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A Concept Approach for Network Slicing in Wireless Mesh Disaster Networks

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***Abstract*—Network Slicing is one of the critical enablers for the upcoming 5G mobile networks. This approach allows the creation of different, separated virtual networks based on the same physical infrastructure. Wireless mesh networks can supply large areas with radio technology-based signals via individual nodes. They are self-organising and self-configuring. This qualifies them to supply larger areas with wireless technology-based communication infrastructure quickly and less complicated. As a result, there are different areas of application for the use of such networks, e.g. restoring communication infrastructure in a disaster area. Applying network slicing within such a wireless mesh network can provide virtual networks adapted to different participants' needs. To adapt network slicing on wireless mesh networks, different aspects have to be considered: Mapping the virtual connections to the pysical infrastructure, slicing the wireless resources and placing the virtual network functions. This work is about a concept for a Network Slicing approach which provides possible solutions for the first two aspects and and first approaches for the last.**

***Index Terms*—network slicing, wireless mesh networks, NFV, SDN**

I. INTRODUCTION

Network Slicing enables the possibility to provide different services with contradicting requirements on the same infrastructure. The network provides a virtual network "slice" for different use cases based on the physical network infrastructure. Network Slicing is one of the critical enablers for modern 5G networks [1]. The concepts proposed so far are only for application in 5G networks to realize the different architectures of eMBB, URLLC and mMTC [10] [9]; wireless mesh networks [14] (WMNs) were not subject of development and research. The approaches for WMNs that exist so far describe either the resource sharing approach in wireless networks or network virtualization. However, an end-to-end network slicing approach has to fulfill the complete functionality of a network that provides specific services. The network architecture of 5G networks and WMNs is entirely different. WMNs have a decentralized architecture and have radio-based connections to other nodes. Additionally, in this particular case, as a disaster network, all functionalities in the network must be provided by the WMN nodes. In a WMN, new nodes can join or leave the network, resulting in topology changes [12]. In contrast to WMNs, in 5G Networks, only the access network part is radio-based. The other parts of the network are wired connections. Data centers for the network functions are also available in these networks. Because new base stations cannot simply join or leave the network, the network architecture of 5G networks is more static than in WMNs. Because of these reasons, it is not possible to transfer the principle of network slicing from 5G networks to wireless mesh networks without further research.

This work introduces a concept to provide network slicing in wireless mesh networks. A network slice is defined as follows: The combination of virtual and physical network functions, the connections between them and the resources of the physical infrastructure. In previous work [2] a method for determining the best possible path between the nodes of the mesh was already shown. The path determination is only one aspect for the network slicing concept. To build a complete slice on a WMN, three aspects have to be considered:

1) Path determination between the nodes,
2) Allocation of wireless resources between the different network slices,
3) (Re)placement of the virtual network functions on the WMN nodes.

This paper is organized as follows: Section two presents related work regarding network slicing in wireless mesh networks. Section three describes the modeling of the wireless mesh network and the network slices based on it. Section four describes the conceptual approach for creating network slices on a wireless mesh network.

II. RELATED WORK

This section describes work that affects network slicing in wireless mesh networks. The work in [3] deals with the interference aspect in a sliced wireless network. The authors provide a management scheme that uses interference between the wireless links for topology decisions. The interference gets a weight based on the priority of the corresponding slice. Based on a weighted sum of the interferences, the proposed algorithm creates a path through the wireless network which has to minimize the interference sum of the other slices to create an optimized path. In [6] the authors describe a way of sending packets over different virtual interfaces in a wireless mesh network. They use this approach to decrease the packet loss in the network, by sending the same packet over multiple interfaces. In [16] and [20] a possibility for resource allocation in the radio network for a single access point is described. The principles of wireless network virtualisation and airtime slicing are used in this works. In [19], the authors describe a replacing approach for service function chains (SFC). A SFC describes a combination of a path and intermediate virtual network functions. The focus of this work lies in the minimization of resource consumption and as few adjustments as possible, through the relocation of VNFs to different network parts that can host them. The work in [17] describes the so called ”middlebox placement problem”, which provides the optimal placing of network functions in a service chain. In this work, the authors use two heuristic algorithms; a greedy algorithm and a algorithm based on simulated annealing, which are used for replacing the network functions rather than changing the path through a network. Another work that mainly focuses on the VNF replacing aspect is [4]. The main focus for optimization in this work is the end-to-end delay of a SFC. The authors also use an heuristic algorithm for optimizing this parameter by replacing the VNFs. Building virtual networks on a shared physical infrastructure refers also to the virtual network embedding(VNE) problem. The VNE-problem describes algorithms to map a virtual network (nodes and links) to an underlying physical network. This includes the resources of the nodes and the links. The authors of [11] created a survey to this problem.

The papers outlined in this section provide an overview of different aspects regarding to virtualization or sharing network capacities. However, these always describe only one aspect that is required for network slicing. None of these works deals with an overall concept that includes the allocation of network resources, the placement of network functions and the determination of paths in a WMN. In this work, therefore, a concept is to be presented that provides a solution approach for each of these aspects. The resulting solution for network slicing in wireless mesh networks will combine these three aspects.

III. SLICE MODELING

A detailed description of the modeling was already introduced in [2] so it will be a slightly more brief description here. The wireless mesh network is modeled as an undirected graph $G(N, E)$, where N are the graph nodes and E are the connections between them. A network slice consists of the following components: Virtual network functions, a priority value to define different slice priorities, and the flows belonging to the slice. Therefore, a slice is described as a subgraph $G_s(N_s, E_s) \subseteq G(N, E)$. Derived from that, one aspect is the mapping of the virtual network functions and the virtual links between them to the underlying physical infrastructure of the WMN. Figure 1 shows the overall WMN graph and the slice graph resulting from the VNF hosting nodes 4, 7 and 18. The slice graph consists of the nodes that host the slice specific VNFs and the nodes that form the connection between them $(3, 8, 13)$. So, for this example, the slice graph consists of the set of nodes $N_s = 3, 4, 8, 7, 13, 18$ and the set of edges $E = (3, 4), (3, 8), (7, 8), (8, 13), (13, 18)$.

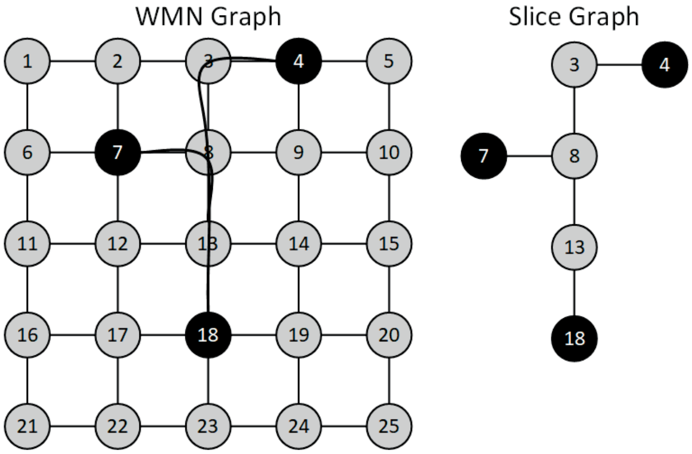

Fig. 1. WMN graph and slice subgraph

The connections E between the graph nodes represent the wireless links of the mesh. The quality of a wireless connection is influenced by a variety of parameters, like signal strength, noise, interference. In this modeling, the quality of a link is indicated by the maximum available bitrate $B(e)$, which depends on all of these parameters. Any flow f on a connection e consumes a part of $B(e)$, which is described as $b_e(f)$. As a result, the number of flows that can work with a specific bitrate, e.g. 10 Mbit/s, a link can supply is limited. The resulting constraint shows (1). A flow f describes a communication relation between a start node, an end node, and intermediate virtual network functions if present.

$$\sum_{f \in F} b_e(f) \leq B(e) \tag{1}$$

The WMN nodes can only host a specific amount of VNFs before their maximum capacity $C(n)$ is exhausted. The value of C is the CPU utilization in per cent: $C \in [0\%, 100\%]$. A VNF v running on a node needs a part of the node’s computing power $c(v)$ which increases the overall value of C. The maximum number of VNFs a node can provide without performance degradation due to CPU overload results from the constraint of (2):

$$\sum_{v \in V} c(v) \leq C_n \tag{2}$$

These two are the main constraints the proposed network slicing approach has to consider. The next section describes possibilities that can form the final concept.

IV. NETWORK SLICING CONCEPT

Based on the results from [2] and the model of slice and WMN, a network slicing concept for wireless mesh network has to consider the following aspects:

- Path determination,
- Wireless resource slicing,
- VNF (Re)Placement.

Path determination is necessary to get the best possible paths through the network between VNF hosting nodes and nodes that are connected to the terminal devices. These paths are the physical representation of the virtual connections of a slice. Wireless resource slicing is always required when more than one slice uses a connection. This can be the case between the

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WMN nodes and in the access network between a node and terminal devices. The reasons are that data traffic from slices should be isolated from each other and slices can have different requirements regarding to transmission rate and stability. Even if the previous aspects are working, it may be necessary to replace individual VNFs. Reasons for this can be a change in the network topology or that the previous procedures cannot fulfill the requirements of the slice. For example, if a lower response time is required. All these aspects together allow for dynamic placement of slices within the WMN while maintaining isolation and the best possible connection quality.

A. Path Determination

The path determination approach was already described in the previous work [2]. However, the network was considered static. Fluctuations in the maximum bit rate and movement of nodes were not taken into account. Three algorithms were tested: A* [13] , Dijkstra [7] and BFS [5]. The results showed that the Dijkstra algorithm had the most efficient results. Also, the differences in the results between Djikstra and A* were very small, which is why only Djikstra is used for further tests. The reason for this is that Djikstra does not need any additional heuristic function.

Based on these results the path determination was tested again in a more dynamic scenario regarding movement and fluctuation. For this purpose, the maximum bitrate was no longer assumed to be static, but to fluctuate on the basis of a normal distribution. In this case, the maximum available bitrate $B(e)$ is calculated by a normal distribution on every link of the graph. The Parameter μ of the distribution is the mean value of the maximum bitrate and σ represents the fluctuation. This was done with different values for μ and σ , to simulate better or worse environmental conditions. The assumed paths were identical with the ones from the previous static test and are shown in Table I. The values for μ and σ used in the simulation are shown in Table II. Good conditions were represented by a higher value for μ, close to 100, and a low fluctuation σ. For worse conditions, the values for μ were assumed to be lower and σ higher.

The WMN was simulated by a graph $G(N, E)$ with 25 nodes and 40 edges as it is shown in Figure 1. Every edge has a parameter for the consumed bitrate. The value of the consumed bitrate increases with every flow that goes over a specific edge. Because Dijkstra belongs to the greedy algorithms, it needs a cost value to work properly. This value increases with the consumed bitrate on an edge, so that the costs increase with the link utilization. Also, the costs using a link with low utilization should be lower than using a link with high utilization when adding the same bitrate value. Therefore, the cost increases exponentially regarding to the maximum available bitrate $B(e)$. If the value for the consumed bitrate is above this value, the costs have to be infinity for the specific edge. The simulation adds the paths to the network one after the other according to Table I and then updates the consumed bitrate values. After adding a path, $B(e)$ is recalculated according to the normal distribution and then the weights of all edges of the graph are recalculated. After all paths are added, the simulation finds the edge with the highest value for the consumed bitrate. These values are printed in Figure 2.

TABLE I
TEST SETUP FOR LINK FLUCTUATION TEST

Flows	From	To	rate
f1	25	6	30
f2	22	2	20
f3	20	16	30
f4	9	12	40
f5	1	19	20
f6	11	24	20
f7	10	16	30
f8	22	15	40
f9	13	24	20
f10	13	5	20
f11	11	14	15
f12	2	25	20
f13	24	12	15
f14	19	6	30
f15	16	4	15

TABLE II
PARAMETERS FOR THE LINK FLUCTUATION

μ	σ
100	1
95	5
90	5
85	5
80	10
70	10
60	10
50	10

This approach refers to the fact that the Signal to Noise Ratio (SNR) of the radio link is lower under worse conditions. To keep packet losses low, a lower Modulation and Coding Scheme (MCS) must then be used, resulting in a lower maximum available bitrate. As a result, fluctuation in the SNR will result in fluctuation in the maximum available bitrate. Fluctuation is used, because the conditions can be different in different parts of the mesh network, so there exist better and worse links. In order to summarize the various influences on the connection quality, a fluctuating maximum bitrate is therefore assumed. In the simulation, the value for $B(e)$ changes always after a new path was added regarding to the normal distribution. Some of the results are shown in Figure 2. The x axis show the number of calculations, 200 calculations were done in total. The y axis shows the maximum link utilization.

The results show, that in the case of fluctuation of bitrate, the Dijkstra algorithm performs better than BFS. It is also shown that increasing fluctuation leads to an increasing fluctuation in the maximum link utilization. The value of for the BFS Algorithm is always constant because it is not using information from the link utilization. So this algorithm will always use the same paths. In summary, it can be assumed that the path determination approach using Djikstra is also usable in dynamic scenarios. Therefore, the first path of the network slicing concept will be the path determination between the slice nodes using the Dijkstra algorithm. If the architecture or the requirements of the slice or the WMN do not change, the paths determined in this way are to be considered constant. To define constant paths through a network, technologies like software-defined networking (SDN) [21] or multiprotocol label switching (MPLS) [15] can be used for implementation in real networks.

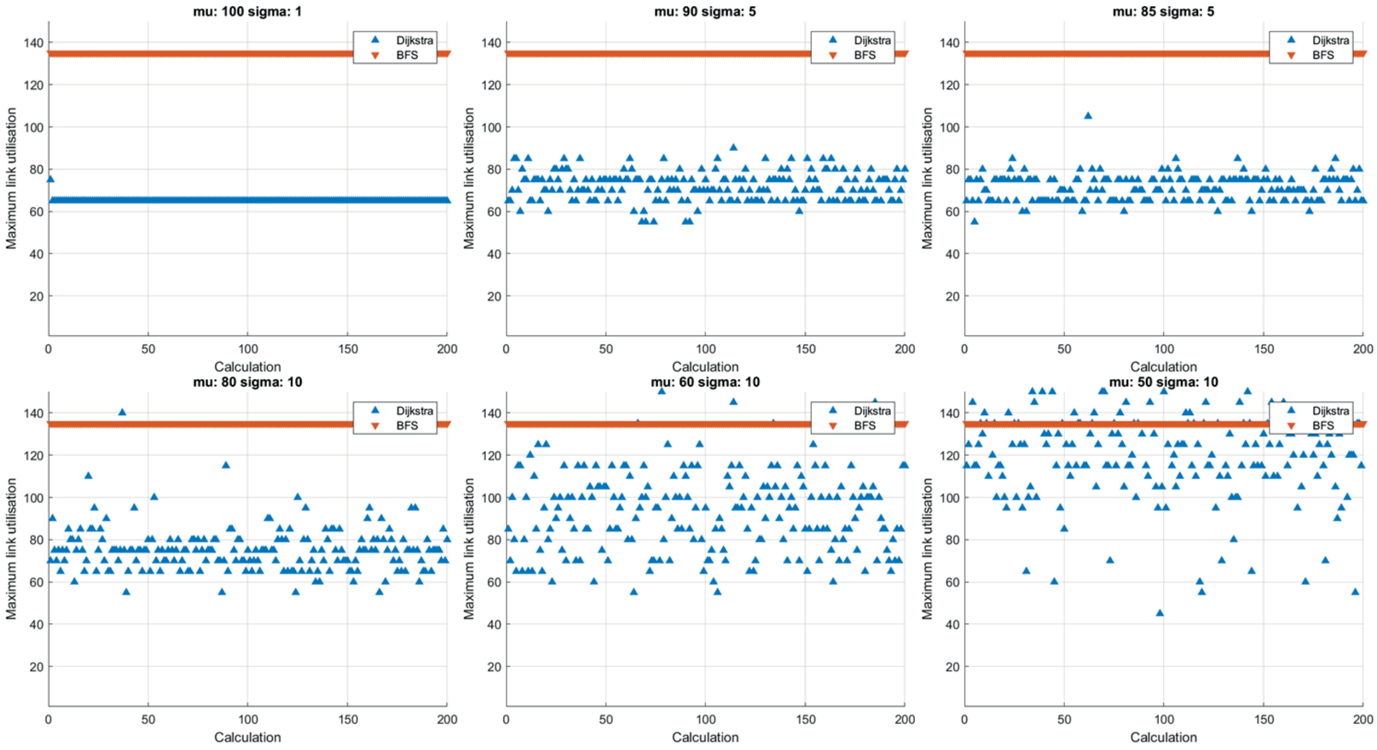

Fig. 2. Results of the path determination test with fluctuating bitrate values

B. Wireless Resource Slicing

To provide isolation between the slices and to ensure their performance, an approach for slicing the wireless resources is necessary. As mentioned in the previous section, the transmission rate on a radio link depends on the link Quality, which is described by the SNR. Another aspect to consider is that radio links are a shared medium. That means, that only one transmitter can use the channel at a time. As a result, more transmitting devices in the same channel also decrease the maximum available bitrate on a wireless link. This section is about a wireless resource slicing approach to ensure isolation and avoid performance degradation.

In this concept, Orthogonal Frequency Division Multiple Access (OFDMA) is used as wireless slicing method. The technology is already used in the IEEE 802.11ax standard. It allows simultaneous transmission on the same channel by splitting this channel into several sub-channels. These sub-channels can also have a different size and a different MCS. This allows it to give different devices more or less robust transmissions with an adaptable maximum available bitrate. An important aspect of this approach is the fact, that the channel splitting is not done continuously. The channel is divided into so called resource units (RUs) with a pre defined length. How this method should be used is shown in Figure 3. The RUs of the channel are divided among the three slices. Slice 1 is allocated more RUs than slice 3, for example. One reason for this is could be that slice 1 requires a more robust transmission. Another important advantage of using this method is that the total number of frames sent could be reduced. This is because data that needs to be transmitted to different clients can be transmitted simultaneously in one frame. In IEEE802.11ax special frame types for multi-user (MU) uplink and downlink transmissions are used. Without this approach, a separate frame would have to be sent for each client [8]. Reducing the overall frames that have to be sent through the network will lead to a less utilization of the wireless links.

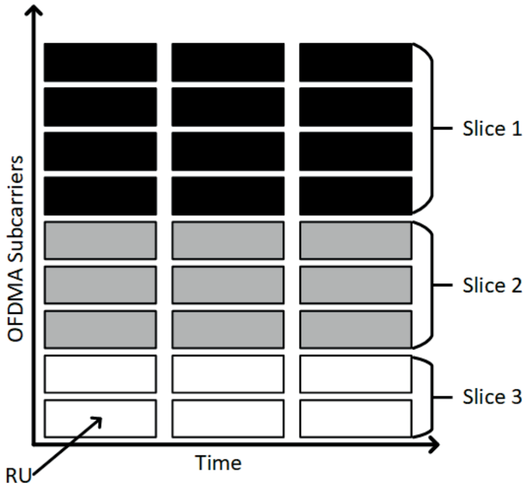

Fig. 3. OFDMA Subcarrier scheme

To validate the assumptions a simulation of the downlink traffic between an access point and multiple clients was done.

As a simulation environment, *Matlab* was used. The simulation is based on a modification of [18]. In the simulation setup, the channel has a bandwidth of 20MHz and is divided into five resource units with different size. A channel consists of 242 sub-carriers in total. In a 20MHz channel, the smallest RU consists of 26 sub-carriers and the largest RU consists of all 242 sub-carriers which is the whole channel. The number of RUs depends on the size of the channel and the size of the RUs. Using the minimum RU size of 26 sub-carriers leads to nine RUs in a 20MHz channel. In this simulation, five RUs with the following sizes are used: RU 1 has 106 sub-carriers and is the largest, the RUs 2, 4 and 5 have a size of 26 sub-carriers and are the smallest. The RU 3 has 52 sub-carriers and is the second largest RU. With this setup it is possible to show two things:

- With larger RUs the transmission with lower SNR values and similar transmission rate is possible.
- With the same MCS, higher transmission rates in larger RUs are possible.

The results of this simulations are shown in Table III and Table IV.

TABLE III
RESULTS FROM THE OFDMA DOWNLINK TEST WITH DIFFERENT MCS VALUES

SNR	RU 1	RU 2	RU 3	RU 4	RU 5
6	0	0	0	0	0
9	13.2	0	0	0	0
12	13.2	0	0	0	0
15	13.2	0	8.8	0	0
18	13.2	0	14.6	0	0
21	13.2	0	14.6	0	0
24	13.2	3.6	14.6	2.4	4.9
27	13.2	12.1	14.6	12.1	12.1
30	13.2	12.1	14.6	12.1	12.1
33	13.2	12.1	14.6	12.1	12.1
36	13.2	12.1	14.6	12.1	12.1

For the results in Table III, RU 1 has a MCS of 16-QAM and a coding rate of 1/2. The RUs 2, 4 and 5 have a MCS of 1024-QAM and a coding rate of 3/4. RU 3 has a MCS of 64-QAM and a coding rate of 3/4. As the results show, the transmission rates are similar, but a much higher SNR is required for the narrower RUs. For the results in Table IV, all RUs have a MCS of 64-QAM and a coding rate of 3/4. The table shows, that all transmissions need the same SNR value for working. It can be seen, that a larger RU size allows a higher transmission rate compared to a smaller RU size. The results show that by using OFDMA it is possible, to have more or less robust transmissions and variable maximum possible transmission rates.

In conclusion it could be said, that this approach allows the separation of the slice specific traffic flows on the physical layer. Additionally it is possible to have flows with different transmission rates and SNR sensitivity on the same network link. Also, this approach has the potential to reduce the traffic overhead in the network because of simultaneous transmission, which makes it more efficient. It is also important to note that this method only needs to be used if the connections from multiple slices are over the same radio link of the WMN. If the radio connection is only used by one slice anyway, such a division is not necessary. Nevertheless, as few flows as possible should use the same link. The optimization of the paths must therefore be prioritized. The reason for this is to keep the required bitrate as low as possible. Transmissions with higher bitrates require a higher MCS, which in turn requires a higher SNR. The transmission is therefore more stable the lower the bitrate that has to be transmitted over it. Therefore, this method does not replace the path optimization from the previous section. An exception to this is the access network, as this is the last connection from the WMN to the end device, path optimization is no longer possible here.

TABLE IV
RESULTS FROM THE OFDMA DOWNLINK TEST WITH IDENTICAL MCS VALUES

SNR	RU 1	RU 2	RU 3	RU 4	RU 5
6	0	0	0	0	0
9	0	0	0	0	0
12	0	0	0	0	0
15	23.8	4.4	11.6	5.9	7.3
18	29.7	7.3	14.6	7.3	7.3
21	29.7	7.3	14.6	7.3	7.3
24	29.7	7.3	14.6	7.3	7.3
27	29.7	7.3	14.6	7.3	7.3
30	29.7	7.3	14.6	7.3	7.3
33	29.7	7.3	14.6	7.3	7.3
36	29.7	7.3	14.6	7.3	7.3

C. VNF Replacement

The third part of the network slicing concept for wireless mesh networks is the placement of the virtual network functions. A distinction must be made between two cases:

- Initial placement of the VNFs in the network.
- Replacement of the VNFs in the network for traffic optimization.

The initial placement is necessary when the virtual network functions have to be placed in the network for the first time. These can be general functions or slice specific ones, if known at the time. Ideally, the initial placement already takes into account the slice affiliation of the functions. Replacement of the VNFs is used when the network is overloaded and no improvement can be achieved with the two previous methods or if the topology of the network has changed. Methods for replacing the VNFs are currently being investigated. The aim is to place the VNFs in the network in such a way that the maximum utilization of the paths is as low as possible. Initial tests with a random-based approach were promising and were able to reduce the average link load. However, the random-based approach, in which the VNFs were randomly repositioned, is intended here only as a reference for comparison with other approaches. In order to evaluate the position of a VNF for optimization, two parameters are to be considered in this concept: The utilization of the node $C(n)$ and the utilization of the connections. The utilization of the node depends on how many VNFs are actually running on it and is already described in the modeling section of this paper. The higher this value, the worse would be the migration of a VNF to the corresponding node. The utilization of the connections describe the traffic load on the nodes links. The higher this value, the more traffic has to be processed by the corresponding node. This leads to the fact that this can no longer have enough capacity for hosting a VNF or that placing a VNF on it will further exhaust the links. The number of packets sent and received via the respective interfaces can serve as a measure for this. In order not to create an imbalance between nodes with different numbers of interfaces, the average value is calculated as it is shown in equation (3).

$$\overline{P(n)} = \frac{\sum_{i}^{I} p(n,i)}{I} \tag{3}$$

In this equation I is the number of connections of a node n. The value $p(n,i)$ stands for the number of packets of a connection i on node n. It is currently part of the research on this approach which of these two parameters is best used. A combination of both is also conceivable.

V. SUMMARY AND CONCLUSION

This paper introduced a concept approach for network slicing in wireless mesh networks based on the three principles: path determination, wireless resource slicing and VNF replacement. It was shown, that the path determination approach from previous work is also working in a dynamic scenario. Even in cases of high fluctuation, the Djikstra algorithm worked better than BFS in most of the cases. The aim of this approach has always been to keep the load on the connections as low as possible. This also optimizes the stability of the connections, which is one of the goals of the overall approach. Therefore, this path determination approach will be used in further work to build a network slicing implementation for wireless mesh networks. To separate data flows using the same connection, the wireless slicing approach using OFDMA will be used. It was shown that this method allows the separation of the channel to enable flows with variable bitrates and SNR sensitivity. This was realized by using different modulation and coding schemes and RU sizes in the sub-channels. It should be noticed, that this method should be used mainly in the access network part or if multiple data flows have to use the same connection in the WMN. The VNF replacement approach is currently under investigation. The aim here is to reduce the overall link load by optimizing the placement of the virtual network functions. This is mainly intended to be used when the path determination no longer provide any improvements or the network topology changes.

All of theses parts have the goal to provide the best network performance for the slices and also increasing the network stability. As shown in the previous sections, the stability in terms of SNR depends on the MCS used. From this it can be concluded that it makes sense to distribute the data streams in the network in order to keep the load on the connections as low as possible. The resulting lower bitrates increase the stability of the network. In cases where data flows have to use the same link, channel splitting and prioritization with OFDMA should be used. There is currently no approach, that combines all of the mentioned solutions to an overall concept for network slicing in wireless mesh networks. Further work will therefore address how these methods can be combined.

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