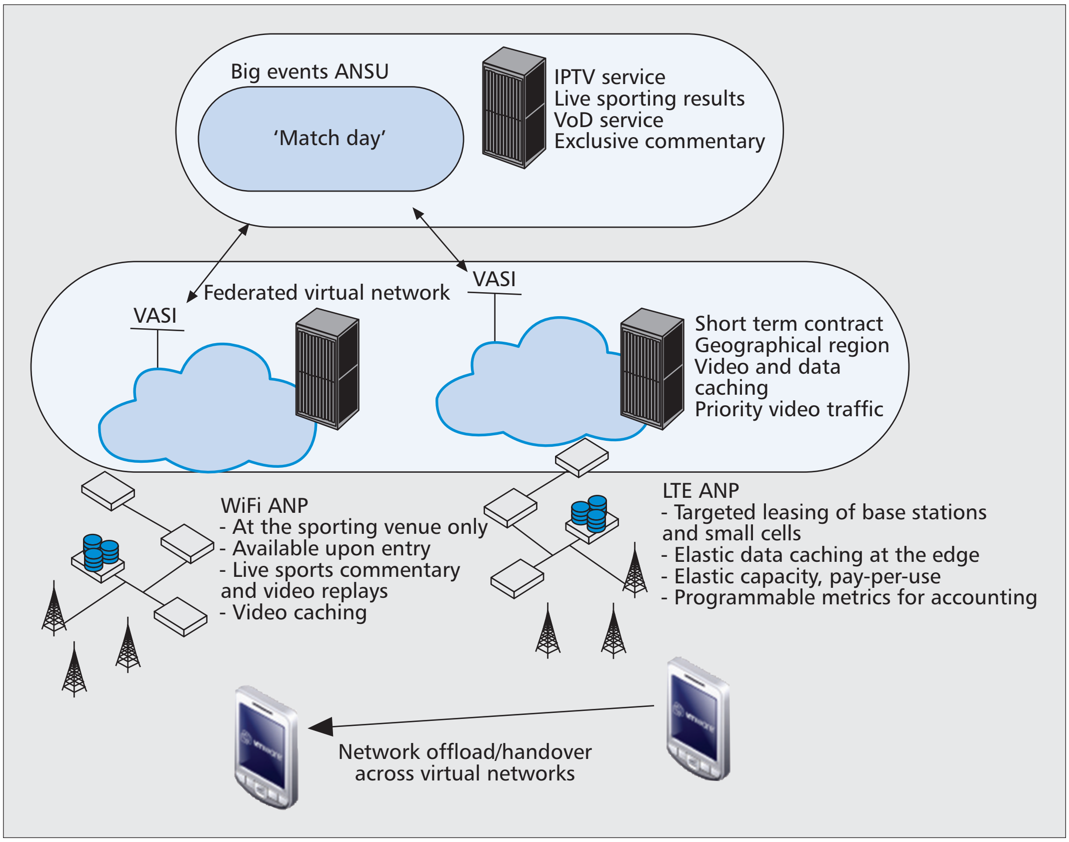

Figure 2. *Big Events MVNO seeks to make use of many network providers to deploy a specialized service to its customers. The service requires features, such as very low latency, that can only be guaranteed by making use of a network operator's provided application programming interface (API).*

many network operators, can be used to federate many networks together so that service providers can build a distributed array of virtual network resources and functions that are all orchestrated to support a service with fluctuating demand. In Fig. 1 we show the potential usage of a new network interface called the virtual access service interface, or VASI.

SCENARIO

In this section we present a realistic usage of the VASI to realize a new type of service which truly illustrates the benefits of EaaS. A new MVNO called *Big Events* (Fig. 2), targets a niche market of sports enthusiasts. For a one-time fee, the MVNO will allow customers to access its value added service called "Match Day" which offers its customers exclusive access network based services. Users can receive

- Guaranteed data rates at the venue
- Streamed live action replays to their mobile handsets
- Exclusive access to real-time sports results and commentary
- Low cost video calls to other customers of the service

To create this service, *Big Events* must compose and federate resources available from two different network operators. *Big Events* acts as an access network service user (ANSU) and will access the resources of access network providers (ANPs). Specifically, *Big Events* federates the resources of a national LTE ANP and a venue-based WiFi ANP. The same service is available for end users from both providers, and includes automatic and seamless handover for customers at the sporting event venue. The "Match Day" service is only available on the day of the sporting event, and depending on the event, may have varying demand.

The new VASI is available from each ANP and is used by *Big Events*' service management system to programmatically plan and reserve virtualized access network resources to sustain the service for customers. It will involve the creation of a virtual network, where content caching and data metering will be enabled into each access network operators' infrastructure. Through content caching and distributed service accounting, there is minimal transit IP traffic, and as much traffic as possible is maintained within each of the ANPs' networks, thus minimizing network load. Also, the service popularity will impact how much resources each ANP must make available for use by the service's customers.

Notably, a pay-as-you-use billing model toward the ANSU can be very suitable to *Big Events*. There is a low overhead involved in setting up the service, so, it can prove to encourage innovation in the delivery of these types of services in the future. We now analyze the key advantages over current approaches and highlight what is not possible in today's state of the art.

Elastic Usage of Access Network Resources

The scenario highlights how an ANP (fixed, wireless, or a combination) can offer access to its resources in a manner that can be requested on demand, much like in the infrastructure as a service model of cloud computing. However, unlike cloud computing, this scenario would enable active sharing of resources at peak times, and the programmatic placement of access network resources, such as content caching and data plane processing. During times of peak usage, the Access Network Provider can dedicate portions of its resources to favor higher paying service users such as *Big Events*, therefore offering more incentives for such services. The scenario also supports many new innovative business models where time/location sensitive data can aid in deciding how resources should be shared. For example, the "Match Day" service takes advantage of service provider policies to perform proactive handovers when in the proximity of federated WiFi access networks.

Delivery of High-Quality Services Directly Provisioned from a Content Provider or Over the Top Provider

The scenario shows how value added services can be directly offered by a content provider who would typically rely on best effort, over the top network access. This way, the content provider has the capability to directly purchase network access resources, and they can offer differentiated levels of content quality to end users. In the scenario, video content of action replays is cached into the virtualized access networks, only taking up storage close to customers of the service, but can be used to offer very high definition video with low latency and lower overall network utilization.

Diversification of Revenue Generation for Access Network Providers

The scenario illustrates the benefits that may be achieved by access network providers, who have a pre-existing deployment of multiple access network technologies. They should be able to substantially increase overall network revenue by making it much easier to offer secure and managed access to selected parts of their access networks to:
- Other network operators
- Content providers
- Brands, all playing the role of access network service users, similarly to such as niche markets as is the case of *Big Events*

Also, network operators can reduce the total cost of ownership of new infrastructure projects by leveraging network sharing that encompasses data offloading.

Challenges beyond State of the Art

This section highlights the state of the art and future challenges related to realizing the concepts of EaaS. We also capture a set of new research directions in each research field analyzed.

Challenges for Network Virtualization

Network virtualization [3] is currently being viewed as a flexible means for which network operators can cope with the growing demand for high-bandwidth diverse services and network efficiency across their networks. Current approaches to network virtualization in Internet service provider (ISP) [7] networks are lacking flexibility and also lack the ability to incorporate the virtualization of a wider set of network resources than just connectivity, such as caching, storage, and data plane processing. Layer 2 and 3 (virtual private network) approaches only abstract the actual data forwarding and do not consider flexible resource elasticity, caching of content, dynamic topology optimization, or programmable data plane processing to support load balancing, multicasting, specific application needs, or more fine-grained access control. More sophisticated techniques, including OverQOS and service overlay network (SON) [8], enable an ISP to request services that constitute a virtual network designed for a particular static class of traffic. Recently, VXLAN, a technology that tries to overcome the inflexibility of Ethernet based virtual LAN (VLAN), is being developed and led by VMWare. This technology is primarily targeted to support the virtualization of large numbers of overlapping virtual network topologies in data center environments.

Network operators are also investigating the use of network virtualization in an effort to improve the flexibility of their networks. Specifically, the Telco Cloud initiative as followed by the FP7 funded Mobile Cloud Networking project describes the transformation of the network operators' infrastructure toward a cloud-computing infrastructure, where applications can be hosted in the operator's network, along with telecommunications-specific network management and control systems. These systems would traditionally be run on dedicated and expensive hardware, and thus offers a great potential to reduce the capital and operational expenditure of network operators. That approach is more focused on reducing the cost of capital expenditure for network operators by enabling more functionality to be pushed to commodity hardware in a cloud. However, it is not focused on leveraging an interface to be designed for and used by service providers to dynamically make use of access network resources.

Current approaches to network virtualization do not go far enough, and EaaS solutions will require the virtualization of many more comprehensive forms of resources. Fixed and wireless access networks are tailored for vastly different access scenarios. A common resource model abstracting these networks to support effective resource virtualization does not currently exist; however, each technology is defined in the appropriate standards bodies.

Fixed and wireless access networks are tailored for vastly different access scenarios. A common resource model abstracting these networks to support effective resource virtualization does not currently exist; however, each technology is defined in the appropriate standards bodies.

New Directions in Network Virtualization —
- New techniques to support the virtualization of access network resources and systems

Much like with cloud computing, the EaaS concept enables service providers to make use of virtualization to programmatically build a dedicated and elastic virtual network, tailored to reach its customers, with agreed quality of service and access to other virtualized access network resources such as caches, storage, and data plane processing.

that consider the requirements of dynamic and on-demand resource pooling, virtualization of data plane processing and caching, and virtualization of heterogeneous access network technologies
- A comprehensive virtual network resource model that can consider the majority of currently deployed access network technologies and coupled systems, including Cable, xDSL, FTTx, Satellite, 3G/4G, Wifi and WiMax
- A virtual access network resource management system that can mediate requests for resources from many external clients, and can monitor current usage of leased resources for clients
- Dynamic spectrum allocation based on access network technology demand in geographical regions

Challenges for Network Programmability

Network programmability is not a new concept and has its origin in active networks research [9], where it describes the application of customized processing by routers and switches on packets that flow through the network. OpenFlow [6] is a networking technology that enables a logically centralized controller to configure per flow forwarding rules into OpenFlow enabled devices. The openness of OpenFlow coupled with the ease of adoption has ignited the use of network programmability in solving many difficult networking challenges, specifically seen in data centers and more recently in large ISP networks.

OpenFlow is also a possible enabler for network virtualization, where a system called FlowVisor [10] has been shown to enable strong network isolation for multiple virtual networks sharing the same physical resources. However, as argued by Sonkoly *et al.* [5], FlowVisor does not programmatically manage the distribution of resources across many virtual network slices. They also argue that a more comprehensive solution to the management of the OpenFlow controllers in a more coordinated fashion is required for any large-scale deployment of virtual networks.

Openflow is also seen as a very attractive technology for large network operators to support more advanced network traffic management features. Philip *et al.* [7] explored the use of OpenFlow to realize e-NodeB virtualization in 3G access networks. Their work aimed to increase the ability of network operators to use others' network infrastructure to serve end users, with minimal impact on users. Software defined networking (SDN) is being explored by network operators to help streamline their network infrastructures and reduce excessive network packet processing. SDN, and network programmability in general, can be used to selectively place key data plane processing elements throughout the access network to help reduce the load of key centralized network components that may be suitable to realize EaaS features in operators' networks.

One of the major advantages of being able to control the flow of mobile data in the access network is to improve the utilization of caching of video data, and to enable more effective usage of elastic resources, as we see in the next section.

***New Directions in Network Programmability* —**
- A network programmability solution that can support the separation of control plane from data plane processing in access networks. These are typically centralized in current access networks, and should support lower control overhead which users are roaming on EaaS.
- A framework to support the coordination of distributed network controllers across multiple access networks that can mediate contention for resources and ensure secure isolation of resources while abiding by business driven objectives.
- Network programmability principles that include data plane processing, such as load balancing, accounting, and multicast that do not exist in current SDN standards such as OpenFlow, which will be specifically tailored for use in virtualized access networks.
- More intelligent control over the flow of mobile data across the access network to help cope with peaks in demand for resources

Challenges for Elastic and On-Demand Service Management

Cloud computing has dramatically transformed the way services are delivered over the Internet today. Much like with cloud computing, the EaaS concept enables service providers to make use of virtualization to programmatically build a dedicated and elastic virtual network, tailored to reach its customers, with agreed quality of service and access to other virtualized access network resources such as caches, storage, and data plane processing. To achieve this, there is a need for dynamic and programmable algorithms capable of provisioning virtual access resources in face of changing requirements and characteristics of services and users, as well as operating environments. Additionally, there is a need for methods and models that predict changes in resource demands, allowing the system to proactively provision the necessary resources, avoiding temporarily suboptimal behavior.

The virtual network embedding (VNE) [11] problem is concerned with mapping virtual network topologies and resources onto the physical substrate. Its fundamental goal is to maximize the number of admitted virtual network requests. Virtual network embedding can be classified based on several characteristics such as static vs. dynamic and centralized vs. distributed. Most algorithms proposed to date are static and centralized. This means that they cannot cope with service, user, and network dynamics, and require full knowledge of the entire physical network topology. Such algorithms are obviously useless in a large-scale scenario spanning multiple physical networks, where virtual resource provisioning should scale elastically. EaaS would require dynamic and distributed VNE algorithms, capable of handling the federation of virtual networks spanning multiple network domains.

Predicting service demand based on service usage patterns can help to proactively manage virtual resource placements. Time series analysis has previously been applied to this problem, with the assistance of artificial neural networks and reservoir computing. Additionally, some research has focused specifically on popularity prediction of multimedia content. These works typically identify correlations between specific video characteristics and future popularity. Famaey *et al.* [12] found that analytical models can be used to predict the distribution associated with specific popularity of video contents. These problems are highly relevant to the EaaS problem space, as mobile users access higher volumes of mobile data and video content.

User mobility prediction is important to future service providers as they can tailor the distribution of resources to proactively meet expected user demand, a feature inherent with EaaS. In EaaS, the main interest lies in the behavior of the aggregated users' mobility and its predictability; this way, it would be possible to anticipate the geographical distribution of the connectivity demand over time. EaaS will need to make use of algorithms that not only consider the present virtual network requests, but also those requests more probable to come up in the short term, consequently achieving a better long-term distribution of resources.

New Directions for Elastic and On-Demand Service Management —

- Virtual network embedding algorithms that operate in a dynamic (i.e., elastic) and distributed fashion, capable of handling federated virtual access networks spanning multiple physical infrastructures.
- Virtual network embedding algorithms that can embed large-scale service requests that consider a wider set of high-level virtualized network resources (e.g., content caches or computing resources) into federated virtualized access networks.
- Techniques to maintain and dynamically grow/shrink virtual networks as a function of business objectives, service demand and user mobility patterns. This will be achieved using heuristic-based online algorithms that can meet strict timing deadlines but trade-off against suboptimal solutions.
- Generic techniques to efficiently redistribute virtualized network resources based on pro-active prediction of user demand based on examining service usage history.

Challenges for Network Sharing and Agreements

Regarding the market, the most related business models are those of MVNOs. Depending on the MVNO value proposition, they may require fine-grained access to network resources, such as bandwidth provisioning and QoS, or very coarse access, such as just billing of data usage. In either case, the MVNO is today highly restricted in how it can access network providers' resources. The EaaS proposition is to dramatically improve MVNO access and usage of resources on a wide range of granularity and with the ability to have rich business models that can harness a range of virtualized access network resources. Although the MVNO is not the only customer of EaaS we envisage, we do consider that they will be among the first adopters of the EaaS solutions.

MVNOs' access to network operators resources has been improved with the emergence of the Third Generation Partnership Project (3GPP) [13], where a recent study reveals that the use of policy within 3GPP, and visiting network components enable some more functionality for the MVNO. However, such techniques have not been explored, and will inherit the problems being faced by current network operators. EaaS asserts that a new network interface should be made available, the virtual access service interface, which will offer a lot more flexibility to MVNOs.

Network function virtualization [1] is an emerging concept that is being investigated by telecommunications network operators as a means to significantly reduce their dependence on expensive telecoms network equipment, while taking advantage of cloud computing concepts for service hosting and delivery. The concept should enable a more comprehensive range of features in the future for MVNOs to take advantage of, including the full range of cloud computing features, but in an operator's network. However, current initiatives are not focused on defining an interface that is readily accessible to third parties such as the MVNO, and only seek to support current interfaces supported by cloud computing initiatives.

Besides the MVNO, current mobile network operators need to be able to effectively collaborate in an effort to reduce the cost of deploying new infrastructure projects. Network sharing aims to:

- Share construction costs
- Potentially share network access

EaaS aims to define a flexible solution for network sharing that can accommodate a wide range of use cases and to promote the wider scale deployment of small cells as a means to share network access and reduce network operators' costs. Current network sharing solutions are proprietary but are starting to show major benefits for some network operators, be it in more resilient back-haul links or dramatic reductions in network costs. Other approaches to enabling a finer grained access to control network resources are often seen from the end user perspective, where mobile applications running on the users handset can issue network directed APIs to request better services [2]. This is not a scalable approach due primarily to the scale of network state that would need to be maintained.

New Directions for Network Sharing and Agreements —

- A VASI that can be used to request the usage of complex "virtualized access network resources" on a large scale
- Analysis and consistency checking of access network provider management policy sets, deployed to guide the operation and management of virtualized access networks
- New network sharing frameworks that can operate at varying degrees of granularity

EaaS aims to define a flexible solution for network sharing that can accommodate a wide range of use cases and to promote the wider-scale deployment of small cells as a means to share network access and reduce network operators' costs.

Through the development of a new novel network interface, virtual networks and functions can be requested on demand to support the delivery of more adaptive services. There are significant challenges ahead.

- Faster and more flexible network agreements to facilitate very short lived virtual networks

Challenges for Access Network Economics

Current state-of-the-art approaches to access network resource sharing [14] generally lack economic merit, as they do not prioritize users in terms of their utility for the service provider. Recent schemes such as hierarchical bandwidth allocation and utility-based load balancing [14] consider access networks with competing and overlapping access technologies. These approaches are not extensible to the EaaS business models, which need to consider much more comprehensive economic models. Similarly, recent work on auctioning of data paths in heterogeneous wireless networks [15] are not suitable for EaaS, as those approaches are not extensible to consider many more types of virtualized resources to be allocated over and above just bandwidth.

EaaS also requires the development of new business models. In particular, previous approaches are limited since they do not virtualize the access network resources but rather rely on attempting to establish end-to-end SLAs among multiple networks, which are difficult to automate, negotiate, and enforce. This is in sharp contrast to EaaS, where the virtualized access network infrastructure greatly simplifies QoS provisioning over the virtualized infrastructure. This creates a novel paradigm of conducting business that empowers novel business models and new network economics issues to be investigated.

New Directions for Access Network Economics —

- New economic models for using overlapping heterogeneous fixed and wireless access technologies in competitive and non-competitive systems
- Innovative access sharing and service provisioning that can provide insight into important regulatory and market issues, such as network transparency and competition, network neutrality, and market power and competition issues
- Market-based resource allocation schemes and policies that take into account both access technology and economic value to ANPs
- Techniques to mediate many potentially competing requests for virtualized resources to maximize resource utilization of resources and the benefit for access network providers
- Use of network economics and game theory to evaluate the business aspects, and new business models

Conclusion

Telecommunication network operators are suffering from falling revenues and unsustainable business models, due to significant investments in infrastructure that are difficult to manage cost effectively. This article presents and analyzes the challenges associated with edge as a service. This new concept decouples the strict ownership relationship between network operators and their access network infrastructure. Through the development of a new novel network interface, virtual networks and functions can be requested on demand to support the delivery of more adaptive services. There are significant challenges ahead regarding network virtualization, network programmability, economical network sharing, and on-demand elastic network management.

References

[1] P. Bosch *et al.*, "Telco Clouds and Virtual Telco: Consolidation, Convergence, and Beyond," *12th IFIP/IEEE Int'l. Symp. Integrated Network Management and Wksps.*, May 2011, pp. 982–988.

[2] L. Baleh, L. Suciu, and J.-M. Bonnin, "Enriched Connectivity-as-a-Service for Dynamic Mobile-Cloud," *2012 IEEE Consumer Commun. and Net. Conf.*, Jan. 2012, pp. 655–60.

[3] N. Chowdhury and R. Boutaba, "Network Virtualization: State of the Art and Research Challenges," *IEEE Commun. Mag.*, vol. 47, no. 7, 2009, pp. 20–26.

[4] N. Chowdhury, K. Mosharaf, and R. Boutaba, "A Survey of Network Virtualization," *Computer Networks*, vol. 54, Apr. 2010, pp. 862–76.

[5] B. Sonkoly *et al.*, "OpenFlow Virtualization Framework with Advanced Capabilities," *2012 Euro. Wksp. Software Defined Networking*, Oct. 2012, pp. 18–23.

[6] N. McKeown *et al.*, "OpenFlow," *ACM SIGCOMM Computer Commun. Rev.*, vol. 38, Mar. 2008, p. 69.

[7] V. Philip, Y. Gourhant, and D. Zeghlache, "OpenFlow as an Architecture for e-Node B Virtualization," *e-Infrastructure and e-Services for Developing Countries*, vol. 42, 2012.

[8] A. D. Keromytis, V. Misra, and D. Rubenstein, "SOS: Secure Overlay Services," Proc. *2002 Conf. Applications, Technologies, Architectures, and Protocols for Computer Communications — SIGCOMM '02*, vol. 32, ACM Press, Aug. 2002, p. 61.

[9] D. Tennenhouse *et al.*, "A Survey of Active Network Research," *IEEE Commun. Mag.*, vol. 35, Jan. 1997, pp. 80–86.

[10] R. Sherwood and G. Gibb, "Flowvisor: A Network Virtualization Layer," *Switch Consortium*, tech. rep., 2009.

[11] A. Fischer *et al.*, "Virtual Network Embedding: A Survey," *IEEE Commun. Surveys & Tutorials*, 2013, pp. 1–19.

[12] J. Famaey *et al.*, "Towards A Predictive Cache Replacement Strategy for Multimedia Content," *J. Network and Computer Applications*, vol. 36, Jan. 2013, pp. 219–27.

[13] R. Copeland and N. Crespi, "Resolving Ten MVNO Issues with EPS Architecture, VoLTE and Advanced Policy Server," *2011 15th Int'l. Conf. Intelligence in Next Generation Networks, IEEE*, Oct. 2011, pp. 29–34.

[14] Z. Yu *et al.*, "Utility-Based Load Balancing in WLAN/UMTS Internetworking Systems," *2008 IEEE Radio and Wireless Symp.*, Jan. 2008, pp. 587–90.

[15] P. Maillé and B. Tuffin, "Price War in Heterogeneous Wireless Networks," *Computer Networks*, vol. 54, no. 13, 2010, pp. 2281–92.

Biographies

Steven Davy (sdavy@tssg.org) is the research manager of the 3MT unit in the Telecommunications Software & Systems Group (TSSG) at Waterford Institute of Technology. He received his Ph.D. in 2008 in telecommunications network Management from WIT. He is currently leading research into future network architectures with a focus on network virtualization and software defined networking.

Jeroen Famaey (jeroen.famaey@intec.ugent.be) obtained a Master's degree in computer science from Ghent University, Belgium, in June 2007. He received his Ph.D. degree on federated and autonomic management of multimedia services, from the same university in June 2012. Since then he has been working as a post-doctoral researcher in the area of network and service management, affiliated with Ghent University and iMinds. His main research interests include autonomic management of network federations, virtualized networks, and multimedia services.

PEDRO NEVES (pedro-m-neves@ptinovacao.pt) received his M.S. and Ph.D. degrees in electronics and telecommunications engineering from the University of Aveiro, Portugal, in 2006 and 2012, respectively. From 2003 to 2006 he was with the Telecommunications Institute (IT), Portugal, and participated in the DAIDALOS-I and DAIDALOS-II European funded projects. In 2006 he joined Portugal Telecom Inovação, Portugal, and participated in several European funded projects. His research interests are focused on cloud services management, including the infrastructure and platform layers.

JUAN-LUIS GORRICHO (juanluis@entel.upc.edu) is an associate professor at the Technical University of Catalonia (UPC), Barcelona, Spain. He received his Ph.D. degree in telecommunications engineering from UPC in 1999. He is an active member of the research group Management, Pricing and Services for the Next Generation Networks (MAPS) in the Telematics Department of the UPC. His most recent research is focused on the application of artificial intelligence techniques to the management of communication networks and the implementation of the context awareness paradigm.

STEVEN LATRÉ (steven.latre@uantwerpen.be) is an assistant professor at the University of Antwerp, Belgium, and the Future Internet Department at iMinds. He received a Master of Science degree in computer science from Ghent University, Belgium, and a Ph.D. in computer science engineering from the same university. His research activity focuses on autonomous management and control of both networking and computing applications. His recent work has focused on quality of experience optimization and management, distributed control, and network virtualization.

EZER GOSHEN (goshen@bandwd.com) has 24 years of experience in the telecommunication market and technology. He is the founder of BandWD and has been working at the company since its establishment in 2004. Prior to BandWD he was one of the founders of Wydeband, a services creation and mediation solutions company (a Radware & Comverse company), and served as CTO and VP R&D. Before that he worked for 10 years as director of R&D and Chief Architect at ECI Telecom. He holds computer engineering M.Sc. and M.B.A. degrees.

MANOS DRAMITINOS (mdramit@aueb.gr) is a researcher in the Department of Informatics of AUEB. He received his Ph.D. from AUEB in 2006 and his postdoc from INRIA Rhône-Alpes, RESO Team in Lyon in 2009. His research interests are in network economics and traffic management, mobile networks, auction theory, mechanism design, e-commerce, business modeling, and regulation. He is the author of the book *Auction Theory for Telecoms*.

JOAN SERRAT-FERNÁNDEZ (serrat@tsc.upc.edu) received his degree of telecommunication engineer in 1977, and his doctorate degree in telecommunication engineering in 1983, both from UPC. He is a full professor of the Department of Telematics Engineering at UPC, where he has been involved in several collaborative projects with different both European research groups and companies, through bilateral agreements and participation in European and national funded projects. His topics of interest are in the field of autonomic networking and service management.

AVI MIRON (mirona@cs.technion.ac.il) is a researcher at the Computer Science Department of the Israeli Institute of Technology (Technion). Graduated from the University of Southern California, Los Angeles, he has participated in a few EU-funded research projects, including BIONETS, 4WARD, SAIL, and ETICS, and now in CONGAS and CLOUDWAVE. Research areas include Internet connectivity, net neutrality, QoS, cloud networks, and fixed/mobile communications in general. He is an experienced high-tech executive and entrepreneur, in both Israel and the United States.