Special Report

Special Report: OpenFlow and SDN – State of the Union

Contents

Intro: Evolution of OpenFlow

Software-defined networking (SDN) has grown to encompass many protocols and software elements. OpenFlow has been identified as one of the leading protocols in the movement and the only defined SDN standard. In past year or two, some questions have emerged about the future of OpenFlow and its current status in the SDN universe. In this report, the SDxCentral research team gets to the bottom of things with an exhaustive investigation on the state of OpenFlow.

First, some background. The SDN revolution was kicked off with the development of OpenFlow in the 2008-2009 timeframe, much of the development taking place among a group of engineers at Stanford University. OpenFlow version 1.0 was released in 2009 and was substantially updated with the release of 1.3 in 2012. The Open Networking Foundation (ONF), a user-led organization focused on SDN, now manages the OpenFlow standard.

Many new technologies are both hyped and later maligned as they emerge, and the innovative OpenFlow has experienced both ends of the spectrum. So where is OpenFlow in the hype cycle? And how can we quantify its success? Our research indicates that both OpenFlow and SDN are alive and well, but these technologies find themselves trapped in an awkward stage of evolution. Their market advantages and efficiencies have been well defined, but commercial deployments are lacking. OpenFlow technology in particular needs to demonstrate its real-world efficacy with a string of high-profile deployments soon, or it risks losing momentum. This would likely damage the SDN movement in general, risking a descent back into the world of fragmented, proprietary solutions, the very scenario that SDN and OpenFlow promised to liberate us from in the first place.

Part of the challenge may have been the early excitement that was generated by OpenFlow when it was developed at Stanford University. This is what led Nicira, a startup that initially invested heavily in OpenFlow, to be acquired VMware for $1.3B in 2012. That set the expectation that OpenFlow technology could spawn a new generation of multi-billion-dollar SDN startups that used OpenFlow technology as the core of the next-generation networking platform.

More recently, questions have arisen about how fundamental OpenFlow is in the SDN movement. Within enterprises, OpenFlow has had limited success, especially in campus networks. There are early adopters in research and education and in some limited verticals like healthcare and logistics companies, but widespread adoption has been elusive. Within datacenters both at enterprises and service providers (carriers and cloud service providers), the traction has likewise been limited aside from the use of OpenFlow with virtual switches (such as OpenvSwitch).

Some major service providers believe that there aren't any production-ready OpenFlow devices that work at scale, and some major vendors don't offer OpenFlow-enabled physical devices or switches for POCs, trials, and potential deployments. At the same time, many of these large service providers and some of the world's largest cloud providers – including Google and AT&T – have been strong proponents of SDN and have embedded OpenFlow technology into their networks. In addition, the major networking vendors are part of ONF and participate in OpenFlow definition and in designing use cases, etc. and claim to ship OpenFlow products.

Why is there a disconnect? What is the reality? What our investigation has found is that many hardware vendors are paying lip service to OpenFlow without providing fundamental support for the technology, which is frustrating many end users. The primary issues involve interoperability and product documentation and support challenges in multi-vendor and hybrid environments. One could think of this as the classic innovator's dilemma, with the incumbent hardware vendors having little business motivation to support an open software product that could render their products obsolete or less competitive.

All of this has the potential to change in the next couple of years, however, as more powerful, programmable chips emerge and the white box market – which has the most potential for OpenFlow – continues to grow in scope. Many

new trials are in process and end users are testing a variety of next-generation SDN and OpenFlow solutions. Several new large-scale adoptions by additional cloud providers and global service providers could draw attention to OpenFlow and open source SDN solutions, tipping the market in its favor. But given our findings, the innovation will likely have to be driven by newer players with a software focus – or the white-box community, rather than the incumbent hardware vendors, who are unlikely to put serious resources behind open SDN technology.

A Note on Methodology: *This report was compiled after two months of research, including one-on-one interviews with more than 15 participants including leading end users (at least 7), members of industry foundations, and technology vendors. Our analysts also looked at research data gathered from our SDN Controller NV Survey, which had responses from a total of 200 participants, including at least 120 end users. To the best of our ability, we have presented an analysis of the aggregate perception of the evolution of OpenFlow today.*

OpenFlow Drivers and Demand

The fundamental innovation of OpenFlow is defining the communication protocol in an SDN environment that enables the SDN controller to interact with the forwarding plane of network devices such as switches and routers, both physical and virtual (hypervisor-based), so it can better adapt to changing business requirements. Technically, this is described as the separation of the control from the data forwarding plane – but a more important way to think about it is the creation of a more flexible switching architecture that abstracts control to software.

These innovations mean that functions that were previously captive to a number of proprietary routing and switching networking products can now be enabled as software only and are no longer captive to a proprietary system. One goal of the SDN movement was to have a collection of standardized hardware boxes that could be operated by separate software control, offering more flexibility and interoperability.

But here's the catch: in order to do this successfully – and enable a broad market for software-only switches – there needs to be a deep and reliable ecosystem of interoperable components and parties that can guarantee hardware and software interoperability. Our research indicates that this is the major challenge of OpenFlow.

That doesn't discourage the ultimate attraction of an SDN environment, according to what end users tell us. In our interviews with market participants, we have found that the same advantages hold true today. That is, the strengths of SDN and OpenFlow-based solutions include:

- Simpler network design and troubleshooting, which can also lower operational costs
- Service agility and the capability to add features faster and allow independent innovation without changes to hardware
- Lower costs for both hardware and support via hardware/software disaggregation

Service providers are still attracted to the potential of OpenFlow for its ability to deliver a disaggregated control and forwarding plane, more flexibility, and lower average costs. In fact, probably the most common critique we hear is that it's not happening fast enough – not that they don't want it.

"OpenFlow provides very good troubleshooting and operations," one large North American service provider engineer told us. "You can manage and control the network in a holistic way — a better end-to-end view. The capability of centralized control and management helps operational activities."

Several users backed this up – that they like OpenFlow – and that they believe it's evolving. The users below pointed out that the IP networking ecosystem took two decades to evolve, and that OpenFlow may just be along a typical evolutionary path for new technology.

Many of the service providers we interviewed are actually using OpenFlow in their network. In fact, we identified two major service providers that are using it to roll out new services, including building their own software and

white boxes to deliver these services. We have identified many core, specific applications for which OpenFlow appears to have significant support (See Appendix: Summary of OpenFlow Support for SDN in Market Products). The service providers we spoke with presented many viable use cases including layer 3 traffic management used in conjunction with routing and BGP, the CORD initiative for carrier data centers, top-of-rack switching (white box), core data switching, SD-WAN gateways, and even packet optical applications. We will go into more detail on the potential use cases and where OpenFlow is being used today, but it's clear that on the service provider side, there is still significant interest in the use of this technology to solve many of their most vexing problems.

Key Deployments & Use Cases

With all of the debate about OpenFlow and SDN progress, it's real-world deployments that will eventually tell the story. Many market participants have expressed frustration that commercial deployment is taking longer to develop than initially thought, but there are actual deployments taking place at both service providers and enterprises, so it's worth taking a look at these in more detail.

Here are some of the deployments that have been observed so far and what's driven them.

Google

Google, which manages one of the largest enterprise networks and cloud deployments in the world, is a big fan of OpenFlow. Engineers with direct experience with OpenFlow point out that it's a key element of the Google architecture.

In a summary report on Google's infrastructure from 2014, Google technical expert Bikash Koley wrote that OpenFlow support is key to Google's SDN infrastructure, which is primarily built with white box switches and commodity hardware. "The only way to get well defined control and data plane APIs on routing HW [hardware] at that time was to build it ourselves," wrote Koley, telling the now well-known story of Google's homegrown network.

http://static.googleusercontent.com/media/research.google.com/en//pubs/archive/42948.pdf

It's important to note that the scale at which Google is using OpenFlow is quite wide: It's using it both inside the data center and to interconnect data centers, which is a wide-area network application. The company also uses OpenFlow to model and implement traffic engineering of the network across data centers, a use case that would work in some of the world's largest service providers.

Other Google executives such as Vint Cerf, vice president, and **Urs Hölzle**, senior vice president of technical infrastructure, have pointed out that OpenFlow is one of the important technologies that drives Google's networking infrastructure. It's important to note that OpenFlow is just one of many networking protocols Google uses, but it is the primary protocol used for communicating control to the data plane from network controllers, working in conjunction with protocols such as BGP and PCE-P.

So, despite OpenFlow naysayers, Google remains the chief proof point that the technology can be implemented at scale to build an SDN network. More recent private conversations with Google engineers have surfaced that OpenFlow continues to be a protocol that Google believes is important and that they continue to support.

Cornell University

In another example, stateside, Cornell University's computing and information scientists deployed NEC's SDN and NV virtualization technology, which is based on OpenFlow. Scott Yoest, IT director of Computing and Information Science at Cornell's College of Engineering, says that SDN technology gives the network better performance and flexibility by allowing traffic flows to be redirected dynamically.

REANZZ, New Zealand

REANZZ is New Zealand's own national research network. **It's running one of its enterprise networks on an SDN switching system** based on OpenFlow, with the goal of providing an open networking environment. REANZZ says this project could pave the way for SDN to be implemented by its members, which include all New Zealand universities, Crown Research Institutes, and leading institutes of technology and polytechnics.

The REANNZ SDN project uses hardware provided by Accton Technology Corporation and Allied Telesis, using OpenFlow-based technology. REANNZ official say that its engineers have also been worked with Big Switch Networks and the Open Network Linux team to evaluate SDN technology

ToulX, France

ToulX, one of France's leading Internet exchanges, is using OpenFlow-based technology to operate and provision its networking infrastructure. The company claims to be the "first Internet Exchange Provider in Europe to fully leverage OpenFlow."

ToulX used a white box switching system designed by Pica8 to program and optimize the network fabric for its exchange, where it is used for Internet traffic peering. ToulX says that it can cut down on network outages and congestion caused by broadcast storms, increasing performance and uptime.

Géant, Switzerland

Technology firm Géant, whose network connects more than 10,000 research institutions such as the CERN physics lab in Switzerland, **said it is deploying SDN** using a combination of Infinera's packet-optical technology, Corsa Technology's programmable switching and routing platform, and the Open Network Operating System (ONOS) SDN controller, which includes OpenFlow as a southbound protocol.

Géant says its network can use this SDN and OpenFlow technology to handle traffic at different layers, including an SDN Layer 3 domain that also routes traffic to the general Internet. This is accomplished with an ONOS application known as SDN-IP, which provides a mechanism to share routing information between legacy and SDN domains. The company says its use of OpenFlow-based controllers is key to the programmability of the network as well as its capability to interact with the packet-optical network.

More Common Use Cases for Reference

Some of the examples above have been cited publicly, but there are also wide range of test deployments and projects that have not been announced as commercial deployments and yet others that have only been described in private.

Below we aggregated the many different kinds of use cases that have been described by both public information and private discussion in both enterprise and service provider operators using OpenFlow.

Some of the use cases we have seen or heard about are referenced below:

Use Case #1: Data Center Switching (white box ToR in leaf/spine deployment)

- At least two major service providers said they are building their own top of rack switches (ToR) for the core using white boxes and OpenFlow technology.
- Service providers cite challenges with commercial vendor operability with OpenFlow as a reason to develop their own white box.
- OpenFlow is typically supported, but white boxes must also support other protocols.
- Typical features desired include bridging, routing, multicast, and ECMP
- At least two major service providers say they are working with chip vendors directly to build their own white box.

- ToR white boxes are likely to support future programmability and languages such as P4.

Use Case #2: Central Office Re-architected as a Data Center (CORD)

- Joint project pioneered by ONOS/ON.Lab and AT&T.
- Value proposition to reduce opex and capex costs and provide an interoperable environment with replaceable commodity hardware.
- Uses OpenFlow control protocol in ONOS-controlled switch
- Control plane services typically include VPN, MPLS tunneling.
- Data plane services can include: WAN optimization, applications priority, parental control.
- Important for delivering applications for cloud access and services.
- Works with OpenStack to deliver NFV services.
- Some service providers cited compatibility issues with other commercial switches.
- More deployments could lead to momentum.
- Has undergone PoC and is in field trials at AT&T.
- Other operators appear to be "watching AT&T" to see what happens.

Use Case #3: Core Packet Transport

- Global service provider told us they are looking at using OpenFlow table type pattern (TTP) to handle port flow, including VLAN and MAC tables.
- Could be used for IP access controllers.
- Several service providers cite value of OAM management.
- Feature set could include switch path protection using OpenFlow.
- Could be applied to wireless in a case where a mobile operator does not have a lot of optical infrastructure.

Use Case #4 Campus Network and WAN access

- SD-WAN switches can enable access policy for WAN access.
- Could be used to monitor and enforce SLAs.
- Other features include application prioritization and other WAN features such as WAN optimization.
- Can be implemented as data-center based switch with software, virtual Customer Premises Equipment (vCPE), or CPE white box.
- Can also include security applications such as policy monitoring or real-time firewall updates.

Key Market Challenges: What's Blocking Broad OpenFlow Adoption?

So, if we know that OpenFlow still holds promise in the minds of end users, what's slowing overall deployments? The overwhelming thing that we hear from industry participants and end users alike is that there is not enough cooperation and interoperability testing in the OpenFlow "ecosystem" to deliver ready-for-market solutions. This may come down to something as simple as all of the features not being supported in a network processor. Or, in the case of incumbent hardware vendors, not providing a thorough list of all supported OpenFlow features and testing such features adequately.

Service providers observe that there are few production-ready OpenFlow devices from incumbent networking hardware vendors. As we've mentioned, this has driven several operators to develop their own white boxes – they like the technology, they just couldn't find anybody else to package it for them.

There are many reasons for this, but it is at the root of many of OpenFlow's barriers to adoption. In interviews with industry participants and service providers, our findings were consistent: Most believe that a full-blown OpenFlow ecosystem that includes incumbent networking vendors has yet to blossom and that this is the primary barrier to adoption, causing several challenges at once.

Let's talk about how this more strategic barrier can link to other barriers to adoption. Here is a list of our findings of OpenFlow's challenges:

- For incumbent networking vendors: Because their business is based largely on hardware, they have a hard time developing the business case of charging for software only, especially when OpenFlow disaggregates software control from the hardware, allowing the software to run on low-cost COTS servers
- Lack of a broad ecosystem among a variety of hardware vendors to support OpenFlow features and guarantees interoperability
- Challenges with scaling OpenFlow to millions of flows necessary in the largest operator environments
- Lack of widely available information on specs supported in individual products
- Market perception and branding

Let's run through each of these in more detail

The Business Case: Incumbents' Dilemma

Why is the business case so important? Many view SDN as "lots of free stuff" because there are many open source projects and code bases available for use in the public domain. This is an oversimplification of the market and ignores the value of open source and how additional value can be created through integration, testing, and support, but it's an issue that comes up in the executive offices of many large, profitable technology incumbents.

If a hardware-based networking vendor is defending its installed base, it has less incentive to jump to the next technology, especially if it is based on widely available open source technology. It's therefore more sensible to "spin" the new technology with a twist – perhaps adding a proprietary edge – to differentiate the product and perpetuate a hardware-based business model.

This basic business challenge raises the question of whether traditional hardware vendors (such as Arista, Cisco, Juniper) have anything to gain from enabling broad OpenFlow support on a white-box scale. In addition, adding OpenFlow support to a product architecture that was not designed for an open SDN environment does not make sense. From a business strategy standpoint, they are focusing on their own proprietary enhancements to SDN instead of OpenFlow. This could be either a conscious or subconscious strategy – but it's something the end users think about every day. With whom do they invest? Where do they place their chips?

"We have a love/hate relationship with incumbent vendors," one major North American service provider told us. "[An incumbent vendor] was trying to lead the effort [on SDN technology], but they created a whole new platform instead of embracing OpenFlow. They have different plug-ins to support brownfield. When it comes to service providers we need a clean reference architecture that embraces new technologies. That's not being supported well by incumbent vendors."

Whether the decisions to stall OpenFlow development are subconscious or conscious, this is a force in the market that is discussed by end users everywhere. And our investigation into vendor support concludes that it's happening in subtle ways on many levels – ranging from providing inadequate documentation or lack of focus on addressing interoperability issues between OpenFlow features on different vendor boxes. At some vendors, it's directly a result of limited resources dedicated to OpenFlow versus those dedicated to non-OpenFlow projects. So while the OpenFlow champions in these companies are working as hard as they can and support the cause, there's a limited number of them.

Key Interoperability and Scaling Issues

The message is loud and clear from both end users and market participants about the technical issues holding back OpenFlow: Interoperability, testing, and ability to scale are still lacking.

This is not an issue with the core OpenFlow technology, but a limitation on the development of key pieces of the ecosystem, including more detailed cooperation between the chip vendors and legacy hardware vendors. The chorus of blame toward the incumbent hardware vendors is pretty strong, with one industry participate telling us "When you implement OpenFlow with a legacy vendor it just doesn't work."

Conversely, we had several people tell us that startups are doing good work, and that there are clean implementations of OpenFlow that can scale to reasonable throughputs – say 100Gbps ports on a switch. But broad proof points of scalable OpenFlow are still lacking.

Here are a few of the technical scalability and interoperability issues we have identified as reported by engineers deploying OpenFlow in production or proof-of-concept testing:

Incomplete Support for Standards

- Some incumbent hardware vendor equipment cannot modify packet headers, limiting their usefulness in routing or switching applications.
- Others can modify L2 headers, but are unable to do L3 rewrites.
- Many hardware implementations have limited matching capabilities – matching VLANs in VLANs for instance (QinQ), MPLS labels, or even IPv6.

Inconsistent Tables Access and Limited Pipeline Management

- Some users report issues with simple OpenFlow 1.0 implementations that only use the TCAM for flow matching, citing the limited number of flows supported and preventing widespread deployment. In general, TCAMs might support at most 2K entries, while exposing the L3 or VLAN tables can get to 128K entries (which work for limited header matches).
- Some vendors do not provide full access to the various tables available on the hardware and force the controllers to conform to their proprietary pipelines. This has forced some controllers (like ONOS) to add an abstraction layer to provide the necessary mapping, adding to complexity and reducing consistency in terms of expected performance from switching equipment.

Disparate Capabilities and Performance across Switches

- Differences in implementation and performance characteristics between different HW depending on whether NPU-based, FPGA-based, or ASIC. Trade-offs between flexibility and conformance with OpenFlow 1.0/1.3/1.4 and performance (number of flows, latency, packet-forwarding rates).
- Even the same ASIC chipset can provide different OpenFlow capabilities based on the implementation of the switching software. Often, incumbent switching vendors will expose fewer capabilities than whitebox manufacturers (both using the exact same ASIC) looking to take advantage of the open OpenFlow movement.
- While providing maximum flexibility and rich OpenFlow support, NPUs tend to max out around 300-600Gbps in aggregate throughput, while ASICs can get to 1-3Tbps of aggregate throughput, but provide limited OpenFlow support (though new ASICs are showing up that can handle 3+Tbps while supporting large routing tables – up to 1M).
- The distinct characteristics of each switch including how much of the pipeline is exposed and feature capabilities (or unexpected edge case handling) limit the portability of implementations and the lack of consistent performance characteristics makes wide roll-out challenging.

- Performance limitations limit the type of implementations possible with OpenFlow today, though by selecting the right hardware platform it is possible to get L3 routing in even large scale networks.

Market Perception and Branding

Another challenge for OpenFlow will be establishing a stronger brand amidst of a clutter of marketing noise. The most successful open source projects, including flavors of Linux, have attained global brand penetration and are now considered checklist items.

One major reason for this is that if end users are going to commit to the technology, they need to see a broad amount of support and momentum behind the project. Brand recognition goes a long way toward instilling this confidence.

Part of this is certainly the competition with the incumbent vendor networking products. They invest heavily in sales and marketing, and to a certain extent OpenFlow needs to become part of the picture.

Conclusion: OpenFlow is Evolving – How It Could gain Momentum

Our investigation into the state of OpenFlow and SDN revealed some interesting discoveries. First, over all, we found that OpenFlow is more highly regarded as a technology than many would attest. Because of its unique positioning as an open source solution, much of these advantages lie "under the cover" and have not been exploited to the maximum. End users, particularly service providers, would like to see the technology evolve further and gain further adoption as they see many advantages to using it in their networks.

On the downside, as we have explained, OpenFlow has some technical and business hurdles. We have confidence that the technical hurdles will be worked out – they are quite common for an innovative technology still in a relatively early stage of development. OpenFlow is moving out of its bleeding edge state and into a more mature development cycle, so we expect to see technical fixes to some of the scaling issues in the next couple of years.

A more challenging issue is the barriers provided by the business challenges. The best technology does not always win – and often new technology threatens the status quo. The networking hardware industry is immense – hundreds of billions of dollars – and has been built up over many decades using the same business model: Selling boxes. Disaggregating the software and hardware in the box and presenting the software as the chief value in networking has proven to be a challenging issue for many incumbent networking vendors, who see this as a reason to delay or at least slow down the process in order to come up with new software-based business strategies. On the startup side, it's very hard to fund startups that can support the largest customers – service providers and webscale cloud providers. Billions of dollars in capital is needed to create a startup SDN ecosystem.

For this reason, as one of our favorite sources in the industry has said, "the incumbents have won the first half of the game." But we have reason to believe that the SDN and OpenFlow story is not over – primarily because of the enthusiasm expressed by several leading-edge users, as well as ratification of the technology by several major service providers. In our one-on-one interviews, service providers in particular praised OpenFlow technology and expressed disappointment that leading commercial vendors were not more cooperative in bringing solutions to market.

So, OpenFlow remains at a critical juncture. It's possible that it will continue to evolve in the open source community and will be championed by a few leading startups as well as service providers and large enterprise customers using it to build their own solutions. Better yet, leading networking incumbent vendors will take strides to document, test, and demonstrate OpenFlow compatibility in their products.

Could OpenFlow gather momentum? Is it stalled? Are different approaches such as P4 a logical step forward that obviates the need for OpenFlow? The answers to these questions are not simple yeses or nos. OpenFlow is evolving and it will continue to evolve over the next few years. Given the success of other open source

technologies, it's silly to dismiss it. There are a number of factors that could lead it to gather momentum in the coming years.

Here are some of the elements we believe are needed to kick OpenFlow adoption into gear:

- Service providers and cloud providers developing their own white-box solutions based on OpenFlow, and "cutting out" commercial vendors will raise awareness of the technology among startups, incumbent vendors, or contract manufactures to evolve a "operator-ready" OpenFlow-enabled white box that can be manufactured at scale.
- Service providers and cloud-scale providers need to pressure incumbent vendors to be more transparent about their OpenFlow interoperability. We see this starting to happen at several service providers.
- Proponents of OpenFlow need to point to the success of open source solutions in the cloud world, and convince other markets (industrial enterprise, service providers) that open source networking, including OpenFlow, will eventually dominate other verticals as well.
- OpenFlow proponents need to focus on the scaling issues, especially multi-table support. These are important technical issues that need to be fixed in order for the technology to become more mainstream.
- OpenFlow proponents need to drive more interoperability efforts, especially partnerships between existing hardware vendors that demonstrate feature compatibility across branded hardware platforms. This requires a concerted effort at the top levels of executive management, to assure such efforts are executed and receive high visibility.
- More effort should be put into identifying OpenFlow success stories and explaining why they worked.
- The industry needs to consolidate around an OpenFlow-focused solution. An important step would be for a large networking player to buy a leading OpenFlow SDN startup, or for several startups to combine efforts in more fruitful alliances.
- The white box market needs to do a better job of documenting support for OpenFlow and shipping more fully featured solutions.

While there is no guaranteed way to drive OpenFlow to the next level, the starting point should be removing the obstacles we came across in our survey of leading voices in the open networking movement. OpenFlow is an integral part of the open networking movement, and in many ways one of the sparks that ignited this move. With the right next steps, OpenFlow can continue to be highly relevant and a driver for an open networking future.

Appendix: Summary of OpenFlow Support for SDN in Market Products

OpenFlow is one of the key protocols supporting SDN products. Support for the OpenFlow protocol is broad, found on over 100's of products, but the approach is varied among existing vendors. Our research found OpenFlow 1.3 as the predominant version supported by more than 23 established networking vendors including both large companies such as Hewlett Packard and Cisco and smaller organizations like Pica8 and Allied Telesis.

Building a robust network solution even with a vendor's own existing networking gear can be a challenge due to the differences in hardware, software, and other variants from the core, to the edge, to the customer premise. Building a multi-vendor solution can exacerbate those challenges. OpenFlow is no different.

Because existing proprietary hardware is so varied, this means there is fragmented support for OpenFlow feature sets. Leading incumbent networking vendors such as Arista, Brocade, Cisco, Juniper (and others) do support OpenFlow, but each piece of networking gear may have limitations or constraints. This may seem like another layer of complexity in an already complex world. However, the end goal of managing a truly software-defined network may well be worthwhile.

Additionally, vendors document support for OpenFlow in as many ways as there are products. Some have complete OpenFlow technical specifications, others have OpenFlow sections in each individual products datasheets, while others only offer press-releases or marketing materials of such support.

SDNs that support flow-based switching provide network operators a brighter more resilient future. The industry appears to be in a 'storming' mode today, and will move to the forming mode in the coming years. OpenFlow is the best positioned, grassroots based technology to provide that future because it is truly open, multi-vendor, and low-cost.

In order to give the community an extensive view of how OpenFlow is being supported in current products, the SDxCentral research team conducted an extensive review of public product documentations, web sites, and announcements. We have complied our review of OpenFlow supported products in the list below.

Disclaimer: *The information was gathered from publicly available documents and company websites – we cannot guarantee the accuracy of these claims. In addition, products listed with OpenFlow "support" may not necessarily be interoperable or compliant in all production environment, and support in many cases is very limited to specific environments. The list below is not intended to be an all-inclusive list, but it is a summary of the vendors and products in the SDN and OpenFlow market that have the most visibility in the SDxCentral community, based on our proprietary database, user surveys, and interviews with users.*

Accton

SDxCentral Directory Listing

www.accton.com

Summary of OpenFlow Support:

- Accton claims support for open network operating systems and distributions and thus directly OpenFlow 1.3 including ONF's Atrium distribution.
- Accton has a wholly owned subsidiary called Edgecore Networks Corporation that specializes in open leaf and spine style datacenter network architectures ranging from 10Gb-E to 100Gb-E.
- Accton has little documentation around support for their capabilities. It states that it has support for Cumulus Linux (which does not support OpenFlow), ONF's Atirum open-source SDN distribution (which supports OpenFlow), and Pica8's PicOS (which does support OpenFlow).
- Accton switches come installed with ONIE (Open Network Installer Environment).

Key products supporting OpenFlow	
• AS7712-32X • AS6812-32X • AS5812-54T	• AS5712-54X • AS5710-54X • AS5600-52X

Allied Telesis

SDxCentral Directory Listing

www.alliedtelesis.com

Summary of OpenFlow Support:

- Supports OpenFlow 1.3
- Allied Telesis was installed at ONF in **full OpenFlow configuration**.
- Allied Telesis positions its products as a complete solution where switches can be managed by Allied Telesis Management Framework and operate in OpenFlow mode for a complete solution that has both management and control planes available to admins.

Key products supporting OpenFlow
• AT-x230 family - 5 switches • AT-x510 family - 11 switches • AT-x310 family - 4 switches • AT-x930 family - 5 switches • AT-DC2552XS - 1 switch

Arista

SDxCentral Directory Listing

www.arista.com

Summary of OpenFlow Support:

- Starting 4.12.3, EOS supports OpenFlow (version 1.0 and 1.1) and with EOS 4.1.5.2F, EOS now supports OpenFlow 1.3 (wire protocol, enhancements to support IPv6 matches and actions, support for the SELECT action group etc.).
- It is not clear if OpenFlow 1.3 is supported on all Arista products. Clearly documented products are outlined below.
- Arista EOS also supports a controller-less mode relying on Arista's DirectFlow to direct traffic to the SDN applications (for example, TAP aggregators). This lets the production network run standard IP routing protocols, while enabling certain flow handling to be configured programmatically for SDN applications. All the 7050 series switches support OpenFlow and DirectFlow, and the topology can be configured via eAPI, Arista's JSON-over-HTTP configuration solution.
- Support for OpenFlow is not well documented throughout the solution, and in fact, many references speak to **only OpenFlow 1.0 support**. However, there are other various documents that state support for OpenFlow 1.3.

Key products supporting OpenFlow
• 7280SE • 7050, & 7050X • 7500 families • (www.enterprisetech.com/2014/07/15/arista-cranks-leaf-switches-100ge-big-data-storage)

Brocade

SDxCentral Directory Listing

www.brocade.com

Summary of OpenFlow Support:

- Brocade supports OpenFlow 1.3: "We offer OpenFlow support across our portfolio, so you can realize the benefits of SDN throughout your data center, WAN, and campus network."
- Brocade says it offers "scalable, SDN-enabled and SDN-ready networking platforms, including the Brocade MLX Series router, Brocade VDX switch, and Brocade ICX switch families."
- Brocade also supports OpenDaylight via its SDN Controller.
- Brocade also supports a matrix set of instructions on various products. Details of implementations can be found at www.brocade.com/content/dam/common/documents/content-types/configuration-guide/nos-700-sdnguide.pdf and other documents.
- There are a myriad of considerations and restrictions when configuring OpenFlow across the various product families.

Key products supporting OpenFlow

Brocade VDX 2741
- Brocade VDX 6740
  - Brocade VDX 6740-48
  - Brocade VDX 6740-64
- Brocade VDX 6940
  - Brocade VDX 6940-36Q
  - Brocade VDX 6940-144S
- Brocade VDX 8770
  - Brocade VDX 8770-4
  - Brocade VDX 8770-8
- Brocade NetIron CES 2000
- Brocade NetIron CER 2000
- Brocade MLXe-4, Brocade MLXe-8, Brocade MLXe-16, Brocade MLXe-32
- ICX 6430, ICX 6450, FCX, ICX 6610, ICX 6650, FSX 800/FSX 1600, ICX 7250, ICX 7450, ICX 7750
- Brocade SDN Controller

Centec

SDxCentral Directory Listing

www.centecnetworks.com

Summary of OpenFlow Support:

- Centec makes a range of "white box" switch hardware.
- Centec claims OpenFlow 1.3 minimum support.
- Claims 1.3.1 support in their Centec V350 box.
- Product includes cut-through forwarding for low and fixed latency.
- Centec specialize in large scale, low latency, high throughput carrier grade solutions.
- Their GoldenGate reference switch runs ONIE with ONF Atrium support

Key products supporting OpenFlow

- GoldenGate 580
- V150
- V330
- V350

Ciena

SDxCentral Directory Listing

www.ciena.com

Summary of OpenFlow Support:

- Ciena and its SDN/NFV division, Blue Planet, both offer software and products that support OpenFlow.
- Ciena has been a member of the ONF since its **founding** in March 2011.
- Ciena's Optical Transport Working Group is charged with figuring out how to extend the benefits of SDN and OpenFlow to the optical network domain.
- Ciena's Blue Planet software is based on over 15 open source components.

Key products supporting OpenFlow

- There is limited to no documented support for OpenFlow on Ciena or Blue Planet websites. There are multiple blog posts that contain an OpenFlow tag, but little else.
- Ciena speaks to applying SDN/OpenFlow to optical transport, and BluePlanet announces demonstrations at OpenFlow World Congress but there is limited documentation on the website regarding compatibility or support.
- Here is an example of multiple demos referenced: www.ciena.com/connect/blog/Transport-SDN-interop-a-QA-with-Lyndon-Ong.html

Cisco

SDxCentral Directory Listing

www.cisco.com

Summary of OpenFlow Support:

- Cisco supports subset of OpenFlow 1.3 and OpenFlow 1.0 functions in various implementations.
- Based on the vast number of Cisco platforms, a number of restrictions and constraints are outlined in detail in the **configuration guide** that makes OpenFlow on Cisco equipment a complex proposition.
- Cisco has a (both) complementary and competitive offer called OpFlex that focuses on policy control and keeping the control in the network vs. controller.

Key products supporting OpenFlow

- Cisco Nexus 9300 Series switches
- Cisco Nexus 3000 Series switches
- Cisco Nexus 31128PQ switch
- Cisco Nexus 3232C switch
- Cisco Nexus 3264Q switch
- A controller can be Cisco Nexus Data Broker (NDB), or any controller compliant with OpenFlow 1.3

Cumulus

SDxCentral Directory Listing

https://cumulusnetworks.com

Summary of OpenFlow Support:

- http://jedelman.com/home/big-switch-cumulus-and-openflow
- Cumulus is a Debian Linux based Network Operating System built to run on various "bare metal/white box" networking hardware.
- Cumulus is one of a few network operating systems designed to create white-box SDN switches. Others include, but are not limited to Big Switch's Switch Light, Pica8's PicOS and more.
- Cumulus is often one of the choices in bare metal switches running ONIE.
- Cumulus is a de facto L2/L3 standard in this space with large partners such as Dell
- OpenFlow is not publicly stated as a focus.

ECI Telecom

SDxCentral Directory Listing

www.ecitele.com

Summary of OpenFlow Support:

- ECI Telecom supports OpenFlow 1.3.
- ECI Telecom is a big proponent of OpenFlow (https://blog.ecitele.com/3-reasons-to-resist-the-urge-to-abandon-openflow)
- Products include the Apollo and Neptune (NPT) packet optical product lines.
- ECI uses LightCONTROL, ONOS based controller
- Company ships LightAPPS SDN applications.
- The company's Applications Software Layer (part of ECI's architecture) SmartLIGHT supports "smart migration" to SDN, enabling customers to enjoy the benefits of SDN applications immediately, on their current installed base.

Ericsson

SDxCentral Directory Listing

www.ericsson.com

Summary of OpenFlow Support:

- Ericsson supports OpenFlow 1.3
- Ericsson thinks that SDN and Network Functions Virtualization (NFV) are complementary technologies and that SDN is an essential and integral component of the NFV transformation.
- Ericsson uses software agents (example: OpenFlow v1.3 agent) to add OpenFlow capabilities to various products.
- The Ericsson SDN solution is a comprehensive package combining the network infrastructure, the OSS/BSS systems and Consulting and System Integration services.

Supported Products
• Ericsson's SDN controller is a commercial (hardened) version of open source OpenDaylight (ODL) SDN controller. • Specific products are not easily identified as each product is specified in its own datasheet as to its support for OpenFlow such as https://www.ericsson.com/res/site_US/docs/2014/connections/iPECS-ES-5652X-DataSheet.pdf, but there appears to be a broad basis of support.

Extreme Networks

SDxCentral Directory Listing

www.extremenetworks.com

Summary of OpenFlow Support:

- Extreme Networks is a member of the Open Networking Foundation (ONF), and has integrated OpenFlow into its portfolio to simplify and automate complex provisioning tasks, as well as allow customers the ability to customize their SDN solution.
- ExtremeXOS Release 15.7 contains an upgrade to version 1.3 of the OpenFlow protocol.
- Like other hardware-based switch vendors, there are multiple limitations and constraints that must be adhered to in order to implement OpenFlow. Example: "Flows implemented using ACL hardware have platform limitations on the simultaneous combinations of flow match conditions that can be supported. These limitations are described in each version of ExtremeXOS Release Notes under the ACL description section, and in the Flow Match combinations table later in this section. When receiving a flow match combination that cannot be supported with the platform's ACL hardware, the switch will generate an OpenFlow error message to the controller."

Key products supporting OpenFlow	
• Summit X440 • Summit X460 • Summit X460-G2 • Summit X480 • Summit X670 • Summit X670-G2 • Summit X770	• BlackDiamond X8 with a single MM module. • BlackDiamond 8K – 8900 (XL-Series) and C-Series with single MM only. • SDN OneController

Fujitsu

SDxCentral Directory Listing

www.fujitsu.com/global

Summary of OpenFlow Support:

- Fujitsu supports the standard OpenFlow 1.3 protocol in multiple products, including the Virtuora SN-V as its control interface.
- Fujitsu has collaborated with other members of the ONF Optical Transport Working Group to develop the OpenFlow extensions that were prototyped and tested in both CDPI (Control Data Plane Interface) and CVNI (Control Virtual Network Interface) forms.
- Fujitsu aligns SDN and NFV as two trends in the optical transport world and delivers an architecture and solution that incorporates both, together.
- Fujitsu has participated in multiple "Demo's" in 2014, but documentation is light for both products and activity in 2015 and 2016.

Key products supporting OpenFlow

- FLASHWAVE CDS
- FLASHWAVE 9500 Packet Optical Networking Platform (Packet ONP9500 platform)
- Virtuora NC, a full-featured virtual network environment based on OpenDaylight, it has been architected to be easily portable to other SDN controllers, such as the emerging ONOS platform.
- Virtuora SN-V, a virtual network control and high-speed data transport system that supports monitoring and troubleshooting functionality.
- Virtuora NFV Manager, provides resource management and orchestration for virtual network functions.
- Virtuora SDN/NFV Applications is an ecosystem of individual functions that offer choices in service creation and operational efficiency. Several applications are available from Fujitsu today, including Dynamic Service Activation and Wavelength Defragmentation.

H3C

SDxCentral Directory Listing

www.h3c.com

Summary of OpenFlow Support:

- H3C supports OpenFlow 1.3
- In February 2016, four S6800 switches and eight S5130-HI switches, designed by Hangzhou H3C Technologies Co., Ltd. (H3C), officially passed the OpenFlow v1.3 conformance test conducted by BII - Global SDN Certified Testing Center (SDNCTC), and won the OpenFlow v1.3 Certificate of Conformance granted by the ONF.

Key products supporting OpenFlow

- H3C VCF Controller
- H3C S6800-4C
- H3C S6800-2C
- H3C S6800-32Q
- H3CS6800-54QT
- H3CS5130-54S-HI
- H3CS5130-54C-PWR-HI
- H3CS5130-54C-HI
- H3CS5130-34C-HI
- H3CS5130-30S-HI
- H3CS5130-30F-HI
- H3CS5130-30C-PWR-HI
- H3CS5130-30C-HI

Hewlett Packard Enterprise

SDxCentral Directory Listing

www.hpe.com

Summary of OpenFlow Support:

- HPE supports OpenFlow on 50 switch models and an SDN Controller.
- Over 30 million installed ports are OpenFlow capable.
- HPE has broad support for OpenFlow 1.3

Controllers (1.0 and 1.3 compliant)

- HPE VAN SDN Controller Software

Key products supporting OpenFlow

- HPE Switch 2920 series
- HPE Switch 3500 series
- HPE Switch 3800 series
- HPE Switch 5400 series v1 and v2 modules
- HPE Switch 6200 series
- HPE Switch 6600 series
- HPE Switch 8200 series v1 and v2 modules

FlexNetwork Switches

- HPE FlexNetwork 5130 EI Switch Series
- HPE FlexNetwork 7500 Switch Series

HI Switch Series

- HPE 5130 HI Switch Series
- HPE 5510 HI Switch Series

Flexfabric Switch Series

- HPE FlexFabric 5700 Switch Series
- HPE FlexFabric 5900CP Switch Series
- HPE FlexFabric 5930 Switch Series
- HPE FlexFabric 5940 Switch Series
- HPE FlexFabric 5950 Switch Series
- HPE FlexFabric 7900 Switch Series
- HPE FlexFabric 12500 Switch Series
- HPE FlexFabric 12900 Switch Series
- HPE FlexNetwork 10500 Switch Series

Aruba

- HPE also has a number of Aruba switches that support OpenFlow

Huawei

SDxCentral Directory Listing

www.huawei.com/en

Summary of OpenFlow Support:

- Huawei supports OpenFlow 1.3
- Huawei has achieved ONF OpenFlow Conformant: Certified Products that include
  - S5700: L3 Ethernet Core Switch with 48 10/100/1000BASE-T, 4 10GE SFP+
  - S7700: L3 Ethernet Switch with 48 10/100/1000BASE-T card
  - S9300: L3 Ethernet Switch with 48 10/100/1000BASE-T card
  - S6720EI: L3 Ethernet Switch with 48 x GE SFP/10 GE SFP+2 QSFP+ 4 x40GE QSFP+
  - S5720EI: L3 Ethernet Switch with 28 10/100/1000BASE-T, 4 Combo SFP Ports and 4 10GE SFP+
  - S12700: L3 Ethernet Core Switch with 48 10/100/1000BASE-T card
  - CloudEngine: Highly versatile, SDN-ready Ethernet switches
- Huawei appears to have fairly robust support for OpenFlow and plans for the future based on its intention to support OpenFlow 2.0 in its documentation. “Huawei further extends OpenFlow and develops Protocol Oblivious Forwarding (POF), which is based on the idea of programmable protocol parsing. POF is widely accepted in the industry and expected to be integrated into OpenFlow2.0.
- Huawei has a family of products called “Agile Switches” which may offer a competing solution to OpenFlow.

Key products supporting OpenFlow

- S5720 series switches (including S5720-SI, S5720-EI and S5720-HI series)
- S6720-EI series switches
- S7700 series switches
- S9700 series switches
- S12700 series switches
- Huawei also claims support in multiple router families including Huawei’s NE40E high-end router and the Huawei CX600 Series Aggregation Router
- More Huawei products could support OpenFlow as documentation was challenging to locate.

Infinera

SDxCentral Directory Listing

www.infinera.com

Summary of OpenFlow Support:

- Infinera is very open about its support for SDN and its application to optical technologies. It participates in many demonstrations with press releases, but again, technical documentation for OpenFlow support is thin.
- Infinera supports OpenFlow, Open Virtual Switch Database and Netconf/YANG, and other protocols in support of SDN
- Infinera is pursuing a multi-vendor 'plug in' strategy.

Key products supporting OpenFlow

- Infinera Open Transport Switch
- Infinera's Cloud Xpress metro optical transport platform
- Infinera's control capabilities

An example of Infinera's demonstrations include https://www.infinera.com/demonstration-of-sdn-enabled-on-demand-100-gigabits-per-second-100g

Juniper Networks

SDxCentral Directory Listing

www.juniper.net

Summary of OpenFlow Support:

- Juniper supports OpenFlow 1.0 and 1.3.
- Juniper also supports its own technology Contrail, which it released as Open Contrail in 2014.
- It is possible to configure certain devices running Juniper Networks Junos OS as OpenFlow-enabled switches. The Junos OS process, openflowd (ofd), handles OpenFlow functionality on these devices. When implementing OpenFlow in an existing network, you must isolate experimental flows from production flows so that normal network traffic is not impacted.
- Not all features are supported on all devices. As an example, OpenFlow over MPLS is not supported on EX9200 Line of Ethernet Switches and QFX5100 Ethernet Switches. Other features are also implemented in a matrix fashion.

Key products supporting OpenFlow

- EX9200 Line of Ethernet Switches
- MX80, MX240, MX480, MX960, MX2010, and MX2020 3D Universal Edge Routers
- QFX5100 Switches

NEC

SDxCentral Directory Listing

www.necam.com

Summary of OpenFlow Support:

- NEC supports OpenFlow 1.3.
- NEC ProgrammableFlow Networking Suite was the first commercially available Software-Defined Network (SDN) solution to leverage the OpenFlow protocol.
- ProgrammableFlow current version (Aug 2016) is V6.3.

Key products supporting OpenFlow

- UNIVERGE PF6800 Network Coordinator
- PF6800 SDN Controller
- PFTAP Controller
- ProgrammableFlow User Interface
- PF1000 Virtual Switch
- PF5240 Switch
- PF5248 Switch

Netronome

SDxCentral Directory Listing

www.netronome.com

Summary of OpenFlow Support:

- Netronome makes the Agilio CX line of intelligent server adapters.
- Adapters range from 10GbE, 25GbE, to 40GbE and come in various profile sizes based on need.
- Adapters support OpenFlow v1.3 and OvS 2.3.90.
- Netronome focuses on network acceleration and offload.

Nokia (including Alcatel-Lucent portfolio)

SDxCentral Directory Listing

https://networks.nokia.com

Summary of OpenFlow Support:

- As of 2014, Alcatel-Lucent appears to have broad support for OpenFlow on the OmniSwitch family with the introduction of the OmniSwitch 6860 family.
- Alcatel-Lucent Enterprise states that its entire product portfolio now has SDN capabilities, including REST APIs, OpenFlow 1.0/1.3 support and integration with Open-Stack plug-ins that provide full network management.
- The OmniSwitch software supports the OpenFlow 1.0 and 1.3.1 versions of the protocol.
- It has been tested to work with various controllers, including Floodlight.

Key products supporting OpenFlow

- Campus Access Switches
  - OmniSwitch 6250 OmniSwitch 6350 OmniSwitch 6450 OmniSwitch 6450-10 OmniSwitch 6855 OmniSwitch 6860(E) OmniSwitch 6865
- Campus LAN Core Switches
  - OmniSwitch 10K OmniSwitch 9900 OmniSwitch 9000E OmniSwitch 6900
- Datacenter Switches
  - OmniSwitch 10K OmniSwitch 9900 OmniSwitch 6900 OmniSwitch 6860(E)
- Hardened Ethernet
  - OmniSwitch 6865 OmniSwitch 6855

NoviFlow

SDxCentral Directory Listing

http://noviflow.com

Summary of OpenFlow Support:

- NoviWare provides the industry's broadest support of the OpenFlow 1.3 and 1.4 specifications, including all actions, instructions and match fields and key OpenFlow 1.5 features such as Copy-Fields action
- OpenFlow pipeline with up to 120 flow tables, up to 1 million wildcard match flow table entries in TCAM and up to 15 million exact match flow entries in DRAM
- OpenFlow queues and meters for implementation of QoS mechanisms
- Extensive O&M features optimized for large scale deployment of OpenFlow switches in carrier, cloud and enterprise networks
- OpenFlow OpenFlow Experimenter-based extensions:
  - L2-L7 matching, packet processing and flow management
  - Experimenter action for Hash on user defined ordered list of OpenFlow fields.
  - Copy-Field action based on OF1.5 also supported on OF1.3 to 1.5
  - MPLS payload matching
  - L2 GRE/GTP/VxLAN/MPLS tunneling protocol encapsulation/decapsulation
  - BFD Link Monitoring

Key products supporting OpenFlow

- NoviSwitch line of OpenFlow switches (1132, 1248, 2116, 2122, 2128, 2150, 21100) supporting 1/10/40/100GE ports and up to 400Gbps
- NoviWare available for license to OEMs users of Mellanox NP5 and NPS
- SDN Scale-Out BGP Router application

Pica8

SDxCentral Directory Listing

www.pica8.com

Summary of OpenFlow Support:

- Pica8's PicOS is a Linux Network Operating System that is capable of running on many "white box/bare metal" switches and supports up to OpenFlow 1.4
- PicOS is similar to other Network Operating systems such as Big Switch and Cumulus and is a choice through ONIE.
- PicOS comes in four editions which focus on L2 switching, switching and routing, SDN and OpenFlow, and a bundle.
- Unlike Cumulus, Pica8 does also sell a line of White Box/Bare Metal switches with their PicOS software preloaded to save customers the hassle of configuration, etc.

Key products supporting OpenFlow

- P3297
- P3922
- P3930
- P5101
- P5401

Quanta

SDxCentral Directory Listing

www.quantaservices.com

Summary of OpenFlow Support:

- Quanta is a bare-metal switch provider and provides numerous switches with ONIE preloaded.
- The bare metal switches come with x86 processor support.
- OpenFlow support is decided by OS installed via ONIE. For example, Cumulus does not support OpenFlow while Big Switch and PicOS do.

Key products supporting OpenFlow

- BMS T3048-LY9
- BMS T3048-LY8
- BMS T3048-LY2R
- BMS T3048-LY2
- BMS T5032-LY6
- BMS T1048-LB9
- BMS T3040-LY3
- BMS T5016-LB8D

Telco Systems

SDxCentral Directory Listing

www.telco.com

Summary of OpenFlow Support:

- Telco Systems are supporting 1.3.1 (1.3)
- September 30, 2014 – Telco Systems announced the release of ViNOX, the first carrier SDN network operating system that includes native support for OpenFlow and Netconf standards in parallel with MEF services and carrier-grade support.

Key products supporting OpenFlow

- EdgeGenie Orchestrator CE 2.0 & SDN/NFV Management System
- Telco Systems ViNOX
- Cloud Metro 10- Ethernet switches
- Cloud Metro 100 - Ethernet switches
- vFirewall
- vRouter
- vProbe

SDNCentral, LLC
955 Benecia Avenue
Sunnyvale, CA 94085 USA
www.sdxcentral.com

The Trusted News and Resource Site for SDx, SDN, NFV, Cloud and Virtualization Infrastructure

Rev B