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► To cite this version:

Ke Chen, Gangxiang Shen, Shuiping Jie, Boping Jiang, Sanjay K. Bose. Availability-Guaranteed Slice Provisioning in Wireless-Optical Broadband Access Networks Supporting Mobile Edge Computing. 23th International IFIP Conference on Optical Network Design and Modeling (ONDM), May 2019, Athens, Greece. pp.70-81, 10.1007/978-3-030-38085-4_7 . hal-03200654

HAL Id: hal-03200654

<https://inria.hal.science/hal-03200654>

Submitted on 16 Apr 2021

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Availability-Guaranteed Slice Provisioning in Wireless-Optical Broadband Access Networks Supporting Mobile Edge Computing (Invited)

Ke Chen¹, Gangxiang Shen^{*1} Shuiping Jie², Boping Jiang² and Sanjay K. Bose³

¹ Soochow University, Suzhou, PR China

² Zhongtian Broadband Technology, Rudong, PR China

³ Indian Institute of Technology Guwahati, Guwahati, India
^{*}shengx@suda.edu.cn

Abstract. A wireless-optical broadband access network (WOBAN) shows promise as potential 5G access infrastructure. Since network slicing allows efficient sharing of physical network resources, we consider the provisioning of availability-guaranteed slices in a WOBAN supporting mobile edge computing (MEC). A new definition for the availability of a slice is proposed accounting for a slice that functions only partially because of the failure of a fiber link, a microwave link, a base station (BS) node, and/or an optical line terminal (OLT). An integer linear programming (ILP) model and a simple but effective heuristic algorithm that balances the network traffic load and maximizes the slice availability are developed to maximally provision availability-guaranteed slices. Simulation results show the efficiency of the proposed approaches.

Keywords: WOBAN, MEC, Slice Provisioning, Availability Guarantee.

1 Introduction

5G access networks carry various applications that require ultra-fast data transfer and flexible device support. WOBAN [1][2] shows promise as potential 5G access infrastructure. To efficiently share physical resources in such a system, it would be desirable to implement network slicing [3][4] to support diverse applications [5], with each slice flexibly running a specific application. Although there have been studies on how to efficiently provision slices in a 5G access network [6], how to guarantee the availability of each provisioned slice is still not well investigated. A guaranteed availability is critical for a service provider to meet its service level agreement (SLA) when provisioning slices to its users [7][8][9]. Therefore, it is vital to address this issue for slice provisioning in a WOBAN.

Our earlier work in [10] reported on a preliminary study maximizing the availability-weighted slice capacity for a sliceable WOBAN, in which, however, the availability of each provisioned slice is not guaranteed. From the SLA point of view, it is more practical to consider slice provisioning with a guaranteed availability for each slice. Therefore, this study focuses on the problem of provisioning availability-guaranteed

slices in a sliceable WOBAN. To formulate the slice availability, four failure scenarios, including the failures of a fiber link, a microwave link, a BS node, and an OLT, are considered. A new definition of availability is made for a slice that functions only partially. To maximize the number of slices provisioned with guaranteed availability, we formulate the problem into an ILP model and develop a simple but effective heuristic algorithm. Simulation results show the efficiency of the proposed approaches.

2 Sliceable WOBAN Supporting MEC

Fig. 1 shows a typical WOBAN example, which contains two passive optical networks (PONs) [11][12] and one wireless mesh network (WMN) [13][14]. Each PON is composed of an OLT and several ONU-BSs, each of which consists of an optical network unit (ONU) and a wireless BS. In the WMN, the ONU-BSs and BSs are connected via microwave links and each BS provides wireless access for local users. Unlike a conventional WOBAN, which merely provides communication capacity for users, here we also consider the computing/storage (C/S) capacity, measured in units of virtual machines (VMs), available at each BS node to support the MEC function [15]-[17] that is critical for the 5G access network [18].

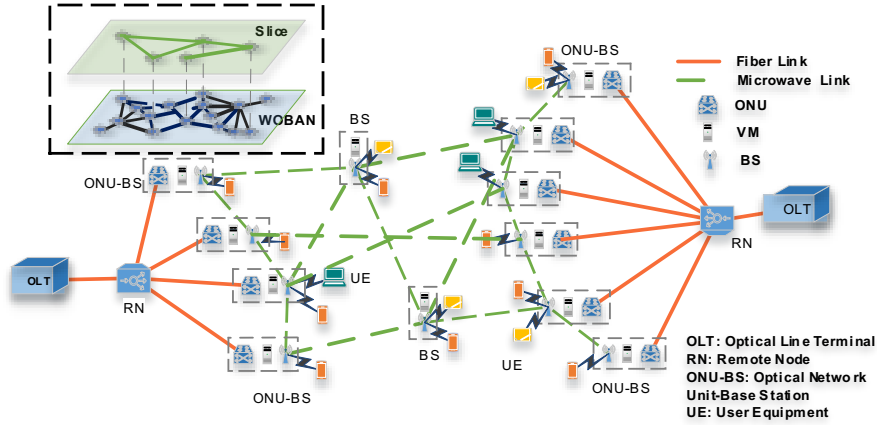


Fig. 1. Example of a sliceable WOBAN [10].

A sliceable WOBAN is a WOBAN that can be divided into multiple slices with each provisioning services for different applications. A slice is considered as an independent network consisting of multiple virtual nodes and virtual links. Fig. 1 also shows the example of a slice, in which virtual nodes are connected via virtual links and are assigned with C/S capacities for supporting MEC. Each virtual node is embedded in a physical node and each virtual link is mapped onto a physical path traversing multiple physical links.

3 Maximizing Number of Slices Provisioned with Guaranteed Availability

Based on a sliceable WOBAN introduced in the previous section, our problem is to maximize the number of slices provisioned with guaranteed availability subject to limited communication and C/S capacities. For this, we first define a new availability measure for a WOBAN slice. This is followed by an ILP model and heuristic algorithms that maximize the number of slices provisioned.

3.1 Definition of Slice Availability

The availability of a system is generally defined as $A = MTTF / (MTTF + MTTR)$, where $MTTF$ is the mean time to failure and $MTTR$ is the mean time to repair of the system [7]. If a system consists of multiple (n) components and the failure of any component would cause the failure of the system, then its $MTTF$ and $MTTR$ can be derived as $MTTF = 1 / \sum_{i=1}^n \lambda_i$ and $MTTR = \sum_{i=1}^n (\lambda_i \cdot MTTR_i) / \sum_{i=1}^n \lambda_i$, where λ_i and $MTTR_i$ are the respective mean failure rate and $MTTR$ of the i^{th} system component. Note that the above equation holds when the probability of a single component failure is much higher than that of a two-component simultaneous failure. This condition is true in most cases since in general $p_1 \gg p_1 \cdot p_2$ where p_i is the failure probability of a component and is typically very small.

To calculate the availability of a WOBAN slice, we first define notations as follows.

Sets:

P	The set of OLTs, each of which corresponds to a PON.
N	The set of BS nodes, which can be ONU-BSs or pure BSs.
L	The set of fiber links. Each optical distributed network (ODN) of a PON is considered as a fiber link between an OLT and multiple ONUs.
M	The set of microwave links in the WMN, each of which connects a pair of BS nodes.
S	The set of slices.
V^s	The set of virtual links in slice s .
K_v^s	The set of the candidate paths in the physical topology that are eligible to establishing virtual link v of slice s .

Parameters:

B_v^s	The capacity required by virtual link v in slice s .
$\theta_{v,k}^{s,x}$	This takes the value of 1 if the k^{th} path for establishing virtual link v in slice s passes BS node x ; 0, otherwise.
$\sigma_{v,k}^{s,p}$	This takes the value of 1 if the k^{th} path for establishing virtual link v in slice s passes OLT p ; 0, otherwise.
$\alpha_{v,k}^{s,l}$	This takes the value of 1 if the k^{th} path for establishing virtual link v in slice s passes fiber link l ; 0, otherwise.
$\mu_{v,k}^{s,m}$	This takes the value of 1 if the k^{th} path for establishing virtual link v in slice s passes microwave link m ; 0, otherwise.

$MTTF_{v,k}^s$ The $MTTF$ of the k^{th} path that can be used for establishing virtual link v in slice s .

$MTTR_{v,k}^s$ The $MTTR$ of the k^{th} path for establishing virtual link v in slice s .

Variables:

$\beta_{v,k}^s$ A binary variable that equals 1 if virtual link v in slice s is mapped onto (or established via) its k^{th} eligible path; 0, otherwise.

A_s The estimated availability of slice s .

Based on the above notations, we can calculate $MTTF_{v,k}^s$ for each virtual link in a slice, which can be seen as a serial system consisting of multiple components, i.e., the physical links and nodes traversed by the virtual link. This is derived as

$$MTTF_{v,k}^s = \frac{1}{\sum_{i=1}^n \lambda_i} = \frac{1}{\sum_{l \in L} \lambda_1 + \sum_{m \in M} \lambda_2 + \sum_{x \in N} \lambda_3 + \sum_{p \in P} \lambda_4} \quad \forall s \in \mathcal{S}, v \in \mathcal{V}^s, k \in \mathcal{K}_v^s \quad (1)$$

where $\lambda_1 = \alpha_{v,k}^{s,l} \cdot \lambda_l \cdot d_l$, $\lambda_2 = \mu_{v,k}^{s,m} \cdot \lambda_m \cdot d_m$, $\lambda_3 = \theta_{v,k}^{s,x} \cdot \lambda_x$ and $\lambda_4 = \sigma_{v,k}^{s,p} \cdot \lambda_p$. Specifically, d_l and d_m are the physical distances of a fiber link and a microwave link in units of km, λ_l and λ_m are the failure rates (in FIT per km) of the fiber link and the microwave link, and λ_x and λ_p are the failure rates (in FIT) of a BS node and an OLT node. Here we assume that a pure BS and an ONU-BS have the same failure rate and require the same repair time. Similarly, we can calculate $MTTR_{v,k}^s$ for each slice virtual link by (2).

$$MTTR_{v,k}^s = \frac{\sum_{i=1}^n \lambda_i \cdot MTTR_i}{\sum_{i=1}^n \lambda_i} = \frac{\varphi_1 + \varphi_2 + \varphi_3 + \varphi_4}{\sum_{l \in L} \lambda_1 + \sum_{m \in M} \lambda_2 + \sum_{x \in N} \lambda_3 + \sum_{p \in P} \lambda_4} \quad \forall s \in \mathcal{S}, v \in \mathcal{V}^s, k \in \mathcal{K}_v^s \quad (2)$$

where $\varphi_1 = \sum_{l \in L} (\lambda_l \cdot MTTR_l)$, $\varphi_2 = \sum_{m \in M} (\lambda_m \cdot MTTR_m)$, $\varphi_3 = \sum_{x \in N} (\lambda_x \cdot MTTR_x)$, and $\varphi_4 = \sum_{p \in P} (\lambda_p \cdot MTTR_p)$. λ_1 , λ_2 , λ_3 , and λ_4 have the same definitions as in (1), and $MTTR_l$, $MTTR_m$, $MTTR_x$, and $MTTR_p$ are the MTTRs of a fiber link, a microwave link, a BS node, and an OLT, respectively. Therefore, (2) calculates the average repair time of a virtual link.

It is important to note that in a network slice consisting of multiple virtual links, a single network failure would not cause all the virtual links to fail as a partial set of virtual links may still be functioning. This implies that when calculating the availability of a slice, we should not simply consider a *zero-one* situation, but consider the capacities of the virtual links that still functions when a network failure is being repaired. This led us to define a new availability, specifically for a partially functioning system, given as

$$A_s = \frac{C_{normal}^s + C_{partial}^s}{C_{total}^s} \quad \forall s \in \mathcal{S} \quad (3)$$

Here C_{total}^s is the time-weighted total capacity provisioned by a slice, C_{normal}^s is the time-weighted total capacity provisioned by the slice during the period that the slice does not incur a failure, and $C_{partial}^s$ is the time-weighted total capacity provisioned by a partially functioning slice when a network failure is being repaired. The three terms are derived as follows.

$$C_{normal}^s = \sum_{v \in \mathcal{V}^s, k \in \mathcal{K}_v^s} (\beta_{v,k}^s \cdot MTTF_{v,k}^s) \cdot B_v^s \quad \forall s \in \mathcal{S} \quad (4)$$

$$C_{total}^s = \sum_{v \in V^s, k \in K_v^s} (\beta_{v,k}^s \cdot (MTTF_{v,k}^s + MTTR_{v,k}^s)) \cdot B_v^s \quad \forall s \in \mathcal{S} \quad (5)$$

In (4), $\beta_{v,k}^s \cdot MTTF_{v,k}^s$ is the *MTTF* of virtual link v if its candidate path k is used for establishing the virtual link. Thus, (4) finds the total time-weighted capacity provisioned by the slice in the period that the slice does not incur a failure. In (5), $\beta_{v,k}^s \cdot (MTTF_{v,k}^s + MTTR_{v,k}^s)$ is the sum of the *MTTF* and the *MTTR* of virtual link v if its candidate path k is used for establishing the virtual link. Therefore, (5) finds the total time-weighted capacity provisioned by slice s .

To derive $C_{partial}^s$, we need to consider the different network failure scenarios, including the failures of a fiber link, a microwave link, a BS node, and an OLT. We first define the total time-weighted capacity provided by a partially functioning slice when one of the four network failure scenarios occurred and the failure is being repaired as follows.

$$B_{partial}^{s,l} = \sum_{v \in V^s, k \in K_v^s} (\beta_{v,k}^s \cdot MTTR_l \cdot B_v^s \cdot (1 - \alpha_{v,k}^{s,l})) \quad \forall s \in \mathcal{S}, l \in \mathcal{L} \quad (6)$$

$$B_{partial}^{s,x} = \sum_{v \in V^s, k \in K_v^s} (\beta_{v,k}^s \cdot MTTR_x \cdot B_v^s \cdot (1 - \theta_{v,k}^{s,x})) \quad \forall s \in \mathcal{S}, x \in \mathcal{N} \quad (7)$$

$$B_{partial}^{s,p} = \sum_{v \in V^s, k \in K_v^s} (\beta_{v,k}^s \cdot MTTR_p \cdot B_v^s \cdot (1 - \sigma_{v,k}^{s,p})) \quad \forall s \in \mathcal{S}, p \in \mathcal{P} \quad (8)$$

$$B_{partial}^{s,m} = \sum_{v \in V^s, k \in K_v^s} (\beta_{v,k}^s \cdot MTTR_m \cdot B_v^s \cdot (1 - \mu_{v,k}^{s,m})) \quad \forall s \in \mathcal{S}, m \in \mathcal{M} \quad (9)$$

Here $B_{partial}^{s,l}$ is the total remaining capacity of slice s weighted by the mean time to repair the failure of fiber link l that affects the slice. $B_{partial}^{s,x}$ is similar to $B_{partial}^{s,l}$ for the failure of a BS node, $B_{partial}^{s,p}$ is for the failure of an OLT, and $B_{partial}^{s,m}$ is for the failure of a microwave link. Then, we can derive $C_{partial}^s$ as

$$C_{partial}^s = \sum_{l \in \mathcal{L}} \frac{\lambda_l \cdot d_l \cdot B_{partial}^{s,l}}{W} + \sum_{m \in \mathcal{M}} \frac{\lambda_m \cdot d_m \cdot B_{partial}^{s,m}}{W} + \sum_{x \in \mathcal{N}} \frac{\lambda_x \cdot B_{partial}^{s,x}}{W} + \sum_{p \in \mathcal{P}} \frac{\lambda_p \cdot B_{partial}^{s,p}}{W} \quad \forall s \in \mathcal{S} \quad (10)$$

where $W = \sum_{l \in \mathcal{L}} (\lambda_l \cdot d_l) + \sum_{m \in \mathcal{M}} (\lambda_m \cdot d_m) + \sum_{x \in \mathcal{N}} \lambda_x + \sum_{p \in \mathcal{P}} \lambda_p$ denotes the mean failure rate of a WOBAN.

Because (3) is nonlinear, we convert it to linear for subsequent ILP modeling. For this, we define a new variable $\varepsilon_{v,k}^s$ to replace the nonlinear term $\beta_{v,k}^s \cdot A_s$ and convert (3) to (11)-(15) as follows.

$$\sum_{v \in V^s, k \in K_v^s} (\varepsilon_{v,k}^s \cdot (MTTF_{v,k}^s + MTTR_{v,k}^s)) \cdot B_v^s = C_{normal}^s + C_{partial}^s \quad \forall s \in \mathcal{S} \quad (11)$$

$$\varepsilon_{v,k}^s \leq \beta_{v,k}^s \quad \forall s \in \mathcal{S}, v \in V^s, k \in K_v^s \quad (12)$$

$$\varepsilon_{v,k}^s \leq A_s \quad \forall s \in \mathcal{S}, v \in V^s, k \in K_v^s \quad (13)$$

$$\varepsilon_{v,k}^s \geq A_s - (1 - \beta_{v,k}^s) \quad \forall s \in \mathcal{S}, v \in V^s, k \in K_v^s \quad (14)$$

$$\varepsilon_{v,k}^s \geq 0 \quad \forall s \in \mathcal{S}, v \in V^s, k \in K_v^s \quad (15)$$

3.2 ILP Model

We develop an ILP model to maximize the number of slices provisioned with guaranteed availability. In addition to the terms defined earlier, the additional sets, parameters, and variables of the ILP model are defined as follows.

Sets:

I^s The set of virtual nodes in slice s .

Parameters:

CS_i^s The C/S capacity required by virtual node i in slice s in units of VMs (for supporting MEC).

B_{max} The maximum transmission capacity of a PON (i.e., the maximum transmission capacity of its OLT).

T_m The maximum transmission capacity of microwave link m .

C_x The total C/S capacity deployed at physical node x .

$\gamma_{i,x}^s$ This takes the value of 1 if virtual node i in slice s is mapped onto physical node x , which means that this slice has local users served by the current physical node; 0, otherwise.

Variables:

δ_s A binary variable that equals 1 if slice s is successfully provisioned; 0, otherwise.

The objective and the constraints of the model are as follows.

Objective: maximize $\sum_{s \in \mathcal{S}} \delta_s$

Subject to:

$$\sum_{s \in \mathcal{S}, v \in V^s, k \in K_v^s} \beta_{v,k}^s \cdot \sigma_{v,k}^{s,p} \cdot B_v^s \leq B_{max} \quad \forall p \in \mathcal{P} \quad (16)$$

$$\sum_{s \in \mathcal{S}, v \in V^s, k \in K_v^s} \beta_{v,k}^s \cdot \mu_{v,k}^{s,m} \cdot B_v^s \leq T_m \quad \forall m \in \mathcal{M} \quad (17)$$

$$\sum_{k \in K_v^s} \beta_{v,k}^s = \delta_s \quad \forall s \in \mathcal{S}, v \in V^s \quad (18)$$

$$\sum_{s \in \mathcal{S}} (\delta_s \cdot \sum_{i \in I^s} \gamma_{i,x}^s \cdot CS_i^s) \leq C_x \quad \forall x \in \mathcal{N} \quad (19)$$

$$A_s \geq 0.99999 \quad \forall s \in \mathcal{S} \quad (20)$$

The objective is to maximize the number of slices provisioned with guaranteed availability. In addition to (11)-(15), we also have constraints (16)-(20). Constraint (16) ensures that the sum capacity of all the slice virtual links that share a common PON should not exceed the maximum transmission capacity of the PON. Constraint (17) ensures that the sum capacity of all the slice virtual links that traverse a common microwave link should not exceed its maximum transmission capacity. Constraint (18) means that a slice is fully provisioned only if all of its virtual links are established. Constraint (19) ensures that the sum C/S capacity required by all the slice nodes should not exceed the C/S capacity at each physical node. Constraint (20) ensures the availability of each slice.

3.3 Heuristic Algorithms

We have developed two heuristics for the above slice provisioning problem which are expected to be computationally easier than the optimization described earlier. Specifically, we consider two types of link metrics when searching for a path for establishing a slice virtual link. The first metric is based on the length of each physical link, referred to as *Heu_length*. Note that the physical length of a link essentially corresponds to the unavailability of the link since they hold a linear relationship. The second metric considers the load of each physical link in addition to its unavailability, referred to as *Heu_load*. The steps of these two algorithms are the same except for the metrics adopted, which include the steps of virtual node mapping and virtual link mapping.

Specifically, in the *Heu_load* algorithm, the metric for the shortest path route searching is defined as follows.

$$c_l = u_l \cdot U_l \quad (21)$$

Here as shown in Fig. 2, u_l is the capacity utilization or load on link l , which is defined as the ratio of the capacity used to the total capacity of the link. U_l is the unavailability of link l , which jointly considers the availability of the source node of the link and the availability of the link itself and is defined as

$$U_l = 1 - A_s \cdot A_l \quad (22)$$

where, as shown in Fig. 2, A_s is the availability of the source node of the link and A_l is the availability of the link itself. For a path traversing k links, we have the following approximation when the unavailability of each link is very small.

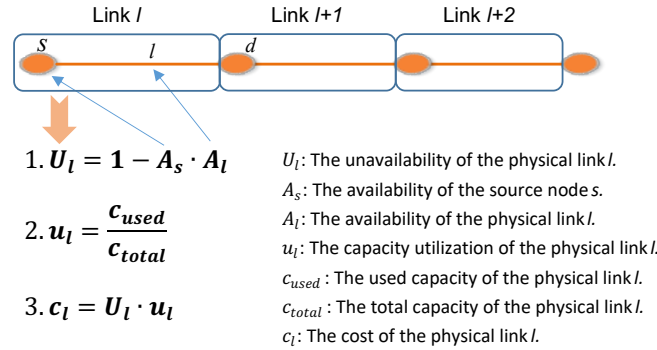


Fig. 2. The link metric calculation.

$$U_p \approx U_1 + U_2 + \dots + U_k \quad (23)$$

where U_k is the unavailability of the k^{th} link, calculated by (22). Therefore, using (21) as a metric to search for the shortest route is essentially to minimize the unavailability of a found route, weighted by the traffic load on each of the traversed links. As

such, the found route can simultaneously balance its traffic load and maximize its availability, thereby achieving efficient provisioning performance.

Based on the above route-searching metric, we next present the detail of the Heu load algorithm.

Algorithm	Heu_Load
Step 1	For a slice request s , map its virtual nodes onto corresponding physical nodes, and judge whether the remaining C/S capacity of each mapped physical node is sufficient to satisfy the demand of the virtual node. If not, fail to provision the slice and stop; otherwise, move to the next step.
Step 2	For each virtual link in s , try to employ the shortest path algorithm to establish the virtual link along physical links with sufficient remaining capacity. The algorithm uses the metric in (21) as the cost of each physical link l for shortest path searching.
Step 3	Repeat Step 2 until either all the virtual links in slice s are established or any one of the virtual links cannot be established due to the lack of link capacity. For the former, move to the next step; for the latter, fail to provision the slice and stop.
Step 4	Compute the availability of slice s ; if its availability is no less than 0.99999, the slice is provisioned successfully; otherwise, fail to provision the slice and stop.

The overall computational complexity of the proposed algorithm is at the level of $O(\|\mathbf{V}^s\| \cdot (\|\mathbf{N}\| + \|\mathbf{P}\|)^2)$, where $\|\cdot\|$ finds the size of the set. Although straightforward, the algorithm is efficient to *jointly consider both the capacity utilization and the unavailability of each physical link*, which can balance the traffic load of the system and maximize the availability of each provisioned slice simultaneously.

4 Simulations and Performance Analyses

We use Fig. 1 and Fig. 3 as our test networks for the following performance evaluation. Fig. 1 consists of two PONs with 10 ONU-BSs, and 2 BSs function as relay to connect the two PONs, between which there are 22 microwave links. Fig. 2 contains 66 ONU-BSs and 9 BSs, placed on a real geographic information system (GIS) map. These ONU-BSs and BSs are shown to be clustered into 5 PONs. Note that for the sake of clarity, we only draw representative links in Fig. 2.

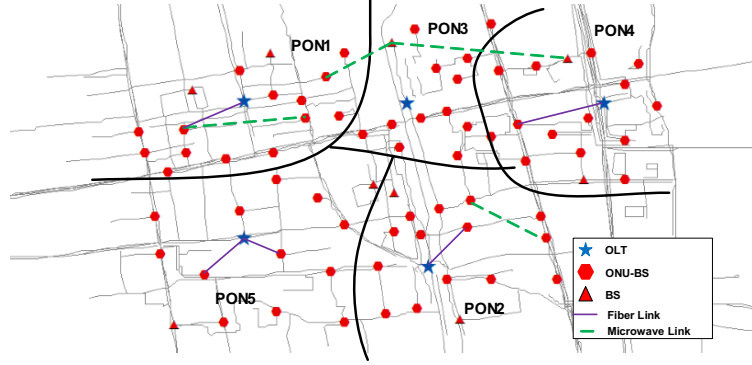


Fig. 3. Test network 2 in a GIS map [10].

The system parameters for the simulations are as follows. We set λ_l , λ_m , λ_x , and λ_p to be 200 FIT/km, 2000 FIT/km, 20 FIT, and 2 FIT, respectively. We also set the MTTRs of a fiber link, a microwave link, a BS node, and an OLT to be 6, 3, 2, and 1 hours, respectively. For each slice, different numbers N of virtual nodes (ranging from 4 to half of the total number of physical nodes) and virtual links (ranging from N to $1.5 \times N$) are randomly generated, and each virtual link in a slice requests for a random bandwidth within the range of [50, 100] Mb/s. The maximum transmission capacity of each PON is assumed to be 10 Gb/s. The maximum transmission distance of a microwave link is 20 km, and its actual transmission capacity depends on its distance. Specifically, for a distance shorter than 10 km, the transmission capacity is assumed to be 3 Gb/s. For a distance (d) between 10~20 km, the transmission capacity is estimated as $3.6 - 0.06 \times d$ Gb/s. The number of microwave links established from/to each physical node is at the most 4. The C/S capacity at each physical node is limited to 100 VMs and each slice node needs 4 VMs. Based on these parameters, we ran simulations to show the following results.

Fig. 4 shows the results of the small network. Specifically, Fig. 4(a) shows the number of availability-guaranteed slices provisioned. With an increasing number of slices requested, the maximum number of slices provisioned increases accordingly, but is eventually saturated when the number of slices requested exceeds a certain threshold. This is because of the limited communication and C/S resources in a physical system. Whenever the physical resources are exhausted, no more slices can be provisioned. In addition, the Heu_load algorithm can provision more slices than that of the Heu_length algorithm. The Heu_load algorithm performs closer to the ILP model. When the number of slices requested is small, they perform similarly and only when the number of slices requested becomes larger that they perform differently. This is because of the extra load-balancing effort by the Heu_load algorithm. The Heu_length algorithm uses the route that has the maximum availability to establish a virtual link, which however ignores the impact of unbalanced load in a network, leading to the blocking of many slices due to insufficient capacity. In contrast, the Heu_load algorithm can balance both the aspects, and therefore demonstrates more efficiency in availability-guaranteed slice provisioning.

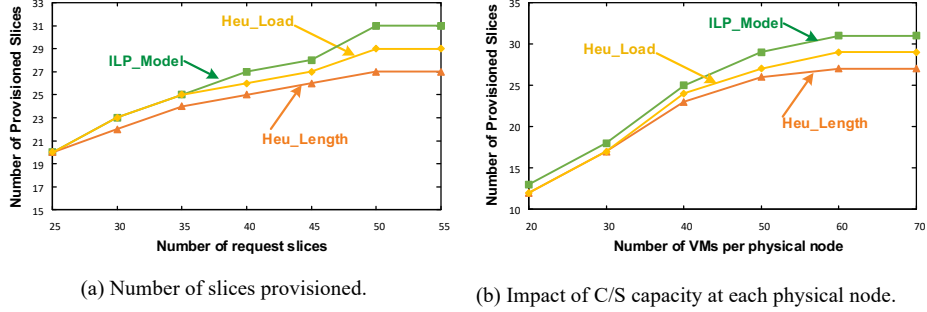


Fig. 4. Results of the small network.

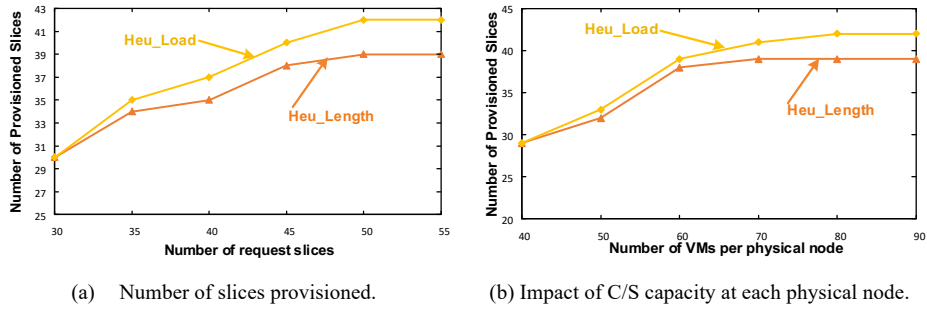


Fig. 5. Results of the larger network.

Fig. 4(b) shows how the C/S capacity at each physical node affects the number of slices provisioned when there are 50 slices to be provisioned in the small network. With an increasing C/S capacity at each physical node, the maximum number of slices provisioned increases, and reaches a saturation level when the C/S capacity exceeds a threshold. This is because, before the threshold, the availability of VMs is more critical in limiting the success of slice provisioning, whereas after the threshold, with sufficient VMs, the link capacity of the system starts to play a more critical role. Again, in Fig. 4(b), we observe that the Heu_load algorithm is efficient to perform closer to the ILP model and outperforms the Heu_length algorithm.

Similar results were obtained for the larger test network shown in Fig. 5. Here due to the computational intractability, we do not provide the result of the ILP model, but show the results of the two heuristic algorithms. We can see that the Heu_load algorithm is more efficient to outperform the Heu_length algorithm to provision more availability-guaranteed slices. This is again attributed to the load-balancing effort made by the Heu_load algorithm.

5 Conclusion

We maximize the number of availability-guaranteed slices provisioned in a sliceable WOBAN that supports MEC. By considering different failure scenarios, a new definition of availability is made for a slice that functions only partially. We formulate the slice provisioning problem using an ILP model, and also develop two heuristic algorithms based on different link cost metrics. Simulation studies show the efficiency of the proposed heuristic algorithm that jointly considers capacity utilization and unavailability of a physical link when provisioning availability-guaranteed slices.

Acknowledgement

This work was supported by National Natural Science Foundation of China (NSFC) (61671313) and the Project of Suzhou Key Laboratory of “Advanced Optical Communication Networks.”

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