Maximizing Availability-Weighted Slice Capacity for Sliceable Wireless-Optical Broadband Access Networks

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Abstract: We consider a sliceable wireless-optical broadband access network (WOBAN) to maximize its availability-weighted capacity. For this, Integer Linear Programming (ILP) models and corresponding *unavailability-minimized* heuristic algorithms are developed. Simulation results show the proposed approaches are efficient to maximize slices' availability-weighted capacity.
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1. Introduction

Future 5G systems will have many applications requiring ultra-fast data transfer and flexible device support. Network slicing is considered a promising technique to meet such diverse requirements [1] where a Wireless-Optical Broadband Access Network (WOBAN) [2] would be a good 5G access option. Here, availability would be important due to the instability of contained wireless links [3]. We focus on maximizing the slice capacity availability for a sliceable WOBAN. Though maximizing WOBAN's availability [3] or resource mapping for a sliceable 5G access network [4] have been considered earlier, to the best of our knowledge, no studies were carried out to jointly implement sliceable resource mapping and maximization of the capacity availability for a WOBAN. This needs to coordinate the resource allocation among different WOBAN slices, instead of a single WOBAN. We consider scenarios of fully provisioned and partially provisioned slices, and develop corresponding optimization approaches. ILP models and corresponding unavailability-minimized heuristic algorithms are developed. Results show the efficiency of the proposed approaches.

2. Sliceable WOBAN

Fig. 1 illustrates an example of WOBAN, which consists of two types of networks, i.e., passive optical networks (PON) and wireless mesh networks (WMN). Each PON has an Optical Line Terminal (OLT) connecting multiple pairs of Optical Network Units and Wireless Base Stations (ONU-BSs). ONU and BS are interconnected via Ethernet for communications between the PON and the WMN. The WMN supports local user access at each BS and microwave links between the BSs. To allow Mobile Edge Computing (MEC)/Fog Computing (FC) using in the 5G era [4], each ONU-BS is deployed with computing/storage (C/S) capacity, measured in units of virtual machines (VMs).

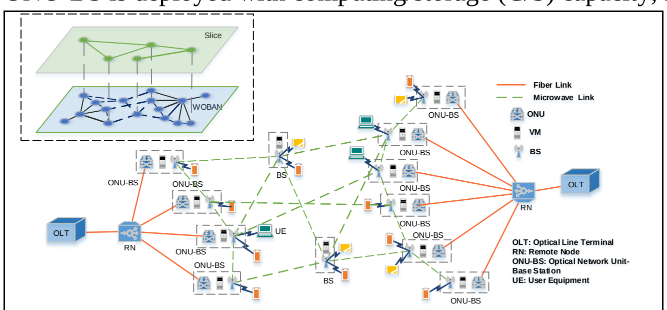

Fig. 1. Example of sliceable WOBAN.

A sliceable WOBAN is divided into multiple slices to provide different applications with virtually independent communications and C/S capacities. Each slice has a set of (virtual) nodes and (virtual) links. Each node provides sufficient access bandwidth and local C/S capacity for user applications. Fig. 1 (left corner) shows an example of a WOBAN slice, where multiple slice nodes are interconnected by multiple slice links. Each slice node is associated with a certain physical node within the WOBAN for slice functionality and user support. Each slice node has a specific number of VMs to provide C/S capacity for MEC/FC.

Splitting a physical WOBAN into WOBAN slices is a resource-mapping problem where the capacity for each slice is maximized to maximize the total available capacity in addition to providing sufficient C/S capacity to each slice node. Depending on whether all the resources are fully provisioned for each slice, two scenarios - *fully provisioned slices* and *partially provisioned slices* - may be considered. A slice is fully provisioned only if all the resources including communication and C/S are provided at the nodes and on the links of the slice. A partially provisioned slice does not fully provision resources to the slice, but satisfies its demand to the extent possible.

3. Maximizing Availability-Weighted Capacity for WOBAN's Slices

A) Availability definition: A general definition for availability is $A = MTTF/(MTTF + MTTR)$, where $MTTF$ is the mean time to failure and $MTTR$ is the mean time to repair. We use $MTTF_{pl}$ to denote $MTTF$ of a PON link that connects a pair of ONU-BSs via an OLT calculated by considering the availabilities of fiber segments and the OLT node that connect the two ONU-BSs. The availability of an OLT is given and the availability of a fiber segment is calculated replacing the following two terms in the availability calculation equation: $MTTF_l = 1/(d_l \cdot \lambda_0)$, where d_l is the physical distance of the fiber segment in units of km and λ_0 denotes the mean failure rate in FIT per km. The availability for a microwave link is similarly calculated by using different appropriate values of the mean failure rate and the mean repair rate. This study sets λ_0 to be 2×10^3 and 2×10^4 FIT/km, and $MTTR$ to be 6 and 3 hours, respectively for the PON and microwave links.

B) ILP models: We aim to maximize the availability-weighted capacity for WOBAN's slices subject to limited resources, including (1) the maximum transmission capacity of each PON system, (2) the maximum transmission capacity of each microwave link, and (3) the maximum C/S capacity at each node (i.e., ONU-BS or BS node). For this optimization problem, we develop its ILP model for the scenario of *fully provisioned slices* as follows.

Sets and parameters: $\boldsymbol{S}$ is the set of slices. $\boldsymbol{P}$ is the set of PONs. $\boldsymbol{N}$ is the set of network nodes which can be ONU-BSs or BSs. $\boldsymbol{ML}$ is the set of microwave links, each of which connects a pair of nodes that can be connected via a microwave link. $\boldsymbol{VL^s}$ is the set of virtual links in slice *s*. $\boldsymbol{VN^s}$ is the set of virtual nodes in slice *s*. $\boldsymbol{K_l^s}$ is the set of the paths in the physical topology that can be chosen to map virtual link *l* in slice *s*. B_l^s is the capacity required by virtual link *l* in slice *s*. CS_i^s is the C/S capacity required by virtual node *i* in slice *s* in units of VMs. BO denotes the maximum transmission capacity of each PON (i.e., the maximum transmission capacity of its OLT). MB_m is the maximum transmission capacity of microwave link *m*. CS_x denotes the computing capacity deployed at physical node *x*. $\alpha_{l,k}^{s,p}$ takes the value of 1 if the k^{th} path for establishing virtual link *l* in slice *s* passes PON *p*; 0, otherwise. $\mu_{l,k}^{s,m}$ takes the value of 1 if the k^{th} path for establishing virtual link *l* in slice *s* passes microwave link *m*; 0, otherwise. $\gamma_{i,x}^s$ takes the value of 1 if virtual node *i* in slice *s* is mapped to physical node *x*; 0, otherwise. This means that slice *s* provides its corresponding applications to the local users of physical node *x*. $a_{l,k}^s$ denotes the availability of the k^{th} path for establishing virtual link *l* in slice *s*. This availability is calculated based on the availabilities of its traversed links and nodes. For example, if a path passes one PON link, one microwave link, and three nodes including source and destination, then its availability can be calculated as $a_{l,k}^s = A_s \cdot A_{pl} \cdot A_n \cdot A_{ml} \cdot A_d$, where A_s, A_d, and A_n are the availabilities of the source, destination, and intermediate physical nodes, A_{pl} and A_{ml} are the availabilities of the traversed PON and microwave links, respectively. We assume a constant availability for each node as 0.9999.

Variables: $\beta_{l,k}^s$ is binary to equal 1 if virtual link *l* in slice *s* is mapped to (or established via) its k^{th} path. δ_s is binary to equal 1 if slice *s* is fully provisioned.

For the scenario of fully provisioned slices, we have its corresponding ILP optimization model as follows:

Objective: maximize $\sum_{s\in\boldsymbol{S},l\in\boldsymbol{VL^s},k\in\boldsymbol{K_l^s}} \beta_{l,k}^s \cdot a_{l,k}^s \cdot B_l^s$, and we have the following constraints:

$$\sum_{s\in\boldsymbol{S},l\in\boldsymbol{VL^s},k\in\boldsymbol{K_l^s}} \beta_{l,k}^s \cdot \alpha_{l,k}^{s,p} \cdot B_l^s \le BO \quad \forall p \in \boldsymbol{P} \quad (1)$$

$$\sum_{s\in\boldsymbol{S},l\in\boldsymbol{VL^s},k\in\boldsymbol{K_l^s}} \beta_{l,k}^s \cdot \mu_{l,k}^{s,m} \cdot B_l^s \le MB_m \quad \forall m \in \boldsymbol{ML} \quad (2)$$

$$\sum_{k\in\boldsymbol{K_l^s}} \beta_{l,k}^s = \delta_s \quad \forall s \in \boldsymbol{S}, l \in \boldsymbol{VL^s} \quad (3)$$

$$\sum_{s\in\boldsymbol{S},i\in\boldsymbol{VN^s}} \delta_s \cdot \gamma_{i,x}^s \cdot CS_i^s \le CS_x \quad \forall x \in \boldsymbol{N} \quad (4)$$

The objective is to maximize the total availability-weighted capacity of all fully provisioned slices. Constraint (1) means that the total capacity of all the slice virtual links that commonly use a PON should not exceed its maximum transmission capacity. Constraint (2) means that the total capacity of all the slice virtual links that commonly pass a microwave link should not exceed its maximum transmission capacity. Constraint (3) implies that a slice is fully provisioned only if all its virtual links are established. Constraint (4) ensures that the total C/S capacity required by each slice node should not exceed the C/S capacity deployed at the physical node.

The ILP model for *partially provisioned slices* is extended from that of fully provisioned slices. A new binary parameter $\tau_{l,i}^s$ denotes if virtual node *i* is an end node of virtual link *l* in slice *s* and a new binary variable θ_i^s indicates if virtual node *i* in slice *s* needs to be provisioned with C/S capacity. The objective function is the same as before. The new constraints in addition to (1) and (2) are as follows.

$$\sum_{k\in\boldsymbol{K_l^s}} \beta_{l,k}^s \le 1 \quad \forall s \in \boldsymbol{S}, l \in \boldsymbol{VL^s} \quad (5)$$

$$\theta_i^s \ge \beta_{l,k}^s \cdot \tau_{l,i}^s \quad \forall s \in \boldsymbol{S}, l \in \boldsymbol{VL^s}, k \in \boldsymbol{K_l^s} \quad (6)$$

$$\sum_{s\in\boldsymbol{S},i\in\boldsymbol{VN^s}} \theta_i^s \cdot \gamma_{i,x}^s \cdot CS_i^s \le CS_x \quad \forall x \in \boldsymbol{N} \quad (7)$$

C) Heuristic algorithm: We develop *unavailability-minimized* heuristics for slice provisioning as follows.

Algorithm	**Scenario of Fully Provisioned Slices**
Step 1	For each slice request *s*, map its virtual nodes to the corresponding physical nodes, and judge whether the remaining C/S capacity of each mapped physical node is sufficient to satisfy the demand of the corresponding virtual node. If not, the slice cannot be provisioned and stop; otherwise, move to the next step.
Step 2	For each virtual link in *s*, try to employ the shortest path searching algorithm to establish this virtual link based on the remaining capacity on the physical links. The searching algorithm is carried out by considering the *unavailability* of each capacity-eligible physical link as its cost to find a path with a minimum unavailability.
Step 3	Repeat Step 2 until either all the virtual links in slice *s* are established in the physical network or any one of the virtual links cannot be established due to the lack of physical link capacity. For the former, the slice is provisioned and for the latter the slice is not provisioned.
Step 4	Compute the availability-weighted capacity of each slice and sum them up to find the total capacity of the network.

The algorithm for the scenario of *partially provisioned slices* is the same as that of fully provisioned slices except for the following differences. In Steps 1 and 2, as long as virtual nodes and links can be mapped, we will do it such that the capacity of each slice can be partially provisioned to the extent possible.

4. Simulations and Performance Analyses

The performance of the proposed approaches was obtained by solving the ILP models and running the heuristic algorithms based on the test networks in Fig. 1 and Fig. 2. Fig. 1 has two PONs with 10 ONU-BSs, relayed by 2 BSs in the middle, in which the actual test topology contains 22 microwave links. Fig. 2 is a WOBAN with an actual city map, where 66 ONU-BSs and 9 BSs are placed and the physical distance between these nodes are found based on the actual Geographic Information System (GIS) data of the map. These ONU-BSs are clustered into 5 PONs. The system parameters for the simulations are as follows: (1) for each slice, different numbers N of virtual nodes (ranging from 4 to the half of the total number of physical nodes) and links (ranging from N to $1.5\times N$) are randomly generated, and each slice link requests for a bandwidth randomly generated within the range of [100, 150] Mb/s; (2) the maximum transmission capacity of each PON system is 10 Gb/s; (3) the maximum transmission distance of a microwave link is limited to 20 km, and its actual transmission capacity depends on its distance. For a distance smaller than 10 km, it is 3 Gb/s. For a distance between 10 and 20 km, the capacity is (3.6-0.06×distance) Gb/s; (4) the number of microwave links established from/to each physical node is maximally 4; (5) the C/S capacity at each physical node is limited to 100 VMs and each slide node requests for 4 VMs.

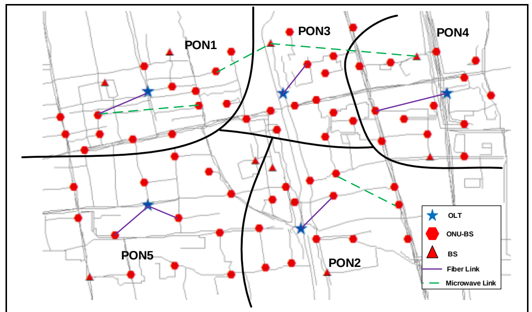

Fig. 2. Locations of ONU-BSs and BSs in a GIS map.

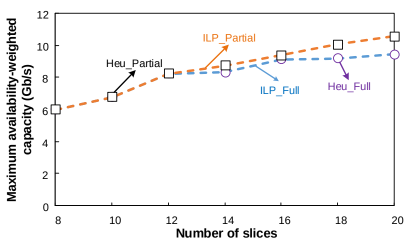

Fig. 3. Results of the small network.

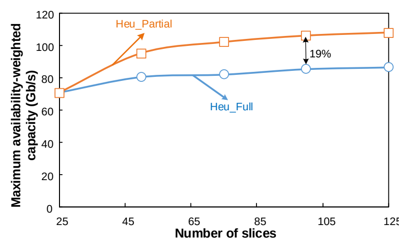

Fig. 4. Results of the large network.

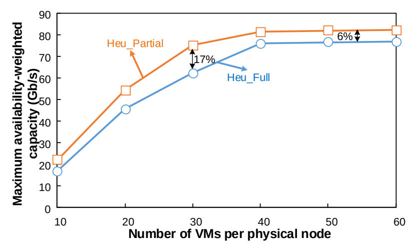

Fig. 5. Impact of # of VMs at each node.

(1) Fig. 3 shows the maximum availability-weighted capacity of the slices as per the objective function in the ILP model for the small test network in Fig. 1. With an increasing number of requested slices, the availability-weighted capacities increase for both provisioning scenarios. When the number of slices is smaller than 12, both provisioning scenarios provide the same slice capacity. Partially provisioned slices can provide more capacity than fully provisioned slices when the number of slices becomes larger. This is because the fully provisioned scenario requires each slice to be fully provisioned, which blocks partially provisioned slices. In contract, the partially provisioned scenario does not show this as it can provision slice capacity to the extent possible. Comparing the results of the ILP models and heuristic algorithms, we see that the latter is very efficient and performs close to the former. **(2)** A similar evaluation (see the results in Fig. 4) was carried out for the larger test network in Fig. 2. We failed to provide the ILP results due to the computational intractability of the ILP models. A similar trend is observed based on the results. Partially provisioned slices can provide more availability-weighted capacity and the performance difference from fully provisioned slices is larger as there are more slices to be provisioned which creates more opportunities for partially provisioned slices. **(3)** We also evaluated how the C/S capacity at each physical node affects the availability-weighted slice capacity when there are 30 slices to be provisioned. These results are shown in Fig. 5. With more VMs deployed at each node, the availability-weighted slice capacity increases, but is eventually saturated when the number of VMs exceeds a threshold, e.g., 40. This is because before the threshold, the availability of VMs plays a role in constraining the success of provisioning slices, but after the threshold, the VMs are sufficient and do not impact the success of provisioning slices.

5. Conclusion

We maximize the availability-weighted slice capacity for a sliceable WOBAN. For different slice provisioning scenarios, two ILP models and corresponding unavailability-minimized heuristic algorithms were developed. Simulation studies showed that the proposed approaches are efficient in maximizing the availability-weighted slice capacity and meanwhile the heuristic algorithms can perform close to the ILP models.

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