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Frick, G

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G. Frick, A. Paguem Tchinda, U. Trick and A. Lehmann
Research Group for Telecommunication Networks
Frankfurt University of Applied Sciences
Frankfurt/Main, Germany
{ frick, paguem, trick, lehmann }@e-technik.org

G. Frick, A. Paguem Tchinda and B. Ghita
Centre for Security, Communications and Network Research
University of Plymouth
Plymouth, United Kingdom
{ gregor.frick, auberlin.paguemtchinda, bogdan.ghita } @plymouth.ac.uk

***Abstract*—This publication deals with distributed NFV orchestration in a WMN-based disaster network. The NFV orchestrator defined by ETSI is designed as a central unit and therefore includes the possibility of a single point of failure. Due to the environment of a disaster, a WMN node hosting this centralized orchestrator might get destroyed at events such as aftershocks resulting in a breakdown of the NFV infrastructure as it cannot be maintained and orchestrated anymore. To eliminate this aspect, requirements for a distributed NFV orchestration are defined. The requirements are categorized into architectural and orchestration specific aspects and are derived from the characteristics of a WMN and the conditions of a disaster environment. A concept for realizing a distributed NFV orchestration in a WMN-based disaster network according to the defined requirements is presented. The architecture consists of five logical layers with each layer fulfilling a specific functionality.

Keywords — NFV, distributed orchestration, WMN, disaster network

I. Introduction

Due to natural disasters such as earthquakes, tsunamis, hurricanes and floods and man-made disasters such as persistent power failures it is essential to create structures to help the affected victims. In [1] an operating communication infrastructure is assumed to be crucial for the rescuing of victims and the management of the rescue teams. Unfortunately, existing communication infrastructures are often destroyed by the disaster, which makes the communication inside the affected regions impossible. [2]

To establish a communication infrastructure for these disaster scenarios, a wireless mesh network (WMN) is suggested by [3]. The WMN consists of battery-supplied outdoor-routers connected to each other for creating a network. New nodes can be added to the WMN, while existing nodes might spontaneously leave the network because of an exhausted battery or aftershocks. By integrating and utilizing network functions virtualization (NFV) in the WMN, the disaster network could be optimized regarding the availability, reliability, cost-efficiency, scalability, lower power consumption, adaptable network configuration and topology.

A crucial aspect regarding the integration of NFV into a WMN-based disaster network consists of the required centralized NFV orchestrator. A WMN-Node hosting the centralized orchestrator might get damaged, destroyed or lose its connectivity to large sections of the network due to additional disasters such as aftershocks and outbreaking fires. This is not beneficial, as it will result in losing the possibility to maintain and orchestrate the resources of the NFV infrastructure (NFVI) and the realized network services (NS). To prevent this scenario of a complete breakdown of the NFVI, the functionalities of the orchestrator needs to be distributed among the WMN nodes of the disaster network.

Besides the elimination of the potential single point of failure of a centralized orchestrator through a possible redundancy realized by a distributed orchestrator, other improvement can be achieved. The workload of the centralized orchestrator can be distributed over several nodes of the distributed orchestrator. Additionally, the network traffic required for the management and orchestration functionality can be optimized through a distributed orchestration. In case of a centralized orchestrator this kind of traffic must be forwarded from a maintained WMN-Node through the whole WMN to the orchestrator. This results in a high load on the connections in the WMN and an increased energy consumption which is needed for the transmission of the messages. In case of a decentralized orchestrator consisting of multiple instances, the traffic can be forwarded to the next local orchestrator instance. This would reduce the load on the links of the WMN. However, additional intra-orchestration traffic between the instances of the distributed orchestrator would be required and the decision-making process becomes more complex than the one of a centralized orchestrator.

This paper is structured as follows. Section II will shortly summarize and explain the NFV Management and Orchestration components as defined by the European Telecommunications Standards Institute (ETSI). In Section III requirements for a distributed NFV orchestration in a WMN-based disaster network are defined and explained. Section IV contains related work regarding distributed NFV orchestration and the integration of NFV into similar distributed environments such as Edge and Fog. The papers of both aspects are shortly evaluated regarding the defined requirements. Section V presents an architectural concept for a distributed NFV orchestration in a WMN-based disaster, considering the defined requirements. This paper will close with the outlining of the conclusions and an outlook regarding future works in Section VI.

II. Network Function Virtualisation Management and Orchestration

The NFV Management and Orchestration (NFV-MANO – see Fig. 1) consists of three functional blocks: Virtual Infrastructure Manager (VIM), VNF (Virtual Network Function) Manager (VNFM), NFV Orchestrator (NFVO) and four data repositories: NS Catalog, VNF catalog, NFVI Instances and NFVI Resources. [4]

A VIM manages and controls NFVI physical and virtual resources in a single domain. This implies that an NFV architecture may contain more than one VIM, each of them managing or controlling NFVI resources from a given infrastructure provider. Each VNF instance is assumed to have an associated VNFM. The VNFM is responsible for the management of the lifecycle of VNFs. A VNFM may be assigned with the management of a single or multiple VNF instance of the same or different type, including the possibility of a single VNFM for all active VNF instances for certain domain. [4]

The catalogues and repositories are databases used for storing different kind of information in the NFV-MANO. This information consists of predefined templates required for the deployment of NS and VNFs (via the NS Catalog and VNF catalog), as well as information regarding active NS and VNF instances (via the NFV Instances) and available and/or allocated NFVI resources (via the NFVI Resources). [4]

The logically centralized NFVO of the NFV-MANO aims to combine more than one function to create end-to-end services. Its functionality can be divided into two categories: the resource orchestration and the network service orchestration. The network service orchestration deals with the instantiation and lifecycle management of the network services. This includes the instantiation of the required VNF(s) in coordination with the VNFM(s) and the topology management of the network service instances. Additionally, it is responsible

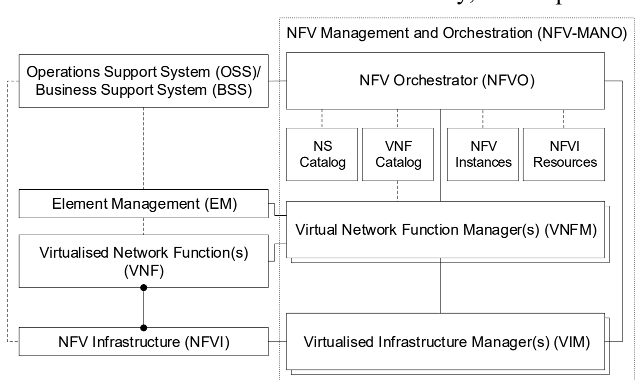

Fig. 1. NFV Framework specified by ETSI [5]

for the policy management and evaluation for the network service and VNF instances (e.g. policies related to scaling, fault and performance, etc.). The resource orchestration provides the NFVI resource management across infrastructure domains including the reservation and allocation of NFVI resources to network services and VNF instances in coordination with the VIM(s). It is also responsible for the policy management and enforcement regarding aspects such as reservation and/or allocation policies. [5]

III. Requirements for a distributed NFV Orchestration in a WMN-based disaster network

To the author's best conscience, the integration of NFV with distributed orchestration into a WMN-based disaster network has not yet been considered by other publications. Therefore, several requirements have been defined for the realization of this aspect. The requirements are separated into two different categories: *Architecture* specific and *Resource and Network Service Orchestration* specific aspects. In the following sections, the requirements of each category are explained and justified in detail.

A. Architecture specific Requirements

Assuming an integration of the NFV framework specified by ETSI into the WMN-based disaster network, the centralized NFVO is inhibiting the possibility of a single point of failure as previously explained. The component responsible for the distributed NFV orchestration in a WMN-based disaster network therefore needs to fulfil architecture specific requirements:

1) Distributed and Decentralised

To prevent the possibility of a single point of failure, the architecture of the NFV orchestrator for the WMN-based disaster network needs to consist of a distributed and decentralized structure. This shall provide the possibility to realize redundant orchestrator units, which increases the availability of the orchestrator and therefore the availability of the complete NFVI and its realized network services.

2) Light-weight communication

Due to the distributed and decentralized architecture of the orchestrator, additional communication is required for the decision-making process of the orchestration. The advantage of the previously mentioned reduction in the amount of traffic required for the node management over a central orchestrator and the resulting energy savings should not be lost. For this reason, the intra-communication between the instances of the distributed orchestrator should be as lightweight as possible. To enable a successful and useful output of the decision-making process, the intra-communication must ensure that the instances are constantly synchronized. Each instance should know and maintain the state and configuration of the other instances and their area of responsibility in the NFVI. This shall make it possible to seamlessly transfer the area of responsibility to another instance in the event of a failure of an incorrect instance.

3) Adaptability/Flexibility

As nodes can be added and removed to/from the WMN, the architecture of the distributed orchestrator must readjust and reconfigure itself if required to adapted to the changes in the network topology. This shall consist of the initialization of new traffic in case of an increase of the network size and the deinitialization of existing instances if the network size decreases. In both cases, responsibilities for parts of the NFVI need to be transferred to oth6er instances.

4) Robust/Fault-Tolerant

Due to the possibility of destroyed nodes in the WMN-based disaster network, the distributed architecture needs to be robust and fault-tolerant. Failing instances of the distributed orchestrator need to be replaced immediately. This might ether be realized by another instance taking over the responsibility of the failing instance or the initialization of a new instance.

5) Secure against violators

The distributed orchestrator must ensure that no attackers or violators can become part of the architecture. This shall prevent the decision-making process during the orchestration from being influenced or compromised by incorrect information. Access to the distributed orchestrator for possible administrative activities (e.g. initialization of specific network services) should also be adequately protected.

B. Resource- and Network Service-Orchestration specific

NFV is designed to run on high volume servers, routers and switches in datacenters. The underlying hardware of the WMN-based disaster network is not able to provide this amount of hardware capacity as it consists of out-of-the-shelf battery-supplied outdoor-routers, which should be highly energy-efficient to ensure a high lifespan of the disaster network. Due to these aspects, the resource and network service orchestration functionality of the distributed orchestrator needs to fulfill the following requirements:

1) Wireless Connection awareness

The WMN-based disaster network is based on the wireless technology Wi-Fi. Since this type of technology is very susceptible to spontaneous and potentially lasting interferences, this aspect must be considered during the allocation of VNFs in the NFVI. In addition to the actual link quality, the general connections between the nodes of the WMN must be considered and constantly monitored. Adding WMN-Nodes could result in new and more performant paths discovered by the underlaying mesh routing protocol. In this case, a relocation of the VNFs might be required to optimize and improve the performance of the corresponding network service.

2) Continuous Resource awareness

Due to the ability of self-configuration and self-organization, a WMN and thus the disaster network can be extended at any time. To extend the NFVI, the distributed orchestrator must seamlessly and automatically integrate the new resources. Also, the failure of WMN nodes and thus of NFVI-Point of Presences (NFVI-PoP) must also be regulated. There are two possible failures in the disaster network: a predictable failure due to an exhausted battery and an unforeseeable failure due to destroyed nodes because of events such as aftershocks and outbreaking fires. Both cases must be handled by the Resource-Orchestration functionality of the orchestrator.

3) Energy-Efficient Resource allocation

Since the WMN nodes are battery-powered, the ability to optimize the energy consumption is one of the main reasons for integrating NFV into the WMN-based disaster network. The Resource- and Network Service-Orchestration functionality of the distributed orchestrator must allocate the network services as energy-efficiently as possible in the NFVI to ensure the longest possible lifespan and therefore the availability of the disaster network. For example, user-traffic flows in the WMN could be optimized so that services (such as web servers) are located close to the respective users. As a result, user traffic would not have to be forwarded unnecessarily in the WMN. If users move to another segment of the WMN, the corresponding service could also be migrated to the corresponding segment in the NFVI.

4) Autonoums deloyment of network services

Due to the disaster environment, an administrator for the distributed orchestrator and therefore the NFVI cannot be expected. The orchestrator must therefore work as autonomously as possible. This also includes the initialization of network services currently required in the disaster network without any external trigger.

IV. Related work

ETSI's NFVO defined in [5] is designed as a logically centralized component making it vulnerable to a single point of failure. [6] mentions that the possibility of a single point of failure in the NFV-MANO system shall be eliminated by deploying the system in a redundant and geographically distributed manner. In this case, the NFVO would remain a central unit, which means that the traffic for maintaining and orchestrating the resources of the WMN-Nodes must still be forwarded through the entire WMN. Furthermore, additional traffic would be required for a permanent synchronization with the redundant unit to ensure a seamless transition in case of failure. In [7] and [8] an architectural option is mentioned, which is dealing with the orchestration across multiple separated NFVI domains. Each domain has an individual orchestrator responsible for the resources in its domain. An additional higher-level Umbrella-Orchestrator is connected to all Domain-Orchestrators to realize domain-spanning network services. Although a partitioning of the WMN into several separate domains would be possible and conceivable, the Umbrella-Orchestrator remains a central unit, whereby the possibility of a single point of failure remains. In [8] a proposal, including recommendations, is made for a reference point between NFVOs in separate NFVI domains for realizing multi-domain network services. Further evaluation of the proposal and its recommendations is required to distinguish its usability for the intra-communication of a distributed orchestration.

[9] proposes a distributed approach to NFV orchestration using belief-desire-intention (BDI) reasoning, addressing the selection of VNFs, their placement in the NFVI and their chaining. This is achieved through the interaction among autonomous software agents, which collectively work in a distributed and decentralized manner. The centralized NFVO and the VNFMs of the ETSI NFV-Framework are replaced by

the BDI agents, which are communicating via the FIPA Agent Communication Language (ACL). Each VNF is represented as a BDI agent, each with its capabilities and beliefs about the network. Through the process of bidding in an auction process according to the beliefs and intentions of an agent an autonomous configuration process for the placement and chaining of VNFs has been achieved, which is able to achieve network resilience during a DDoS attack scenario. Depending on the number of agents, the number of exchanged messages scales by a factor of 10. Assuming every WMN node will host at least one agent, the traffic required for this concept will be too high. Additionally, the beliefs of an agent about the network topology in the WMN might be very limited and a resource-efficient output of the VNF placement auction process is doubtful.

In [10] a cross domain network service orchestration framework X-MANO is presented. X-MANO is effectively deployment-agnostic and can be used in hierarchical, peer-to-peer and cascading (or recursive) configuration. The concept of having a large NFVI divided into several domains managed by several hierarchical orchestrators seems promising. It would be possible to divide the WMN into several logical domains, but the NFVI of the WMN-based disaster network is not static since new nodes can be added at any time or integrated nodes can get lost. X-MANO does not take this aspect of adaptability and flexibility into consideration. There is also a lack of an approach for the information that need to be transmitted between the orchestrators for a complete realization of the concept.

[11] presents a fog computing framework for the management and orchestration of smart city applications in 5G wireless networks. The framework consists of a fully-integrated fog node management system alongside a foreseen application layer Peer-to-Peer fog protocol based on the OSPF routing protocol for the exchange of application service provisioning information between fog nodes. Each fog node makes decisions using a machine learning algorithm and the information it receives from other fog and cloud nodes via the fog protocol. The approach should enable the realization of NFV orchestration aspects, such as the lifecycle management of network services. However, this aspect remains largely unconsidered, as the main aspect lies on resource provisioning of IoT services. Considering this approach in the WMN-based disaster network, a highly complex computational and energy-heavy machine learning algorithm would be required to distribute the complete NFV management and orchestration functionalities among the WMN nodes. In addition, a complementary of the required cloud node, including its global view about the infrastructure at all time, cannot be provided in the disaster network. However, the approach of the fog protocol appears promising for the distributed NFV orchestration in the WMN-based disaster network.

In [12] a fully programmable NFV Orchestration architecture for edge data centers is presented. Through its topology-awareness and the server-centric topology of an edge data center, the centralized orchestrator can take advantage of the node position to place VNFs in servers that are already part of the path between source and destination. As the server-centric topology can also be mirrored onto the WMN, some aspects of the described approach for realizing the VNF allocation and chaining might be utilizable. However, their actual orchestrator remains a centralized orchestrator.

A complement to NFV is mobile-edge computing (MEC), which provides IT and cloud-computing capabilities with the radio access network (RAN) near mobile subscribers [13]. While MEC and NFV can co-exist in a network, [14] suggests an approach where ME applications can also be interpreted as VNFs and NSs, allowing them to be orchestrated by an NFVO, eliminating the need for an additional Mobile Edge Orchestrator (MEO). This would allow the realization of MEC specific use cases such as RAN-aware content optimization, distributed content and DNS caching as well as application-aware performance optimization. Those use cases are improving the network efficiency and customer experience and would therefore increase the network efficiency and throughput of the WMN-based disaster network. However, the MEO and the NFVO in the concept proposed in [14] remain centralized components.

V. Architecture of a Distributed NFV-Orchestrator for a WMN-based Disaster Network

To realize a distributed NFV-Orchestrator for a WMN-based disaster network, a concept of the orchestrator's architecture was developed, which makes it possible to realize the defined requirements. The architecture of the distributed orchestrator is based on five logical layers (see Fig. 2) which are explained in the following sections: the *WMN-based NFVI Layer*, the *VIM Layer*, the *NFVI-Clustered Layer*, the *Distributed Data Storage Layer* and the *NFV-Orchestration Layer*.

A. *WMN-based NFVI Layer*

The *WMN-based NFVI Layer* consists of the actual battery-supplied outdoor-routers. Each WMN-Node in the disaster network is realizing a NFVI-PoP and provides its hardware and virtualization layer to the NFVI. Each node provides WMN-related as well as hardware- and virtualization layer-related information to the higher layers. The WMN-related information contains of the nodes knowledge about the WMN such as connections and routes as well as their capacity and quality, which are discovered by the used mesh routing protocol.

Previous research in [15] has evaluated the performance of different routing protocols regarding their use in the disaster network. The evaluation indicates that the protocol HWMP provides the best performance in terms of network adaptability.

B. *VIM Layer*

The *VIM Layer* defines a VIM for every NFVI-PoP in the WMN-based disaster network. A VIM is theoretically able to monitor multiple NFVI-PoPs. However, a VIM requires to permanently monitor the resources and the virtualization layer of its NFVI-PoPs for being able to notify an orchestrator at crossing of a defined threshold. By defining a VIM for every NFVI-PoP and therefore every WMN-Node, the required monitoring traffic remain locally on the nodes and is not forwarded through the WMN. Traffic regarding the

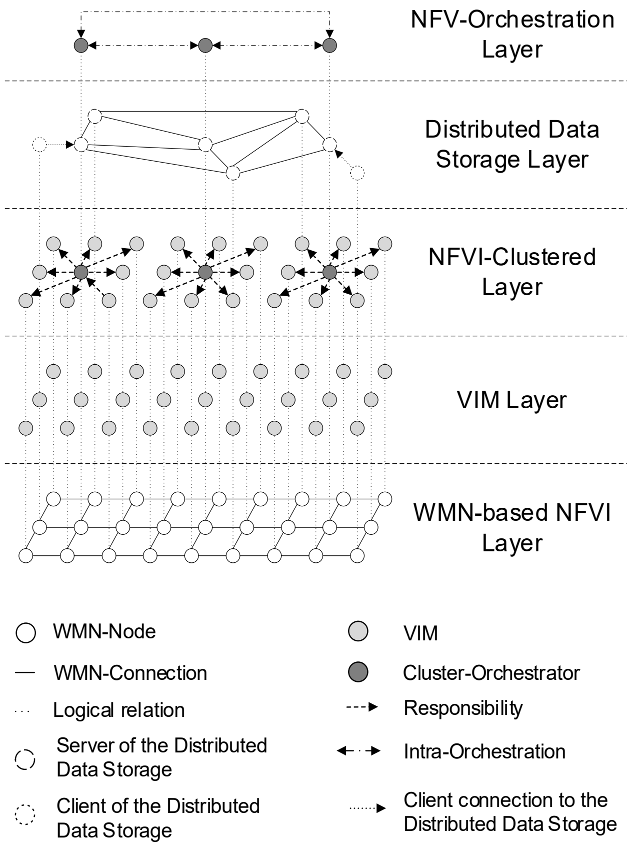

Fig. 2. Layers of an architecture for a distributed NFV orchestration in a WMN-based disaster network

management and orchestration of the NFVI-PoPs will only occur during the orchestration of the resources initialized by an orchestrator and during the notification of the VIM towards an orchestrator.

By retrieving and monitoring the information provided by the *WMN-based NFVI Layer* below, the VIM can provide meaningful information for an orchestrator.

C. *NFVI-Clustered Layer*

The *NFVI-Clustered Layer* consists of logical clusters on top of the *VIM Layer*. Each cluster defines the area of responsibility for a Cluster-Orchestrator responsible for orchestrating and managing the resources and network services in its cluster. The Cluster-Orchestrator realizes these aspects by communicating with the VIMs in his area of responsibility. Based on the retrievable information, a Cluster-Orchestrator can make decisions regarding the orchestration of resources within its cluster.

In the case of a new node being added to the WMN-based disaster network, the node will be connected to its locally nearest cluster. A new cluster will be created, in case of a cluster size increasing to a certain level, that a new node requires a significant number of hops in the *WMN-based NFVI-Layer* to reach its Cluster-Orchestrator. After initializing a new cluster including the assignment of a corresponding Cluster-Orchestrator, adjoining clusters might be rearranged to achieve evenly cluster sizes. Through the rearrangement of the clusters, adaptability and flexibility is achieved for the distributed orchestrator and thus for the WMN-based disaster network.

D. *Distributed Data Storage Layer*

The *Distributed Data Storage Layer* offers the possibility to store and save data and information in a reliable manner. An important feature of this layer is the ability to automatically create, distribute and manage redundancies of imported data and information. This makes it possible to achieve a high degree of reliability. The layer its realized by the Cluster-Orchestrators and an additional Backup-Node in each cluster, which are together creating and maintaining the reliable distributed data storage. The Backup-Node is added for an additional level of resilience to this layer. In case of a Cluster-Orchestrator failing, the data stored in the Distributed Data Storage Layer are still locally available in each cluster. The functionality of this layer is used for various aspects.

The Cluster-Orchestrators will use the layer to store and update the current NFV configurations and states in their cluster, which offers serval advantages. On the one hand, it relieves the actual communication between the Cluster-Orchestrators since any Cluster-Orchestrator can read in the complete configuration of other clusters at any time if it will be required. If a Cluster-Orchestrator fails, the configuration and state of the cluster is not lost, so that a new instance of a Cluster-Orchestrator can be put into operation immediately. Due to this aspect, it is important that the layer is automatically generating and maintaining redundancies of the stored data. Additionally, it needs to support a permanent synchronization of the stored files and the corresponding redundancies to ensure that the accessible data are always the most recent ones.

The *Distributed Data Storage Layer* also provides the possibility to store the current topology of the WMN. A Cluster-Orchestrator can request the current connections and their capacity from the VIMs inside its cluster and store and maintain these information in the layer. By reading out all entries, a directed graph can be created that the Cluster-Orchestrator can use for the algorithm required during the allocation of VNFs.

Lastly, some services later realized as a VNF might create sensible data, which shall not be lost at a failure of the WMN-Node hosting this VNF. In this chase, the corresponding WMN-Node can create a client connection to the Distributed Data Storage Layer via its Cluster-Orchestrator and store the data of the VNF in the layer and not locally. Due to the automatically created redundancies, a new VNF can be created using the stored sensible data in case of a failure.

E. *NFV-Orchestration Layer*

The *NFV-Orchestration Layer* is used for the intra-orchestration communication of the Cluster-Orchestrators. Due to the usage of the *Distributed Data Storage Layer*, a continuous transmission of configuration and state information of each cluster is not required. The communication taking place in this layer is event-driven and deals with the cluster-wide coordination regarding the NFV orchestration and the management and partitioning of the *NFVI-Clustered Layer*.

In case of the initialization of a new network service or the optimization of an already deployed network service, a Cluster-Orchestrator retrieves the available NFV configuration and state information of all clusters using the *Distributed Data Storage Layer*. Through this retrievable global view over the *WMN-based NFVI Layer*, the Cluster-Orchestrator will determinate the optimal placement and chaining of the required VNFs and notify the corresponding Cluster-Orchestrator with the appropriate configurations for their cluster. Additionally, NFV related failures will be handled via the intra-orchestration communication. In case of a local failure that cannot be solved by the corresponding Cluster-Orchestrator, such as the loss of a large proportion of resources in the local cluster, an event will be send to the other Cluster-Orchestrator indicating the requirement of an immediate intervention for bypassing and solving the failure by redeploying failing VNFs in adjoining clusters.

Regarding the management of the *NFVI-Clustered Layer*, the Cluster-Orchestrators will coordinate the partitioning of the clusters. This consists of the creation of a new clusters by initializing a new Cluster-Orchestrator, as well as the removal of existing clusters. In both cases a rearranging of the adjoining clusters is required. The case of a failed Cluster-Orchestrator is also dealt with by promoting a new Cluster-Orchestrator in the corresponding cluster or by taking over the responsibilities by an existing one.

The integration of a quorum-based voting procedure into this layer, in which other Cluster-Orchestrators must verify the proposal of a cluster-wide orchestration decision, is possible and conceivable, as this entails an additional synchronization within this layer.

VI. Conclusion

In this publication a distributed NFV orchestration for a WMN-based disaster network was examined and presented in detail. *Architecture specific* and *Resource- and Network Service-Orchestration* specific requirements for the distributed orchestration have been defined. The requirements were derived from the characteristics of a WMN and the environment of a disaster. Related work in the field of distributed NFV orchestration as well as the integration of NFV into similar environments such as Fog and Edge have been briefly examined regarding their approach and compared with the defined requirements. A concept for a distributed NFV orchestration in a WMN-based disaster network was presented, which consists of the logical clustering of the WMN. Each cluster is maintained and orchestrated by a Cluster-Orchestrator. Cluster-wide coordination regarding the NFV orchestration is achieved via the intra-orchestration communication. To realize this concept an architecture is proposed consisting of five logical layers with each layer fulfilling a certain functionality. Those layers are the *WMN-based NFVI Layer*, the *VIM Layer*, the *NFVI-Clustered Layer*, the *Distributed Data Storage Layer* and the *NFV-Orchestration Layer*. Through this proposed concept a distributed NFV orchestration for a WMN-based disaster network can be achieved which is among other things adaptable and robust.

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