VNE^2: A Virtual Network Embedding Framework Based on Equivalent Bandwidth in Fiber-Wireless Enhanced 5G Networks

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ABSTRACT
Fiber-Wireless (FiWi) enhanced 5G networks have gained a lot of popularity due to its advantageous anytime-anywhere access for end users with high bandwidth capacity and long distance. The scheduling and allocation of the heterogeneous resources in FiWi can be tackled through network virtualization. However, existing works on End-To-End (ETE) Quality of Service (QoS) guarantee of Virtual Network Embedding (VNE) ignore the random nature of network traffics, leading to non-negligible queuing delay. Moreover, the flexibility of resource allocation for link embedding is also ignored by constraining the same amount of allocated resources for all links on each physical path. In this paper, we highlight flexible and delay-guaranteed VNE design in FiWi enhanced 5G networks and propose a VNE framework based on Equivalent bandwidth (VNE^2). The equivalent bandwidth is defined as a set of resources to be allocated to physical links on the path that a virtual link is embedded while guaranteeing ETE QoS. Furthermore, in order to bring the superiority of flexible resource allocation into full play, diversity of the amount of resources in the equivalent bandwidth for each virtual link is allowed to maximize Infrastructure Provider (InP) profit. Simulation results demonstrate that VNE^2 can improve network performance in aspects of InP profit, virtual network acceptance ratio and ETE delay.
Keywords: Fiber-Wireless, 5G, virtual network embedding, equivalent bandwidth.

1. INTRODUCTION

The Fifth Generation (5G) foresees 1000-fold gains in capacity, extremely high data rates reaching 10Gbps and connections for at least 100 billion devices. The cost-saving fiber infrastructure is a promising candidate for small cell backhaul, that is Fibre-Wireless (FiWi) enhanced 5G networks [1-2]. For 5G service providing, the End-To-End (ETE) Quality of Service (QoS) guarantee is very important. Besides, with the emergence of Over the top (OTT) content, network virtualization is capable of shielding heterogeneous features of Physical Networks (PNs) and providing customized service to Virtual Networks (VNs) through Virtual Network Embedding (VNE) [3]. Existing works embed a virtual link using a consecutive transmitting path with same amount of allocated resources over its links [4-5]. However, for Poisson distributed traffics, the same amount of allocated and requested resources leads to waiting delay approaching infinity. Moreover, the potential possibility of deploying diverse amount of resources for links on an embedding path has been ignored, which is beneficial for overcoming bottleneck links and accepting more VNs. This paper focuses on flexible and delay-guaranteed VNE design in FiWi enhanced 5G networks. A Virtual Network Embedding framework based on Equivalent bandwidth (VNE^2) is proposed. Specifically, taking both bandwidth and delay requirements of virtual links into account, the equivalent bandwidth of virtual links are calculated for resource allocation. Furthermore, the InP profit can be improved by allowing different physical links on an embedding path allocating different amount of bandwidth. More importantly, our VNE^2 can be fitted into most of existing VNE algorithms for link embedding.

2. NETWORK MODELS AND PROBLEM STATEMENT

2.1 Network models

Denote G^V the set of VNs, each VN $G_k^V=(N_k^V,L_k^V)$ in G^V has a sojourn time of T_k and consists virtual node set N_k^V and virtual link set L_k^V. Each virtual node $n_{k,i}^V \in N_k^V$ has CPU demand $c_{k,i}^V$, node type demand $\varsigma_{k,i}^V$, preferred location $lct_{k,i}^V$ and maximum embedding location offset demand $\Delta lct_{k,i}^V$. Note that the node type is either A for "access" or F for "forward", that is, $\varsigma_{k,i}^V \in \{A,F\}$. Each virtual link $l_{k,j}^V \in L_k^V$ has bandwidth demand $b_{k,j}^V$ and delay constraint $d_{k,j}^V$. The physical networks are represented by $G^S=(N^S,L^S)$, where N^S and L^S indicate the sets of physical nodes and links respectively. The location and type of physical node $n_x^S \in N^S$ are denoted by ς_x^S and lct_x^S, and the CPU capacity of n_x^S is C_x^S. As for node type, we specify $\varsigma_x^S \in \{OLT, ONU, SBS\}$ for different physical nodes, i.e., Optical Line Terminal (OLT), Optical Network Unit (ONU) and Small cell Base Station (SBS). For physical link $l_y^S \in L^S$, its bandwidth capacity is B_y^S. The load of l_y^S is denoted by f_y^S.

2.2 Equivalent bandwidth model

In this section, we define equivalent bandwidth for virtual link $l_{k,j}^V$ by considering $b_{k,j}^V$ and $d_{k,j}^V$. We first formulate the mean delay of data packets on $l_{k,j}^V$ while assuming physical link l_y^S allocates $\psi_{k,j}^y$ amount of resources to $l_{k,j}^V$.

According to [6], the packet transmitting process can be described as M/G/1 queuing system. The mean queuing time of packets on $l_{k,j}^{V}$ that is embedded onto l_{y}^{S} is given by

$$w_{k,j}^{y}=\frac{\lambda_{k,j}\overline{S^2}}{2\left(1-\rho_{k,j}^{y}\right)}=\frac{b_{k,j}^{V}\psi_{k,j}^{y}\overline{S^2}}{2L^{PK}\left(\psi_{k,j}^{y}-b_{k,j}^{V}\right)}, \tag{1}$$

where L^{PK} denotes average packet length and $\lambda_{k,j}=b_{k,j}^{V}/L^{PK}$ is the arrival rate of packets. The load factor is $\rho_{k,j}^{y}=\lambda_{k,j}/\mu_{k,j}^{y}$ for service rate $\mu_{k,j}^{y}=\psi_{k,j}^{y}/L^{PK}$. $\overline{S^2}$ denotes the second moment of packet service time. Generally, $l_{k,j}^{V}$ is embedded onto a physical path $p_{k,j}^{S}$. Thus, the total ETE delay can be formulated as:

$$t_{k,j}=\sum\nolimits_{y\in p_{k,j}^{S}}\left(w_{k,j}^{y}+L^{PK}/\psi_{k,j}^{y}\right), \tag{2}$$

including queuing time and transmitting time of all links along the path. In order to bring the superiority of flexible resource allocation into full play, a diverse amount of allocated resources for links on $p_{k,j}$ is allowed, that is $\psi_{k,j}^{y}=\psi_{k,j}^{y'}$ is not always true for $y,y'\in p_{k,j}^{S},y\neq y'$. Therefore, the equivalent bandwidth of $l_{k,j}^{V}$ is

$$\arg\min_{\left\{\psi_{k,j}^{y},\forall y\in p_{k,j}^{S}\right\}}\left\{\sum\nolimits_{y}\psi_{k,j}^{y}\mid t_{k,j}\le d_{k,j}^{V},\psi_{k,j}^{y}\le b_{y}^{S},\forall y\in p_{k,j}^{S}\right\}. \tag{3}$$

The equivalent bandwidth intends to find a set of allocated resources along $p_{k,j}^{S}$, i.e, $\left\{\psi_{k,j}^{y},\forall y\in p_{k,j}^{S}\right\}$ to minimize the sum of consumed resources, while guaranteeing ETE delay demand. By means of allocating different amount of resources to links on each path, there are possibilities that the bottleneck links whose residual bandwidth capacity is lower than others would not result in unsuccessful embeddings. Thus, the VN acceptance ratio and InP profit will be increased. In order to find optimal equivalent bandwidth in (3), we propose following theorem.

Theorem 1 Let $\overline{\psi_{k,j}^{y}}$ denote the mean value of $\left\{\psi_{k,j}^{y},\forall y\in p_{k,j}^{S}\right\}$, the problem in (3) is equivalent to

$$\arg\min_{\left\{\psi_{k,j}^{y},\forall y\in p_{k,j}^{S}\right\}}\left\{\sum\nolimits_{y}\left|\psi_{k,j}^{y}-\overline{\psi_{k,j}^{y}}\right|\mid t_{k,j}\le d_{k,j}^{V},\psi_{k,j}^{y}\le b_{y}^{S},\forall y\in p_{k,j}^{S}\right\}. \tag{4}$$

Proof We first prove the theorem using a special case where there are two hops in $p_{k,j}^{S}$. Let $M:=b_{k,j}^{V}\overline{S^2}/2L^{PK}$. Assume there exists a ψ_0 so that $t_{k,j}\le d_{k,j}^{V}$ when $\psi_{k,j}^{1}=\psi_{k,j}^{2}=\psi_0$ and assume we should increase $\psi_{k,j}^{2}$ by $\Delta'>0$ if we decrease $\psi_{k,j}^{1}$ by $\Delta>0$ in order to guarantee $t_{k,j}\le d_{k,j}^{V}$. Thus, $\psi_{k,j}^{1}=\psi_0-\Delta$, $\psi_{k,j}^{2}=\psi_0+\Delta$, we have

$$\frac{M\left(\psi_0-\Delta\right)}{\psi_0-\Delta-b_{k,j}^{V}}+\frac{L^{PK}}{\psi_0-\Delta}+\frac{M\left(\psi_0+\Delta'\right)}{\psi_0+\Delta'-b_{k,j}^{V}}+\frac{L^{PK}}{\psi_0+\Delta'}=2\frac{M\psi_0}{\psi_0-b_{k,j}^{V}}. \tag{5}$$

Through algebraic operations, it gives

$$\frac{Mb_{k,j}^{V}\left(\psi_0-b_{k,j}^{V}\right)+Mb_{k,j}^{V}\Delta\Delta'/\left(\psi_0-b_{k,j}^{V}\right)}{\left(\psi_0-b_{k,j}^{V}\right)^2+\left(\psi_0-b_{k,j}^{V}\right)\left(\Delta'-\Delta\right)-\Delta\Delta'}+\frac{L^{PK}\psi_0+L^{PK}\Delta\Delta'/\psi_0}{\psi_0^2+\psi_0\left(\Delta'-\Delta\right)-\Delta\Delta'}=\frac{Mb_{k,j}^{V}}{\psi_0-b_{k,j}^{V}}-\frac{L^{PK}}{\psi_0}. \tag{6}$$

Based on the fact that higher Δ leads to higher Δ' and $\Delta\Delta'$, it can be observed from (6) that, in order to maintain the equality for given $b_{k,j}^{V}$, L^{PK}, $\overline{S^2}$ and ψ_0, $\Delta'-\Delta$ should be higher too, meaning that $\psi_{k,j}^{1}+\psi_{k,j}^{2}$ will increase for increasing Δ. Therefore, $\min\psi_{k,j}^{1}+\psi_{k,j}^{2}$ is equivalent to $\min\Delta$ as well as $\min\Delta'$, that is $\min\left|\psi_{k,j}^{1}-\psi_0\right|+\left|\psi_{k,j}^{2}-\psi_0\right|$. It can be further transformed to $\min\left|\psi_{k,j}^{1}-\psi_{k,j}^{2}\right|$ and $\min\sum_{y}\left|\psi_{k,j}^{y}-\overline{\psi_{k,j}^{y}}\right|,y=\{1,2\}$. Thus, the theorem is proved for this special case. The proof can be easily extended to multi-hop paths and finally prove the theorem.

Theorem 1 indicates that in order to solve (3), we should find a set of $\left\{\psi_{k,j}^{y},\forall y\in p_{k,j}^{S}\right\}$ whose values are as similar as possible. Extremely, we have $\psi_{k,j}^{1}=\psi_{k,j}^{2}=\cdots\psi_{k,j}^{y}=\cdots,\forall y\in p_{k,j}^{S}$ when there are enough resources.

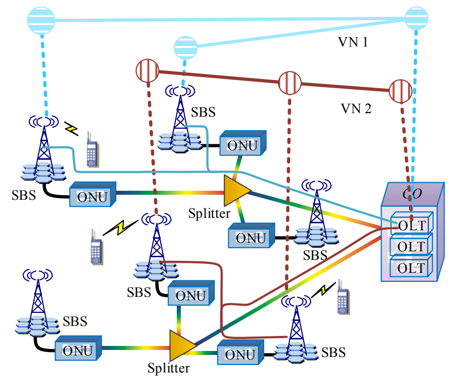

Figure 1. VNE in FiWi enhanced 5G networks.

Table 1. Parameter settings.

Symbol	Values
α, β, γ^{n}, γ^{l}	5, 1, 1, 1
L^{PK}, $\overline{S^2}$	1000 bits, 1e-9 s
κ	5
T_k	$E(20)$
$c_{k,j}^{V}$	$U(10,20)$
$b_{k,j}^{V}$	$U(2,10)$ bps
$d_{k,j}^{V}$	$U(0.0005,0.001)$ s
C_{x}^{S}	$U(200,500)$ for ONU/OLT $U(50,100)$ for SBS
B_{y}^{S}	1000 Mbps for optical links 100 Mbps for wireless links

2.3 Virtual network embedding based on equivalent bandwidth

The VNE problem by definition is a process of allocating resources that belong to InP to VNs managed by Service Providers (SPs) according to resource demands, as shown in Fig. 1. Each SP can deploy customized services to serve users on its VN using leased resources. For InP, the profit for leasing resources is

$$Profit(G_k^V) = T_k * \{\alpha\left[\gamma^n \sum_{i\in N_k^V} c_{k,i}^V + \gamma^l \sum_{j\in L_k^V} b_{k,j}^V\right] - \beta\left[\gamma^n \sum_{i\in N_k^V} c_{k,i}^V + \gamma^l \sum_{y\in N^S}\sum_{j\in L_k^V} \psi_{k,j}^y\right]\}, \tag{7}$$

where α and β represent the revenue and cost of each unit of resource respectively and γ^n and γ^l are weighs of node and link resources. With the objective of $\text{Maximize}: \sum_{k\in G^V} Profit(G_k^V)$, general VNE constraints [7] are introduced. It includes all-different node embedding constraint (different nodes from same VN should be embedded onto different physical nodes), resources demands and capacities constraints of CPU and bandwidth, flow conservation and disjoint link embedding constraint (each virtual link should be embedded onto a consecutive path) etc. It is specified that virtual nodes whose types are A and F should be embedded on OLT and ONUs/SBSs respectively. We further add delay constraint as $t_{k,j} \le d_{k,j}^V, \forall k \in G^V, j \in L_k^V$.

3. HEURISTIC ALGORITHM

Algorithm 1 VNE^2 for FiWi enhanced 5G networks

Input: G^V, G^S, α, β, γ^n, γ^l
Ouput: $\chi_{k,i}^x, \psi_{k,j}^y, \forall k \in G^V, i \in N_k^V, x \in N^S\ j \in L_k^V, y \in L^S$
1. **for** $G_k^V \in G^V$, **do**
2. Embed its virtual nodes to get $\chi_{k,i}^x, \forall i \in N_k^V, x \in N^S$;
3. Embed its virtual links using LINK_EMBEDDING($l_{k,j}^V$) to get $\psi_{k,j}^y, \forall j \in L_k^V, y \in L^S$;
4. **end for**

Procedure 1 LINK_EMBEDDING($l_{k,j}^V$)

1. Compute κ paths $P_{k,j}$ using k-shortest path algorithm;
2. **for** path $p_{k,j} \in P_{k,j}$ **do**
3. Rand links on $p_{k,j}$ in the increasing order of their residual bandwidth capacity;
4. **for** link $y \in p_{k,j}$ **do**
5. Compute the average bandwidth ψ_0 that each unallocated link should provide to satisfy $t_{k,j} \le d_{k,j}^V$;
6. $\psi_{k,j}^y \leftarrow \min\left\{B_y^S - f_y^S, \psi_0\right\}$, $f_y^S \leftarrow f_y^S + \psi_{k,j}^y$
7. **end for**
8. **if** $t_{k,j} \le d_{k,j}^V$ **then break; end if**
9. **end for**

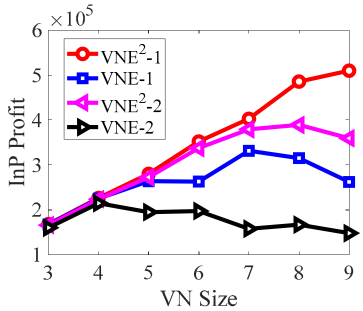

Figure 2. InP profit under different VN sizes.

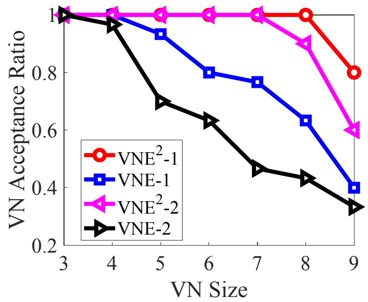

Figure 3. VN acceptance ratio under different VN sizes.

As the problem of VNE has been proved to be NP-hard, heuristic algorithms have been put forward to obtain maximum InP profit while satisfying resource and delay requirements. In VNE^2, we propose a novel virtual link embedding method to meet the requirements of ETE delay of virtual links and carry out link embedding process in a more flexible manner by allowing different amount of allocated resources for links on each embedded path. Note that our VNE^2 framework is compatible with most of VNE algorithms as long as they have separated link embedding stage so as to be replaced with our equivalent bandwidth-based link embedding method.

The VNE^2 framework is described in **Algorithm 1**, where existing VNE approaches can be applied with modified link embedding method as in **Procedure 1**. The node embedding results are characterized by $\chi_{k,i}^x, \forall k \in G^V, i \in N_k^V, x \in N^S$, which equals to 1 if $n_{k,i}^V$ is embedded onto physical node x and 0 otherwise. For virtual link $l_{k,j}^V$ with embedded or to-be-embedded end nodes, κ shortest paths are calculated as path set $P_{k,j}$. We will choose the shortest one that generates feasible equivalent bandwidth solution. For each path $p_{k,j} \in P_{k,j}$, the average bandwidth resource ψ_0 that guarantees $t_{k,j} \le d_{k,j}^V$ is allocated to each link y on $p_{k,j}$. ψ_0 can be determined using binary search method in searching space of $\left[b_{k,j}^V, \text{Inf}\right]$ where Inf is a sufficient large value, e.g., capacity of optical links. In case there exist links whose residual bandwidth is less than ψ_0, links with less residual bandwidth capacity are allocated in priority. The minimum of residual bandwidth capacity and ψ_0 is the final amount of resources to allocate. In this way, optimal equivalent bandwidth can be obtained according to **Theorem 1**. A new ψ_0 will be found for each link y by considering the rest of unallocated links on $p_{k,j}$.

4. SIMULATION RESULTS AND DISCUSSIONS

In the simulation, we deploy 1 OLT, 4 ONUs and 36 SBSs randomly in an area of 300m*300m. Parameter settings are shown in Table 1 where $E(a)$ denotes exponential distribution with mean value a and $U(a,a')$ indicates uniform distribution between a and a'. We fit our VNE^2 framework into general VNE algorithms, labelled as VNE-1 for one-stage VNE [7] and VNE-2 for two-stage VNE [7], and label our methods as VNE^2-1 and VNE^2-2 respectively. We vary VN size (number of virtual nodes in each VN) and VN arrival rate in the simulations. Moreover, according to (1), the queuing time will reach infinity if the service rate ($\psi_{k,j}^y / L^{PK}$)

equals to arrival rate ($b_{k,j}^{V} / L^{PK}$). Thus, we modify VNE-1 and VNE-2 approaches by allocating $b_{k,j}^{V} + 0.1$ Mbps resources to virtual link $l_{k,j}^{V} \in L_k^V, \forall k \in G^V, j \in L_k^V$.

Under different VN sizes, Figs. 2-5 depict the performance of InP profit, VN acceptance ratio (i.e., number of successfully embedded VNs over total number of VNs), average ETE delay, and delay satisfaction ratio (i.e., number of embedded virtual links with satisfied ETE delay over total number of embedded virtual links), respectively. It can be observed that VNE^2 gains higher InP profit and VN acceptance ratio and less average ETE delay than respective baseline VNE methods. A 100% of delay satisfaction ratio is obtained compared with about 50% ~ 80% in VNE-1 and about 40% ~ 60% in VNE-2. The performance comparisons under different VN arrival rates are shown in Figs. 6-9, where VNE^2 outperforms baseline VNE methods as well. Overall, the proposed VNE^2 framework can improve VNE performance in both InP profit and ETE delay.

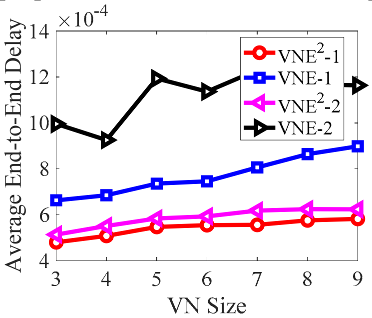

Figure 4. Average ETE delay under different VN sizes.

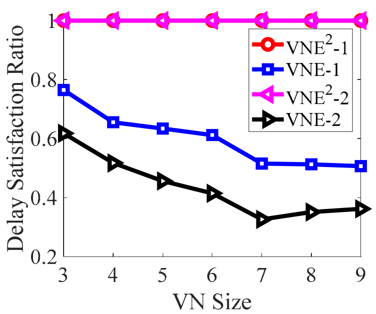

Figure 5. Delay satisfaction ratio under different VN sizes.

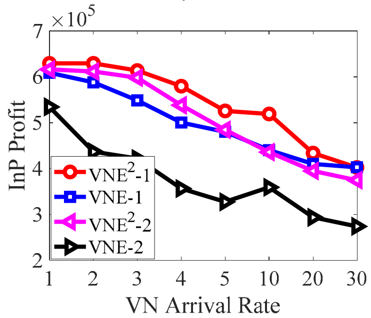

Figure 6. InP profit under different VN arrival rates.

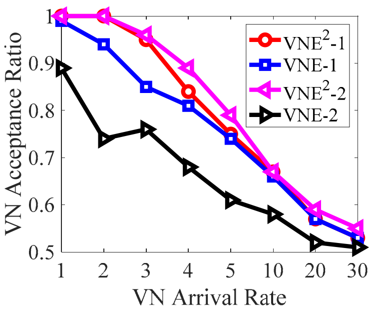

Figure 7. VN acceptance ratio under different VN arrival rates.

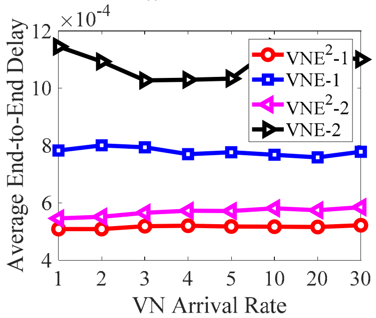

Figure 8. Average ETE delay under different VN arrival rates.

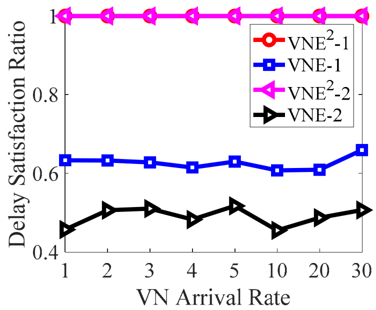

Figure 9. Delay satisfaction ratio under different VN arrival rates.

5. CONCLUSIONS

This paper emphasizes on flexible VNE framework in FiWi enhanced 5G networks. The equivalent bandwidth is considered for ETE QoS guarantee, based on which, flexible resource allocation for each virtual link is designed for InP profit improvement. More importantly, the framework can be fitted into any existing VNE algorithms as long as they have separated link embedding stage to achieve lower ETE delay and higher InP profit.

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