



# Embedding of virtual network requests over static wireless multihop networks



Donggyu Yun<sup>a</sup>, Jungseul Ok<sup>a</sup>, Bongjhin Shin<sup>b</sup>, Soobum Park<sup>b</sup>, Yung Yi<sup>a,\*</sup>

<sup>a</sup> Department of Electrical Engineering, KAIST, Daejeon, South Korea

<sup>b</sup> Communication Lab., LIG Nex1, Seongnam-City, Gyeonggi-do, South Korea

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## ABSTRACT

Network virtualization is a technology of running multiple heterogeneous network architecture on a shared substrate network. One of the crucial components in network virtualization is virtual network embedding, which provides a way to allocate physical network resources (e.g., CPU and link bandwidth) to virtual network requests. Despite significant research efforts on virtual network embedding in wired and cellular networks, little attention has been paid to that in wireless multi-hop networks, which is becoming more important due to its rapid growth and the need to share these networks among different business sectors and users. In this paper, we first study the root causes of new challenges of virtual network embedding in wireless multi-hop networks, and propose a new embedding algorithm that efficiently uses the resources of the physical substrate network. We examine our algorithm's performance through extensive simulations under various scenarios. Due to lack of competitive algorithms, we compare the proposed algorithm to five other algorithms, mainly borrowed from wired embedding or made by us, partially with or without the key algorithmic ideas to assess their impacts.

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## 1. Introduction

Network virtualization is a powerful technology that allows multiple heterogeneous network architectures over a shared physical network, shortly called a *substrate network* (SN). Major applications include testing of new network protocols, such as PlanetLab [1] and Emulab [2]. Network virtualization also enables multiple service providers to offer customized services with different requirements and features, e.g., a streaming video network with low delay and high bandwidth or a financial service network with high reliability and security guarantees, over a common physical substrate network.

In a virtualized network environment, the SN providers accept and run multiple virtual networks (VNs), where the

substrate nodes serve the nodes in a virtual network and the physical paths configure the virtual links. Since multiple VNs are bound to share the common underlying physical resources, the *VN embedding problem* that finds an efficient embedding of each VN to substrate resources, is very important in order to support as many requests as possible and/or minimize the substrate network resources for embedding.

In this paper, we consider a VN embedding problem over wireless multi-hop networks. We focus on the key difference – inter-link interference – in wireless multi-hop networks from wired networks, whose challenges are summarized next. A typical embedding for a VN consists of the following procedures: (a) search plausible candidate embeddings for the given VN request, (b) assess their qualities in terms of a target objective, e.g., minimization of substrate resource usage or revenue maximization, and (c) select the best candidate among the feasible ones.<sup>1</sup> From

\* Corresponding author. Tel.: +82 42 350 5486.

E-mail addresses: [dgyun@lanada.kaist.ac.kr](mailto:dgyun@lanada.kaist.ac.kr) (D. Yun), [ockjs@lanada.kaist.ac.kr](mailto:ockjs@lanada.kaist.ac.kr) (J. Ok), [bongjin.shin@lignex1.com](mailto:bongjin.shin@lignex1.com) (B. Shin), [sbpark93@lignex1.com](mailto:sbpark93@lignex1.com) (S. Park), [yiyung@kaist.edu](mailto:yiyung@kaist.edu) (Y. Yi).

<sup>1</sup> We say that an embedding is feasible when the physical substrate network has enough resource to support the embedding.

the above procedures, we see that two primitives are necessary in embedding: (i) checking the feasibility of a candidate embedding and (ii) quantifying the embedding's quality. Note that these two primitives are easy to support in wired networks. Feasibility can be simply checked by comparing the physical layer's remaining resource with the resource required by the existing and new embeddings. The quality of the embedding is typically quantified by computing the total amount of resource occupied by the embedding. There, embedding challenge is due to computational intractability just coming from the large search space of candidate embeddings.

However, in wireless embedding, both primitives are harder to check, and even need to be defined appropriately. This is because *the resource allocated over a link makes an indirect impact on the actual remaining resource over other neighboring links due to inter-link interference, and both primitives are coupled with the underlying MAC*. A MAC protocol (e.g., 802.11), has its unique capability of supporting the assigned rates over each link, meaning that the feasibility check will lead to different results, depending on the underlying MAC. Regarding the quality comparison metric, as an example, consider two embeddings  $E_1$  and  $E_2$ , where the aggregate amount of resource required by  $E_1$  exceeds that by  $E_2$ . However,  $E_1$  can be preferable if the embedded nodes and links in  $E_1$  are in less interfering regions, because it is likely that more future requests will be accepted.

Our approach and main contributions towards efficient embedding in wireless multi-hop networks are summarized as follows:

- (1) *Feasibility check*. We propose two solutions: (i) sufficiency-based approach and (ii) simulation-based approach with smart embedding. First, in the sufficiency-based approach, we use a graph-theoretical sufficient condition based on weighted graph coloring, which, if met, feasibility is guaranteed. Second, in the simulation based-approach, we limit the space of candidate embeddings, so that the conflict graph<sup>2</sup> of the embedded substrate network<sup>3</sup> always satisfies a specific pattern, called PBG (Polynomially Bounded Growing) graph. To check the feasibility of a candidate embedding, we simulate the substrate network, and the PBG property enables us to check the feasibility polynomially and performs arbitrarily close to the optimal one.
- (2) *Quality comparison metric*. We choose a simple quality metric (for a candidate embedding) that is designed to decrease when less overall loads are imposed on the SN by the embedding. While VN nodes are one-to-one mapped to the SN nodes, a VN link can be mapped to a path in the SN and the metric is designed so that the amount of link-interference of in the path is minimized.

- (3) *Efficient candidate searching*. The key to an efficient embedding algorithm lies in how to smartly search a limited set of “good” candidate embeddings. We repeatedly test a candidate embedding that is chosen by merging the node and link mapping process for a limited number of times. The joint link and node mapping process simultaneously considers the amount of available node resources in the node mapping and the degree of newly generated interference to the network in the link mapping. This selection of nodes and links are coupled with the comparison metric.

Potential applications of VN embedding over wireless multi-hop networks are as follows: With increasing number of mobile users, accelerated by proliferation of smart phones, wireless access technologies are becoming diverse, widespread, and broadband. Of many types of access networks, wireless multi-hop networks are expected to be used as an inexpensive way to provide last-mile Internet access. In fact, several cities are currently deploying municipal wireless mesh networks [3]. In the mobile network market, a growing number of Mobile Virtual Network Operators (MVNOs) reaches over 430 worldwide in 2010 [4]. MVNOs do not own the wireless network infrastructure, and lease part of the physical infrastructure from Mobile Network Operators (MNOs) to provide customized mobile services. MVNO virtualization is currently active mainly at the access part (thus for single-hop wireless). However, it may be possible that wireless mesh/backbone become more popular in the future, where virtualization is likely to be extended to multi-hop wireless networks. In addition, similar to PlanetLab, Orbit [5] which is a wireless network testbed consisting of  $20 \times 20$  nodes can be an another example of virtualization over the wireless multi-hop network. The virtualization in Orbit relies on “network-level” slicing that each VN reserves time slices so that the VN requester can access all the resource during the reserved time slices. In this paper, we aim at a slicing with finer-granularity, called “link-level” slicing, so that different VNs are just ensured to be coupling-free and distinct substrate network resources can be utilized by different VN requests simultaneously.

We consider only inter-link interference modeled based on a graph-theoretic relationship, and do not consider wireless links' time-varying characteristics due to e.g., SN nodes' mobility, i.e., the capacities of links are assumed to be fixed. Although this does not reflect the practice perfectly, our work can be an important step towards efficient embedding over wireless multi-hop networks, since handling inter-link interference is one of the major obstacle there, such as the approach in wireless link scheduling research (see e.g., [6] for a survey). We expect that our work is connected to research on more practical algorithms reflecting the full wireless features in the future.

## 2. Related work

Recently, there has been research interest regarding virtual network embedding over wired networks, e.g., [7–12] and/or embedding in single-hop cellular networks [13],

<sup>2</sup> It is the graph that represents interference relationships among wireless links. Refer to 4.3 for a more detailed explanation.

<sup>3</sup> It is a subgraph of the substrate network consisting only of nodes and links which serve some virtual network requests.

where the embedding problem turns out to require computationally intractable complexity for optimality, and thus various heuristics have been proposed. More challenging issues in multi-hop networks are involved mainly due to the complex interference among links and its severe coupling with network topology. These challenges require a new design of embedding algorithms. Recently, NVS in [13] is proposed for virtualization on wireless single-hop networks. NVS provides an effective wireless resource allocation over cellular networks, by separating slice scheduling and flow scheduling. However the VN embedding problem essentially asks the mapping correspondence between a VN node/link and SN node/path beyond the scope of resource allocation.

Related work on embedding in wired networks mainly focuses on addressing computational challenges by restricting the problem space in different dimensions or proposing heuristic algorithms [7–9]. For example, only bandwidth requirements are considered in [7,8] or all VN requests are assumed to be given in advance [8,9]. The authors in [7–9] also considered the substrate network with infinite capacity, consequently accepting all incoming VN requests. On embedding problems over SN with limited resources, multi-commodity flow detection based algorithms are proposed in [10,11], where node embedding methods also consider their relation to the link embedding stage similar to our work. All algorithms in [8–11] separate node and link embedding process, i.e., all VN nodes are embedded before embedding VN link embedding. A single-stage wired embedding algorithm is also proposed in [12] which tries to find a subgraph isomorphism of the VN via a *backtracking* method. There, the algorithm imposes a limit on the length of substrate paths that will embed virtual links and checks feasibility whenever a new VN link is embedded: if it is infeasible, it is backtracked to the last feasible embedding.

### 3. Wireless VN embedding problem

#### 3.1. General embedding problem

We first describe a general embedding problem, followed by the unique features that need to be considered in wireless embedding in Section 3.2.

##### 3.1.1. Substrate network

Denote a substrate network (SN) by an undirected graph  $G^S = (N^S, L^S, A_N^S, A_L^S, I)$  (Table 1), where  $N^S$  and  $L^S$  are

**Table 1**  
Summary of major notations.

| Notation          | Description  |
|-------------------|--|
| $G^S$             | Substrate network                                    |
| $N^S, L^S$        | Set of substrate nodes and links                     |
| $\text{CPU}^S(n)$ | CPU resources of SN node $n \in N^S$                 |
| $\text{CAP}^S(l)$ | Capacity of SN link $l \in L^S$                      |
| $d_l$             | Number of interfering links with SN link $l \in L^S$ |
| $G^V$             | Virtual network                                      |
| $N^V, L^V$        | Set of virtual nodes and links                       |
| $\text{CPU}^V(n)$ | CPU requirement of VN node $n \in N^V$               |
| $\text{BW}^V(l)$  | Bandwidth requirement of VN link $l \in L^V$         |

the sets of nodes and links, respectively. The  $A_N^S$  refers to the set of node resources, e.g., CPU resource or hard-disk. We assume that only CPU resource is considered in this paper, which can be readily extended to other resources. The  $A_L^S$  is the set of link resources. Let  $\text{CPU}^S(n)$  be the amount of CPU resource of node  $n \in N^S$ , and  $\text{CAP}^S(l)$  be the capacity of link  $l \in L^S$ . We also denote by  $P^S$  the set of all paths in  $G^S$ . We will focus on the case when the links in  $L^S$  are wireless.

##### 3.1.2. Virtual network

A virtual network (VN) request is denoted by an undirected graph  $G^V = (N^V, L^V, C_N^V, C_L^V, D^V)$ , where  $N^V$  and  $L^V$  are the set of nodes and links of the virtual network, respectively.  $C_N^V$  and  $C_L^V$  denote the set of node and link requirements. As an example, let  $\text{CPU}^V(n)$  and  $\text{BW}^V(l)$  be the CPU and bandwidth requirements for the virtual node  $n \in N^V$  and the virtual link  $l \in L^V$ . These requirements can be also interpreted as *constraints* for embedding i.e., to accept a VN request, the amount of allocated substrate resources for each virtual node and link should be more than required.  $D^V$  implies that the VN request should be served for the duration of  $D^V$ . With a little abuse of notation, we also denote by  $L(n)$  the set of the links connected to the node  $n$  in both  $G^V$  and  $G^S$ .

##### 3.1.3. Embedding problem

We define an embedding  $E$  from  $G^V$  to a subset of  $G^S$  as a mapping

$$E : G^V \rightarrow (N^*, P^*, R^N, R^L)$$

where  $N^* \subset N^S$ ,  $P^* \subset P^S$  and  $R^N, R^L$  are the node/link resources allocated to the  $G^V$  by embedding  $E$ . We consider an *online* virtual network requests scenario, where a sequence of VN requests arbitrarily arrive and stay in the network over time. We consider a time-slotted system, indexed by  $t = 0, 1, \dots$ . For an embedded VN request  $G^V$ , the SN provider earns revenue  $R(G^V)$  which is proportional to the total amount of the requested resources in the VN request, i.e.,

$$R(G^V) = \sum_{n \in N^V} \text{CPU}^V(n) + \alpha \sum_{l \in L^V} \text{BW}^V(l), \quad (1)$$

where the constant  $\alpha$  reflects the relative importance in node and link resources, chosen by a virtual network operator. This weighted method is one of the typical ways to handle multi-objective optimization problem, like in the previous works [10,11].

Then, the SN provider's revenue  $R(t)$  at time slot  $t$  becomes

$$R(t) = \sum_{g \in \mathcal{G}^V(t)} R(g), \quad (2)$$

where  $\mathcal{G}^V(t)$  be the set of VN requests served at time slot  $t$ . Since VN requests arrive and depart arbitrarily over time, we set a goal of our embedding algorithm to maximize the time-averaged revenue, given by:

$$\max \lim_{T \rightarrow \infty} \frac{\int_0^T R(t) dt}{T}. \quad (3)$$

### 3.2. Wireless embedding

#### 3.2.1. Wireless link capacity

The capacity of a wireless link is time-varying unlike that of a wired one. We restrict our attention to the case of providing the long-term average capacity to the link resource requirement in a VN request. Thus, we model the capacity of each link to be fixed, which is a time-averaged value. This seems to be reasonable since the time-scale of embedding arrival and departure is much slower than that of channel variations.

#### 3.2.2. Interference model

The most distinct feature of wireless networks lies in existence of interference among concurrent transmissions. The matrix  $I$  is the  $|L^S| \times |L^S|$  matrix which represents the interference relationships for wireless links, where  $I_{ij} = 1$  if links  $i$  and  $j$  interfere with each other, and 0 otherwise. Denote by  $d_i$  the number of interfering links with  $i$  in the SN. The interference matrix depends on the physical layer techniques as well as the employed MAC. In literature on modeling wireless networks, a hop-based interference model is popularly used, e.g., one-hop for FH-CDMA and two-hop for 802.11-like systems. However, our description can be readily extended to any graph-based interference.

#### 3.2.3. MAC model

We assume a MAC with  $\epsilon$ -throughput-optimality for some  $\epsilon > 0$ . Roughly, a MAC is said to be *throughput-optimal* if it can stabilize any arrival rate vector over the SN links whenever possible (see the seminal paper [14] for a formal definition).  $\epsilon$ -throughput-optimality means that a MAC can support only a  $\epsilon$ -reduced version of the arrival rates supported by a throughput-optimal MAC. We can regard  $\epsilon$  as a reduction factor that is due to any kind of implementation overhead, e.g., message passing. We note that recently there also exists a research on so-called optimal CSMA, e.g., [15–17] that is close to throughput-optimal by simply and locally controlling CSMA parameters.

#### 3.2.4. VN request

In wireless embedding, VN requests can be classified into *wireless-agnostic* and *wireless-aware* ones. Wireless-agnostic requests are service-oriented ones, which pay no attention to where there requests are actually served, wireless or wired. As an example, an on-line game service provider may just want to lease some network resources from a physical substrate network provider, where the game users can use some wireless devices or computers connected to the residential wired Internet. Wireless-aware requests are the ones which take care of all the wireless issues, e.g., a protocol tester who intends to test whether his/her protocol works well or not over a wireless mesh network. In this paper, we focus mainly on wireless-agnostic requests, but our algorithm can be slightly modified for wireless-aware requests as well (see Section 7).

## 4. Challenges in wireless embedding

### 4.1. Handling online VN requests

The VN request arrivals and departures are not known in advance, and may be quite random. In this unpredictable situation, the on-line embedding algorithm to achieve the objective (3) requires the statistical properties of VN requests and the large search space, where a mathematical tool such as dynamic programming can be used to solve the problem. Clearly, the issue of handling online, unpredictable VN requests also exists in the embedding over wired substrate networks.

### 4.2. Hardness of embedding quality comparison

After searching a multiple of candidate embeddings for a given VN, the next step is to quantify how good the embeddings are. Comparing their qualities is expected to have the following requirements:

- R1. *Simplicity*. Short computation time for comparison is necessary due to existence of a large number of candidate embeddings, for which a simple comparison metric should be developed.
- R2. *Efficiency*. The devised metric should appropriately reflect the changes in the available substrate resources for the requests in the future.

In wired substrate networks, R1 and R2 are easy to meet, since the amount of available substrate resource is just the original amount of the resource subtracted by the resource assigned in embedding previous requests. However, in wireless multi-hop substrate networks, as discussed earlier, measuring the amount of the available resource is ambiguous. We can interpret the available (or remaining) bandwidth resource of a wireless link as its capacity multiplied by the time portion that it can be activated additionally. Therefore, the amount of available resource over each link is determined by the employed link scheduling (at the MAC layer). However, wireless networks operate a dynamic scheduling algorithm which let the set of activated links over time. This makes exact calculation of the amount of available resources practically impossible.

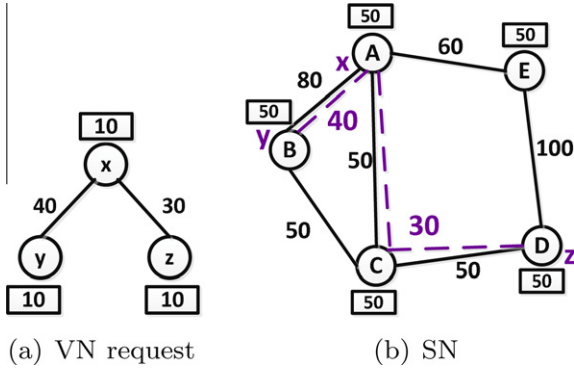
### 4.3. Feasibility checking

#### 4.3.1. Wired vs. wireless

We consider an example in Fig. 1 to explain the unique challenges in the feasibility check for wireless embedding. Note that feasibility check is an important primitive in embedding to check if there is enough resource for a candidate embedding to be supported in the SN. The SN in Fig. 1b can be interpreted either as a wired SN or a wireless SN. We assume that no prior VN requests are served in the SN, and the interference in the wireless SN is one-hop based, i.e., any two links with one-hop distance interfere. Consider a candidate embedding in both of wired and wireless SNs in which

*Node mapping* :  $x \rightarrow A, y \rightarrow B, z \rightarrow D$

*Link mapping* :  $(x, y) \rightarrow (A, B), (x, z) \rightarrow (A, C, D),$



**Fig. 1.** (a) A VN request. (b) An embedding in SN, The SN is either wired or wireless. If it is wireless, the interference is one-hop based, e.g., links (A,C) and (C,D) interfere. The numbers in the box and on the links represent the amount of CPU resources and link bandwidths.

Recall that (A,C,D) is a path in the SN. In the wired SN, feasibility check can be easily done by individually checking the feasibility of node and link resources. Although the mapping is feasible in wired SN, the same embedding is *infeasible* in the wireless SN, because there is no way of serving either (A,C) and (C,D) at one instant and providing the (long-term) bandwidth of 30 at each link. This is because link (A,C) and link (C,D) should be acted as the virtual link (x,z) during  $0.6 (= \frac{30}{50})$  portion of the time, but they cannot be activated simultaneously due to interference. This shows the difficulty of checking feasibility, where individual resource check at nodes and links is insufficient and a more complex checking procedure should be considered.

#### 4.3.2. Formalism

The root causes of hardness in feasibility check in wireless embedding can be understood more clearly by introducing a notion of *conflict graph*. A conflict graph graphically captures the interference relation between any pair of links by transforming the original graph for a given interference matrix: a link becomes a node and two links are connected if they interfere. For a candidate embedding, consider the *potential normalized load* of a substrate link  $l$ ,  $\lambda_l = \text{Req}(l)/\text{CAP}^S(l)$ , where  $\text{Req}(l)$  is the required aggregate bandwidth of VN requests already being served and a new candidate embedding. Then, the candidate embedding becomes feasible if there exists a scheduling scheme which provides the long-term average rates of  $\lambda_l$ . This has been traditionally studied in the context of weighted graph coloring for the conflict graph, known to be an NP-hard problem. Another way of understanding this problem from the control and networking theoretic perspectives is whether the system can be stabilized or not by some scheduling algorithm, assuming stochastic packet arrivals with mean  $(\lambda_l)$  over each link [14].

#### 4.4. Searching candidate embeddings

Section 4.1 discussed the challenge of unpredictable on-line requests. Sections 4.2 and 4.3 deal with the issue of

comparing embeddings' quality and checking feasibility. The final step is to determine the set of candidate embeddings as a search space. This is necessary because searching all candidates embeddings is computationally impossible. Obviously, this problem also appears in the wired embedding, yet the problem in wireless embedding is further coupled with feasibility check as well as quality comparison metric. Thus, based on the appropriate comparison metric definition and the feasibility checking mechanism, the question of which embedding to try first and which embedding is finally selected will be decided accordingly.

### 5. Embedding algorithm

#### 5.1. Algorithm overview

The framework of our algorithm is described in Fig. 2 and **WEM** (Wireless Embedding). First, we simply explain how dynamic requests are processed, in which we take a similar approach to that of wired embedding, and then elaborate on the embedding algorithm for a VN request in the subsequent subsections, which is our major focus of this paper.

##### 5.1.1. On-line requests

Serving incoming VN requests as fast as possible may be one criterion of handling on-line requests. However, a more crucial capability required by SN is to prevent the VN request from being blocked due to inefficient SN resource management. To that end, we divide the time into a sequence of windows whose duration determines how frequently the embedding process is run. This is dependent on the SN provider's operation decision, e.g., an hour or a day. Over one time window, we collect a group of arriving requests and process one-by-one. Since it may be impossible to accommodate all the incoming requests within a certain time window, we need to smartly decide the requests that will be served. One approach mentioned in wired embedding [10] is that the SN provider may prioritize the VN requests to maximize the earned revenues, for example, by serving the requests in the order of revenues.

We now describe **WEM**, the embedding algorithm for a VN request.

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#### WEM: Wireless Embedding algorithm for a VN request

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- Step 1.** Decide the embedding order of VN nodes.
  - Step 2.** Select the  $K$  SN "root" nodes, each of which maps the first VN node (chosen by **Step 1**) in the  $K$  candidate embedding trials.
  - Step 3.** Choose  $K$  candidate embeddings, where each candidate embedding process starts from each root node (chosen in **Step 2**) and sequentially embeds other remaining VN nodes and links according to the order in **Step 1**.
  - Step 4.** Evaluate  $K$  candidate embeddings based on a comparison metric, and take the highest-quality embedding candidate that passes feasibility check.
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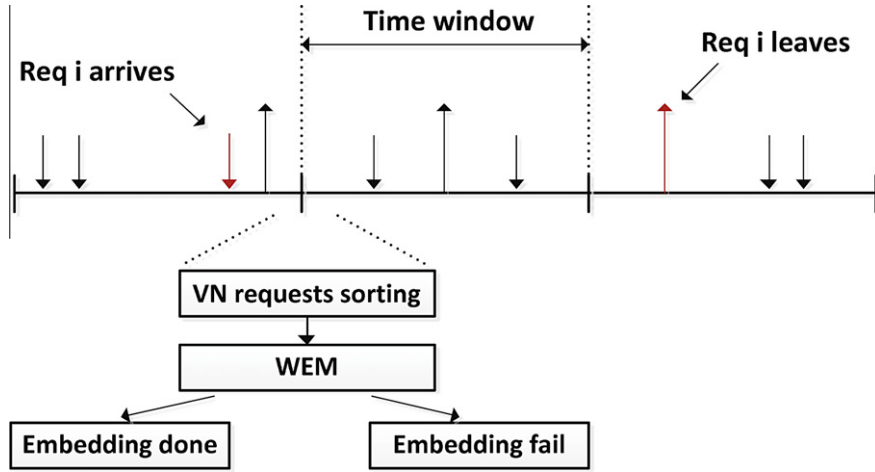


Fig. 2. Embedding framework for dynamic VN requests.

### 5.1.2. Key ideas

Our algorithm is designed to ensure to tackle the challenges in Section 4. Scarce resources in wireless networks should be efficiently utilized, whereas the impact of wireless interference in many algorithmic components are appropriately handled while striking a balance between efficiency and running time. In our algorithm, we first choose  $K$  embeddings (**Step 3**), where  $K$  is the search number, and in each candidate embedding, we choose the “root” SN node (**Step 2**) that maps to the first VN node (which is chosen by a selection rule, **Step 1**). Afterwards, VN links and nodes are mapped simultaneously. This is because interference is coupled with both nodes and links, e.g., a node with many incident links is likely to be in the region with severe interference. Finally, we choose the one that has the best quality and passes the feasibility check (**Step 4**). We now provide the details in each step in conjunction with the design rationales. To help the readers to understand, we will use the example in Fig. 3 in all explanations.

## 5.2. VN node sequence and SN node selection

### 5.2.1. VN node sequence

In **Step 1**, we first determine the mapping sequence of VN nodes in any embedding candidate. To that end, we define the notion of *extended required node resource*: for a VN

node  $n$ ,  $\text{CPU}^V(n) + \alpha \sum_{l \in L(n)} \text{BW}^V(l)$ . This notion captures the CPU resource plus the aggregate bandwidth resource required by the node's incident links. The node with highest extended required resource is firstly embedded due to higher embedding difficulty. We embed the rest of the nodes in ascending order of hop distance from the first node.

### 5.2.2. SN node selection

In **Step 2**, we choose a starting root node in SN for each candidate embedding. Since we try  $K$  embeddings,  $K$  starting root nodes should be selected. We use a similar metric to that in **Step 1**. We sort all the SN nodes in the decreasing order of the following *extended remaining node resource*: for an SN node  $n$ ,  $\text{CPU}_{\text{Rem}}^S(n) + \alpha \sum_{l \in L(n)} \text{BW}_{\text{Rem}}^S(l)$ , where  $\text{CPU}_{\text{Rem}}^S(n)$  is the *remaining* CPU resource available for new VN requests and similarly  $\text{BW}_{\text{Rem}}^S(l)$  is equal to  $\text{CAP}^S(l) - \text{Req}(l)$ . The extended remaining node resource quantifies the amount of remaining node resource considering the bandwidth resource of connected links to the corresponding node. It means that we prefer to try the root node which has enough resource.

**Example.** In Fig. 3a, since node  $a$  has the highest extended required resources, the embedding sequence is  $a, c, b$ . Both  $b$  and  $c$  are one hop apart from  $a$ , here, we give a higher priority to  $c$  because its extended required resources is higher than  $b$ 's. It can be easily shown that node  $C$  has the highest extended remaining resources in Fig. 3b.

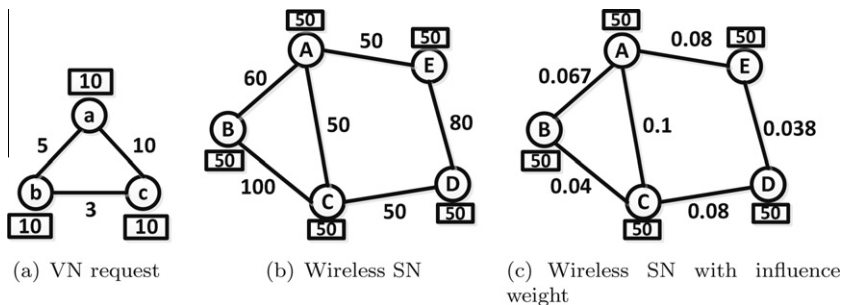


Fig. 3. An example of VN and SN to explain WEM. No existing VNs in service and one-hop interference model are assumed in the SN.

### 5.3. Searching candidate embeddings

#### 5.3.1. Overview

In this subsection, we elaborate on **Step 3**, where, starting with a given root SN node in an embedding candidate, we finish the embedding candidate by mapping other remaining VN nodes and links. The overview of the process is as follows: We define a notion of *influence weight* assigned to all SN links (to quantify interference in their neighborhoods). We then map the VN nodes to the SN nodes, so that the required link bandwidth between two VN nodes are satisfied as well as minimize the aggregate influence weight of the mapped *SN path*. This process is a joint link and node embedding that takes into account our intention to prefer less interfering regions with higher capacity (and thus more efficiently utilizing SN resources).

#### 5.3.2. Influence weight and distance

The *influence weight*  $d_l(l)$  of an SN link  $l$  represents the intensity of overall interference that the link  $l$  affects its neighboring links.  $d_l(l)$  is the number of its interfering links (including itself) divided by  $CAP^S(l)$ , i.e.,  $d_l(l) = (d_l + 1)/CAP^S(l)$ .  $d_l(l)$  implies the influence of embedding one bandwidth resource unit onto the link  $l$  to the network available resource in the sense that it forces the link  $l$  to be activated and forbids its neighboring  $d_l$  links to be activated at least  $1/CAP^S(l)$  portion of the time. Then, the influence weight for a *path* is the sum of influence weights of all links in the path. The *influence distance* of two SN nodes is the minimum influence weight among the paths connecting those two SN nodes. Fig. 3c illustrates an example of the influence weights.

#### 5.3.3. Joint VN node and link mapping

We now explain how the VN nodes are embedded in conjunction with the VN links. Assume that we handle  $i$ th VN node  $n_i^V$  in the sequence by **Step 1**. Let  $\mathcal{A}(n)$  be the set of already embedded VN nodes adjacent to  $n$  in  $G^V$ . Assuming that the SN node for  $n_i^V$  is decided (whose rule will be explained shortly), the embedding of added VN links between  $n_i^V$  to all the VN nodes in  $\mathcal{A}(n)$  is done by the shortest paths in terms of influence weight subject to each path has enough path bandwidth to satisfy the bandwidth requirement of the corresponding VN link added due to node embedding.

We now describe the rule for selecting the SN node  $n_i^S$  which will embed  $n_i^V$ :

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Embedding of  $i$ th VN node  $n_i^V$  with added VN links.

---

$$n_i^S \in \arg \min_{n \in N^S} \sum_{u \in \mathcal{A}(n_i^V)} \left( BW^V(\overline{u, n_i^V}) \times d_l(E(u, n)) \right),$$

s.t. “bandwidth requirements by added VN links,”  
(4)

where  $\overline{a, b}$  is the virtual link between  $a$  and  $b$ ,  $E(u)$  is the SN node that serves a VN node  $u$  and  $d_l(E(u), n)$  is the influence distance between  $E(u)$  and  $n$ .

---

The node embedding rule is designed to minimize the aggregate “load stress” added by embedding a new VN node. The load stress is measured by the aggregate bandwidth requirement weighted by the influence distance over the new SN paths. Weighting with the influence weight is due to our design rationale of avoiding the region with less capacity and high interference.

**Example.** We now illustrate the process using Fig. 4 that magnifies the algorithm of this subsection from the example in Fig. 3. We assume that we consider a candidate embedding, where the first VN node  $a$  and the root SN node is  $C$ . Since the next VN node is  $c$ , we find the SN node which has the shortest influence distance from  $C$ , which is node  $B$ .  $c$  is embedded to  $B$  and VN link  $(a, c)$  is mapped to link  $(C, B)$  (Fig. 4b). We next search the SN node which will serve node  $b$ . We calculate the (bandwidth requirement) weighted sum of influence distances from node  $C$  and  $B$  to each of nodes  $A$ ,  $D$ , and  $E$ . That is: for  $A$ ,  $5 \cdot 0.1 + 3 \cdot 0.067 = 0.701$ , for  $D$ ,  $5 \cdot 0.08 + 3 \cdot (0.04 + 0.08) = 0.76$  and finally for  $E$ ,  $5 \cdot (0.08 + 0.038) + 3 \cdot (0.067 + 0.08) = 1.031$ . Thus, node  $b$  is embedded to node  $A$ , and link  $(a, b)$  and  $(c, b)$  are embedded to link  $(C, A)$  and  $(B, A)$ , respectively (Fig. 4c).

#### 5.4. Comparison metric

$K$  candidate embeddings are now ready, and we are in the stage of quantifying their qualities based on a metric which we explain in this subsection (**Step 4**). For a candidate embedding  $E$ , we define the embedding comparison metric  $\sigma(E)$ :

$$\sigma(E) \triangleq \sum_{l \in L^S} (d_l + 1) \times \lambda_l(E),$$

where  $\lambda_l(E)$  is the potential normalized load of link  $l$  for  $E$ , and recall that  $d_l$  is the number of interfering links with  $l$ . Note that link  $l$  forbids  $d_l$  links to be activated at least  $\lambda_l$  portion of the time. The potential normalized loads weighted by  $d_l + 1$  captures the amount of offered loads considering interference (including itself). Following such intuition, we prefer a candidate embedding with smaller value of  $\sigma$ .

The metric  $\sigma$  is devised to be *fully compatible* with our joint node and link embedding algorithm in Section 5.3. Suppose that a VN link  $l^V$  is embedded to an SN path  $\mathcal{P}$ . Then, the increment of  $\sigma$  is given by:

$$\begin{aligned} \sum_{l \in \mathcal{P}} \frac{BW^V(l^V)}{CAP^S(l)} \cdot (d_l + 1) &= BW^V(l^V) \sum_{l \in \mathcal{P}} \frac{d_l + 1}{CAP^S(l)} \\ &= BW^V(l^V) \sum_{l \in \mathcal{P}} d_l(l). \end{aligned}$$

Comparing (4) and the equation above, we observe the equivalence in this equation. In other words, the searching process in Section 5.3 tries different regions to search  $K$  embeddings by starting from the root nodes in different regions, and their quality comparison is based on the metric that is instilled in node and link embedding.

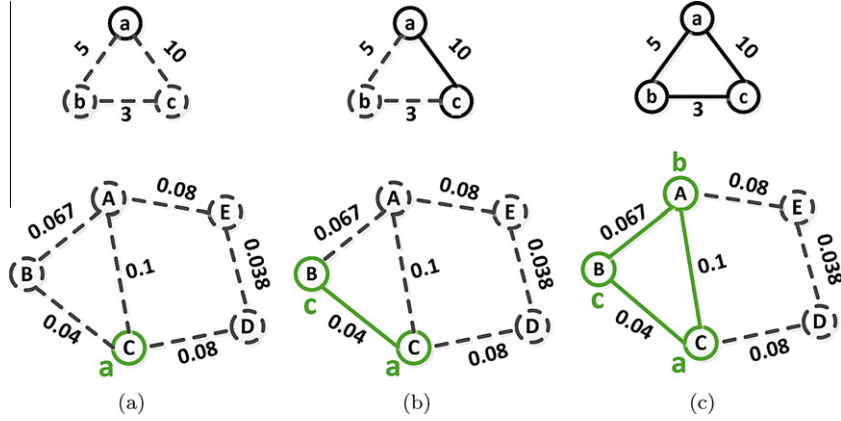


Fig. 4. Example of making a candidate embedding.

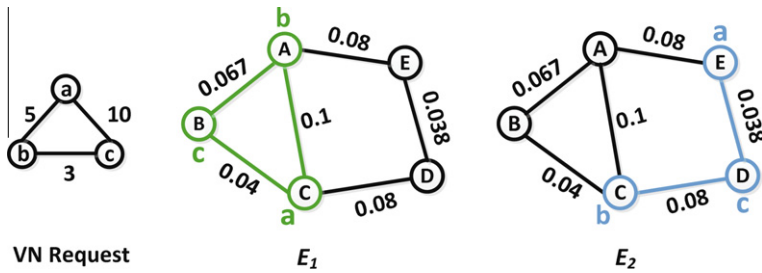


Fig. 5. Two candidate embeddings for a given VN request.

As an example, consider two candidate embeddings  $E_1$  and  $E_2$  in Fig. 5. Note that virtual link  $(a, b)$  is embedded to path  $(E, D, C)$  in  $E_2$ . Since  $\sigma(\cdot)$  can also be expressed by  $\sum_{l \in L^S} \text{Req}(l) \times d_l(l)$ ,  $\sigma(E_1) = 10 \cdot 0.04 + 5 \cdot 0.1 + 3 \cdot 0.067 = 1.101$  and  $\sigma(E_2) = (10 + 5) \cdot 0.038 + (3 + 5) \cdot 0.08 = 1.21$ . Thus,  $E_1$  is preferred by the metric.

### 5.5. Checking feasibility

We finally select the embedding with the highest quality metric, which passes feasibility check (Step 4). We now provide two candidate ways of checking feasibility.

#### 5.5.1. Exploiting sufficient conditions

As discussed in Section 4, checking feasibility is computationally intractable. One can apply a sufficient condition for a given potential normalized load (recall its definition in Section 4.3). A well-known sufficient condition is that for any link  $l$  (a vertex in the conflict graph), the sum of normalized loads of  $l$  and  $l$ 's connected vertices in the conflict graph is less than or equal to 1 (see e.g., [18] for the formal proof). Clearly, the fact that the sufficient condition is not met does not imply that the tested embedding is infeasible. However, using this sufficient condition is not a bad idea, because adding new requests should be conservative such that existing virtualization service should not

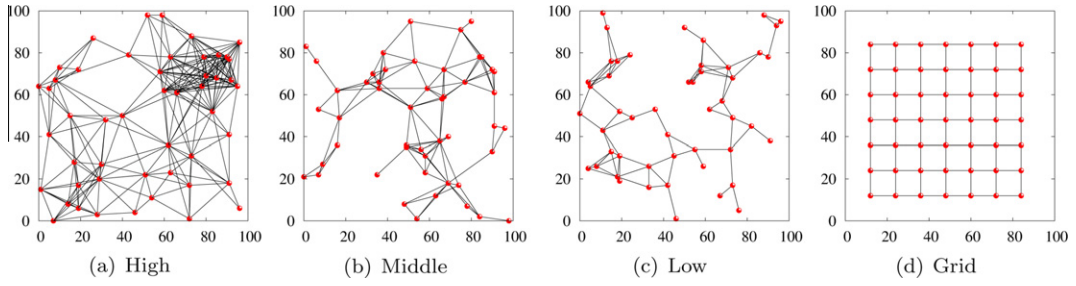
be interrupted and also the approach of sufficient condition is computationally attractive.

#### 5.5.2. Simulation via smart embedding

In spite of computational merit of the sufficient condition, its quality can be bad for some network topologies, i.e., missing feasible embeddings. Also, for a VN request, an embedding algorithm may not need to produce the result very fast. If we spend a reasonable amount of time, yet achieving more accurate feasibility check, the SN provider is expected to earn larger revenue.

We can examine embedding feasibility by actually simulating a MAC (or its variant) for the potential normalized load  $\lambda = (\lambda_l)$ . In other words, we generate stochastic arrivals over each SN link  $l$ , where the arrival mean is same as  $\lambda_l$ . However, just performing simulation does not solve computational intractability. When  $\epsilon = 1$ , simulating the so-called *Max-Weight* can provides us with the result of feasibility check. However, it is widely-known that *Max-Weight* requires to solve an NP-hard problem (MWIS: Maximum Weight Independent Set problem) at each time instance. Note that our underlying MAC is  $\epsilon$ -throughput-optimal. For a general  $\epsilon > 0$ , which requires an  $\epsilon$ -approximate algorithm of MWIS, the technical challenge is that MWIS does not allow PTAS (Polynomial Time Approximation Scheme) [19].





**Fig. 6.** Tested substrate network topologies: (a–c) are random instances with different densities. The grid topology includes 49 ( $7 \times 7$ ) SN nodes. In (a–c), the transmission ranges are uniformly random over  $[100, 200]$ ,  $[75, 150]$ , and  $[50, 100]$ , respectively. The resulting number of links ranges from 80 to 240.

To achieve efficiency in conjunction with a reasonable complexity, (e.g., polynomial), we perform *smart embedding*. The idea of smart embedding is to restrict the use of SN nodes and links so that the conflict graph of the embedded substrate network satisfies a special geometrical property—*polynomially bounded growth*.<sup>4</sup> Recall that the embedded substrate network is a subgraph of  $G^S$  consisting only of nodes and links serving some VN requests. With polynomial growth, we can find a polynomial time algorithm which arbitrarily approximates the original problem. For example, we allow a suboptimality gap  $\epsilon > 0$ , then the complexity, which is a function of  $\epsilon$ , is polynomial with network size. We refer the readers to, e.g., [19,20] for  $\epsilon$ -approximation algorithms of MWIS in PBG graphs.

### 5.5.3. Comparison

Two methods have different design rationales: (i) sufficient condition—using the entire space of SN and coarse feasibility checking or (ii) simulation via smart embedding—using a limited space of SN but finer feasibility checking at cost of increasing complexity. It is interesting how two methods perform, which will be presented in Section 6.

## 6. Performance evaluation

We develop a wireless embedding simulator (available in public [21]) to evaluate the proposed algorithm. Due to the scarce use-cases of running virtualization over wireless multi-hop networks, we vary many simulation parameters. We note that the crux of the simulation environment lies in the parameter configuration that enables us to test how our algorithm performs under reasonably heavy loads, because under low loads every algorithm will perform well by accepting most of the incoming VN requests. Thus, the absolute values of some parameters are not highly crucial, because we can make diverse, targeted situations by changing other parameters, e.g., how aggressively the virtual network requests arrive, and how sufficient the SN resources are.

<sup>4</sup> Let  $G = (V, E)$  be a graph and  $d(u, v)$  be the hop-distance between node  $u$  and  $v$ . Then  $r$ -neighborhood of a node  $v$  is denoted by  $\Phi(v, r) = \{v \in V | d(u, v) \leq r\}$ . We say that  $G(V, E)$  is a polynomially bounded growing (PBG) graph with a polynomial function  $p(r)$ , if  $|\Phi(v, r)| \leq p(r)$  for any  $v$  and  $r$ .

## 6.1. Simulation environment

### 6.1.1. Setup

We set up a grid square ( $500 \times 500 \text{ m}^2$ ), where an SN will be configured. This seems to be a reasonable size of a wireless mesh network. However, irrespective of the network size, by (randomly) changing the transmission radius of a node, we obtain the effect of testing other size of wireless mesh testbeds. We change the transmission radius of the nodes from 75 to 150 on average (see three resulting topologies in Fig. 6). We randomly place 50 substrate nodes on the grid square. Any two nodes are assumed to be connected if they are within the transmission range of each other. We also tested three resource weight values:  $\alpha = 1$ ,  $\alpha = 5$  and  $\alpha = 10$ . We set  $\alpha = 10$  as the default value because we expect that the link resources are more scarce in wireless multi-hop networks.

We generate highly various cases of the request loads, by varying (i) the amount of SN resources and (ii) arrival intensity. To that end, the arrival process of VN requests is modeled to follow a Poisson process with an average which ranges from 1 to 8 per time window. Each VN request stays at the SN during the holding time following an exponential distribution with a mean of 4 time windows. The duration of time window is not again crucial, which can be 1 h or 1 day (depending on SN providers' policy), but the important fact is that we create the scenarios of from low to high loads under our diverse parameter settings. The amount of CPU and bandwidth resources in SN and VN is randomly selected for each link/node, so that the number of VN requests can range highly diverse from 10 to 100 (when only per-node or per-link resource is considered). To that end, the CPU resources of nodes and link capacities are set to follow a uniform distribution between 100 and 300 units in SN, and between 1 and 10 units in VN. Note that other value configurations can achieve our goal of testing different loads. To test a VN network with diverse sizes, we randomly select the number of VN nodes between 4 and 10, where two VN nodes are connected with a probability uniformly distributed over  $[0.2, 0.6]$ .

With regard to the MAC, a two-hop interference model, known to suitably capture the MAC with RTS/CTS-like control messages as in 802.11 DCF, is adopted in our evaluations. We assume that  $\epsilon = 0.3$ , i.e., 30% of MAC's suboptimality and overheads, which is used in simulation-based feasibility check. We expect that 30% subopti-

mality is reasonable for practical MAC protocols, depending on the employed MAC. However, we verified through simulation (not presented due to space limitation) that the overall trends do not severely depend on interference models as well as the amount of MAC suboptimality. The number of candidate numbers are also varied from 2 to 12 (the default is 8).

### 6.1.2. Tested algorithms

To the best of our knowledge, there does not exist competitive embedding algorithms in wireless multi-hop networks. However, we devise some candidate algorithms to provide the readers fair comparisons. In all algorithms, we select eight candidate embeddings for each VN request (i.e.,  $K=8$ ). The reason for this value will shortly be provided in the simulation results. We use random topologies with *middle* density in Fig. 6, unless explicitly specified. We tested six algorithms to see the effect of the key features in our algorithm, as summarized in Table 2.

Recall that there are two main features of our algorithms: (F1) joint node/link embedding and (F2) a notion of influence weight that quantifies a link weight which is used to select an embedded SN path. Regarding (F1), we artificially make three classes (*none*, *medium*, and *full*) based on existing algorithms in wired networks, and two classes for (F2) (*hop* and *interference*). In (F1), *none* corresponds to the greedy algorithm in [10]: VN nodes with a higher demand are embedded to the SN nodes with higher remaining resource and VN links are embedded to the corresponding shortest paths. *medium* corresponds to a slightly modified algorithm in [9], where first, the cluster of SN nodes that will serve VN nodes are determined, and then, the SN node with the highest available resource becomes the cluster center and the other nodes are chosen sequentially based on their distances from the already selected substrate nodes. Similarly to *none*, VN nodes with a higher demand are embedded to the cluster nodes with higher available resource and VN links are embedded to the corresponding shortest paths. *full* corresponds to our proposed algorithm. Both *medium* and *full* share the feature that embedded SN nodes should be closely placed. The difference is that in *medium*, the inter-distance between VN nodes is not considered, whereas in *full*, two VN nodes with shorter distance are embedded to two SN nodes with shorter distance. In (F2), no algorithms in wired networks consider interference, e.g., [12]. Thus, to purely focus on how the influence weight affects the performance, we choose algorithms without the influence weight as *hop*, so the SN path is computed just by considering the number of hops.

**Table 2**

Tested algorithms: *inter/full* corresponds to our proposed algorithm.

| Link weight  | Link/node coupling |                  |                          |
|--------------|--------------------|------------------|--------------------------|
|              | None               | Medium           | Full                     |
| Hop          | <i>Hop/no</i>      | <i>Hop/mid</i>   | <i>Hop/full</i>          |
| Interference | <i>Inter/no</i>    | <i>Inter/mid</i> | <i>Inter/full (ours)</i> |

## 6.2. Main results

### 6.2.1. Impact of feasibility check methods

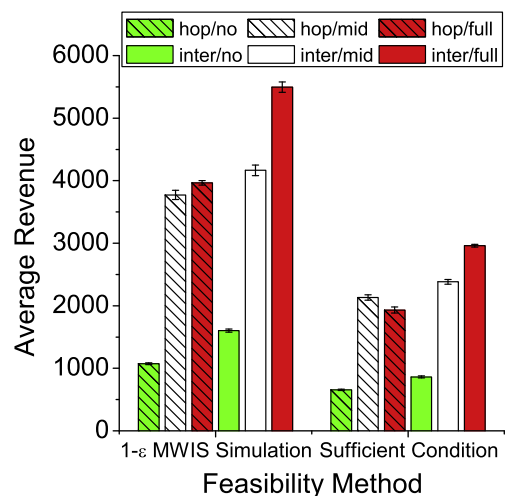
We first consider the results of comparing two feasibility checking methods, shown in Fig. 7. We observe that the simulation-based method significantly outperforms the sufficient condition based method (about two times). From this, we can see that rather than fully utilizing SN resources with an inaccurate feasibility check, it is more desirable to apply a strict checking method even with a slightly limited usage of SN resource. We apply the simulation based feasibility check to the rest of the simulations. Note that all tested algorithms are equipped with the same feasibility checking method for fair comparison.

### 6.2.2. Impact of SN density

We now start to compare the performance of tested algorithms. We look at the impact of different SN densities, shown in Fig. 8a. In all graphs, *inter/full* outperforms other algorithms. An interesting observation here is that as SN density increases, e.g., see the high density case, the importance of considering interference in the link weight becomes stronger. Thus, the performance gap between *inter/full* and *inter/mid* is small, whereas *hop/full*'s performance gap from *inter/full* increases, compared to other lower SN density cases.

### 6.2.3. Impact of VN topology

VNs may often have special topological structures such as tree, hub-and-spoke, and star. This topology depends on the type of virtualization service. For example, a game service with a single server is likely to form a star topology. We study this topological impact. Fig. 8b shows the avg. revenue comparison for tree, star, and random topologies. We observe that in star topology, four algorithms, *hop/mid*, *hop/full*, *inter/mid*, *inter/full*, do not lead to a large performance gap. We analyze this observation as follows: In star topology, all links are connected to a “center” VN node. Then, severe *local concentration* is experienced around a node: all VN links should be embedded to the paths concentrated around the SN node which embeds the center



**Fig. 7.** Avg. revenue for feasibility check methods.

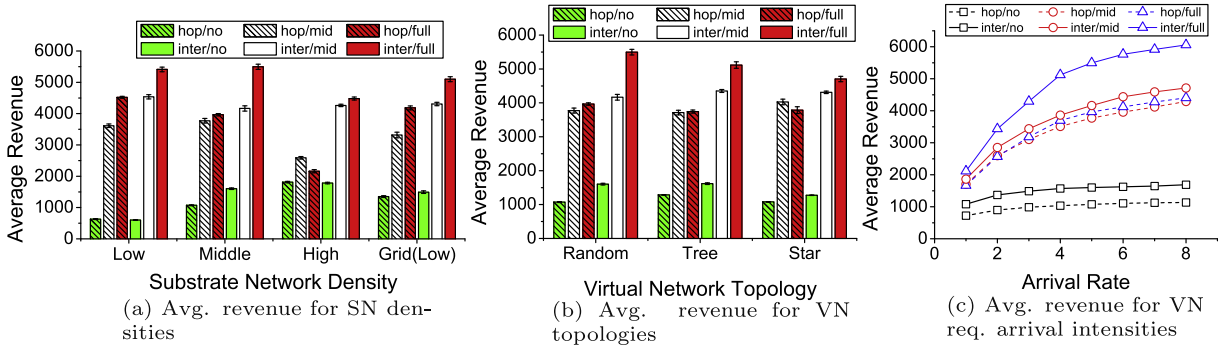


Fig. 8. Comparison of tested algorithms for different scenarios.

VN node. This load concentration prevents a big star topology from being embedded in all algorithms, and only small star topologies are accepted. This trend is supported by the results for the tree topologies, whose degree of concentration is between random and star topology, where the performance gap is in between those two topologies. However, we still observe that joint consideration of node and link is crucial in improving the performance.

#### 6.2.4. Impact of VN arrival intensity

We also vary the VN arrival intensities by testing various arrival rates, ranging from 1 to 8, as shown in Fig. 8c. First, in all algorithms, the revenue curves are concave with “diminishing returns.” This is because for low arrival rates, bigger VN topologies (and thus, bigger revenues) can dominate the total earned revenue. However, for high arrival rates, in addition to those big VNs, only small VNs take effect in increasing revenues. Second, All algorithms are grouped into three classes in terms of average revenue performance, where (i) joint link/node embedding is crucial, (ii) interference-aware link weights leads to additional revenue increase. This implies the importance of the two key features in *inter/full*. We can also notice that the revenue starts to be saturated at rate six from Fig. 8c. since the compared algorithms will not show different performance for uncontested scenario (i.e., low VN request rates), we set the VN arrival intensity to six for other simulations.

#### 6.2.5. Impact of search number $K$

The search number should strike a balance between the running time and efficiency. Fig. 9 shows the average revenue as well as running time as  $K$  increases. We vary the number of SN nodes using *middle* SN density. Fig. 9 shows that after  $K = 8$ , the revenue saturates, whereas the computation time increases linearly. The computation time also increases more sharply with the increasing number of SN nodes, because the number of SN links also increases due to the fixed SN density. The choice of this search number  $K$  may depend on the SN and VN sizes. The simulation results imply that a small search number out of the huge search space may be sufficient enough. Fig. 9 also implies that our algorithm is computationally tractable, because the algorithm generates the embedding results in the order of seconds, which is reasonable in practical applications.

#### 6.2.6. Impact of the amount of SN resources

Compared to the setting in the previous scenarios where each SN link has 100–300 units of capacity, we increase/decrease all SN link capacities by double/half (see Fig. 10). Since the VN arrival intensity is kept the same, changes in SN link capacities make us to consider “heavily congested” or “lightly congested” scenario. As shown in Fig. 10, the proposed algorithm produces a higher revenue than others regardless of the amount of SN link resources. To see which algorithmic components contributes to the revenue increase, we separately plot *coupling effect (CE)* and *interfer-*

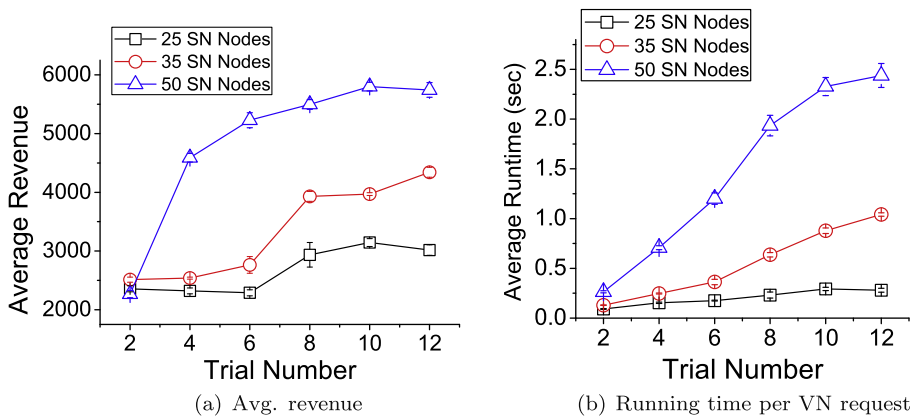


Fig. 9. Effect of the number of considering candidates.

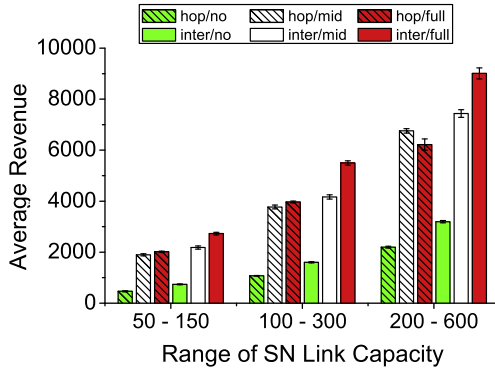


Fig. 10. Avg. revenue for different SN link capacities.

Table 3

CE: coupling effect, ICE: interference consideration effect, for different SN link capacities.

| Link cap | 50–150 (%) | 100–300 (%) | 200–600 (%) |
|----------|------------|-------------|-------------|
| CE       | 369        | 343         | 282         |
| ICE      | 136        | 139         | 143         |

ence consideration effect (ICE). The coupling effect is quantified by the revenue ratio of *inter/full* to *inter/no*, and the interference consideration effect is measured by the revenue ratio of *inter/full* to *hop/full*. As the SN has less link resources, CE increases from 369% to 282% (refer to Table 3). Note that the virtue of a well-coupled algorithm comes from that it enables VN links to be embedded onto shorter SN paths. Thus, the effect of combining node/link embedding process is magnified when available link resources are not enough. On the other hand, the variations of ICE are small. Since the relative amounts among link resources remain the same, the influence of link interferences on embedding is not changed significantly.

#### 6.2.7. Impact of resource weight

We produce the results for other values of resource weight, i.e.,  $\alpha = 1$  and  $\alpha = 5$  which assigns less weight to link resource, compared to the case of  $\alpha = 10$  (see Fig. 11). The superiority of *inter/full* are demonstrated regardless of  $\alpha$ . A remarkable point in this scenario is that the percentage of revenue increase induced by using *inter/full* are kept almost equal, as shown in Table 4. It implies that  $\alpha$  is directly related to the revenue (Fig. 11) but hardly affects the embedding process. Indeed, all modules that exploit  $\alpha$  value in embedding process (e.g., deciding the order of VN nodes, finding SN root node) are common in all tested algorithms.

#### 6.2.8. Summary

First, the effect of joint node/link embedding is large. The node embedding in a “non-coupling” algorithm does not consider the neighborhood interference of SN nodes, and thus, with a limited search number, it is highly likely to choose inefficient embedding candidates. Second, a more accurate feasibility check is necessary for efficient embedding. This accuracy comes with the cost of additional time, but it is still reasonable in practical cases. Third, considering wireless interference as the link weight

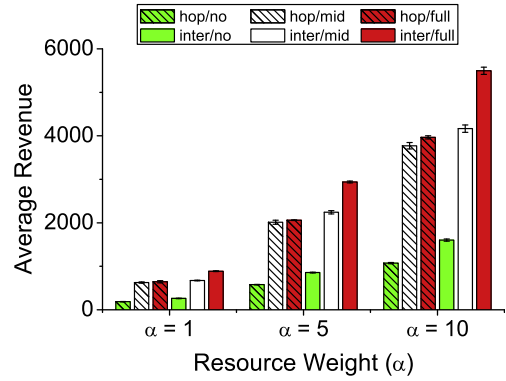


Fig. 11. Avg. revenue for different resource weights.

Table 4

CE: coupling effect, ICE: interference consideration effect, for different resource weights.

| $\alpha$ | 1 (%) | 5 (%) | 10 (%) |
|----------|-------|-------|--------|
| CE       | 340   | 343   | 343    |
| ICE      | 138   | 142   | 139    |

is also important, where in some cases, the performance gap amounts to about 35% for the algorithms that are unaware of interference. Fourth, VN topology may significantly impact the effect of embedding algorithms, especially in wireless multi-hop networks, due to resource concentration at nodes that leads to the generation of bottlenecks.

## 7. Conclusion and discussion

In this paper, we propose an embedding algorithm over wireless multi-hop networks. The key challenges in wireless embedding originate from inter-link interference, which renders feasibility check and candidate embedding search challenging. The main features of the proposed algorithm are joint node/link embedding and interference-aware link weight. We conclude this paper by presenting future work and discussions.

- Our proposed algorithm may leave some rooms for further improvement, but our findings on the key features are expected to provide useful implications to the embedding algorithm research in wireless multi-hop networks. One can extend our algorithm to more practical MACs, e.g., 802.11 DCF, where our key ideas can be utilized except for feasibility check. Although it is not the scope of this paper, feasibility check in 802.11 may be borrowed from many research papers on admission control in 802.11-based multi-hop networks, see e.g., [22], which is left as an interesting future work.
- In our paper, we develop our algorithm for the fixed link capacity, which is averaged over time, based on the possible time-scale difference between VN request dynamics and channel variation speed. However, it may be possible to develop a more efficient embedding algorithm if the time-varying nature is explicitly considered, especially when the request dynamics is fast. In this case, MAC can exploit the channel time-varying nature more explicitly,



so that MAC-level efficiency can be improved, resulting in the improvement of embedding efficiency.

- We describe the algorithm with focus on *wireless-agnostic* VN requests. For *wireless-aware* VN requests, the algorithm can be extended as follows: There, the feasibility condition of an embedding becomes more complex, since it is necessary to deal with all information about which VNs lease how much resources from every SN links to capture only the inter-interference influences, whereas we just need to know the amount of required aggregate bandwidth of each link for wireless-agnostic requests. However, the feasibility condition for wireless-agnostic case is more restrictive in the sense that a feasible embedding is also feasible in wireless-aware case. In regard to selecting candidate embeddings, as in our algorithm, the algorithm for wireless-aware requests is also desired to allocate the resources from SN components (having more available resources) to a VN. Thus, our algorithm is highly likely to show good performance as well.

## Acknowledgements

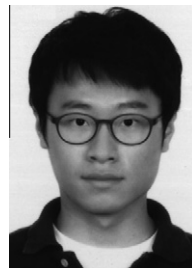
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**Donggyu Yun** received the B.S. and the M.S. in electrical engineering from the KAIST, Daejeon, South Korea, in 2009 and 2011. He is currently working toward the Ph.D degree in electrical engineering at KAIST. His research interests include virtual network, future internet, greening of network systems.



**Jungseul Ok** received the B.S. in electrical engineering from the KAIST, Daejeon, South Korea, in 2011. He is currently working toward the Ph.D degree in electrical engineering at KAIST. His research interests include virtual network, network economics, future wireless communication systems, and green communications.

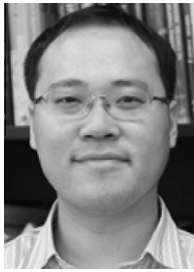


**Bongjhin Shin** received her B.S. degree in Electronic Engineering from Sogang University, Seoul, Korea, in 2003 and her M.S. and Ph.D. degrees in Electronic Engineering from the same University in 2005 and 2011, respectively. Her research interests include multihop networks, advanced network systems, and the 4th generation networks. She is a research engineer at LIG Nex1, Korea where she is focusing on development of communication devices.



**Soobum Park** received the B.S. in electrical engineering from KAIST, Daejeon, South Korea, in 2001 and the M.S. in the school of information and communication from Hanyang University, Seoul, South Korea, in 2006. Currently, he is a research engineer at the communication research center in LIG Nex1. His research interests include military communications, mobile ad hoc networks, cognitive radio, future wireless communication systems.





**Yung Yi** received his B.S. and the M.S. in the School of Computer Science and Engineering from Seoul National University, South Korea in 1997 and 1999, respectively, and his Ph.D. in the Department of Electrical and Computer Engineering at the University of Texas at Austin in 2006. From 2006 to 2008, he was a post-doctoral research associate in the Department of Electrical Engineering at Princeton University. He is now an associate professor at the Department of Electrical Engineering at KAIST, South Korea. He has

been serving as a TPC member at various conferences including ACM Mobihoc, Wicon, WiOpt, IEEE Infocom, ICC, Globecom, ITC, and WASA. His academic service also includes the local arrangement chair of WiOpt 2009

and CFI 2010, the networking area track chair of TENCON 2010, the publication chair of CFI 2011–2012, and the symposium chair of a green computing, networking, and communication area of ICNC 2012. He has served as a guest editor of the special issue on Green Networking and Communication Systems of IEEE Surveys and Tutorials, an associate editor of Elsevier Computer Communications Journal, and an associate editor of Journal of Communications and Networks. He has also served as the co-chair of the Green Multimedia Communication Interest Group of the IEEE Multimedia Communication Technical Committee. His current research interests include the design and analysis of computer networking and wireless systems, especially congestion control, scheduling, and interference management, with applications in wireless ad hoc networks, broadband access networks, economic aspects of communication networks, and greening of network systems.