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# Software-Defined Access Networks

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## ABSTRACT

Control-plane functions are migrating from dedicated network equipment into software running on commodity hardware. The Software-Defined Access Network (SDAN) concept introduced here extends the benefits of Software-Defined Networking and Network Function Virtualization (NFV) into broadband access. In a SDAN, access-network control and management functions for broadband access are virtualized, to streamline operations, speed services creation, and enhance broadband customer satisfaction, particularly in multi-operator environments. This article examines industry drivers, identifies software-definable control and management functions for broadband access, and presents some specific usage scenarios for the SDAN.

## INTRODUCTION

Software defined networking (SDN) today generally involves advanced "virtualized" configuration and control of network elements (NE), generally with a controller such as OpenDaylight or Floodlight communicating with protocols such as OpenFlow [1], OpenNaaS, or the OpenGrid-Forum Network Service Interface (NSI). Many networking-related functions can be virtualized with Network Functions Virtualization (NFV) [2]. SDN focuses on control of network routing and switching, and touches on network management. However, SDN can also be viewed in a wider context that includes multi-carrier or multi-provider networks [3, 4]. There are many control and management functions required for broadband access, which, similar to SDN and NFV, can migrate from embedded firmware in dedicated network equipment into software controllers running on commodity hardware in a private or public cloud. This article extends the concepts of SDN and NFV into the realm of broadband access by presenting the concept of the Software-Defined Access Network (SDAN) [5].

The SDAN is built on a common control plane that virtualizes the infrastructure, separating the control plane from the data plane. The SDAN provides a common interface and a unified touch point for policy, control, and management. Network control and management is programmable, which allows open innovation of agile services. The SDAN concept may be applied to any type of broadband access: digital subscriber lines (DSL), cable modems, fiber-to-the premises (FTTP), fixed wireless, or other types of broadband access networks. WiFi delivers at least 50% of Internet traffic delivered on fixed lines to the "nomadic" consumers at the customer end of the broadband line, therefore control and management of WiFi should be included in the SDAN. An integral aspect of the SDAN is that, unlike traditional SDN, advanced management and control down to the PHY level are highly desirable and beneficial features.

Competitive multi-operator environments are common in many territories, particularly for DSL services. Virtualization of broadband access control and management in multi-operator environments is a theme of the SDAN. Competitive environments generally have a wholesale network provider responsible for the underlying infrastructure, and retail service providers responsible for interfacing to customers and providing services. There may be two levels of wholesaler: one for the physical cabling network, and one for the network equipment such as DSL Access Multiplexers (DSLAMs). Also, a third party may be responsible for management functions and management infrastructure (cloud). The SDAN can work with physical cable and port-level unbundling, and with logical "bit-stream" unbundling.

SDAN uses a "controller" in a data center or cloud to perform control and management functions for broadband access networks, and the SDAN moves some compute and storage functions from NEs into the controller. SDAN also provides a common interface to the controller functions that can be accessed by multiple operators in competitive environments.

Figure 1 depicts how the SDAN can glue together disparate retail and wholesale providers. A logically centralized system authorizes and arbitrates requests for data and control, and implements an abstraction layer that interfaces between equipment interfaces, the centralized functions, and the common interface used by the retail providers. This is essentially multi-tenancy, although the functionality may be distributed. In Fig. 1 retail provider A allows their service to be defined and controlled by the wholesale provider, while retail provider B defines services and controls them.

This article presents the SDAN concept, first identifying industry trends that advance this concept. Then separate sections discuss the network management and the data-plane control functions envisioned for the SDAN. A few specific

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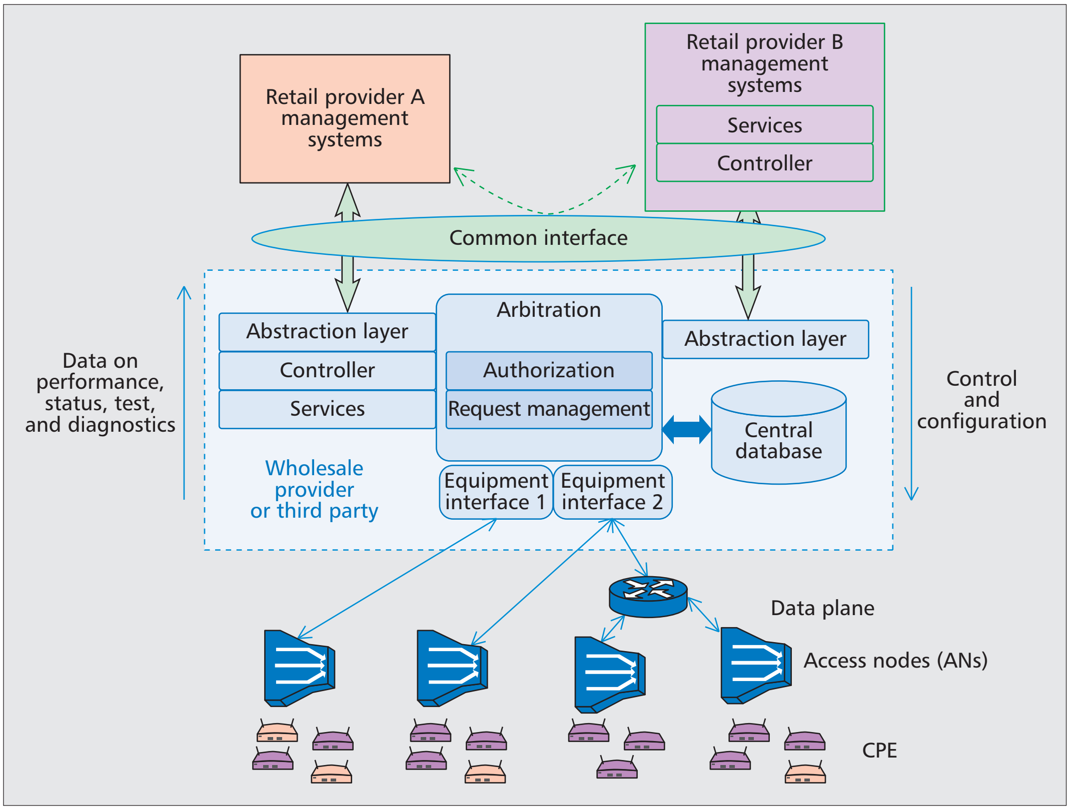


**Figure 1.** SDAN for multi-operator environments.

examples of SDAN usage scenarios are given, and some general conclusions are drawn. Figure 2 shows the conceptual network layers used for this article's purposes. This article focuses on the controller and management layers, and touches on the services layer.

## Industry Drivers

A number of trends are converging to drive the development of the SDAN, as depicted in Fig. 3 and described further in this section.

### Software Defined Networking

The increasing capability and availability of cloud infrastructure is being leveraged to remove control plane functions from network elements. This removal allows control functions to be supported by low-cost computing in more centralized architectures, which also support more advanced network configuration and management. The flexibility and upgradability offered by cloud resources and server virtualization are extended further into the network, specifically into access networks and even into premises networks.

SDN does have drawbacks and is expected to complement legacy networks instead of replacing them, in many cases. Communications between NEs and controllers may consume much network bandwidth, and there are robustness issues, but these are being reduced by network enhancements such as increased bandwidth and storage of state information on NEs. Remote storage and control can introduce problems with data concurrency, but mechanisms should be defined to synchronize all controllers' configuration actions and databases,

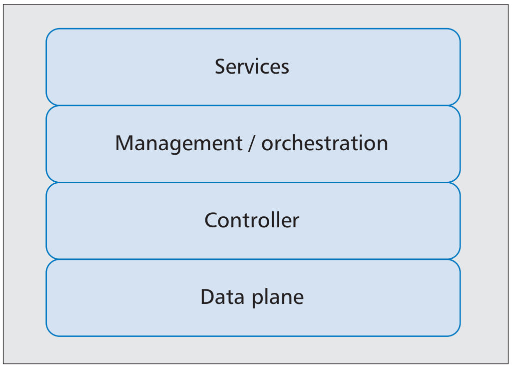


**Figure 2.** Conceptual network layers.

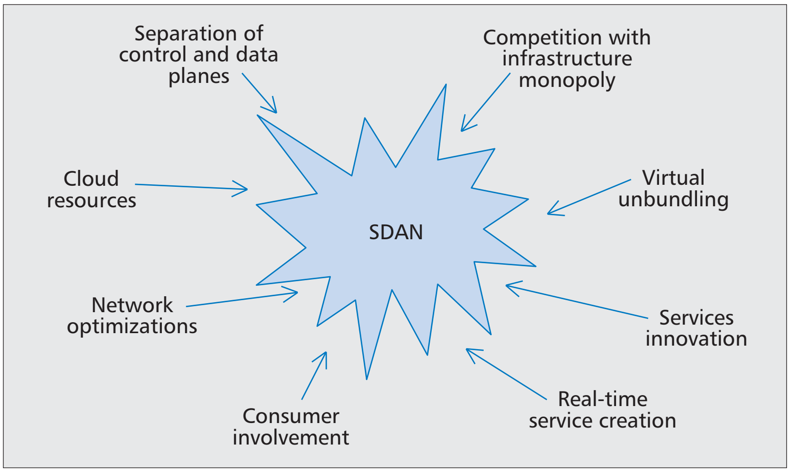


**Figure 3.** Drivers behind the SDAN concept.

*The increasing capability and availability of cloud infrastructure is being leveraged to remove control plane functions from network elements. This removal allows control functions to be supported by low-cost computing in more centralized architectures, which also support more advanced network configuration and management.*

Element Management Systems (EMS), and Network Management Systems (NMS). A number of security issues also need to be addressed.

### NATURAL INFRASTRUCTURE MONOPOLY

Consumers in many countries have benefited from competition in broadband, particularly with local-loop unbundling (LLU) using DSL in Europe and elsewhere. With LLU, each competitive provider installs their own DSL Access Multiplexer (DSLAM) at an exchange or central office (CO) and leases the copper from a wholesale or network provider. New competitive providers have been created, lowering costs to consumers and expanding service offerings and service/application innovation. Wholesale providers have also benefited directly since the overall broadband-subscriber population has increased. Further, regulatory scrutiny decreases within a competitive industry.

DSL "Vectoring" eliminates much of the crosstalk between DSLs, and vectored VDSL2 has recently become the choice of several major network-infrastructure/service providers globally. Vectoring has highest performance if all lines terminate at a street cabinet or remote terminal (RT) on a single (or logically single) DSL Access Multiplexer (DSLAM). These cabinet deployments create somewhat of a "natural infrastructure monopoly" since it is often uneconomical for multiple providers to deploy DSLAMs at each cabinet.

Vectored and non-vectored DSLAMs in a single location can be made to coexist with management solutions such as Dynamic Spectrum Management (DSM) [6, 7]. DSM can also enhance line speeds and stability, and DSM can be greatly enhanced in multi-operator environments with the coordinated data sharing, optimization, and control possible with the SDAN.

Fiber-to-the-home (FTTH) or fiber-to-the-premises (FTTP), and cable networks can also be considered natural infrastructure monopolies, since although they could be overbuilt, this is generally considered uneconomical. These trends are pushing regulators to severely restrict loop unbundling, threatening the existence of competition as super-fast broadband emerges, which would increase costs to the consumer, lower super-fast broadband penetration, and most importantly discourage innovation in applications and services that has driven the world economy's growth in the last decade.

### COMPETITION

As physical loop unbundling diminishes with fiber-deep architectures, there are increasing efforts to continue competition with Virtual Unbundled Loop Access (VULA) [8], using bitstream-level resale at the Ethernet layer instead of at the IP layer. Virtual unbundling at the Ethernet layer enables class-of-service differentiation, multicast, and so on, similar to physical unbundling. This is a start, but the SDAN can build on VULA to enable virtual unbundling that is nearly indistinguishable from physical unbundling, especially in its ability to encourage competitive innovation and differentiation, and to drive economic growth of broadband services.

There are many more physical and operational aspects of loop unbundling beyond just VULA that can be reproduced in a new regime with a single infrastructure provider, such as services definitions, management, and other operations. These impact backhaul aggregation networks, Access Nodes, and CPE. Without SDAN nearly all control functions are performed by the wholesale provider, such as traffic management through tunnels or VLANs in the backhaul, configuring the Access Node, performing line diagnostics, and operations such as troubleshooting. With SDAN nearly of these functions can be largely offloaded to the retail provider, providing the retailer significant latitude in defining service offerings. This must be done carefully, to control access permissions, arbitrate conflicts, ensure fair resource utilization, and guarantee reliability for the underlying physical infrastructure.

Smartphones have already placed some network control in the cloud. Consumers can become more involved by opening SDAN functions through a consumer-device interface such as an intuitive app, which releases consumer choice of services and service qualities. Consumers can further be informed about their service quality, and can then rebalance their service choices in an informed positive feedback loop. As consumers become more absorbed by Internet services, they want high-level diagnostics on their connections, and especially want to rapidly resolve service-affecting troubles. With a simple interface, consumers can be enticed into value-added services such as requesting a temporary speed boost.

### EMERGING IMPLEMENTATIONS AND MANAGEMENT CONSIDERATIONS

While the SDAN moniker is introduced in this article, SDAN-like concepts and functionality have existed in various forms, such as the "intelligent network." As with a SDN, common standardized interfaces are crucial for the SDAN. There are many MIBs and APIs for broadband management that have achieved some level of standardization; however the industry still lacks a globally accepted and used standard, particularly for the Northbound interface from Access Nodes (AN; the DSLAM, OLT, or CMTS). Such a standard could clarify, limit, and simplify messaging between wholesale and retail providers. The recent ATIS report on SDN and NFV provides an overview of related standards [9].

ETSI NFV is examining access network virtualization, including moving complex processing from the DSLAMs into the network, and multi-tenancy [2]. The TM Forum has defined a growing set of interfaces that are designed to manage converged networks and has developed guidelines, tools, and an API to help overcome the challenges of delivering services in a multi-cloud environment [10]. The Distributed Management Task Force (DMTF) has created interoperable specifications for management of IT environments, and is working on cloud and virtualization. The Open Data Center Alliance℠ (ODCA) is standardizing cloud federation and management. The ITU-T standardizes management primitives for optical and copper access, and the ITU-T SG11/Q4 Q.SBAN project is working on scenarios and signaling requirements for software-defined Broadband Access Network (SBAN).

Cloud and virtualized infrastructure standards are emerging in the Organization for the Advancement of Structured Information Standards (OASIS) Topology and Orchestration Specification for Cloud Applications (TOSCA). Open source projects can rapidly define "standard" APIs, such as OpenStack for NFV, and OpenFlow for SDN. NETCONF is a newer protocol for exchanging configuration information from a management platform and is endorsed by the Open Networking Foundation (ONF) for configuration. YANG is the data modelling language for the format of data used by NETCONF to exchange data. For information on NETCONF and YANG, see IETF RFC 6241, RFC 6244, and RFC 6022.

The Broadband Forum (BBF) is starting to be active in NFV and SDN for access networks [11]. In the UK, the Network Interoperability Consultative Committee (NICC) has initiated a new study on DSM Data Sharing, exploring shared multi-operator control of DSL access networks.

Some wholesale operators are beginning to virtualize access network control and management. Telekom Austria [8] offers layer 2 virtual unbundling including unbundled backhaul and CPE. Both bandwidth per subscriber and bandwidth per DSLAM are selectable with defined QoS. Retailers can access fault, status, and configuration parameters.

## Open Access Network Management

This section considers architectures for abstracting access network management and providing an open management interface. Diagnostic data and configurations can be made available to all operators in multi-operator networks, and even directly to the consumer. The architecture should be arranged to work for and appeal to all parties involved, and to provide fair resource allocation.

Retail providers could gain access to some diagnostics and configurations through wholesalers at the network end of the access lines, and some management functions could also be performed through the customer end of the line.

Such architectures would require careful consideration of security aspects, and impacts between providers. Security considerations include: authentication; identification of broadband lines under the purview of the requesting provider; authorization only for accessing appropriate data; admissible control actions; and the interpretation of control requests. The SDAN framework can unify policy, regulation implementation, and policing.

### Why?

Streamlined and automated operations provide benefits to wholesale infrastructure providers, retail service providers, vendors, and consumers. OpEx is lowered for the providers, a standardized common interface simplifies vendors' requirements, and most importantly consumers can get better service and benefit from new possibilities in applications innovation. The SDAN enables new service concepts to be easily trialled and implemented, allowing innovation and creativity to flourish. Agile services can be rapidly adapted to consumer needs. Network operators want to entice consumers with service upgrades in real time, and the SDAN enables such dynamic services.

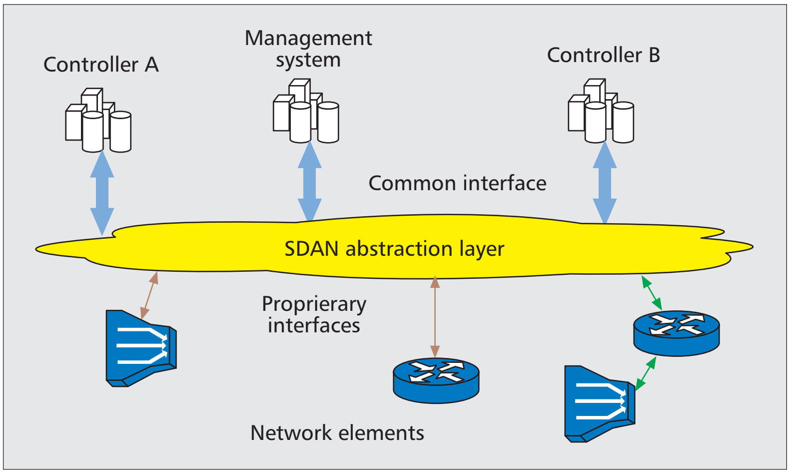


**Figure 4.** SDAN implementation via an abstraction layer.

A common interface can enable services differentiation, and allow real-time access to performance monitoring and fault data. Presenting a single, consistent interface lowers management costs for all parties involved in broadband service delivery. With DSL or FTTdp using copper transmission, sharing data can enable increased performance via Dynamic Spectrum Management (DSM), and joint use of shared neighborhood information for diagnostics.

Incumbents can save OpEx by automating interactions with competitors. Multi-line optimizations using shared broadband data enhances the performance of both incumbent and competitor's lines, and enhanced maintenance improves customer satisfaction. Multi-line optimizations include at least DSM levels 1 and 2 [6, 7] on DSL networks, and traffic assignment on PON or cable modem networks. These improvements benefit the incumbent by increasing the overall broadband footprint. Subscribers can either upgrade their service with their existing retailer, or they may move to an entirely different type of broadband access. SDAN-empowered incumbents can increase their total number of access lines (including unbundled), increasing revenue and lowering their costs.

### How?

Data can cross the common interface in real-time. A common interface may be explicitly standardized as a set of messages, schema, or APIs. Or the interface could be constructed with an abstraction layer consisting of adapters between existing management and control interfaces such as SNMP and a standardized common interface, MIB, or data model, as shown in Fig. 4. This can leverage new and existing interface work as described earlier. A retail service provider can request data or control actions; these are interpreted, translated, and executed through the SDAN abstraction layer. The abstraction layer may also limit the frequency or numbers of messages and admissible ranges of values.

Implementation may be centralized or dis-

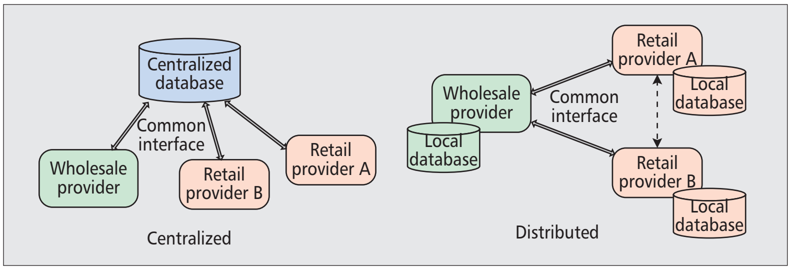


**Figure 5.** Centralized vs. distributed SDAN architectures.

tributed, as shown in Fig. 5. A centralized SDAN architecture divides the central management and management database with multi-tenancy, abstracting the access network into multiple logical access networks. The centralized infrastructure could be operated by the wholesaler, retailer(s), or a third party. A distributed SDAN architecture shares data and control functions through a standardized common interface, with each provider maintaining their own computation and database resources. Distributed architectures may alleviate concerns of overly restrictive central control, but they raise concerns about data concurrency and the frequency and volume of messaging.

## SDAN Network Element Control

A number of control functions that are currently performed by broadband NEs could be migrated into a separate controller. This includes relatively slowly-varying scheduling, administrative, and policy functions. Multi-provider unbundled environments can share many control functions while presenting separated virtual instances to each provider. Moving computationally intensive functions to a more central point also eases administration.

Figure 6 gives a simplified view of broadband access network elements. The aggregation network is the part of the network connecting the Access Nodes to the BNG. The RG is sometimes also called "CPE." The Access Node (AN), such as a DSLAM, Optical Line Terminal (OLT), or Cable Modem Termination System (CMTS), is the network termination for the last mile connection to the customer.

### Software-Definable Access Network Functions

Network Functions Virtualization (NFV) uses commodity hardware to provide Virtualized Network Functions (VNFs) through software virtualization techniques. Features can be software-defined to allow rapid changes in service definitions, and sharing of service components in "service chaining." Many functions of broadband networks such as authorization, advanced diagnostics, setting forwarding rules, and so on, can be virtualized. Virtually upgrading network elements via software decreases hardware obsolescence and is operationally easier to implement. Operators can rapidly update software instead of waiting for new feature releases from large vendors.

### Backhaul or Aggregation Network

Broadband access aggregation networks are closed systems managed by a single provider that are glued together with static layer 2 configurations. The SDAN can dynamically manage these settings and allow multiple providers to create new business applications.

**Apply SDN with Aggregation Network Switches:** "Classic" SDN applications to routing and switching functions can certainly be used with broadband. Broadband aggregation networks generally employ some type of layer-2 logical network separation such as stacked virtual local area networks (VLANs) or tunneling. This can be generalized using SDN, and is being explored by the Broadband Forum [11].

**Ethernet Layer, Virtual Unbundled Loop Access (VULA):** Unbundling with VULA at the Ethernet layer enables functions including multicast, and different classes of service. A simplified view of Ethernet aggregation is shown in Fig. 7. Here competition is at the Ethernet layer rather than at the physical layer, and the ability for resellers to compete is limited without SDAN since services and management-layer functions may not be controlled by the retail provider.

**Virtualize the BNG/BRAS:** The Broadband Network Gateway (BNG) is between the aggregation network and other networks such as the Internet, or service-specific networks such as voice or video [11]. A BNG can also be called a Broadband Remote Access Server (e.g. BRAS). The BNG is an IP edge router where bandwidth and QoS policies may be applied. BNG virtualization, virtualizing BNG hardware to offer multiple instances to multiple retail providers, has already been trialled.

**Virtual Aggregation Network Unbundling:** Some network providers are already unbundling the aggregation network. Here, each retail provider can lease various quantities of backhaul bandwidth at various SLA levels [8].

**Physical Aggregation Network Unbundling:** Fiber feeder is generally multi-stranded, and not every strand or wavelength is used by the incumbent provider, so these unused resources may be unbundled. A certain amount of fiber feeder may be installed by a retail provider who then accesses an unbundled network interface on the access node.

### Access Node

Broadband access network control and management centers around the Access Node — the DSLAM, OLT, CMTS, and so on — and the associated EMS and NMS.

Each retail service provider can use their own virtual access node. Virtualizing the access node would be similar to server virtualization, allocating virtual machines under the supervision of a hypervisor. Each virtual access node could only consume a limited amount of resources (physical ports, processing, network bandwidth, etc.) which is allocated so that they don't conflict with each other. Virtualized access nodes, however, may only appear in the long term. An abstraction layer between the access nodes and the management systems could separate network resources between retailers similar to a virtualized access node, except for assigning processing resources that are purely internal to the access node.

### PREMISES NETWORKS AND CPE

***Wires-Only: Reseller Provides CPE*** — "Wires-only" service is being introduced in the UK [12]; in this case a retail provider leases a DSLAM port at a VDSL cabinet and the copper line to the customer. The retail provider is responsible for providing and managing the gateway or CPE. Management may be split between the wholesale provider and retail provider, both within a given protocol layer and among protocol layers, and parts of the aggregation network may also be partially owned or controlled by the retail provider. Using wires only, in conjunction with the SDAN migrating management and control into a commonly accessible data center, can allow virtual unbundling to operate in a way that is nearly distinguishable from physical unbundling.

***Network-Enhanced Residential Gateway (NERG)*** — The residential gateway performs a wide range of functions, and some of these can migrate back into a "virtual CPE" located in the network. Security functionality and some traffic conditioning can be performed in the virtual CPE, as well as enhanced services such as parental control or virtual PBX. Machine-to-machine (M2M) communications may require multiple stacks, which can be supported in the network-located CPE functionality. The NERG can support enhanced diagnostics and troubleshooting.

***WiFi, Femtocell, Small-Cell Management*** — Past the broadband line, into the customer premises, lies a plethora of LAN and home network technologies. While this may seem the furthest from the cloud, it could actually be best suited to cloud management. Tales of bizarre mis-configurations in home networks abound, and the numbers of home networked devices is rapidly increasing. Most consumers neither can, nor want, to actively manage their home networks, and so services that automate and remotely manage home networks are increasingly useful to consumers and to broadband service providers who field many support calls related to home networks.

Wireless premises networks make good examples. A cloud-based controller can assign resources such as frequency bands and time slots to femtocells, small cells, and base stations, coordinating resource assignments across such heterogeneous networks. Resources can be controlled in near real-time, with tradeoffs between users managed to ensure fairness.

Broadband services are practically dependent on Wi-Fi, and Wi-Fi can similarly be controlled, with channel assignments and even station associations optimally allocated across multiple Wi-Fi access points.

***Customer Line Management, via CPE, Smartphones, Apps*** — The access network quality can be managed from the customer's end of the line, to lower costs and enable self-install. Customer-end management may be performed by the wholesale service provider, retail service provider, consumer, or a third party such as a Geek Squad™. The customer can receive information and perform some broadband management through an application or app. Consumer apps can interface to the cloud-based SDAN control and management systems, providing targeted diagnostics to the consumer to restore service and improve broadband performance. An intuitive and simple interface can provide a greatly simplified version of network management to the consumer. This helps providers save money by eliminating trouble calls, and the consumer has increased satisfaction from being empowered.

CPE can also apply cross-layer optimizations and cross domain (access and premises networks) optimizations for further improvements. CPE may also enhance controllable functionality such as line test and noise cancellation.

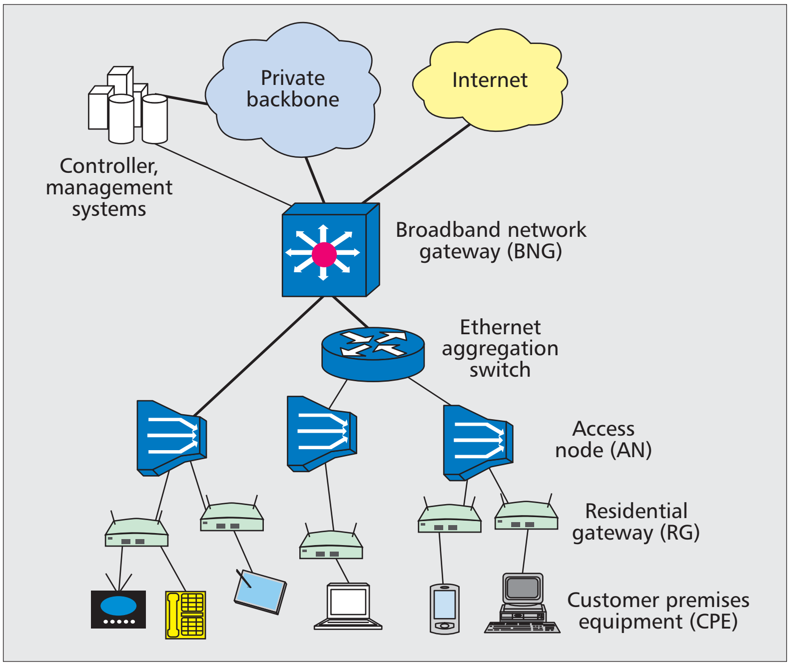


**Figure 6.** Broadband access network elements (NE).

## EXAMPLE SDAN USAGE SCENARIOS

A few use cases showing some specific usages of the SDAN, and potential benefits, are outlined here.

### BANDWIDTH ON DEMAND

Broadband customers are often assigned a restricted bit rate, and sometimes a limit on overall monthly usage. Bandwidth restrictions are enforced by the BNG or the access node, or both. The SDAN can allow customers to request higher speeds on demand, for example to speed a large download [13]. The SDAN can control policy including bit rates and priorities and thereby mediate the traffic demands of multiple subscribers in real-time to ensure fair resource utilization in the network.

### SERVICES DIFFERENTIATION

The SDAN can help empower retailers to differentiate their service offerings and better plan their networks. Retailers can compete on QoS, to enable business class services with service level agreements (SLA), or innovative consumer services such as extra low-delays for gamers. Upsell opportunities can be identified and targeted. The SDN allows the dynamic creation and

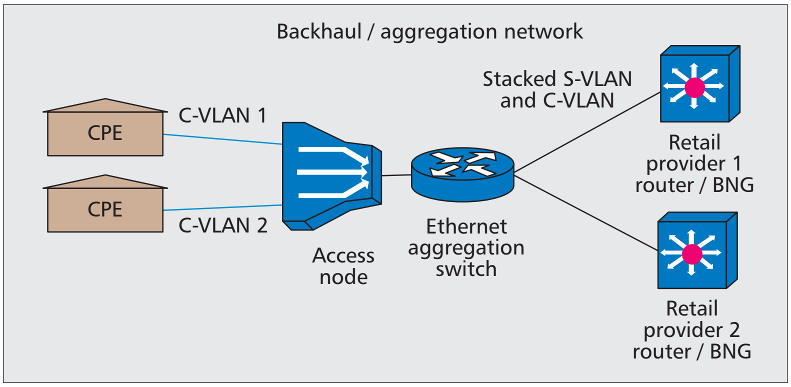


**Figure 7.** Simplified view of Ethernet aggregation with VULA.

modification of service offerings. Unifying policy control in software allows policies to change dynamically, unlike embedding policy control in access nodes and BNGs.

### New Business Models

The SDAN can extend the concept of Network as a Service (NaaS) into broadband access. New business models can be created between wholesale infrastructure providers and retail operators. Services can be built on top of the SDAN, chaining or modifying network-related VNFs to create new service offerings. Retail provider businesses may operate at different levels of scope, providing only subscriber management, or also providing a level of network diagnostics and optimization, or even near-total control of virtually-segmented network resources.

These new business models and competitive alternatives can help drive the broadband industry to offer higher-level services and new service offerings that increase customer satisfaction and drive demand.

### DSL Dynamic Spectrum Management (DSM)

DSM allows multi-line optimization in the face of crosstalk between DSLs, resulting in improved line speeds and line stability in many cases [6, 7]. Sharing of data on cable-plant, configuration, and performance enhances multi-line optimizations and can increase the performance of all providers' lines. Impacts of one line's crosstalk on another line can be monitored in real-time, and reconfigured on-the-fly, instead of using conservative static rules. Real-time variations can be correlated on multiple lines, for example a DSL sending higher power may correlate to a different provider's neighboring DSL receiving crosstalk that causes errors.

A DSM example is shown here, where downstream bit rates of VDSL were calculated via simulation with and without an SDAN architecture implementing DSM by sharing DSM data. This assumed VDSL2 Profile 17a, 0.5 mm, and a single network endpoint. The line lengths are uniformly spread from 300m to 575m, with up to 25 lines in the cable binder, and an average of 15 percent of lines in the cable are active and are equally likely to be vectored or non-vectored. With SDAN, the lines share data and participate in joint optimization of transmit spectra using the Iterative Waterfilling (IWF) DSM technique [6], and the vectored lines all achieve at least 100 Mb/s. Without SDAN the non-vectored lines are limited to transmit only below 2 MHz, the maximum static spectrum that ensures the vectored lines achieve at least 100 M/s. Figure 8 shows that using the SDAN for DSM data sharing can approximately double the line speeds in this case. Other tradeoffs can be implemented with SDAN and DSM to further increase speeds on chosen lines.

### Fault and Performance Monitoring and Test

The SDAN can automate monitoring, fault, and performance management operations between wholesale and retail providers, saving OpEx by automating interactions and improving customer satisfaction. Real-time monitoring is enabled for retailers. Use of cloud-based network monitoring can greatly enhance fault correlation, for example the root cause of multi-line faults may be identified across multiple providers' lines, and then fixed with a single dispatch. Programmable capability can allow retail providers to control the re-profiling or reconfiguration of their line settings, and to control the transitions between profiles.

### FTTdp

Fiber to the distribution Point (FTTdp) architectures are emerging that only use copper over the last few hundred meters from a Distribution Point Unit (DPU), extending fiber nearly to the customer while avoiding the considerable cost of installing fiber into a customer premises. The DPU is a very small, low-power device that needs to be energy efficient [14]. Computationally complex control and management functions should be performed remotely instead of in the DPU, which can be supported through an NFV abstraction layer [2]. Examples of such functions include QoS policies, filtering, multicast group control, dynamic address provisioning, authentication, authorization, and accounting. Virtualization can also support multi-tenancy and enable virtual unbundling of some functions.

### Customer Diagnostics

Customers have increasingly complex premises and home networks. Automated help systems for configuration and diagnostics will be increasingly called for from the consumer. One method of providing this is via a smartphone app that communicates with the CPE to extract diagnostics data from the CPE. The app then also communicates to a cloud-based SDAN system that analyzes the data and provides guidance, or automated re-configuration, to assist in repairing or enhancing the performance of the premises network and devices. This can also involve CPE that are specifically enhanced to extract diagnostics data from the customer premises and interact with the SDAN. CPE may also have additional capabilities such as noise cancellation that can be configured through a customer interface to the SDAN. Customer-end diagnostics can enable broadband customer self-install.

## SUMMARY AND THE ROAD AHEAD

Network capacity and complexity are exponentially increasing, and the cost of cloud-based computing and storage in large-scale data centers is decreasing just as rapidly. Broadband service offerings and customer broadband behavior are becoming increasingly sophisticated. Computation and storage on network elements is becoming prohibitively expensive by comparison, and network control functions will migrate into the cloud wherever feasible. In the case of access network elements, such a migration can also lower OpEx by minimizing the number of "touch points" needed to manage the network.

Using the SDAN for network management in virtual multi-operator environments is also a theme of this article. The SDAN can streamline inter-operator operations, lowering costs for wholesale and retail operators. Virtual competitive environments also allow innovative services creation, increasing the spread of superfast broadband.

Proliferation of the SDAN can advance by creating or corralling together a standardized common interface and a common architectural understanding. Relatively simple cloud-based systems for broadband network diagnostics, optimization, and configuration can serve as initial platforms for SDANs, with more involved control functions evolving as the broadband industry matures.

## REFERENCES

[1] Open Networking Foundation, https://www.opennetworking.org/index.php.
[2] ETSI GS NFV, "Network Functions Virtualisation (NFV); Use Cases," V1.1.1, 2013-10; available at http://docbox.etsi.org/ISG/NFV/Open/Published/.
[3] S. Sezer *et al.*, "Are We Ready for SDN? Implementation Challenges for Software-Defined Networks," *IEEE Commun. Mag.*, vol. 51, no. 7, July 2013.
[4] A. Devlic, W. John, and P. Skoldstrom, "A Use-Case Based Analysis of Network Management Functions in the ONF SDN Model," *Proc. European Workshop Software Defined Networking* (EWSDN), 2012, 25-26 Oct. 2012, pp. 85–90.
[5] K. Kerpez and G. Ginis, "Software-Defined Access Network (SDAN)," *Proc. 48th Annual Conf. Information Sciences and Systems*, CISS 2014, March 19, 2014.
[6] ATIS Std. 0900007 (2012), *Dynamic Spectrum Management Technical Report*, Issue 2.
[7] NICC ND-1513 (2010), *Report on Dynamic Spectrum Management (DSM) Methods in the UK Access Network*.
[8] M. Merka, "VULA, Virtual Unbundled Local Access, the Austrian Example," TNO DSL Seminar, June, 2012, The Hague, Netherlands.
[9] Operational Opportunities and Challenges of SDN/NFV Programmable Infrastructure, ATIS-I-0000044, 2013.
[10] TM Forum Multi-Cloud Management http://www.tmforum.org/DigitalServices/13907/home.html.
[11] Broadband Forum TR-147, "Layer-2 Control Mechanism for Broadband Multi-Service Architectures."
[12] NICC ND1436 (2013) *"Wires-Only" VDSL2 Modem Test Plan*.
[13] Active Broadband Networks, "Software-Defined Networking (SDN) Transforms Broadband Service Management" whitepaper, Sep. 2013
[14] J. Maes *et al.*, "Pushing the Limits of Copper: Paving the Road to FTTH," *Proc. IEEE Int'l Conf. Commun.*, ICC 2012, pp. 3149–53.

## ADDITIONAL READING

[1] Broadband Forum TR-252, "xDSL Protocol-Independent Management Model."

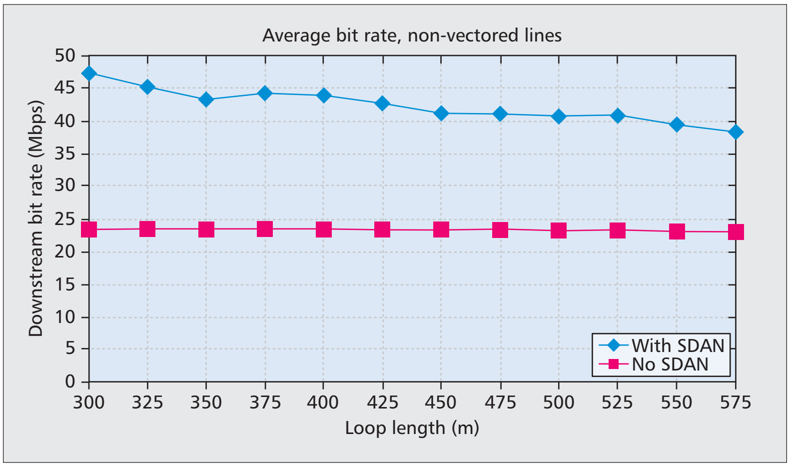


**Figure 8.** Example of the benefits of participating in SDAN.

## BIOGRAPHIES

KENNETH J. KERPEZ received his Ph.D. from Cornell University in 1989. He worked at Bellcore and Telcordia for 20 years, and now works at ASSIA. Dr. Kerpez became an IEEE Fellow in 2004 for his contributions to DSL technology and standards. He has many years of experience working on networks of all sorts, including DSL, fiber access, home networks, wireless systems, broadband service assurance, IPTV, IP QoS, and triple-play services.

GEORGE GINIS is senior vice president of DSL marketing with ASSIA, Inc., overseeing marketing and development of DSL network management products for service providers. He was elected a Fellow of the IEEE in 2013 for his technical contributions to DSL, including his work in inventing vectoring technology. He holds a diploma in electrical and computer engineering from the National Technical University of Athens, and M.S. and Ph.D. degrees in electrical engineering from Stanford University.

JOHN M. CIOFFI received his BSEE, 1978, Illinois; PhDEE, 1984, Stanford; Bell Laboratories, 1978-1984; IBM Research, 1984-1986; EE Prof., Stanford, 1986-present, now emeritus. He founded Amati Com. Corp in 1991 and was officer/director from 1991-1997. He currently is Chairman and CEO of ASSIA, Inc. His specific interests are in the area of high-performance digital transmission. Cioffi is the recipient of numerous highly prestigious awards and has published over 600 papers and holds over 100 patents. For more, see http://web.stanford.edu/group/cioffi/.

MARC GOLDBURG is EVP and CTO of ASSIA. His prior positions include CTO of ArrayComm and Member of Technical Staff at MIT Lincoln Laboratory. He has a Ph.D. from Stanford University, an MSEE from the University of Washington, and a BSE from Princeton Universtiy, all in electrical engineering. He is a Fellow of the IEEE and was selected as *Scientific American*'s Communications Researcher of the Year in 2002.

STEFANO GALLI received his Ph.D. in electrical engineering from the University of Rome (Italy) in 1998. He is the Director of Technology Strategy of ASSIA, where he leads the company's overall standardization strategy. Prior to this position, he held the role of Director of Energy Solutions for Panasonic and Senior Scientist at Bellcore. He is also serving as CIO and Member of the BoG of ComSoc, and as Rapporteur for the ITU-T Q15/15 standardization group on Smart Grid Communications. He is an IEEE Fellow and received several awards, including the 2013 IEEE D.G. Fink Best Paper Award, the 2011 IEEE ComSoc D.W. McLellan Meritorious Service Award, and the 2010 IEEE ISPLC Best Paper Award.

PETER SILVERMAN is Director, Standards and Technical Marketing at ASSIA Inc. Prior to employment at ASSIA he has been employed at Bell Laboratories, Ameritech, 3Com, and Valo Inc., before taking his current position at ASSIA in 2005. He has edited numerous international telecommunications standards, and is co-author of two books, *Understanding Digital Subscriber Line Technologies* (Starr, Cioffi, Silverman, Prentice-Hall, 1999) and *DSL Advances* (Starr, Cioffi, Silverman, Sorbara, Prentice-Hall, 2003), and 10 patents.