Virtual Wireless Network Mapping: An Approach To Housing MVNOs On Wireless Meshes

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***Abstract*—Virtual network (VN) mapping is a useful tool for mapping VNs to physical mesh networks. This study extends the idea of mapping VNs from the wired world to the wireless domain by showing its potential applications. Since the generic VN mapping problem is NP-Hard, this study shows how the wireless VN mapping problem can be simplified and be used instead as a mechanism for provisioning wireless points of presences (POPs) as additions to conventional cellular voice and data services. Two heuristic algorithms GSA and GDR are proposed for producing a 2-phase solution to the mapping problem, which corresponds to conventional network deployment process. The results obtained from the VN mapping algorithms proposed here can be used for comparison of overall performance achieved by deploying a particular type of physical network. Further, using this setup, the network operator can determine the costs and benefits associated with setting wired or wireless links on the physical network. Performance is determined based on perceived revenue, and substrate utilization.**

I. INTRODUCTION

A virtual network (VN) topology can be defined as a topology description that when realized on a physical network of nodes, results in the VN behaving exactly like a physical network with the same specification. The VN topology description is usually dictated by application or the service providers requirement, while the physical network is designed to support a diverse set of VN topologies. This fundamental design paradigm of decoupling the physical network design from the VN design allows the mobile network operators (MNOs) to provide a more generalized access infrastructure, which finds wider application, resulting in better utilization of hardware and spectrum. As shown in the Figure 1, Mobile virtual network operators (MVNOs) can request supplementary WiFi / cellular coverage from these MNOs for providing additional capacity to their clients while not owning any (backhaul or access) network hardware themselves. One important aspect in such a setup is an algorithm for mapping the MVNO's request to the MNO's network. The mapping algorithm needs to provision capacity at the wireless point of presence (PoP) where the additional service is desired, and provisioning of capacity from the PoP through all nodes on the path to the network sink, which connects to the core network. The focus of this paper will be on addressing the mapping problem.

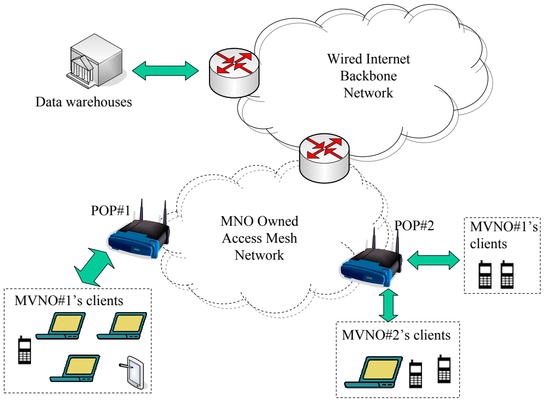

Fig. 1. Mobile virtual network operators (MVNOs)- This broad architecture diagram depicts how the backhaul, mesh network operator, and the MVNOs operate together. A mechanism for mapping would be needed to support MVNOs on the mesh operator's infrastructure.

The problem discussed in this paper is different from the mapping problem with conventional wired networks because: (1) Wireless VN mapping, which is the application we discuss in this paper, is concerned only about last-mile connectivity, rather than emphasis on obtaining a topology on the physical network[1], which is typical in wired VN mapping. (2) Since the physical network is a wireless mesh, accounting of resources at every node for the purposes of mapping are very different from that in the wired domain. Taking these requirements into consideration, we propose wireless virtual network mapping (WVNM) algorithms.

Specifically, the contributions of this study will be:

1) We discuss and motivate how a VN mapping algorithm would prove useful in the context of wireless mesh backhaul infrastructure that is connected to virtualized hardware.
2) Through this study, we show how a wireless network mapping problem may be simplified from an arbitrary sub-graph isomorphism problem to a resource allocation problem.
3) Our study takes into account a cost function based on the working of CSMA radios, a popularity metric based on demand at particular PoPs, and a mechanism for supporting bidding across multiple requests.
4) Results from the simulations are used to show working of the algorithms in both wired and wireless meshes, and the performance with the GSA and GDR algorithms.

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[1] It is important to note that eventually capacity allocation for the MVNO leads to the creation of a virtual topology for that MVNO across the backhaul network. However, specific topology do not serve any purpose for our application, and hence are not considered in requests.

The rest of the paper is organized as follows. Section II discusses related work in the area of VN mapping. Following this, Section III formally defines the problem and explains our approach to virtual wireless network mapping. Section IV presents results from the simulations under different scenarios. Finally, Section V discusses the conclusions and future directions of the study.

II. RELATED WORK

Several efficient VNMP heuristics have been proposed in the past years [7], [14], [10], [8], [13]. Some of these studies deal with data rate constraints for wired links [8], while some studies assume that the link mapping is known before hand [10]. In [7] the mapping is done by simulated annealing, but the problem is limited to topology constraints. Ref. [13] presents a two stage mapping algorithm, handling the node mapping in a first stage and doing the link mapping in a second stage, based on shortest path and multi-commodity flow detection. However, none of these approaches deal with mapping on wireless meshes, where resources of the underlying mesh are closely tied with allocations due to the presence of carrier sense, and interference. We discuss how a wireless mesh may be provisioned to provide capacity to virtualized hardware (BTS or APs) running at different PoPs. The backhaul mesh itself may be virtualized to allow the MVNOs to run customized protocols. However, we do not delve into those details here. In terms of wireless hardware support for virtualization, studies have shown how access points [3], [6] and basestations can be virtualized [5], [4]. These virtualized components can be used as the edge components on our shared mesh network.

III. WIRELESS MAPPING METHODOLOGY

A. Mapping Approach Overview

Wired VN mapping relies on enforcing network topologies to the underlying substrate. However, we note that in our context of wireless VNs, we do not care about the topology for reaching the network sink itself, but rather only about provisioning at the PoP where additional coverage is desired, and any path through the mesh which will connect the requested wireless PoP to the sink. Solutions for wired network embedding are usually implemented as a variant of the subgraph isomorphism problem [12] which is known to be NP-Hard. In this case, since we do not care about the mesh topology for reaching the core network, we propose decomposing the mapping process as a two-step approach:

- **Step 1:** The first step of the problem involves analyzing the capacity of the physical network described by the graph of the physical network G_p by determining the *cost* metric at each node.
- **Step 2:** And the second step would be to use the set of incoming requests for mapping radio resources at appropriate PoPs.

For performing the first step the mesh network operator can leverage from a comprehensive body of literature that deals with mesh planning and resource allocation and management [9]. Though we will propose an approach for performing this allocation, we will not focus much on this part of the mapping process. For solving the second step of the problem, we propose and evaluate two mapping algorithms: (1) GSA and (2) GDR, which will be discussed in detail in the following sections. We will begin with a description of the approach taken for pre-processing and resource allocation on the physical substrate.

B. Physical Substrate Pre-Processing

There are comprehensive approaches for resource allocation [9], which we do not discuss here, but rather focus on a simple approach for resource provisioning. Our mapping algorithms discussed later will work independently of this substrate resource allocation strategy. Capacity allocated at every PoP as a part of this substrate pre-processing phase is defined in terms of bandwidth. This bandwidth at the PoP will be used to provide wireless connectivity to clients at the PoP. This resource allocation strategy would require accounting of appropriate capacity on the nodes on-path to the network sink. Before we begin, we present some assumptions:

- Every transmitter in the physical substrate is able to send frames at different physical rates to different destinations depending on link conditions to the receiver. This is the default behavior of standard 802.11 radios, and is also supported by libraries [2] and standard rate control algorithms.
- For our model, we consider that each node is running a version of the CSMA-CA [11] protocol, which is fair across contending nodes.

Our substrate pre-processing phase aims to achieve equal resource allocation at all physical nodes in the network. In order to achieve this, we need information on routing path of packets from every node to the network sink. This allows us to calculate $\sum_{i=i}^{N} F_i^k$ which is the sum of fraction of air-times (F^k) used at every node i on the path to the sink from the node k. This value is further compensated by the air-time loss at neighbors of all intermediate nodes because of common carrier sense regions. Routes are deliberately selected such that no active path with hidden nodes are created. Hence, we are now able to determine the cost of reaching the network sink from every node in the physical network, and we can use this information to calculate the maximum possible transmission rate from every node. We can easily incorporate multiple sinks in the mesh network as long as the routing strategy for every node is known. However, this extension is not discussed further in the study.

C. Greedy Static Allocation (GSA)

Before we delve into the actual mapping algorithms, we will describe how the PoP mapping requests are made by MVNOs. The PoP mapping requests contain the following 3-tuples: (1) *Characteristic descriptor* of the PoP, (2) Capacity desired at the PoP, and (3) Bid for that desired characteristic and capacity at the PoP. We define the characteristic descriptor of a PoP as any metric that could be used to describe the PoP. Examples

Algorithm 1: The greedy static allocation (GSA) strategy for resource mapping at wireless PoPs on the mesh.

```
Input: $\{V_p, L_v\}$
Output: $\{M, Rev, Cap\}$
$Cap = Rev = 0$;
# $Sort\ \ phyiscal\ \ nodes$
$V_p = sortPhyNodes(V_p, cost, popularity)$;
for $i$ = $1 : num\_p\_nodes$ do
    $L_v = SelectUnMappedVnodes(L_v, V_p(i))$;
    $N = size(L_v)$;
    # $Generate\ \ knapsack\ \ parameters$
    $Values = revenueAchievable(L_v)$;
    $Weights = capacityRequiredAtPoP(L_v)$;
    $Capacity = phyCapacity(V_p[i])$;
    # $Invoke\ \ knapsack.$
    $amount = sack(weights, values, capacity)$;
    $items = find(amount)$;
    $mapped\_nodes = L_v(items)$;
    # $Calculate\ \ allocations.$
    if $items > 0$ then
        $V_p = UpdatePhy(mapped\_nodes)$;
        $Cap = Cap + CapAlloc(mapped\_nodes$
        $Rev = Rev + Value(mapped\_nodes)$;
        $PopulateMappings(M, items)$
```

of characteristic descriptors are: location type (movie h coffee shops, schools), or degree of density metric (der populated, medium density, sparse). In this case, we pro using a *popularity metric* as a characteristic descriptor[2]. capacity desired at every PoP is defined in terms of aggregate bit rate desired at that PoP. Finally, we define the bid as the aggregate amount in any units that an MVNO is willing to pay for that capacity at that PoP. The bidding amount can be based on using simple proportional pricing approaches, to the use of Nash games [1] based pricing strategies, depending on individual bidding strategies by MVNOs. This approach allows complete de-coupling of the pricing model from the mapping problem.

The GSA and GDR algorithms focus purely on maximizing the network operators revenue. This revenue is calculated as the sum of mapped requests across all MVNOs. The basic idea of the GSA algorithm is as described in algorithm 1. Using the pre-processed and pre-provisioned physical substrate, the physical nodes (V_p) are sorted in a descending sequence of their $\frac{popularity}{cost-per-bit}$, and provided as an input along with a list L_v of virtual PoP requests. The *cost-per-bit* at every node is the summation of airtime across all nodes along the path (including the neighbors in carrier sense range) required for sending one bit from that node to the sink. Now, the algorithm selects each of the sorted physical nodes and determines their characteristic descriptor. Using this descriptor (popularity/location/density etc) as the selection criterion, we select all PoP requests (from possibly different MVNOs) which are matching. Using these requests, we populate the standard weights, capacity and value parameters for initializing a knapsack. By solving a $0-1$ knapsack using dynamic programming for that physical substrate node, we are able to fit the best possible combination of incoming requests, that will yield maximum revenue for the network operator. Once mapping of the pre-provisioned capacity at the current physical node is completed, the algorithm moves to other physical nodes in the list.

Algorithm 2: Algorithm for greedy dynamic re-allocation of the physical substrate's resources and mapping of the PoP requests from the MVNOs.

```
Input: $\{node, sink, req\_cap\}$
Output: $\{R_p\}$
# $Det.\ \ sink\ \ path$
$P_p = getSinkPathNodes(node, sink)$;
$R_p = getRate(node, P_p, req\_cap)$; # $CS\ \ losses.$
$R_p = accountCS(node, P_p, R_p)$;
# $Prev.\ \ allocations.$
$R_p = cmpAlloc(node, P_p, alloc, R_p)$;
if $req\_cap < max\_cap(node)$ then
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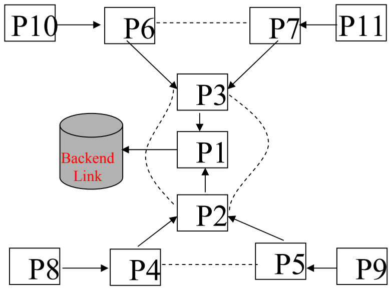

Fig. 2. Star-type topology used for the evaluation of performance of the virtual network mapping algorithms.

D. Greedy Dynamic Re-Allocation (GDR)

The generic structure of the GDR algorithm is the same as that of the GSA algorithm. However, this approach goes one level deeper in the mapping process by dynamically re-provisioning resources allocated in *Step* 1 on the physical nodes for achieving revenue maximization. The pseudo-code for the GDR approach is the same as that for the GSA approach, the only difference being a condition that checks if

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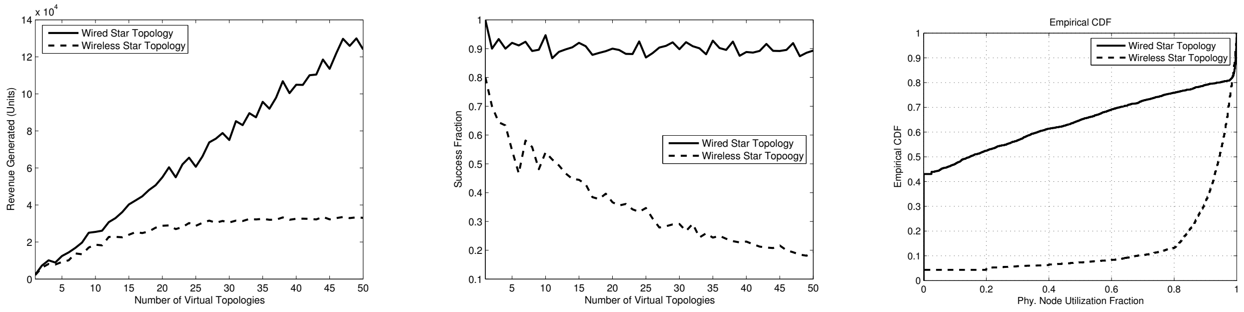
[2] It is to be noted that though we use popularity as a metric in our study, our mapping algorithms can work with any other characteristic descriptors.



(a) Revenue Generated (b) Success Fraction (c) Substrate Node Utilization

Fig. 3. Comparison of mapping on wired and wireless networks for the same physical layer rates on the star topology.

the aggregate requested capacity at the PoP is greater than that is currently provisioned. If this is the case, the GDR algorithm does a re-provisioning request to the re-allocation module described in Algorithm 2. As described, the re-allocation module computes the maximum possible rate that can be achieved at that physical node to the sink. This value is then decremented based on the carrier sense losses and previous allocations made on that path to the sink from previous mappings. Using this information, it selects and allocates from the lesser value among 1) the maximum capacity at that node, and 2) the aggregate requested capacity. This re-provisioning of resources is similar to that done in *Step* 1, and is done by setting up appropriate routing, and radio resource provisioning on all nodes in the path to the sink.

IV. EVALUATION AND ANALYSIS

A. *Impact on Substrate Selection*

In this section, we will discuss how the current modeling setup, can be used for determining how the selection of a particular networking technology on the substrate can impact overall revenue generation from VN mapping. Such an analysis allows the network provider to perform a cost-benefit study before making a decision to deploy the mesh as a wired/wireless network. Specifically, if the benefits are significantly higher, the network operator may decide to deploy the substrate as a wired, wireless or a hybrid network.

To keep the comparison fair, we consider the same requests and topologies for both the wired, and the wireless cases. Specifically, to highlight the impact of a large number of carrier sense regions on the virtual network mapping, we consider a star-type topology shown in the Figure 2. Popularity for each of the physical nodes are defined randomly. All other characteristics such as the physical layer rate and timing constraints of the network are kept the same in both cases. The number of requested topologies are varied from 1 to 50. The goal is to see the impact of wireless links, in the presence of varying amount of PoP mapping requirements.

The amount of revenue generated is defined as the sum of the allocated bids from the mapping requests. The results are as shown in the Figure 3(a). We observe that there is a large amount of difference in the revenues generated by the wired and the wireless networks. This difference in revenue is mainly due to the difference in capacities of the networks, caused due to high carrier sense cost in the wireless network, which is absent in the wired network.

The fraction of the virtual topology mapping request which are successfully mapped to the physical substrate are as shown in the Figure 3(b). As expected, the results show a non-increasing trend as all the capacity is allocated. We also observe that though the fraction of request being mapped fall significantly for the wireless network, the mapping fraction remains almost constant for the wired network, indicating that the capacity is not reached yet for the same. This result corroborates with the findings from Figure 3(a), where the revenue from the wired network is always increasing, and does not reach a plateau indicating that the capacity of the underlying network is not reached.

Finally, the cumulative distribution function for the physical node utilization is as shown in Figure 3(c). We see that the CDF of the physical node's capacity allocation increases linearly because there is no dramatic increase in mapping costs due to CSMA in the wired case, as opposed to that seen in the wireless case. This metric would prove useful in deciding the physical network based on load distributions.

B. *GSA versus GDR performance*

We will now compare the performances of the GSA and the GDR algorithms. Comparison is done by evaluating mapping performance on the same wireless substrate and the same set of virtual topology requests on the star topology physical mesh.

Figure 4(a) shows the amount of revenue generated with both the algorithms as a function of the number of requested virtual topologies. We observe that both algorithms are able to generate higher revenue for more requests. Results show that the GDR algorithm is able to generate more revenue as compared to the GSA algorithm by performing re-allocation. We observe that for a maximum of 50 requested topologies, the revenue generated by the GDR algorithm is higher by approximately 84% for the same physical setup[2].

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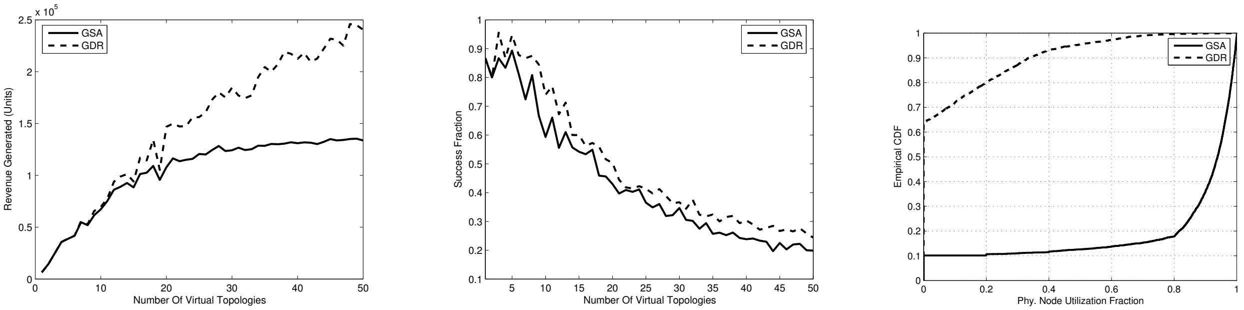
[2] Note that the absolute revenue metrics are immaterial and can always be translated into tangible currency units based on costs of setting up the network.



(a) Revenue Generated (b) Success Fraction (c) Substrate Node Utilization

Fig. 4. Performance comparison of the GSA and the GDR algorithms with the Star physical topology.

Figure 4(b) shows the fraction of mapping requests that were successful for increasing number of virtual topology requests. We observe that the success fraction measurements are similar for both the GSA and the GDR algorithms. This is because the capacity of the physical network is same due to the same network setups for both algorithms. However, the revenue for the GDR algorithm shown in Figure 4(a) is higher because it is able to better allocate resources at the most profitable physical nodes.

The cumulative distribution function for the physical node utilization is as shown in Figure 4(c). As seen in the previous results, the mapping performance of the GSA algorithm is as observed previously, and we have a small fraction ($< 20\%$) of physical nodes with allocation less than almost 80%. Performance of the GDR algorithm is significantly different. We observe that the algorithm does greedy re-allocation of resources at the most profitable physical nodes, because of which we have a huge percentage of the physical nodes that will have very less utilization, and a selected few which will high allocation based on demands. It is to be noted that these results are obtained with a uniform distribution for generating requests. If these requests are skewed towards a particular probability value, the benefits achieved from the GDR algorithm will be much more significant.

V. CONCLUSIONS AND FUTURE DIRECTIONS

This study describes a novel application of virtual network mapping in the wireless context. We present the GSA and GDR algorithms for provisioning wireless points of presence which provide supplementary coverage to mobile network operators. Preliminary evaluation of the algorithms show that the proposed mapping models could be used for determining optimum physical network type based on the number and type of requests. Results with the greedy re-allocation strategy proposed in the GDR algorithm show that baseline revenue performance of the GSA algorithm can be improved by up to 84%. Future work involves testing these strategies across a wider range of physical network topologies, and performance with multiple network sinks.

Acknowledgments

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