A service industry perspective on software defined radio access networks

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Abstract: Despite the rapid growth of service science, relatively little attention has been paid to the service architecture requirements in software defined radio access networks (SDRAN). In this concept paper, we propose to repurpose cloud computing network services to address issues specific to SDRAN. In particular, a multi-level backhaul slicing approach derived from cloud computing networks is discussed as a way to mitigate interference limited networks with a frequency reuse factor of one. Experimental demonstration of the control plane implementation in a virtual cloud network is presented, and implications on service provider development and training are also discussed.

Keywords: software defined networks; radio access networks; RANs; software defined radio access network; SDRAN; service science, management, and engineering; SSME, software defined networking; SDN.

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1 Introduction

The service sector has steadily grown to become a dominant part of our global economy, particularly in developing nations, as noted by Maglio et al. (2010) and Wu et al. (2011). The impact of the service economy is perhaps greater in the technology disciplines, where the emergence of new service offerings parallels the growth of smart cities, academic institutions, and the so-called digital knowledge economy described by Spohrer (2015). One example is cloud computing, which has introduced the concepts of infrastructure, platform, security, and software as a service within the past five years. Information technology (IT) service professionals perform tasks such as designing, installing, managing, and maintaining systems for computation, networking, and storage. Practitioners in this field are transforming legacy data centres and communication networks into next generation architectures, characterised by dynamic workloads, elastic scale-out resources, and highly virtualised infrastructure, and on-demand, self-provisioned services. Collectively, these technologies are causing one of the most significant disruptions in the long history of IT, as noted by Mell and Grance (2011), DeCusatis et al. (2013) and Lai et al. (2015). The impact is evident on many large technology service providers; for example, IBM pretax income from services accounts for over 40% of the company's total income, exceeding the contributions from selling computer hardware and software according to Spohrer (2015). Further, also according to Spohrer (2015), IT services are the fastest growing revenue component for IBM, exceeding $60B in recent years; by contrast, hardware and software sales *combined* barely reach half that amount. Within the past decade, the field of service science has emerged to provide an inter-disciplinary framework for the development of new service offerings. Since this field is relatively new, many areas are still under investigation. In particular, the impact of next generation IT technology on the wireless communication industry, and its implications for the IT service industry, have not yet been thoroughly explored.

Wireless infrastructure is becoming increasingly complex, driven by the need to support exponentially increasing amounts of mobile traffic over a limited amount of spectrum bandwidth, wireless infrastructure is becoming increasingly complex. As an example, major US carriers such as Verizon and AT&T both have less than 100 MHz of spectrum available nationwide for LTE applications (for example, see Guidipati et al., 2015a, 2015b; Sasirekha et al., 2015). This lack of available spectrum creates a number of problems for radio access network (RAN) service professionals, including architectural concerns with spectral allocation. Traditionally, a RAN is treated as a collection of base stations, which are interconnected by backhaul links (either fibre optic cable, copper cable, or wireless backhaul links may be employed). As spectrum becomes limited, network architectures compensate by using increasingly dense designs (sometimes known as cell splitting). Such designs can force adjacent base stations to operate on the same channel. This is known as a frequency reuse factor of one, and it makes network management significantly more complex. For example, the radio resource management decisions made at one base station can affect nearby base stations (such as when a given user selects a portion of the spectrum to use for transmission at a given power level). This can lead to an interference-limited network, requiring some form of network management coordination among disparate base stations.

In principle, a dense network can improve transmission quality for each user by pushing critical infrastructure closer to the end user. Similar problems have been addressed in service provider network architectures for cloud computing. A cloud service provider (CSP), which desires to provide a mixture of services with different traffic requirements (video on demand, voice over IP, etc.), needs to determine whether to distribute network intelligence closer to the end user, or cluster it in a central location. Previous authors have proposed the use of a service oriented approach for event management in cloud computing (Kostantos et al., 2015), service oriented architectures (De Francesco et al., 2015), and frameworks for supply chain management (Moynihan and Dai, 2015). It has been suggested by Guidipati et al. (2015a) that all RAN base stations deployed within a given geographic area should be abstracted as if they were a single base station with a logically centralised control plane. This is the same approach used by CSPs who deploy software defined networking (SDN) in their cloud access networks. It follows that we should be able to apply some of the network architecture principles developed for CSPs to the emerging field of software defined radio access networks (SDRANs). For example, concerns with interference limited cell splitting networks may be addressed using multi-level control plane architecture for virtual slicing of a wired backhaul network between base stations, in the same way that this solution has found applications to CSP network service virtualisation.

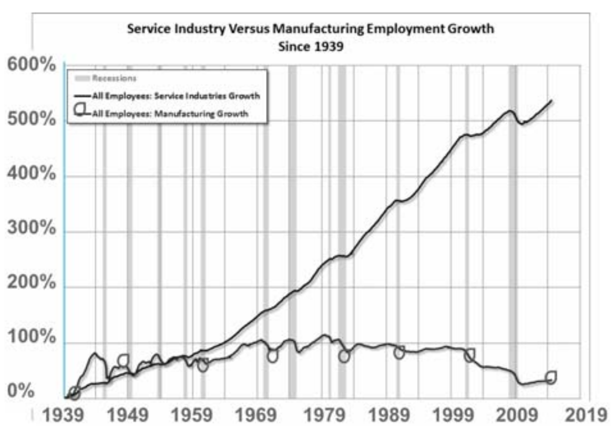
Just as server abstraction (operating system and programming languages) have superseded the requirement for all computers to be programmed in low level assembly language, SDRAN provides application programming interfaces (APIs) which automate many aspects of network management that are currently performed by low level, manual commands. This is quite different from the approach used by traditional distributed network architectures, which had no central management plane and thus were faced with significant issues when frequency reuse one networks emerged.

In this paper, we describe a conceptual framework for service offerings in SDRAN networks, based on extensions of the principles used in CSP networks. We propose a concept for an SDRAN system. The test bed described in this paper serves as a prototype for ongoing testing and development of SDRAN architectural principles. The specific contributions of this work include development of a test bed which demonstrates basic SDRAN principles, additional theoretical background on the SDRAN framework, and a perspective on SDRAN from the service industry, including the potential impact of SDRAN on service skills required for the networking practitioner. Following a brief overview of the service sciences and an introduction of common network service design principles, we discuss how these principles may be applied to SDRAN. We discuss abstraction and virtualisation of SDRAN resources, and potential impacts on deployment time for new services and performance of software-defined network appliances. Experimental results from a 100 km metropolitan area CSP network will be presented to illustrate the benefits which can be realised using a software defined approach to the RAN. Finally, we discuss the implications of SDRAN on training programs for service practitioners, and suggest areas for future research.

2 Brief overview of service science

By most estimates, the service economy has far outstripped other sectors such as agriculture and manufacturing (see Figure 1). Many researchers and practitioners have come to challenge the conventional definition of service, as producing outcomes which are intangible, heterogeneous, instantaneous, and perishable (at least in comparison with goods and hardware). Within the past decade or so, it was recognised that this definition was inadequate for the modern service economy, in particular failing to differentiate products from services. In 2004, a more substantial definition and operational framework was introduced, known as service dominant logic (SDL), a term used by Vargo and Akaka (2009) and Rhee (2015). Within the SDL perspective on service, we can redefine service as a collaborative process between providers and recipients for the co-creation of value. The concept of value co-creation (innovation which creates value through a combination of suppliers providing new functionality and users requesting this functionality) is fundamental to this approach. There is little value in a service provider offering features which the market neither needs nor wants, and conversely there is no value creation when a user requests service features that differ from what any supplier can provide. Only through the intersection of provider and user can we realise value added services.

Figure 1 Service industry employment growth over time, as compared with manufacturing and agriculture (see online version for colours)



Source: See http://www.businessinsider.com (accessed 8 October 2015)

Concurrent with the adoption of SDL, a disciplinary framework was introduced by IBM known as service science, management, and engineering (SSME) according to Spohrer (2015). Service science is thus the application of knowledge to co-create value and the study of diverse, interconnected, complex, value co-creation systems in business. SSME advocates a multi-disciplinary, context-dependent approach that goes beyond modelling existing service offerings, and strives for radical innovation in service deployments. This discipline remains in its early stages of development, however there have been many encouraging achievements including conferences, training programs, and academic-industry liaisons.

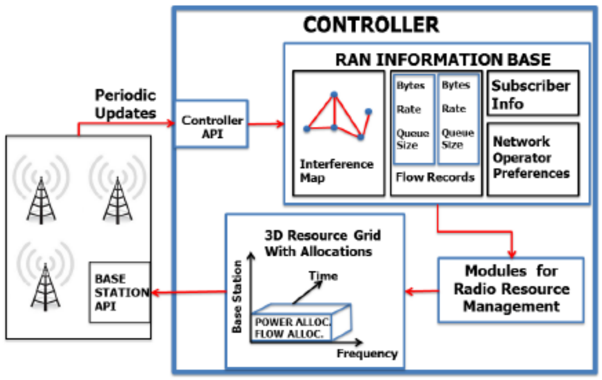
Given the SSME focus on collaboration and multi-disciplinary innovation, the International Society for Service Innovation Professionals (ISSIP) was founded in July 2012. Consisting of nearly 1,000 individual members and over a dozen corporate and academic sponsors, ISSIP has a global mission to proliferate smart service systems and drive educational, research, professional development, and policy decisions. ISSIP has partnered with other technical societies, including the IEEE, on initiatives such as the NIST global smarter cities challenge discussed by Spohrer (2015), which endeavours to bring leading-edge technology and services to major metropolitan areas. This includes the design and deployment of advanced communication networks as part of the urban infrastructure, such as ubiquitous, reliable, low cost wireless networks and intelligent wired communication between network service provider hubs and cloud computing centres.

Eight working groups within ISSIP focus on different facets of emerging technology In particular the software-defined networking (SDN) working group promotes research and education related to next generation communication networks. In this context, value co-creation encompasses several network design features and principles, including service reuse, network provisioning time, time to value for new network features, automation of common service tasks, optimisation of service tasks, and more. The remainder of this paper will discuss a contextual framework for applying these network service industry principles to software-defined networks. Parallels between software-defined cloud networks and RANs will be presented, suggesting the benefits to be realised from SDRAN architectures.

3 Resource allocation in SDRAN

In this section, we discuss several aspects of service management, which can be applied to a SDRAN. The relative benefits of SDRAN compared with traditional approaches to RANs will also be described. Service reuse refers to the importance of developing new service offerings, which can be leveraged across multiple applications, or adapting an existing service offering to a new purpose. This is an important principle, since it helps control manpower costs and improves efficiency by eliminating duplication of effort. We recognise that the design principles developed for SDN in a cloud computing data centre may be similarly applied to the control plane of an SDRAN. In a cloud computing network, the routers within and between data centre servers can be abstracted to create a single control plane, effectively treating a collection of networking resources as if they were one large switch. This same approach can be applied to the backhaul network interconnecting base stations in an SDRAN, as suggested by Guidipati et al. (2015b) and illustrated in Figure 2.

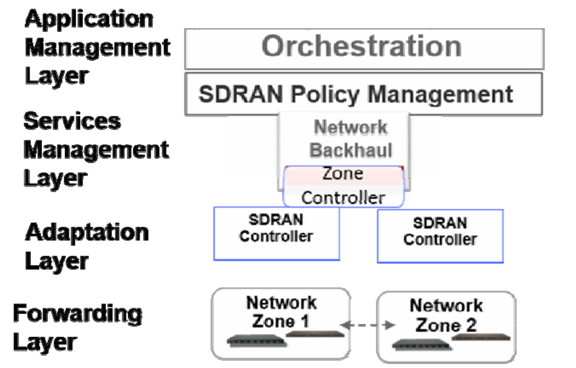
Figure 2 Basic architecture for SDRAN controller as used in SoftRAN (see online version for colours)



Source: Based on proposals by Guidipati et al. (2015b)

Separation of the data plane from the management/control plane in an SDRAN, and providing a centralised network controller, offers similar benefits. For example, just as conventional data centre networks consisted of routers, which make hop-by-hop decisions about traffic flow, a conventional RAN uses a distributed control plane spread across many independent devices. Coordination between these devices can be extremely difficult. Just as a cloud data centre network uses the same routing hardware regardless of the application, a RAN is not application aware and has no end-to-end context for making transmission decisions between widely separated base stations. A centralised, software-defined control plane with a standardised, programmable API can address this issue. Further, a programmable network controller can be implemented as part of a modular, layered control plane architecture in both SDN and SDRAN applications. There are well known benefits to a layered control plane, including loose coupling or partial isolation between layers as proposed by DeCusatis et al. (2014b). This allows each software layer to be developed independently of the layers above it, and optimised independently of those layers. In this approach, the underlying hardware may often be commoditised, i.e., replaced by standard x86 servers. This becomes possible, in part, because higher level functionality has been abstracted into a software control plane.

Figure 3 Four layer software management stack for SDRAN, including centralised multi-zone network controller (see online version for colours)



A centralised SDRAN control plane can also be made application aware through a layered software stack. A version of the CSP software architecture stack for network control was given by Manville (2013), and subsequently modified for SDRAN networks, is proposed in Figure 3. Note that the upper level or application layer orchestration receives input from the SDRAN devices at the lower layers; this facilitates implementation of end-to-end quality of service levels. Just as essential elements of a cloud network can be abstracted to the controller, the SDRAN controller can make traffic routing decisions across many backhaul nodes at once. In a cloud computing network, for example, certain types of traffic can be isolated for special treatment. High bandwidth, long duration flows (so-called 'elephant flows') can be segregated to their own sub-network to avoid congestion. Rather than have each data centre switch make local routing decisions, the SDN cloud network controller owns all the routing tables for every switch in the network. Further, a controller can take into account factors, which are not normally accessible to a distributed control plane, such as the end-to-end flow duration and application or transport level traffic priorities. Similarly, SDRAN controlled base stations can select operating frequencies for traffic flows across geographically distributed base stations to avoid contention in a dynamic, interference-limited network.

Automation of common tasks is important to reducing service management costs, and to providing control of large, complex systems. Traditional data centre network applications from a decade ago were statically provisioned, and did not require significant re-provisioning during their operating lifecycle. As new applications emerged (video on demand, mobile computing, big data/analytics), applications came to require dynamic re-provisioning on shorter and shorter time scales. Many cloud computing systems have long passed the point where manual provisioning alone is sufficient to keep up with application demand. Automation of the control plane has rapidly become an indispensable function for clouds, and SDRAN networks are poised to take advantage of these same benefits. Automation provides faster time to value by enabling rapid instantiation of new features and service/revenue opportunities. Consider provisioning of optical packet networks between multiple cloud data centres in a metropolitan area (about 100 km radius). Conventional data networks relying on manual provisioning of each network device along the traffic path could take days or weeks to reconfigure new services as noted by Manville (2013) and DeCusatis et al. (2014a). Using SDN, we have demonstrated dynamic re-provisioning of a 100 km optical network between three enterprise-class data centres in under one minute, a capability suggested by the modelling work of Sher-DeCusatis and DeCusatis (2014). If we replace the data centres with SDRAN base stations using this control plane architecture, similar improvement can be expected.

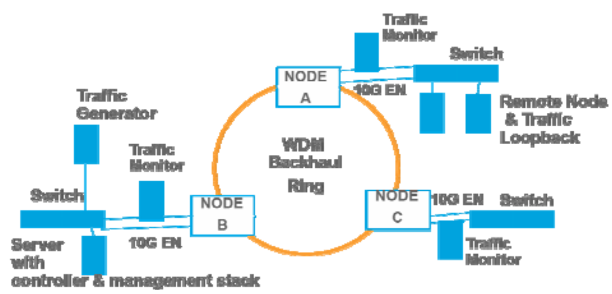
Once the network control plane is automated, we can introduce a feedback control loop to optimise performance over time. Network optimisation is greatly facilitated by a centralised controller, receiving input from commodity hardware at lower layers of the management stack. In one example from DeCusatis et al. (2013), a large Fortune 500 financial client was able to improve workload utilisation on their servers and network from 10% to over 40%. This resulted in significant cost savings from avoiding the purchase of new equipment, more energy efficient operation of existing equipment, and improvements in service level achievements. Reduction of over-provisioning in networks has been shown to reduce energy consumption by a third or more according to DeCusatis et al. (2014a). While optimisation of SDRAN is in the early stages, it is not unreasonable to expect similar performance improvements.

4 Multi-tier virtual network slicing

In the previous section, we mentioned possible application performance concerns associated with centralised control of a RAN, especially for applications, which require time sensitive access to large volumes of data. We have demonstrated a dynamic bandwidth provisioning approach for service offerings in a cloud data centre SDN network, which should be directly applicable to base station backhaul networks using SDRAN. Such an approach is well suited to aligning network capacity with user spectrum demands. This section will briefly describe the approach for multi-layer control planes in a software-defined nodal network, and propose a conceptual architecture for SDRAN.

To address the limitations associated with densely packed cells in an SDRAN network, a centralised controller may be employed to allocate bandwidth on the backhaul network between geographically distributed base stations. The creation of virtual sub-networks or network slices in the control plane can be extended down to the level of individual users, if desired. Each slice of the backhaul network can manage its bandwidth allocation independently of all other slices, using its own network controller (note that this does not have to be the same type of controller used to slice the backhaul network in the first place). This two level management system provides additional flexibility when optimising overall bandwidth utilisation. We have previously demonstrated such a multi-tier, network slicing management plane for CSPs, using a test bed at the New York State Centre for Cloud Computing and Analytics which has been discussed previously by DeCusatis et al. (2013) (similar principles can be applied regardless of the backhaul infrastructure). Studies of SDN vs. conventionally routed data centres have shown an improvement in meeting service level conditions of up to 30% based on work by Sher-DeCusatis and DeCusatis (2014); similar improvements may be possible using SDRAN.

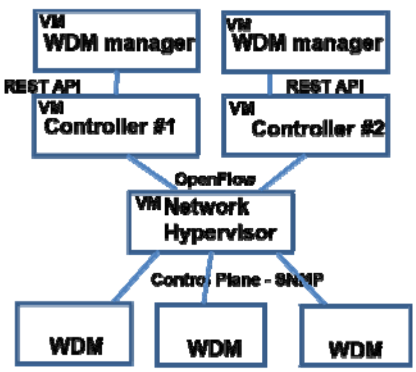
Figure 4 Packet over optical WDM test bed using SDN and network hypervisor control (see online version for colours)



The test bed used for our cloud computing experiments is shown in Figure 4, consisting of a 125 km single-mode fibre backhaul ring interconnecting three metropolitan area data centres (or base stations). The sites in this example are interconnected with a dense wavelength division multiplexing (WDM) platform (Adva FSP3000), including excess, discretionary wavelength pools which can be applied to the optical packet connections. Note that the approach described here is applicable in general to optical backhaul providers, even if they do not use the specific vendor equipment discussed in our test bed. Each site also contains inexpensive demarcation point hardware (Adva XG210), which serves as a traffic monitor or traffic injection source for test purposes. The data centres (or base stations) are interconnected via 1/10 GBps ethernet links in this example, although other forms of connectivity could easily be used. Servers at each location host virtual machines (VMware environment), which contain software defined network (SDN) controllers and a network hypervisor for the WDM optical backhaul equipment.

The software management plane for this test bed is illustrated in Figure 5. We have created an extension for open source SDN controllers and the WDM network hypervisor (a piece of software known as ‘Advalanche’), which performs dynamic bandwidth provisioning based on OpenFlow 1.3.1 (the results would not be changed if we had used OpenFlow 1.4 or 1.5). The SDRAN centralised control plane would use a similar approach, likely a combination of Advalanche and the WDM network hypervisor to slice the backhaul network into two or more virtual network segments, each of which can be assigned to a different cell. Each cell is then able to use an open standards-based SDN controller of their choice to optimise bandwidth allocation within their slice of the network. Our test bed demonstrates the Floodlight controller in one slice, and the open daylight controller running at the same time in another, logically independent slice. Each tenant can also optimise their individual WDM bandwidth using Advalanche, which may be called from either floodlight or open daylight; each tenant's controller can also provision network resources within a given cell. We have also created a graphical user interface which can optionally be used with the controllers and hypervisor, and which supports wireless mobile management interfaces (smartphones or tablets) that do not have good native support from the network controllers.

Figure 5 Software control plane architecture for CSP with two tenants (see online version for colours)



The XG210 is a small, inexpensive piece of hardware, which performs non-invasive traffic monitoring in the backhaul network. This triggers automated re-provisioning of connections in response to bandwidth requirements. We have experimentally achieved end-to-end re-provisioning in under a minute for a wide range of applications, including video on demand services and storage backup/recovery services; it is thus reasonable to expect similar performance for virtual radio base station appliances. Prior to the introduction of software-defined provisioning, an end-to-end solution as presented in this testbed would take several days or longer to be provisioned. We have shown that it is possible to implement end-to-end provisioning within a few minutes. The latency contributions of software defined provisioning are negligible compared with the achieved performance increase. Further, additional wavelengths for the affected application may be provisioned from an available wavelength pool, or by re-allocation of discretionary wavelengths from other applications (depending on existing quality of service agreements).

5 Service professional education

Recent interest in SDRAN is disrupting conventional RAN architectures and administration policies. Mobile applications such as social media are driving this transformation at an accelerating pace. The emerging internet of things (IoT) also relies in part on an extensive network of wireless remote sensors from a variety of geographically dispersed sources, which must be collected for centralised analysis using a dynamic, next generation RAN. Applications such as the IoT are expected to invert the conventional network traffic patterns; instead of high traffic volumes and persistent flows on relatively few routers near the network core, we expect high volumes of short duration connections at the network edge. The large number of transient edge connections in the IoT will be a significant security challenge for networks without a centralised policy management system. Traditional RAN architectures are not well suited to these applications, having been designed primarily for static workloads, manual reconfiguration, and distributed, hop-by-hop management of network devices.

Since there is no single point in a conventional network which can enforce service levels, redundant connections, or network security, conventional RANs rely on highly skilled network architects and administrators to approximately translate their business requirements into a series of manual network provisioning commands. SDRAN with backhaul virtual slicing enables us to automate network resource provisioning, and through higher level orchestration creates application-aware networks. While previous sections of this paper have discussed technological improvements for SDRAN networks, these changes have even broader implications for the network service industry and for network education and certification programs. Preparing for network administrative and service roles traditionally involves complex, vendor-specific practitioner certification exams, which rely on memorising network device configuration commands and learning how to implement hop-by-hop distributed networks. While these are valuable skills, the programming knowledge, which benefits modern software defined applications, has historically been de-emphasised for networking service practitioners, for example as discussed in Wilcox and Wilcox (2013). This approach has begun to change. For example, to provide high availability the network administrator no longer needs to manually provision two or more redundant physical connections. Instead, using APIs in an SDRAN network, it is possible to write a script instructing the network controller to dynamically fail over traffic to a path with lower service priority, and automatically switch back once the fault had been corrected. The ability to program network infrastructure APIs is rapidly emerging as a key differentiating skill for radio network architects and administrators, and will soon become a requirement for most employers.

There are many examples of the close connection between advanced networking technologies and the services industry. Instead of building and maintaining their own private data centres, many companies are becoming increasingly reliant on cloud computing services. According to industry analysts, today 20% of the Fortune 1000 use cloud computing for some applications, and half of them will be storing customer-sensitive data in the public cloud by 2016 according to Spohrer (2015). A renewed emphasis on data networks for cloud computing is also disrupting conventional telecommunication companies, who are rapidly trying to transform into CSPs.

In order to promote new service offerings, processes, and business models, which reclaim value for network clients, the service profession has begun to transform networking infrastructure using SDN and NFV. Just as server abstractions (operating system and programming languages) have superseded the requirement for all computers to be programmed in low level assembly language, SDN provides APIs which automate many aspects of network management that are currently performed by low level, manual commands. This is quite different from the approach used by traditional network switches and routers, which employ a distributed architecture (each switch only understands how to route data packets to the next hop in the network). Since there is no single point in a conventional network which can enforce service levels, redundant connections, or network security, most data centres presently rely on network architects and administrators to approximately translate their business requirements into a series of provisioning commands which are manually entered into each switch on the network. SDN enables a centralised network controller, which automates these functions and through higher level orchestration creates application-aware networks.

These changes have broad implications for the network service industry and for network education and certification programs. The programming knowledge, which benefits modern SDN deployments, has historically been de-emphasised for networking service practitioners. It was felt that IT administrators did not want or need to learn programming, which was more appropriate for traditional computer science disciplines. With the introduction of SDN/NFV, this approach to network administration education has begun to change. For example, to provide high availability the network administrator no longer needs to manually provision two or more redundant physical switches. Instead, using APIs in an SDN network, it is possible to write a script instructing the network controller to dynamically fail over traffic to a path with lower service priority, and automatically switch back once the fault had been corrected.

There have been several reports on the need to reform service education, as well as reports on the transformative power of early training curriculum redesign efforts in this field (see for example, McNickle, 2014; Maghaddom, 2015; Papapanagiotoo et al., 2012). The need for rapid evolution in this area has never been more apparent; according to industry analysts, most of the top networking-related jobs in 2014 did not exist just a few years ago. A recent survey of 800 top service industry executives indicated that their number one obstacle in leveraging IoT and new networking technology is the lack of appropriate skills according to McNickle (2014). In an effort to address this skill gap for future network practitioners, the Institute for Service Industry Professionals (ISSIP) has recently formed a working group on SDN and network virtualisation. The mission of this group includes promoting education related to SDN and software defined service, assessing the impact of SDN on required knowledge and skill sets, and providing guidance to a consortium of academic and industry participants.

A key principle of the service industry is value co-creation, which can be applied to industry/academic partnerships in SDN education. Academic institutions generally tend to value the creation and dissemination of knowledge, as well as the education of their students. Industry generally exists to create value for its investors and provide useful goods or services. It is thus in the interest of both parties to expand the current state of the art in key fields such as networking which enable both student job opportunities and potentially large consumer markets. We have endeavoured to apply this approach to the software solutions developed at the New York State Centre for Cloud Computing and Analytics, through our academic and industry partnership programs. As suggested by results from the previous sections, significant progress is being made in the reeducation of the network administration workforce to accommodate trends in SDRAN.

6 Conclusions

While service science is an emerging field, it holds great promise for enabling next generation IT systems that fully exploit concepts such as resource virtualisation and abstraction while providing increase velocity for service delivery. Repurposing and adapting existing service offerings to new environments are efficient ways to achieve value co-creation between service providers and their clients. Applying this approach to software defined network infrastructure for smart cities, it should be possible for SDRANs to generate value co-creation for smart city designs (that is, SDRANs can provide features which smart cities find useful and consumable). Following the principle of service re-use, we propose extending the software defined network management approach of CSPs to emerging SDRAN architectures. The benefits of a centralised controller, separation of the data and control planes, and abstraction of the management interface were discussed in this context. Our cloud services test bed has demonstrated reductions in service provisioning from days or weeks to minutes, reduced energy consumption by 30%, and reduced service cost by 40% through elimination of over-provisioning, without compromising quality of service agreements (without the use of software control plane optimisation, typical SDRAN networks may be over-provisioned by a factor of 4:1 to 10:1 or more). Further, we propose adapting a multi-layer CSP management stack to virtual network slicing in the SDRAN backhaul, to mitigate problems associated with small, densely packed cells. The impact of these changes on SDRAN professional education programs was also discussed.

Future work in this area will concentrate on analytic modelling of more general problems of SDRAN network resource allocation, which are well known to both CSPs and RAN administrators. The optimal placement of network control plane functionality (closer or further from the end user) can be modelled as a combination of locationing and dimensioning problems for a given traffic matrix. This work may be extended to specific SDRAN environments, and used to augment the application aware network orchestration discussed in this paper.

References

De Francesco, A., Di Napoli, C., Giordano, M., Ottaviano, G., Perego, R. and Tonellotto, N. (2015) 'MIDAS: a cloud platform for SOA testing as a service', *International Journal of High Performance Computing and Networking*, Vol. 8, No. 3, pp.285–300.

DeCusatis, C., Cannistra, R. and Carle, B. (2014a) 'A demonstration of energy efficient optical networks for cloud computing using software-defined provisioning', *Proc. IEEE GreenCom*, November [online] http://www.ieee-onlinegreencomm.org/program.html.

DeCusatis, C., Cannistra, R. and Hazard, L. (2014b) 'Managing multi-tenant services for software-defined cloud data center networks', *Proc. 6th Annual IEEE International Conference on Adaptive Science & Technology (ICAST)*, Covenant University, Nigeria.

DeCusatis, C., Marty, I., Cannistra, R., Bundy, T. and Sher-DeCusatis, C.J. (2013) Software defined networking test bed for dynamic telco environments', *Proc. SDN & OpenFlow World Congress*, Frankfurt, Germany.

Gudipati, A., Erran Li, L. and Katti, S. (2015a) 'RadioVisor: a slicing plane for radio access networks', *Proc. HotSDN*, Hong Kong, China [online] http://stanford.edu/~adityag1/files/radio-visor.pdf (accessed 24 January 2015).

Gudipati, A., Perry, D., Erran Li, L. and Katti, S. (2015b) 'SoftRAN: a software defined radio access network', *Proc. HotSDN*, Hong Kong, China [online] http://web.stanford.edu/~skatti/pubs/hotsdn13-softran.pdf (accessed 24 January 2015).

Kostantos, K., Kyriazis, D. and Themistocleous, M. (2015) 'Real time event management in cloud environments', *International Journal of High Performance Computing and Networking*, Vol. 8, No. 3, pp.212–221.

Lai, J., Jiang, L., Lei, M., Abdollahpouri, A. and Fang, W. (2011) 'Software-defined cellular networking: a practical path towards 5G', *International Journal of Communication Networks and Distributed Systems*, Vol. 14, No. 1, pp.89–105.

Maglio, P., Kieliszewski, C. and Spohere, J. (Eds.) (2010) *Handbook of Service Science*, Springer-Verlag, NY.

Manville, J. (2013) 'The power of a programmable cloud', *Proc. OFC Annual Meeting*, Anaheim, CA, Paper OM2D.2.

McNickle, M. (2014) *SDN Education, Tech Target* (posted July 2013) [online] http://searchsdn.techtarget.com/feature/SDN-education-Universities-tackle-SDN-course-content (accessed 3 March 2014).

Mell, P. and Grance, T. (2011) *The NIST Definition of Cloud Computing*, NIST special publication 800-145, US Department of Commerce [online] http://csrc.nist.gov/publications/nistpubs/800-145/SP800-145.pdf (accessed January 24, 2015).

Moghaddam, Y., Bess, C., Demirkan, H. and Spohrer, J. (2015) 'How to thrive as IT professionals in a converging ICT world', *Journal of Information Technology Management*, March, Vol. 27, No. 3, pp.24–28.

Moynihan, P. and Dai, W. (2015) 'A rule based service framework for supply chain management', *International Journal of High Performance Computing and Networking*, Vol. 8, No. 1, pp.28–46.

Papapanagiotoo, I., Falkner, M. and Devetsikiotis, M (2012) 'Optimal functionality placement for multiplay service provider architectures', *IEEE Transactions on Network and Service Management*, March, Vol. 9, No. 3, pp.359–372.

Rhee, S. (2015) *NIST Cyber-Physical Systems Global City Challenge* [online] http://service-science.info/archives/3691 (accessed 24 January 2015).

Sasirekha, V., Chandrasekar, C. and Ilangkumaran, M. (2015) 'Heterogeneous wireless network vertical handoff decision using hybrid multi-criteria decision-making technique', *International Journal of Computational Science and Engineering*, Vol. 10, No. 3, pp.263–280.

Sher-DeCusatis, C.J. and DeCusatis, C. (2014) 'Developing a software defined networking curriculum through industry partnership', *Proc. ASEE Annual Meeting*, Hartford, CT [online] http://asee-ne.org/proceedings/2014/index.html (accessed 24 January 2015).

Spohrer, J. (2015) *Thinking about Value: Service Science, Management, and Engineering*, IBM University Programs presentation to the Royal College of Art [online] http://www.slideshare.net/spohrer/2030-inspire-students-to-build-it-better-20150113-v3 (accessed 24 January 2015).

Vargo, S. and Akaka, M.A. (2009) 'Service dominant logic as a foundation for service science: clarifications', *Journal of Service Science*, Vol. 1, No. 1, pp.32–41 [online] http://sdlogic.net/Vargo_Akaka_2009_SS.pdf (accessed 24 January 2015).

Wilcox, L.C. and Wilcox, M.S. (2013) 'A review and evaluation of engineering education in transition', *IEEE Proc. 8th International Conference on Computer Science and Education (ICCSE)*, Sri Lanka.

Wu, J.S., Yang, S.F. and Lin, A.C. (2011) 'Joint radio resource management in heterogeneous wireless networks by using combined fuzzy logic and MADM', *International Journal of Internet Protocol Technology*, Vol. 6, No. 3, pp.135–145.