Chapter 2

Background

This chapter is divided into three main sections. The first section explains the concept of SDN and further looks at its history from its inception until today. In the second section, NFV is discussed through multiple research papers that are relevant to the topic, in order to get a comprehensive understanding of previous work. In the final section, we explain the technologies used in this project that are important to know when reading the Implementation chapter.

2.1 Software-defined networking

Before looking closer at the main concept discussed in this thesis, namely NFV, it is important to have a general understanding of the historic landscape that helped shape NFV. NFV is a concept derived from SDN that aims to further develop and improve some of the fundamental ideas behind SDN, like better manageability and control. As SDN was a concept years before NFV was introduced, it is natural to start by discussing SDN before moving on to NFV, in order to cover the complete story of NFV.

SDN aims to transform network management from a complex and tedious task to a simple and fast task. The terms *Control plane* and *data plane* are heavily used when discussing SDN. In traditional networking, switches and routers possess both a control plane and a data plane. The control plane is defined as the software logic of the device. This is where the device makes routing decisions for the incoming network packets. The data plane is served by the control plane and is responsible for conducting the actual forwarding of network packets. Both planes are equally important in order to fulfill the network's purpose of successfully carrying packets from A to B. Because the planes are defined as two separate entities, it is of course possible to separate them. The control plane and data plane doesn't have to reside on the same device. In fact, this is a coupling that is quite unnecessary, that makes network management and configuration overly complicated and tedious. Decoupling the data plane from the control plane is the main motivation behind the SDN movement. The idea is to move the brains of the network (i.e., control plane) from each of the networking devices into a central server, known as the controller. The controller has a complete view of all the data planes residing within the network. Complete network knowledge allows the controller to easily identify ideal routes. Network switches know exactly how to treat incoming packets based on information received from the controller.

2.1.1 SDN's emergence

This section will look at how the new way of managing network routing emerged through two Standford-based research projects. This new way of thinking about networking gained a lot of attention and quickly received its own term, namely SDN.

Ethane

Work involving separating the control plane from the data plane of regular networking switches started already in 2004, but failed to achieve much attention from the research community. Vendors were concerned that a standard API that allows the controller to communicate with the data plane would result in increased competition. Additional concerns involving security risks also factored in on the failed attempt to gain traction around the subject [1]. Two years later, in 2006, an early version of the SDN we know today started taking form at Stanford University, through the project of Ph.D student Martìn Casado, called Ethane [2]. The Ethane project proposes a new network architecture that is completely different from the the legacy network architecture we know today. Ethane was implemented in Stanford University's network and supported over 300 hosts for four months. The experiment demonstrated how powerful a centrally controlled network can be and showed great promise in many other aspects. Ethane inspired researchers to start working on an open-source communications protocol for SDN networks.

Clean Slate Program

Ethane impressed Stanford professor Nick McKeown to such a degree that it led to the start of a program called the *Clean Slate Program* [3]. The Clean Slate Program was made to explore the possibilities for future networks, using knowledge acquired from modern research and forget about how networking has been done traditionally. In 2008, program director McKeown, et al. released a paper describing a protocol called OpenFlow [4], under the auspices of the Clean Slate Program.

OpenFlow and SDN

OpenFlow allows devices to communicate directly with the data plane of switches a network. The protocol is open-source, intended for other researchers and network vendors to use freely in the exploration of new networking solutions. OpenFlow opened up for enormous possibilities in the design of new network solutions for both network vendors and researchers.

In February 2009, journalist Kate Greene published an article in MIT Technology Review called *TR10: Software-Defined Networking* [5]. The article describes McKeown's and his colleagues' work on OpenFlow. According to McKeown, this is the first time the term *software-defined networking* was used and it has stuck around since then [6]. Two months after the article was published McKeown held a presentation at the IEEE INFOCOM 2009 Keynote Talks, named *Software-defined Networking* [7]. The presentation is thoroughly explains the ideas cultivated in the Clean Slate Program and attempts to enlighten the research community about the opportunities of SDN. McKeown presents four important concepts of SDN that they had to keep in mind when developing OpenFlow. In the following list, statements from McKeown's presentation are represented as headers. Each sentence should be read with a "We need..." prefix.

1. **A clean separation between the substrate and an open programming environment**

   This statement refers to the decoupling of the control plane from the data plane. The control plane is the programming environment. The programming environment shouldn't have a predefined connection to the substrate (i.e., data plane).

2. **A simple hardware substrate that generalizes, subsumes and simplifies the current substrate**

   SDN switch hardware should look similar to hardware in current switches, but has to be simpler and generalized. Generalized hardware is important in order to move away from vendor specific devices.

3. **Very few preconceived ideas about how the substrate will be programmed**

   One of the main ideas of the Clean Slate Program was to forget about the complexity of current network implementations and rather implement network technology based on experience and knowledge accumulated in the years since Internet's inception.

4. **Strong isolation**

   The OpenFlow network treats all network traffic as *flows*. When a new packet from host A to host B reaches a switch, the controller will decide what action the switch should take (e.g., allow, deny, re-route) and then install the flow policy into the switch's flow table. Continuous packets from host A to host B will automatically be handled by the switch without involving the controller. Strong isolation refers to the ability to clearly define which flows can/cannot communicate.

McKeown held three more talks the same year on the subject of SDN. It seems like McKeown was successful in creating an interest for SDN and OpenFlow in the academic community, as we see a great increase in the number of articles and papers published on the subject in the years that follow. At the same time, the industry also starts taking a vast interest in the field of SDN.

2.1.2 SDN in the industry

Software solutions and concepts proposed through academic projects should ideally have some sort of real-world applicability and relevance. A way of identifying real-world usefulness is by looking at adoption in the industry. This section takes a look at how SDN has influenced the industry and how SDN has been influenced by the industry itself.

Open Network Foundation

After OpenFlow's initial release, research on SDN skyrocketed. The industry responded quickly to this new trend by starting the Open Network Foundation (ONF), a non-profit trade organization backed by many of the largest technology companies in the world [8]. For the first few years, after the organization's foundation in 2011, the main focus was aimed at SDN and OpenFlow. The organization was looking at optimal ways of implementing SDN in enterprise networks and most importantly, standardizing OpenFlow. In order for OpenFlow to be efficient in the industry, it was important that it adhered to an common and vendor agnostic standard. We started seeing OpenFlow support across multiple networking vendors already the same year as ONF was established. Even though it seemed so at the time, it is important to remember that OpenFlow isn't synonymous to SDN. Network vendors were still working on their own their own implementations and communication protocols in order to stay ahead of the competition. For instance, in 2014, Cisco released OpFlex, as a counter to OpenFlow [9].

Competition

The traditional network architecture remained almost unchanged for decades, until the SDN phenomenon suddenly started catching on. SDN changed the competition in the networking realm completely. This lead to a fierce competition, that involved many of the largest technology companies in the world. The need for innovation and new solutions was crucial in order to not fall behind. An example of the heavy competition that went on at this time can be seen in the summer of 2012, when VMware bought SDN company Nicira in order to enhance their virtualization platform [10]. Oracle quickly picked up on VMware's aggressive approach and countered by buying SDN company Xsigo, a former competitor of Nicira [11].

SDN is still an unclear term

Originally, SDN was a well defined term that described the separation of the data plane from the control plane. Although the definition of SDN hasn't formally changed over the years, the industry has changed it into something different. At SDN's peak, it was very important for companies to stay ahead of the market. Companies did so by developing new software-based functionality that helped ease network configuration and automation. This functionality was often labeled as *SDN*, even though it had nothing to do with the original definition of the term. SDN effectively became an umbrella term for any software that helps ease network configuration and automation.

Martìn Casado, who inspired the development of OpenFlow, stated the following in an interview on OpenFlow and SDN [12]:

> I actually don't know what SDN means anymore, to be honest. Now it is just being used as a general term for networking, like all networking is SDN. SDN is now just an umbrella term for cool stuff in networking.

2.1.3 Research grants

In order to get gather deeper knowledge into the real-world importance of a research topic, it can be helpful to look at call for proposals and grants issued in conjunction with the calls. A call for proposal is often associated with a Research & Innovation program or something similar. Programs like this have a political goal of making the world a better place to live by identifying and addressing problems, improving solutions and increasing efficiency in any field, depending on the intentions of the program. A call for proposals is usually the action that allows a Research & Innovation program to reach its goals. The call enables researchers from all around the world to participate in solving the issues highlighted in the program. It is also a crucial for many academic researchers to find grants that are relevant to their research in order to get the financial support they require to continue their research. When a research program initiates a call for proposals, researchers can submit project proposals that they believe will help solve parts of the problem. By looking at various research programs and accepted projects, we can get a better understanding of how the rest of the world views certain topics.

In this thesis, we wanted to see if we could find research programs that were willing to finance SDN projects. We assume that if a research program is willing to finance research on SDN, it means that there is a certain realism to it outside of the research community itself. Realism and attention outside the specialized research community is important and is what all researchers strive towards. Below we discuss two of the research programs we found that have financed SDN research. Both research programs are initiated by the European Commission.

FP7-ICT

This was a research program that started in 2007 and ended in 2013. One of the research areas for this program was "Network and service infrastructure stability and security", which is where SDN can help contribute. The SDN project we found that has been accepted by this program is called SPARC [13]. The SPARC project was started July 2010 and ended in September 2012. They used OpenFlow extensively in order to split the network, in terms of control, forwarding and data processing. OpenFlow was only two years old at the time and can be considered as a somewhat new protocol still. This fact that this project was approved as part of this program shows how important the OpenFlow protocol was at the time. Even though the protocol is now over 10 years old, it is still a widely used and continuously developed protocol. The SPARC project had an overall budget of €3 million. The EU contributed €2 million to the project.

Horizon 2020

Horizon 2020 is the biggest EU research program to ever exist. It has nearly €80 billion of funding over a period of 7 years. The program was started in 2014 and is planned to last until 2020. A quote from the project's home page explains the ambitions of the project [14]:

> The goal is to ensure Europe produces world-class science, removes

> barriers to innovation and makes it easier for the public and private sectors to work together in delivering innovation.

It is important to keep in mind the ambitions of the program when looking at accepted projects. ENDEAVOUR [15] is one of the accepted project that goes under the category of SDN. The project aims to include SDN on top of Internet Exchange Points (IXPs) and create a sort of market place for services running on such locations, effectively enabling collaboration between content and data center environments. As part of the project, they studied Netflix's content delivery network [16]. They conclude in the research article they published on the study, that IXPs ability to boost content delivery on a global scale are vastly understated. IXPs are crucial in order to deliver large amounts a traffic, with little delay, in a reliable manner on a global basis. Based on their findings within Netflix's content delivery network, the authors prove their research to be highly relevant and that further research should be carried out on the subject [17]. The ENDEAVOUR project had an overall budget of €4,4 million. The EU contributed €3,3 million to the project.

2.1.4 Network function virtualization

In this section, we take a brief look at how NFV was introduced to the world, the NFV architecture and NFV's popularity on the Internet.

NFV emerged naturally from the concept of SDN. Like SDN, NFV also facilitate software in order to enhance network functionality. When looking at the diluted definition of SDN, it can be said that NFV is simply just a part of SDN. However, looking at the original definitions of SDN and NFV, they are two separate concepts that are related, but very different in their implementations. SDN wants to centralize network control by separating the control plane from the data plane of network devices. NFV looks to virtualize network middleboxes in order to reduce required hardware and move toward the modern cloud paradigm. These are two completely different concepts when looking at their definitions and should therefore be discussed separately.

European Telecommunications Standards Institute

European Telecommunications Standards Institute (ETSI) is a standards organization working on developing standards for the telecommunication industry. The organization has over 800 members from the ICT industry [18], including many of the biggest technology companies in the world. In October 2012, a white paper on NFV was released by ETSI [19]. The paper was initiated by many of the largest carriers that are part of the ETSI organization and was the first time the term NFV had been used. The white paper was published as part of the "SDN and OpenFlow World Congress", which says something about how the industry view SDN and NFV as two closely connected concepts. The paper is written as an introduction to NFV and highlights some of the benefits of virtualizing network functions. It also explains why NFV is related to SDN and how they can function efficiently together.

Earlier in this chapter, we mentioned that there is an organization called ONF that manages and develops OpenFlow in the industry. OpenFlow is the industry standard for SDN and is even part of the title of the SDN congress.

NFV on the other hand is developed by a group representing ETSI, a different standards organization. The authors of the NFV white paper recognize this and state that they intend to work closely with organizations such as ONF. It is a positive sign that the authors recognize this and want to develop future solutions in cooperation with SDN organizations. This keeps a strong bond between SDN and NFV which is important in order to create efficient solutions that facilitate the best of both concepts. Cooperation is particularly important because of the fact that SDN and NFV are stand-alone concepts that don't directly depend on each other, which means they could be developed separately without involving each other. Some effort is needed by both organizations in order to develop the concepts in close connection to each other.

Components of the NFV-MANO

NFV-MANO (NFV management and network orchestration) is the de facto NFV management standard and is used extensively by researchers when implementing NFV solutions. In order to get an understanding what NFV-MANO is and its related components, we present a list of terminology explanations, defined in [20]:

Virtualised Network Function (VNF): implementation of an NF that can be deployed on a Network Function Virtualisation Infrastructure (NFVI).

Virtualised Infrastructure Manager (VIM): functional block that is responsible for controlling and managing the NFVI compute, storage and network resources, usually within one operator's Infrastructure Domain (e.g. NFVI-PoP).

Virtualised Network Function Manager (VNFM): functional block that is responsible for the lifecycle management of VNF.

Network Functions Virtualisation Management and Orchestration (NFV-MANO): functions collectively provided by NFVO, VNFM, and VIM.

Network Functions Virtualisation Infrastructure (NFVI): totality of all hardware and software components that build up the environment in which VNFs are deployed.

Network Functions Virtualisation Orchestrator (NFVO): functional block that manages the Network Service (NS) lifecycle and coordinates the management of NS lifecycle, VNF lifecycle (supported by the VNFM) and NFVI resources (supported by the VIM) to ensure an optimized allocation of the necessary resources and connectivity.

All of these definitions are direct excerpts from the ETSI group specification that defines terminology for the main concepts in NFV [20]. Out of these architectural building blocks, it is NFV-MANO, NFVI and VNF that are most commonly referenced in NFV research papers. The NFV-MANO is the management framework for all NFV components. Implementing the NFV-MANO is important in order to properly utilize the benefits of virtualization technology. Without a good management framework, things like better network configuration, maintenance and automation would not be possible to achieve, meaning most of the idea behind NFV would be wasted. The NFVI is the abstraction layer that allows VNFs to run on top of commodity hardware. In order to achieve the functionality of the NFVI, a hypervisor must be implemented. VNF is a term we've already used extensively in this thesis. A VNF is simply a network function that runs inside a VM.

Popularity on the Internet

As mentioned in the section above, NFV was presented as a concept in 2012. Before we proceed to look at research and publications related to NFV, we would like to look closer at NFV's popularity on the Internet in general. In order to achieve this, we established a timeline, from 2011 to present day. 2011 should be a sufficient year to start the timeline, as NFV was introduced in 2012. We filled our timeline with data based on results from a Google Trends search on "Network function virtualization". Google Trends is an online visualization tool that plots historic search data based on keywords or topics that the user wants to look at. When looking at a single search string it shows the popularity of the specific string, relative to itself. This makes it easy to see when a topic was a topic started getting attention, when it peaked and when it started slowing down. In the case of NFV, we can see in Figure 2.1 that it started gaining momentum in 2013 and peaked sometime in the middle of 2015. Since around 2016, it seems NFV has started gradually decreasing in terms of popularity on the Internet. Although NFV isn't at its most popular today, it is still a widely discussed topic that we see more of in the years to come. One of the reasons for the gradual decrease in popularity is likely due to the immense popularity of IoT and related concepts. This will be discussed later in the chapter.

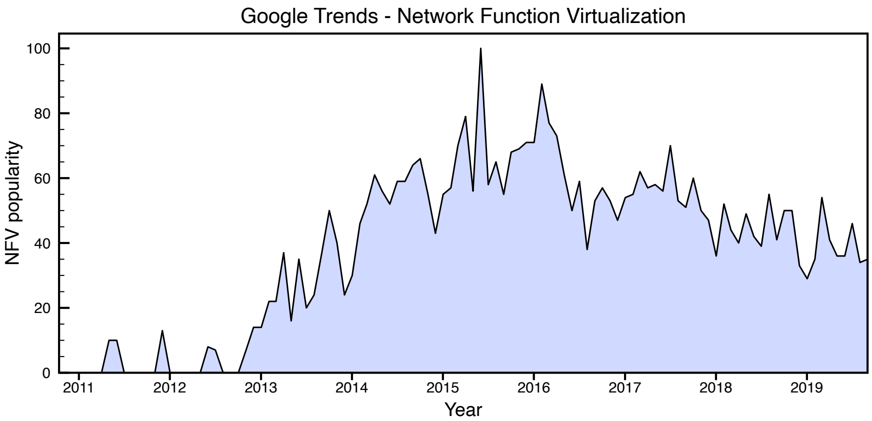

Figure 2.1: Network function virtualization's popularity on the Internet from inception to present day.

2.2 Research and NFV

In this section, we explore and explain NFV through academic and industry research conducted on the topic. We start by looking at NFV's popularity throughout the years within the research community. Then we explain the literature search and taxonomy that was used as a base for writing the rest of the subsections. The next subsections look closely at the research that has been conducted on NFV, in terms of challenges, achievements, solutions and future prospects.

2.2.1 Popularity in research

In order to create an overview of NFV's popularity amongst researchers, we looked at three of the most popular journals for NFV publications and counted the number of articles that discuss NFV. The following journals were picked: "Computer Networks", "IEEE Transactions on Network and Service Management" and "IEEE Internet of Things Journal". Our general rule of thumb when classifying a paper as NFV-related, was that NFV was at least mentioned and discussed in a couple of sentences. NFV did not have to be the main focus of the research paper. We went through each of the journals' publications year by year, in order to create a timeline that depicts NFV's popularity in the research community by year. Our findings for each of the journals are presented below.

Computer Networks

Computer Networks is an archival journal from Elsevier, publishing papers related to the computer communications networking area [21]. Figure 2.2 shows the published articles related to NFV from 2014 to 2019. No relevant article was published before 2014 in Computer Networks. We see a rapid increase in the number of articles published from 2014 to 2015, before a heavy decrease in 2016. We didn't find any particular reason for this sudden decrease in published articles. As we don't see the same pattern in other journals, we chose not to investigate it further. We still see a good amount of publications in later years, with no clear signs of a future decrease in publications.

IEEE Transactions on Network and Service Management

IEEE Transactions on Network and Service Management publishes archival quality papers that advance the state-of-the-art and practical applications of network and service management [22]. In Figure 2.3 we see a steady increase in the number of published articles from 2015 to 2018. In this journal, 2015 was the first year an NFV-related article was published. We see a decrease in publications in 2019, but as the literature search was conducted a couple of months before the end of 2019, it cannot be said for sure that there will be a decrease in published articles this year.

IEEE Internet of Things Journal

IEEE Internet of Things Journal is a relatively new journal that publishes articles on the various aspects of Internet of Things (IoT) [23]. We thought this journal to be interesting, as it seems NFV is gradually being dragged into the

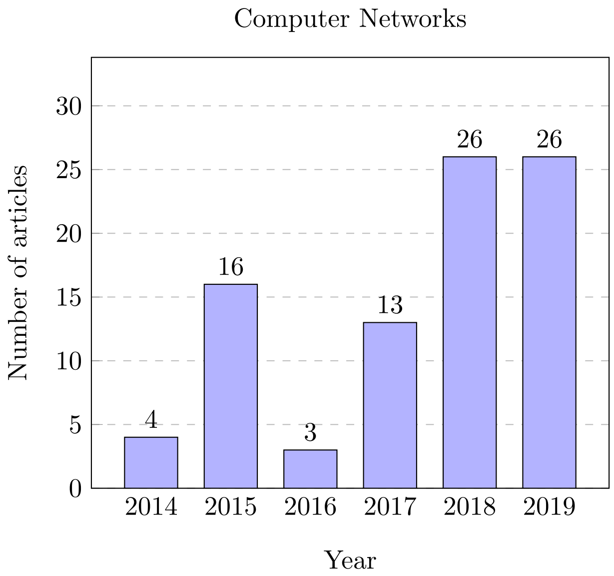

Figure 2.2: Distribution of NFV-related articles published in Computer Networks.

world of IoT, which will be further discussed in a later section. In Figure 2.4 we see that it takes a couple of years before NFV really starts receiving attention from the IoT community. In the first few years, there are barely any articles discussing NFV, before it suddenly starts receiving attention in 2017 and 2018. So far in 2019, NFV hasn't been much of a popular topic in the IoT community, at least not in this particular journal.

Popularity on the Internet vs. Popularity in research

Figure 2.5 is twofold. The upper half depicts the result from Google Trends when searching for "Network Function Virtualization". It gives a rough estimate of NFV's popularity on the Internet since its inception until present day. The plot that can be seen in the bottom half of the figure shows the distribution of NFV publications in three journals. By NFV publication we mean all articles that at least discuss NFV in a couple of sentences. The figure uses the exact same timeline on the x-axis for both the popularity and publication plots. This is purposely done in order to directly compare the general NFV popularity on the Internet with NFV's popularity amongst researchers. We can see that the distribution is quite similar, but with a couple of years delay in terms of popularity within research. NFV started gaining popularity on the Internet around the exact time NFV was introduced to the world, autumn 2012. Research on NFV barely started getting some attention in 2014 and started to become a popular topic in 2015 and onward. The offset between Internet and research popularity can be explained by the natural publication delay which is part of the research process. The topic was likely already picked up and started being worked on by researchers late in 2012 and throughout 2013 and 2014. Because of the extensive research process it usually takes a while from when a research

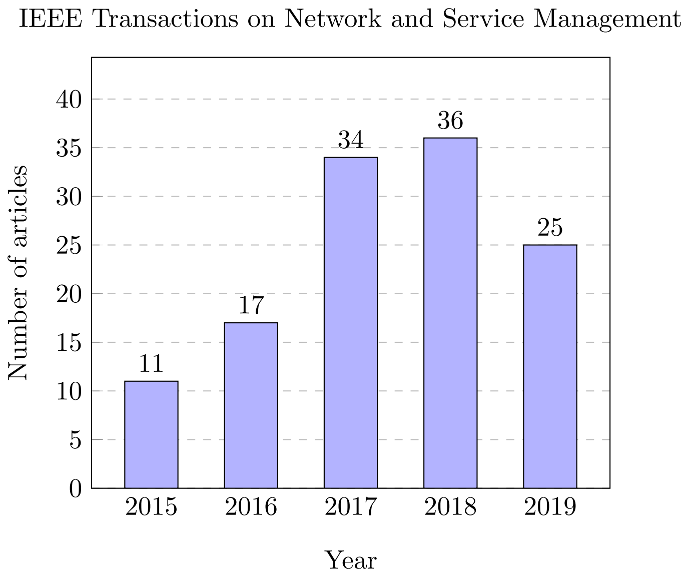

Figure 2.3: Distribution of NFV-related articles published in IEEE Transactions on Network and Service Management.

project is started until a publication sees the light of day. Usually there is a somewhat technical implementation or algorithm that has to be designed, then the article itself has to be written and lastly go through an extensive peer review process before it can be published. The assumption that the natural research publication delay is the reason for the offset is logical in the case of NFV. It is interesting to see how similar the two plots look, when taking the delay into account. There is a clear visual correlation between NFV's popularity on the Internet and within the research community. It is a good sign for NFV that the general public on the Internet follow the evolution of NFV closely together with the research community. This gives NFV a certain degree of realism and proves that this is something that the world believes in. Based on the plots, there are signs that NFV is on a decrease in terms of popularity, but it is still too early to say for certain how popular NFV will be in the future.

2.2.2 Literature search

We performed online searchers in a way that was designed to get a versatile and comprehensive view of important research conducted on the topic of NFV throughout the years. We mainly used Google Scholar when performing the online literature searches. The initial searches were general, looking for papers containing the key phrase "Network Function Virtualization". We started by examining the most cited papers in order to get a better understanding of what research the community valued the most. Some of the most cited papers were comprehensive surveys [24, 25]. The surveys helped us understand previous research and led us toward other relevant papers. A problem we noticed after we had collected quite a few papers from citation based searches and the surveys, was that most papers are from 2015 or earlier. There are two reasons for this.

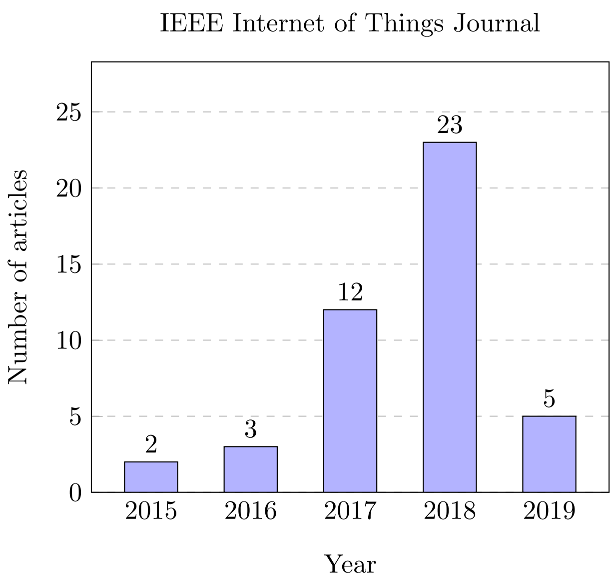

Figure 2.4: Distribution of NFV-related articles published in IEEE Internet of Things Journal.

Firstly, a research paper usually needs to be publicly available for a few years before citations start adding up. Both because it can take some time for other researchers to notice and appreciate the work when it's completely new and that older papers naturally get more citations because they've been made available to the community for a longer amount of time. Secondly, both of the surveys we explored when looking for other relevant research, were published in 2015. A natural step in the searching process was to look for papers newer than 2015, in order to get the full story on NFV research. Newer research articles don't have as many citations as older articles, which makes it harder to find high quality papers. Fortunately, we learned a lot from looking at the more established NFV research. We already knew about the challenges and directions the research was taking and had a good understanding of which journals, conferences and magazines we should prioritize when looking for high quality articles.

Taxonomy

We created a taxonomy that was designed to extract key information out of every article we read and found relevant. The taxonomy was created on a spreadsheet and gave us a great overview of all the NFV related research that was processed through the literature search. Each row in the taxonomy contains key information about a single NFV article. The left column in Table 2.1 shows the categories defined in the taxonomy. In the right side column, the type of information we specifically looked for in each category is defined. For instance, the affiliation category lets us see the distribution of papers coming from academia, industry or a mix of these. This gives us valuable information about the research topic, in terms of incentives and motivation. By sorting on publication year, the taxonomy is able to reveal various patterns that was hard

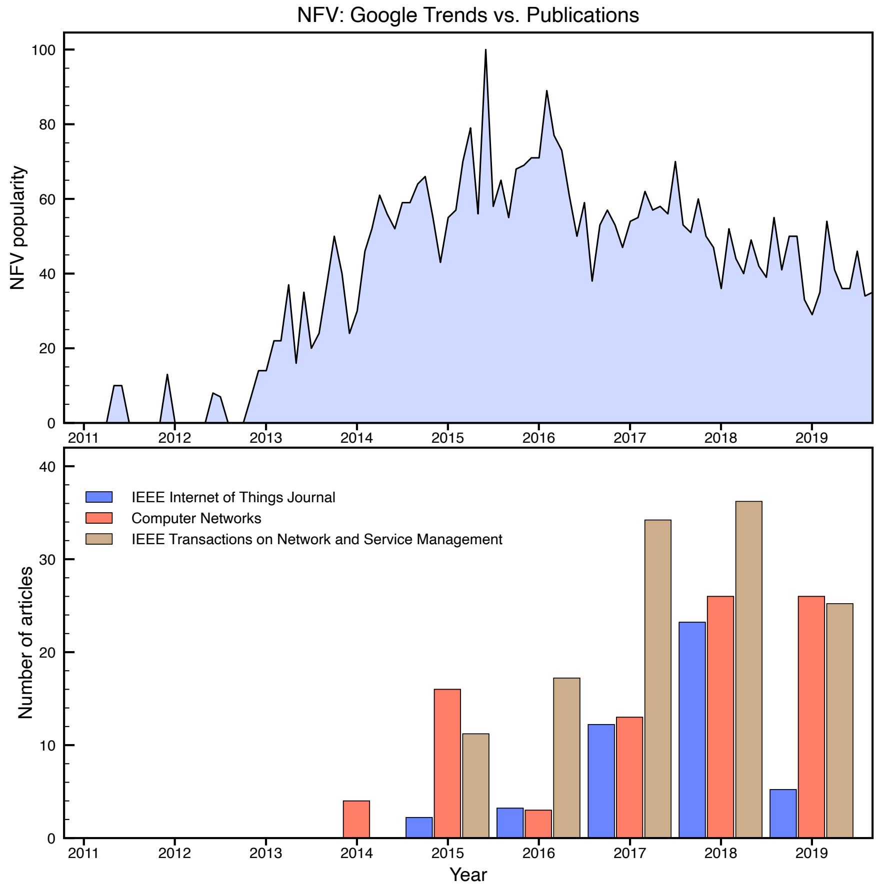

Figure 2.5: NFV's popularity on the Internet compared to NFV's popularity in the research community (by looking at the number of publications related to NFV each year).

to notice when processing the articles one by one.

While performing the literature research we learned a lot about the NFV research landscape and obtained a general understanding of NFV's development throughout the years. We gained a decent understanding of what research within the field is being focused on and what type of research that seem less relevant. This, of course, constantly changes throughout the years. Based on the knowledge we gained, we decided to complete our taxonomy at 20 research articles. We feel the statistics and patterns would be close to the same if we continued classifying articles more articles. The taxonomy can be viewed as the foundation for the remaining discussions in this section.

As an example, we can look at the "Affiliation" category. The affiliation category lets us see the distribution of papers coming from academia, industry or a mix of these. This gives us valuable information about the research topic, in terms of incentives and motivation. By sorting on the publication year of the articles, the taxonomy revealed various patterns that were hard to notice when processing the articles one by one. We had decided that the taxonomy

Table 2.1: Information extracted from each article categorized in our taxonomy.

Taxonomy	
Category	**Extracted information**
Year	Article publication year
Title	Article title
Authors	All authors involved
Approach	Exploration Optimization Simulation Theoretical Comparative Case
Context	Real life Established problem Imagined scenario
Takeaway	Open-source?
Perspective	Networking Infrastructure and service
Affiliation	Academic Industry Mixed
Venue	Journal Conference Magazine

was complete when it had reached 20 research papers. 20 papers should be a sufficient basis in order to detect patterns and/or anomalies that can help us better understand the research topic.

2.2.3 The relationship between academia and industry

Earlier in this chapter we mentioned that ETSI was the organization that initiated the NFV movement, which makes it safe to say that NFV emerged from the industry. On the other hand, the concept of SDN emerged through the OpenFlow protocol which was a purely academic project. NFV is tightly coupled with SDN, and it is fair to say that even though the industry created the concept of NFV, it indirectly originates from academia. In this section we look at how NFV has affected the different research communities. It is especially interesting to see the degree of impact it has had on academia. Has academia embraced NFV in the same way they did SDN, or is it mainly a term belonging to ETSI and the industry in general?

There is a close collaboration between industry and academia

The first thing that becomes clear when studying the research conducted on NFV, is that the industry is heavily involved compared to related topics, such as SDN. In the taxonomy we see that only a few articles are of pure academic character (i.e., written at a university or similar institution). Most of the research we found when conducting our literature search were performed in col-

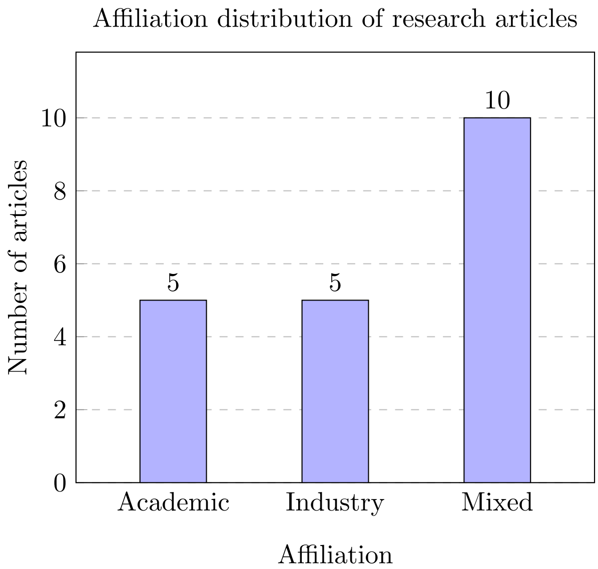

Figure 2.6: Number of articles published by academia, industry and both. Based on our taxonomy.

laboration between academia and industry. Figure 2.6 depicts the distribution of affiliation from the articles classified in our taxonomy. Ten of the articles we classified were written in collaboration between academia and the industry. Five articles were purely academic and five articles purely industrial. The fact that most papers are written in collaboration between industry and academia seem to be true for the complete NFV research landscape. Based on our taxonomy, only 25% of all articles on NFV are purely academic. 20 articles aren't enough to state this for a fact for the whole NFV research area, but it still is remarkable to see how heavily involved the industry is when it comes to NFV research.

NFV has primarily had a networking focus, but the focus might change to cloud in the future

NFV is primarily about changing they way networking is done. It aims to completely replace all legacy network hardware/middleboxes with VMs. The virtualization architecture that NFV proposes is very similar to the cloud computing architecture that has already dominated the server infrastructure for years. Networking architecture, on the other hand, has been standing almost still for decades with little novel solutions proposed to fix the hardware problem. One of the reasons networking wasn't part of the cloud computing adventure is related to the difficulty of moving network functions from dedicated hardware to commodity hardware. Also, problems regarding service chaining of network functions have to be addressed. These are two of the main issues that virtualization of network functions brings, compared to server virtualization seen in cloud computing. There is no doubt that the cloud computing paradigm has inspired the development of NFV. After all, NFV is based on the same technology and model used in cloud computing (i.e., VMs running on commodity hardware).

The greatest challenge for NFV is making VNFs perform to the same level as network functions running on specialized hardware. By specialized hardware, we mean hardware that implements hardware acceleration (HWA).

Hardware acceleration (HWA) is a term used for software that needs an extra boost in hardware in order to perform optimally. It is heavily used by networking devices in order to meet the packet processing demands of modern networks. If a sub-optimal middlebox is placed within the enterprise network it will quickly become the bottleneck for all network traffic flows going through it, effectively reducing the overall network bandwidth, causing massive delays for end users. NFV is meant to run on commodity hardware. Commodity hardware is meant to be as generic as possible and therefore doesn't implement specialized hardware functionality the way networking equipment does. OpenANFV [26] is a framework implemented in OpenStack that enables the possibility for hardware acceleration in an NFV environment. As NFV is meant to run on commodity hardware, most NFV research doesn't focus much on HWA. Still there are researchers that view HWA as an important in order to make NFV perform optimally [27]-[30].

Because the cloud architecture highly resembles NFV in many ways, some of the research conducted on NFV, view NFV as more of an cloud/infrastructure problem rather than a pure networking problem. In [31], they propose an NFV management system that lets cloud customers allocate virtual network resources seamlessly. Customers can easily change their network infrastructure in terms of VNFs and service chains by sending requests to the management system. A system like this, is similar to the management systems that already exist for cloud infrastructures and will therefore integrate nicely. NeFuCloud [32] is a system similar system that also aims to integrate network management with cloud management.

Many research papers propose heuristic algorithms to solve the NFV optimization problem. They look for a solution for optimal VM placement in data centers, usually taking service chaining into account. There are a multitude of research papers published years before NFV emerged, addressing almost the exact same issue for cloud computing. Optimizing VM placement is of course highly relevant for cloud computing as well, because the architecture uses the same hardware and virtualization technology as NFV. Because of the close similarities, one can say that a lot of the optimization issues seen in NFV is closely correlated to cloud computing optimization. Although the authors try to solve a networking problem, it can be argued that this type of research also belongs to general infrastructure/cloud computing research. The main difference between cloud and NFV optimization of VM placement is that in most research on NFV optimization, service chaining is an important issue. A network policy is decided by the network manager and has to be enforced by directing the network flow through the required network functions in a certain order. Service chaining adds additional complexity to the optimization issue. Many researchers look at the network function placement problem as an Integer Linear Programming (ILP) problem [33]-[36]. ILPs are NP-complete, which is why heuristics are often proposed for this type of problem.

Although some research focus on nesting NFV with cloud architectures or solving problems previously seen in the cloud domain, most of the renown research on NFV seem to have a pure networking perspective. NFV itself brings enough challenges that have to addressed and fixed in order for it to work properly in an enterprise setting. If networking devices displayed the exact same issues as regular servers did before the the cloud computing era, it is likely that VNFs would already be an integrated part of the cloud.

NFV was proposed seven years ago, but still we see little adoption by enterprises. We will later discuss the future of NFV and take a closer look at the research direction it is taking. Currently, the recognized research articles on NFV are primarily focused on networking. Most of these articles are published around four years ago and doesn't tell much about the direction NFV is currently taking. By looking at publications from recent years, we can see that the way researchers apply NFV and think about NFV is changing. We will further discuss this later in the section.

Publications appear in multiple venues regardless of affiliation

Academic and industry driven institutions are working closely together in order to make NFV feasible for enterprise settings. If the industry didn't believe NFV had potential to be facilitated in enterprise networks, they wouldn't be as highly involved in the research process as they are. Research conducted by both industry and academia is made available to the public and other researchers through journals, conferences or magazines. These publication venues have different standards and criteria that need to be fulfilled before an article is accepted and published. Articles published in scientific journals need to go through a thorough peer review process and are often viewed as high quality papers. It of course depends on the specific journal the article was published to as well, as some journals are valued higher than others. Journals often accept only archival quality papers, which tells something about the comprehensiveness and completeness of a paper. Journals articles are therefore often rated higher than conference or magazine articles, which doesn't have the same requirements.

Where articles are published can tell something about the quality of the work. For instance, if most academic papers were published in highly rated scientific journals and most industry papers were published in magazines, it would be a strong indication that academia produces higher quality research on the topic than the industry. That isn't to say that conference papers or magazine articles are low quality papers, they just lack the comprehensiveness of a journal paper.

Figure 2.7 depicts the distribution of which venues are published to by academia and the industry. The mixed category contains research papers that are written in collaboration between the two. As we can see from the distribution, there are no obvious signs that make any specific research affiliation stand out. Our findings show that there is no correlation between affiliation and venue. Academic papers and industry papers are published with a seemingly even spread across multiple venues. It is reassuring to know that the industry is involved in multiple venues, as it says something about their investment in the field of NFV.

The relationship is strong between industry and academia

Based on what we discussed above, it is certain that the relationship between industry and academia is strong in the case of NFV. It is a good sign that the industry is heavily invested in the research. Usually, it is the job of academia

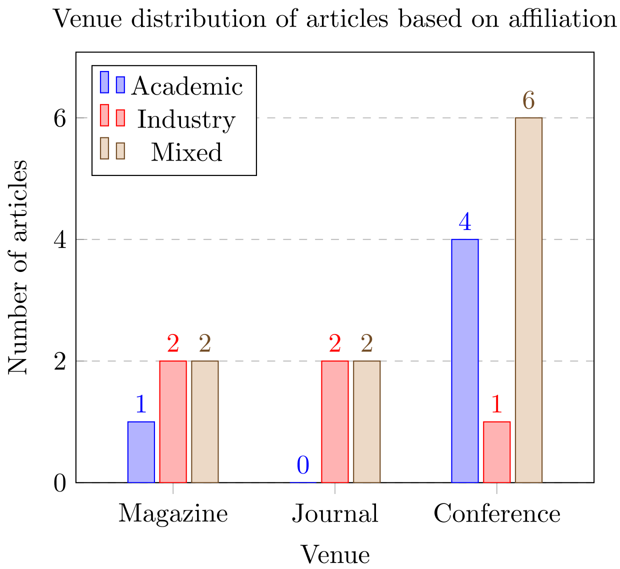

Figure 2.7: Number of publications in magazines, journals and conferences by academia, industry and both. Based on our taxonomy.

to explore and research new fields. Academia takes the burden of conducting the time consuming operations that are needed in order to make a technology or solution enterprise-ready. Examples of such operations can be: prototyping, optimizations, simulations and lab experiments. For NFV it's different. The industry is heavily invested in the research that is usually left to academia. Another good sign is that most research initiatives in the NFV landscape are carried out in collaboration between industry and academia. For the sake of NFV and its future, it's positive that the industry is heavily involved in the research process. It reassures us that the industry truly believes in NFV and would like to make it enterprise ready sooner rather than later.

2.2.4 Real-world impact

One might think that after seven years of research, with heavy involvement from the industry, that NFV would be enterprise-ready. Based on the literature and the research we currently have available it's hard to tell if this is true or not. Although, it is natural to think that if NFV in fact was enterprise-ready, it would already be massively deployed in most enterprise networks, because the advantages it promises are too good to ignore. In this section we would like to look at the takeaways that have emerged from the many years of research on the topic. We also look at how NFV has been tested in order to make it ready for real-world infrastructures.

Few takeaways, especially in recent years

First, we should define what we mean by takeaway. A takeaway in the context of NFV is any open-source software or publicly available software solution developed and presented in research articles on NFV. Without emerging technologies, solutions or prototypes that stick out, there is little consistency in the systems that are being researched and tested across the board. For instance, the OpenFlow protocol was a result of a university research project and was made publicly available for others to experiment with. The OpenFlow protocol enabled a massive amount of publications on the SDN subject and it's because of this single protocol that SDN evolved into what it is today. There are little sign of any emerging solutions in NFV that have helped shape NFV to the same magnitude OpenFlow did with SDN. Although NFV hasn't seen any stand-out solutions, there are some takeaways that are important to mention.

We performed a separate literature search to the one we did for the taxonomy, specifically looking for software takeaways. Table 2.2 shows some of the open-source and non-open-source software that have emerged from the years of NFV research. The table displays a list of the name of software that have been developed and used as part of NFV research. The table also shows the release year for the given software, as well as the number of times the research paper introducing the software has been cited in other papers. A paper with many citations is recognized by the community as high quality, which is why many researchers choose to cite it in their work. The release year should always be taken into account when looking at citations, because it can take some years before a particular research paper is being picked up and recognized by the community. Papers that have been publicly available for a longer time naturally get more citations. Research papers with hundred of citations, like in the case of ClickOS and OpenNF, can be described as highly valuable contributions within a specific research field, in this case the field of NFV.

ClikOS [37] is a virtualized software platform that is designed to efficiently run VNFs on commodity hardware. In the research paper, the authors claim it to be highly effective, in that it can run hundreds of middleboxes and offer millions of packets per second processing speeds, with low packet delays. One of the most positive aspects of the ClickOS project is that the solution is available for anyone to use, meaning other researchers can implement systems that run ClickOS in order to further innovate within the field. ClickOS was published in the early days of NFV and advertised the possibilities NFV could offer on commodity hardware, making it one of the most cited papers on the subject.

OpenNF [38] is a control plane designed to integrate SDN with NFV. A framework that can control both forwarding state and network function state is needed in order to fulfill service level agreements while at the same time manipulating and monitoring network traffic, and minimizing OPEX. The evaluation shows that OpenNF is effective and produces minimal overhead. The research paper on OpenNFV was released in 2015 and was one of the first to propose a well functioning architecture for SDN and NFV integration. As NFV is a byproduct of SDN, it is completely natural to combine these concepts, instead of keeping them entirely separate.

Although ClickOS and OpenNF are good examples of software solutions that stand out, they never became de facto solutions like OpenFlow. Both solutions have been important in many research project since their inception, but never crucial to a point that they have been taking over the research landscape. Outside these two solutions, there are little truly influential solutions to speak of for NFV. As can be seen in the table, new NFV solutions are still being developed, but it is hard to say anything about their value as of yet. Most of the

Table 2.2: NFV Software

Open-source	**Release year**	**Citations**
ClickOS [37]	2014	602
OpenNF [38]	2015	434
OpenNetVM [39]	2016	91
GNF [40]	2015	32
RestQ [41]	2018	24
NFPA [42]	2015	22
libVNF [43]	2017	1
DeMONS [44]	2018	1
Non-open-source	**Release year**	**Citations**
E2 [45]	2015	203
OpenANF [26]	2014	67
VGuard [46]	2015	29
Splitbox [47]	2016	22
CoFence [48]	2016	12

publicly available NFV software we found struggle to get much recognition from the research community.

Several NFV tools have been been developed throughout the years of NFV research. Some of the developed tools are open source, while other tools are merely described in the research paper with little to no insight into the source code. It can be argued that a paper that proposes a new software solution without making the source code available for other researchers and the industry, is of less value than papers that do so. The massive success of OpenFlow can be attributed to the fact that the authors published everything online for others to use freely. In addition to the open-source NFV tools previously discussed, there have also been developed tools in connection to NFV research that aren't open-source. The bottom half of Table 2.2 shows some of the developed NFV software that hasn't been made available to the public. As we can see from the table, the general number of citations are lower for research papers describing the non open-source software, than the open-source software seen in the table displayed above. This could of course be coincidental, but could also say something about the value of making the software publicly available.

E2 [45], is the most recognized non open-source software we were able to find. It is a comprehensive NFV management framework that can be used for all functionality revolving around NFV. It is meant to be a framework that lets software developers focus on implementing innovative and efficient VNFs without thinking of the underlying architecture. A newly developed VNF can easily be inserted into the E2 framework and things like fault-tolerance, scaling, etc, are taken care of. One interesting thing to note about this paper is that the authors claim the software solution to be open-source. From what we can see, there are no signs of E2 ever being publicly available on the Internet. That isn't to say for sure that it never was made available to the public, but it is unusual to remove open-source software from public availability, at least when the research paper promotes it as open-source.

Currently, no de facto NFV solution exists. If such a solution had been developed and recognized as the go-to solution in the first few years of NFV, the research landscape would probably look quite different. Most research would then focus on improving, reinforcing and adding to this single solution. The chances of an enterprise-ready solution emerging from the research in such a case would drastically increase. Instead, research on NFV has been too scattered and it seems to be little cohesiveness to the research. NFV seems to be in a stalemate, where researchers struggles to find optimal solutions to the problem.

NFV solutions are mainly based on imagined scenarios

As discussed in the last section, we do have some systems that are readily available to be used by the industry. The systems are introduced to the world through research papers that are written by both academic and industry researchers. The software itself is usually not described in much technical detail in such papers, especially not when published in journals or conferences. The authors rather focus on the overall architecture, how the software fits in a real deployment and most importantly results. Results are presented in the evaluation part of a research article and presents the contribution of the implemented software or system. In engineering, the performance of such systems are often times the properties the authors choose to focus on. Performance metrics can be many things, depending on what the authors are looking to test. Examples of such metrics can be: bandwidth, latency, throughput, CPU usage, memory usage, etc.

Some of the research carried out on NFV promises extraordinary results in terms of performance. By looking at the evaluation results of platforms such as NetVM [49], one would think that the main NFV issues were already solved and NFV was enterprise ready. It is curious that there are well functioning systems out there, that are proven to perform to exceptional levels, but still we don't really see much NFV deployments in real-world settings. Enterprises would have every incentive to switch to NFV already if a well-functioning solution already existed. After all, part of the job of researchers is to do the heavy lifting of exploring and experimenting until a technology or solution is polished enough to be ready for real-world environments. If that job was already complete, like some research implicitly states, NFV would have been widely deployed already.

A likely explanation to why NFV still isn't widely deployed, despite promising results, is that most research conducted on NFV is based on imagined scenarios. Research papers that are built on such scenarios start by explaining the problem and how the authors want to address it. They continue by explaining their line of thought, the system architecture and how the software works in an overall sense. The next section of the paper explains how they tested the software by running various simulations, either on physical hardware in a lab or pure software simulations. The collected simulation data is usually analyzed and discussed before the paper is concluded.

Algorithms, often in form of heuristics are important in order to solve optimization issues related to NFV. Papers that are proposing algorithms often follow the same structure as explained above, where the algorithm(s) is/are first explained, then proven to be effective by presenting the results from various simulations. Software simulations are the most common approach for testing optimization algorithms. In [50] they perform trace-driven simulations to test their algorithms. A trace-driven simulation uses data from observations previously made in other real-world systems as input to the simulation software.

They carry out the simulations by applying the algorithm(s) to the simulation scenarios, to see if the algorithm(s) increases efficiency in the way intended by the researcher. Although software simulations are most common for testing optimization algorithms, there are cases where optimization algorithms are tested in more realistic settings. In [51] they test the efficiency of their heuristic algorithm in a three-tier data center network.

The problem with papers based on imagined scenarios is that the authors are testing their solutions through controlled simulations either with synthetic data in lab environments or through software simulation, both of which don't carry the same characteristics as real-world deployments. The authors are conducting the tests on their own terms and are aiming to make their software perform to the best possible level in this very narrow context. This is definitely the easiest way of conducting testing and is a good way of advertising a solution's potential. The realism of such simulations vary from paper to paper. Some authors use simulation data that is similar to real-world data, and create complex lab environments in order to resemble a real-world environment. Other authors opt to implement simpler environments with two or three devices in order to reduce complexity and focus on the important characteristics of the solution. Simulated experiments described in papers based on imagined scenarios should be considered carefully in order to get a better understanding of the potential real-world feasibility of the implementation. Imagined scenarios can be some of the reason NFV hasn't quite made it into the industry yet, despite showing promising and sometimes exceptional results.

Real tools, synthetic data

There is a good mix between optimization and exploratory research. Optimization aims to increase efficiency of a solution compared to current solutions, while exploratory research proposes new ways of tackling a problem, often by introducing new software. A mix of optimization and exploratory research is often what is found within engineering and there have been many success stories throughout history (e.g., OpenFlow). In other words, there is nothing wrong with the general approach to the problem that we observed in our literature search.

A common denominator amongst most exploratory research papers on NFV is that they use real tools combined with synthetic data. This means that the authors are developing real tools that in all practicality could be deployed in real systems. But in order to test the tools they use synthetic data. In other words, the experiments consist of one real-life component and one component where the level of realism is dependent on the wishes of the researchers. It is difficult to properly compare the NFV tools that have been developed because the researchers conduct synthetic experiments that are unique to each research project.

Few takeaways

It is fair to say that the takeaways in the NFV domain are scarce. We found a couple of popularized software solutions, but not anything that stood out in the sense that it has helped shape the NFV landscape to particularly meaningful degree. Results obtained through testing in lab environments or software simulations doesn't in itself help toward the goal of making NFV an integral part enterprise network solutions. Readily available open-source solutions that are easy to deploy and also proven to work through real-world testing is something that NFV currently lacks. Researchers continue to work toward making NFV a valuable solution that will be a natural part of future networks in general.

2.2.5 Why are people uncertain?

The question we would like a better answer to is: "Why are people still uncertain when it comes to NFV?" We have already made quite a few clarifications and statements as to why there still seems to be uncertainty within the industry when it comes to NFV. The following list points out the key observations that have been discussed in this section:

- The relationship between academia and industry is strong in regards to NFV research.
- The main focus of the research conducted on the topic seem to be related to networking, but also tend to lean toward infrastructure and service, which belong to the domain of cloud computing.
- Research papers are published in multiple venues, regardless of affiliation.
- There are few takeaways in terms of open source software that can be used by other researchers or the industry.
- NFV researchers mainly focus on imagined scenarios, with little real-world experimentation.
- There is a steady mix of optimization and exploratory research.
- Authors that propose real implementation of NFV tools use synthetic data when testing the software.

Some of the observations are highly positive for the future of NFV, while others aren't. One of the most interesting parts about NFV research is that it was initiated by the industry and that the industry has been highly involved in the research, probably more so than academia. This is a great sign that the industry at least has knowledge about the many advantages that NFV brings. Academia and industry are still struggling to make NFV fit into a networking environment and it's especially hard to find good solutions of replacing legacy networking equipment entirely. Research still has a long way to go to reach the goal of full function virtualization in the networking realm. Ideally, the networking part of the enterprise IT infrastructure should look similar to the cloud computing infrastructure, which enables the possibility of integrating network middleboxes seamlessly into the cloud.

If we conducted literature searches for mainstream technologies that emerged from research, it is likely that we would make many of the same observations as we did for NFV, even though NFV has yet to become mainstream. The key difference is that for popular technologies we would likely find more cases of real-world experimentation that to a certain degree proves the technology's worth, compared to simulated studies. We struggled to find real-world cases for NFV, which could be one of the reasons people are still uncertain about its real-world applicability.

If cases exist, then they're published elsewhere

Based on our literature search, we concluded that few real-world cases of NFV experimentation exist. That doesn't mean that we can say for certain that there are no cases out there. As the industry is heavily involved in the research, it is likely that multiple real-world experiments have been performed. The reason we conclude that there are little real-world research is that it didn't turn up in our literature search. Results from real-world scenarios may be published places we didn't consider, as we mainly looked for popular research papers in renown venues. It also may be the case that many of the attempts of real-world deployments are documented by the industry research facilities, but never been made publicly available. In other words, if we want answers to the question of NFV's feasibility in real-world deployments, research venues are not a good place to look.

Even though we didn't find much in terms of real-world NFV experimentation, there is one article that stood out. In [52], they extend the ETSI's NFV MANO architecture by integrating common IoT services. The authors argue that the convergence of NFV, 5G and fog computing is unavoidable and has therefore created this new and improved architecture that integrates all the technologies/concepts. They present two use cases that show how this architecture works. Fog hardware boxes and cameras that are involved in the experiments are installed in the city of Barcelona. They thoroughly explain the data flow within the architecture and show how NFV fits into the popular topic of IoT.

This is an important paper that we believe tells much about the future of NFV and its direction. NFV used to be a popular topic after its arrival in 2012. But as 5G and IoT started to become increasingly popular topics, NFV research started to decrease in popularity. We will still see a lot of research on NFV, but often times NFV takes a side role and is discussed in relation to IoT, 5G or fog computing. It seems NFV has changed its research direction.

NFV will be found in use cases, but mostly as a side role

Nowadays, IoT is the hottest topic within the field of data and communication technology. IoT is a concept that has become increasingly big with the raise of 5G. 5G is an enabler for IoT, while fog computing is a concept that is a natural part of IoT. Both 5G and fog are natural parts of IoT and are often discussed in IoT research papers. IoT's immense popularity affected research on NFV, as researchers started to look toward this new and exciting concept instead. Research involving the reduction in network complexity and cost through virtualization became less important. NFV was forced to change direction and become a part of the new IoT paradigm. NFV is easy to integrate with IoT because it is based on virtualization, which makes it modular, flexible and light-weight, all of which are important attributes in the world of IoT.

Today, NFV is still a highly popular and relevant technology that is being mentioned in a multitude of publications. The biggest difference from the first few years of NFV research is that today's articles often discuss NFV in relation to IoT, 5G or fog. The NFV research landscape has changed in that NFV is now being used as a supportive technology to enable sophisticated IoT services together with 5G and fog. We think that for the future, research with NFV in the main role will continue, but the majority of papers mentioning NFV will be primarily focused on IoT. As IoT and 5G are already highly popular it is likely that there will be many real-world NFV experiments in the future, with NFV as a supportive technology. Even though the original goals for NFV isn't being prioritized like they used to, the new direction for NFV seem promising. NFV will continue to remain relevant through its natural integration with IoT.