Virtual Network Function Embedding in Multi-hop Wireless Networks

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Abstract: The use of Network Function Virtualization (NFV) and Software Defined Network (SDN) provides opportunities to offer services with lower CAPEX/OPEX for service providers and deploy new services quickly. However, it will introduce new challenges. One of the main challenges is an optimized placement of the virtualized functions based on the characteristics and available resources of the network. Placement of Network Functions (NFs) can affect the path traffic flows take and consequently bandwidth usage in the network. While most of the research is focused on the challenges of NFV in wired networks, it can also be applied to wireless networks. However, the specific differences between the wired and wireless networks should be considered. In this paper, we are expanding one of the comprehensive placement methods in the wired networks which use Integer Linear Programming (ILP) to place a chain of NFs. The extended model formulates the main characteristic of the wireless networks which is a scarcity of bandwidth due to interference. As our results show, the interference in the wireless networks increases the bandwidth usage and consequently the average NF deployment cost. To address this, we can either increase the number of nodes or the nodal resources to achieve higher placement success rates.

1 INTRODUCTION

A Service Chain (SC) is a chain of high-level services, where each service is composed of Network Functions (NFs). A chain of NFs with predefined parameters is referred to as a Service Graph (SG). The placement of all NFs of an SG can be referred to as a Network Function Embedding Problem (NFEP). NFEP can be explained as a way to map the Virtual Network Functions (VNF) and the links between them to the physical network. There are several types of algorithms proposed to solve the NFEP. Previous studies are mostly focused on the placement of NFs in wired networks while the use of NFV can bring comparable advantages to wireless networks. NFV introduced new possibilities to wireless networks such as network virtualization. Where subscribers can customize their exclusive access networks while using the shared infrastructure. The amount of literature on wireless network virtualization shows the importance of NFV in the wireless networks. However, there are only a few papers considering the problem of NFEP in wireless networks. To our knowledge, none of the proposed methods for NFEP in wireless networks include the effect of interference in their optimization model. It is assumed that the interference is being handled by using orthogonal channels in the network. However, this is only possible where we have multi-channel multi-radio networks. Even in those networks, there is interference.

We included the effect of interference in our optimization model. In (Sahhaf et al., 2015), the NFEP has been formulated as an optimization problem which can be solved with Integer Linear Programming (ILP). In this method, the objective is to minimize the mapping cost based on the requirements of the NFs and available resources in the network. The cost of mapping is based on the consumed resources by the NFs in the physical network which includes: (i) The total units of CPU, memory, and storage used by NFs in physical nodes. (ii) The total units of bandwidth used by virtual links in the physical network.

The modeling results have been observed and compared to the wired ones in order to analyze the effect of interference on the ratio of accepted requests. Based on the results and different scenarios modeled with MATLAB, a couple of solutions have been provided to increase the acceptance ratio in wireless multi-hop networks. The remainder of this pa-

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per is organized as follows: Section II discusses related work on NFEP and the characteristics of the optimization models introduced in the related papers. Section III introduces the optimization model, its constraints, variables, and objective function. Section IV describes the modeling environment and results. We conclude the work in Section V.

2 RELATED WORK

Solving NFEP is known to be NP-hard (Sahhaf et al., 2015). Designing a heuristic algorithm can be a solution for this matter. As our aim is to study the effect of a multi-hop wireless network on the placement of NFs, we only consider exact solutions in this paper. The exact solution in most of the proposed approaches formulates NFEP using Linear Programming and can be differentiated based on the constraints and the objective function.

The amount of work on NFEP is considerable. Most of the works in this domain are related to wired networks. In (Bouet et al., 2015), the authors used Integer Linear Programming (ILP) in order to find an optimum solution for placing Deep Packet Inspection (DPI) as a VNF in the network. In the proposed method, the objective function is to minimize the activation and maintenance cost of the virtual DPI (vDPI) and the considered constraint is the network's available bandwidth. In (Mohammadkhan et al., 2015) the authors used Mixed Integer Linear Programming (MILP) to find an optimum solution. The proposed optimization is based on maximizing the number of services that can be supported in a switch. In this solution, the constraints are based on the number of free cores, tolerable delay of flows and links' bandwidth. The objectives of (Mohammadkhan et al., 2015) are minimizing maximum link utilization and maximum core utilization, which leads to the distribution of load between available resources. Leivadeasa et al. proposed a Mixed Integer Programing (MIP) formulation with the nodes' capacity and the bandwidth of the links as the constraints in (Leivadeas et al., 2017). It considers minimizing activation, maintenance cost, and load balancing among the resources as the objective function (Leivadeas et al., 2017). (Botero et al., 2012) is another proposed method based on an ILP which aims at minimizing the resource consumption and energy saving by turning off unused resources. Finally, as mentioned earlier, (Sahhaf et al., 2015) is considering the available resources of the nodes, the available bandwidth of the links and the requested QoS as constraints and minimizes the resources usage.

The topic of NFV in wireless networks has received a significant attention in the literature, where most of the focus is on wireless network virtualization. (Riggio et al., 2015) talks about virtual WiFi where kernelbased virtual machines are used as a virtual wireless LAN device. The authors of (Riggio et al., 2015) provide an integer linear programming for placing the VNFs in a hybrid wireless network were there are forwarding nodes, some with processing capacity, and some are access points. In this paper, the optimization method is designed without considering the effect of interference. Its authors assumed that Orthogonal Frequency Division Multiple Access (OFDMA) is being used in order to handle the problem of interference. (Lv et al., 2012) considers the embedding of virtual wireless mesh gateways and the virtual links between them. The problem of interference between the wireless links has been solved by considering multi-radio multi-channel networks. Its authors assign orthogonal channels to the neighboring links. The same method has been used in (Park and Kim, 2009) where the interference is being handled separately from the optimization model. To our knowledge, none of the papers considering NFEP in the wireless networks include the effect of interference in their optimization model. We model the interference and provide the related formulation in order to consider interference as one of the constraints.

3 OPTIMIZATION METHOD

As the service requests arrive over time, the embedding algorithm decides where to place the NFs in the physical network subject to various constraints. Each request has an associated duration. If the request is accepted, the required resources will be assigned and when the request expires the used resources will be released.

We are using Integer Linear Programming (ILP) as the optimization method. ILP consists of two parts, an Objective function which calculates the cost of each mapping and chooses the one with the lowest cost, and the constraints, which apply the limitations we have with regard to the resources in the physical network. ILP will choose the mapping that satisfies all of the constraints and minimizes the objective function. In this section, we define the variables, constraints and the objective function similar to the optimization method in (Sahhaf et al., 2015) and then introduce the extension of the model and the added constraint for multi-hop wireless networks.

3.1 Input Parameters

- Sets
  - N_p, set of physical nodes where u is representing node $u \in N_p$.
  - L_p, set of physical links where $E_{uv} \in L_p$ is representing the physical link connecting node u to v.
  - F, set of flows where f is representing flow $f \in F$. Each flow f consists of a set of requested NFs with required resources, SG_f.
  - N_f, set of NFs where $i \in N_f$ represents NF_i in flow f.
  - L_f, set of virtual links between NFs of flow f, where $e_{f,ij} \in L_f$ represents the virtual link which connects NF i to j.
- Constants
  - C_u, available processing units in physical node u.
  - $c_{f,i}$, requested processing units for NF i of flow f.
  - M_u, available memory units in physical node u.
  - $m_{f,i}$, requested memory units for NF i of flow f.
  - S_u, available storage units in physical node u.
  - $s_{f,i}$, requested storage units for NF i of flow f.
  - $BW_{E_{uv}}$, available BW over the physical link between node u and v.
  - $bw_{f,e_{ij}}$, requested BW for the link that is connecting NF, i to j in flow f.
- Decision Variables
  - $x_{f,i,u}$, a binary variable where one means that function i from flow f is placed in physical node u.
  - $F_{f,e_{ij},E_{uv}}$, a binary variable which is equal to one when the virtual link between NFs i and j is mapped to one or more physical links and physical link E_{uv} is one of them. In the case of mapping a virtual link to multiple physical links all the related variables must be set to one.

3.2 Objective Function

As mentioned before, the objective is to minimize the placement cost. The cost consists of resources that are used in the physical network which include nodes' resources (processing, memory, and storage) and links' BW. Term 1 shows the objective function where the first part considers the nodes' resources and the second part the BW usage. Term 2 is a more detailed version of Term 1, expressing the same objective function in terms of the notation introduced earlier.

$$\sum_{u\in N_p}\sum_{i\in N_f} cost(i,u) + \sum_{E_{uv}\in L_p} cost(f,E_{uv}) \tag{1}$$

$$\sum_{u\in N_p}\sum_{i\in N_f}(c_{f,i}+s_{f,i}+m_{f,i})*x_{f,i,u}+$$
$$\sum_{E_{uv}\in L_p}\sum_{e_{ij}\in L_f}(bw_{f,e_{ij}}*F_{f,e_{ij},E_{uv}}) \tag{2}$$

3.3 Constraints

Constraints are sets of equalities and inequalities which are defined based on the conditions the optimization model must satisfy. Over-assignment of the physical resources will be prevented by the constraints. The first three constraints ensure that the summation of processing, memory and storage units of the placed NFs do not exceed each node's resources.

$$\sum_{i\in N_f} c_{f,i}x_{f,i,u} \le C_u, \forall u \in N_p \tag{3}$$

$$\sum_{i\in N_f} m_{f,i}x_{f,i,u} \le M_u, \forall u \in N_p \tag{4}$$

$$\sum_{i\in N_f} s_{f,i}x_{f,i,u} \le S_u, \forall u \in N_p \tag{5}$$

Inequality 6 prevents over-assignment of bandwidth in each physical link.

$$\sum_{E_{uv}\in L_p}\sum_{e_{f,ij}\in L_f} bw_f F_{f,e_{ij},E_{uv}} \le BW_{E_{uv}}, \forall E_{uv} \in L_p \tag{6}$$

Each virtual link between the NFs can be mapped to one or more than one of the physical links. In case a set of physical links connected to each other are chosen to connect two NFs, Eq. 7 makes sure all the related physical links are chosen.

$$\sum_{E_{uv}\in L_p, u=src} F_{f,e_{ij},E_{uv}} -$$
$$\sum_{E_{uv}\in L_p, u=dst} F_{f,e_{ij},E_{uv}} = x_{f,i,u} - x_{f,j,u} \tag{7}$$
$$\forall e_{ij} \in L_f, \forall u \in N_p$$

Last but not least each NF should be placed in the physical network once.

$$\sum_{u\in N_p} x_{f,i,u} = 1, \forall i \in N_f \tag{8}$$

3.4 Extended Model for Wireless Networks

The basic model is designed for wired networks. In order to extend the model to be applicable to wireless networks, a couple of changes must be made in the constraints and objective function. The BW usage of wireless links is different from wired ones. In a wired network, it is sufficient to require that the summation of required bandwidth for the mapped virtual links should not exceed the physical link's bandwidth. In multi-hop wireless networks, where nodes share access to the common shared channel, using each link will affect the adjacent links' available bandwidth. In order to consider this effect, we have to model the interference between wireless links. We use the interference model in (Kunz et al., 2012) and redefine the constraint for wireless links.

The interference in wireless networks can be modeled based on either the protocol or the physical model. Each of these models defines conditions for a successful transmission in the wireless network (Jain et al., 2005). In our optimization model, we used the protocol model. We assume in the case of a single wireless channel, d_{uv} expresses the distance between nodes u and v, and all nodes have the same identical transmission range R. With these assumptions, the transmission from u to v is successful if the following two conditions are satisfied:

- $d_{uv} \leq R$
- Any node k, such that $d_{ku}, d_{kv} \leq R$, is not transmitting.

These two conditions imply that transmission in the link between nodes u and v will affect the BW usage of all the links whose transmitter is within transmission range of the sender or the receiver. To formulate this as one of the constraints in the optimization, an interference set has been defined for each link. It consists of all the links that are connected to the nodes in the transmission range of the sender or receiver.

$$\forall E_{uv} \in L_p :$$

$$intset_{E_{uv}} = \{E_{u'v'} | d_{u'u} \vee d_{v'v} \vee d_{v'u} \vee d_{u'v} \leq R\}$$

Then for the bandwidth constraint, instead of inequality 6, we have The following E.q 9. Where for each of the wireless links E_{uv} the cumulative BW used by mapped virtual links to the physical link E_{uv} and to the physical links in the interference set of E_{uv} shouldn't exceed its available BW.

$$\sum_{e_{ij} \in L_f} bw_{f,e_{ij}} F_{f,e_{ij},E_{uv}} + \sum_{e_{ij} \in L_f} \sum_{E_{u'v'} \in intset_{E_{uv}}} bw_{f,e_{ij}} F_{f,e_{ij},E_{u'v'}} \leq BW_{E_{uv}} \tag{9}$$

Also the second term in the objective function changes to the following term in order to consider the cost of BW usage due to interference.

$$\sum_{u \in N_p} \sum_{i \in N_f} (c_{f,i} + s_{f,i} + m_{f,i}) * x_{f,i,u} + \sum_{E_{uv} \in L_p} \sum_{e_{ij} \in L_f} (bw_{f,e_{ij}} + \sum_{E_{u'v'} \in intset_{E_{uv}}} bw_{f,e_{ij}}) * F_{f,e_{ij},E_{uv}} \tag{10}$$

4 MODELING RESULTS

Our main goal is to apply the existing and extended optimization method for placing NFs in multi-hop wireless networks and study the impact of the wireless network characteristics on the results. We also implemented the basic method as a way to capture the NF placement under the assumptions of a wired network. The placement rate and placement costs then serve as a benchmark to compare our results against. We first applied our extended model to a wired network topology and observed the differences in the results. Next, we generated a number of multi-hop wireless topologies and placed SGs based on both our extended model and the basic model. In order to see the impact of our approach in bigger networks we increased the number of nodes and observed the results as a function of network size.

In this section, we describe the modeling environment and its characteristics, then introduce the measurement metrics. In the end, we discuss the results of the modeling.

4.1 Modeling Environment

We used MATLAB to solve the ILP. The wired network topology was chosen to be the same as the small network in (Sahhaf et al., 2015) which was chosen from the Internet Topology zoo (Knight, 2010). We used the 'BT Europe' topology which has 25 nodes and 37 edges. In order to generate wireless topologies, we used the same method as (Kunz et al., 2012) where the nodes are randomly deployed in a square area, based on a uniform distribution. The square area grows with the number of nodes such that the average node density is constant and ranges from $346 * 346m^2$ for the 10 nodes network to $600 * 600m^2$ for the 30 nodes network (Kunz et al., 2012). The links in the wireless network are based on the transmission range and all of the generated topologies are connected.

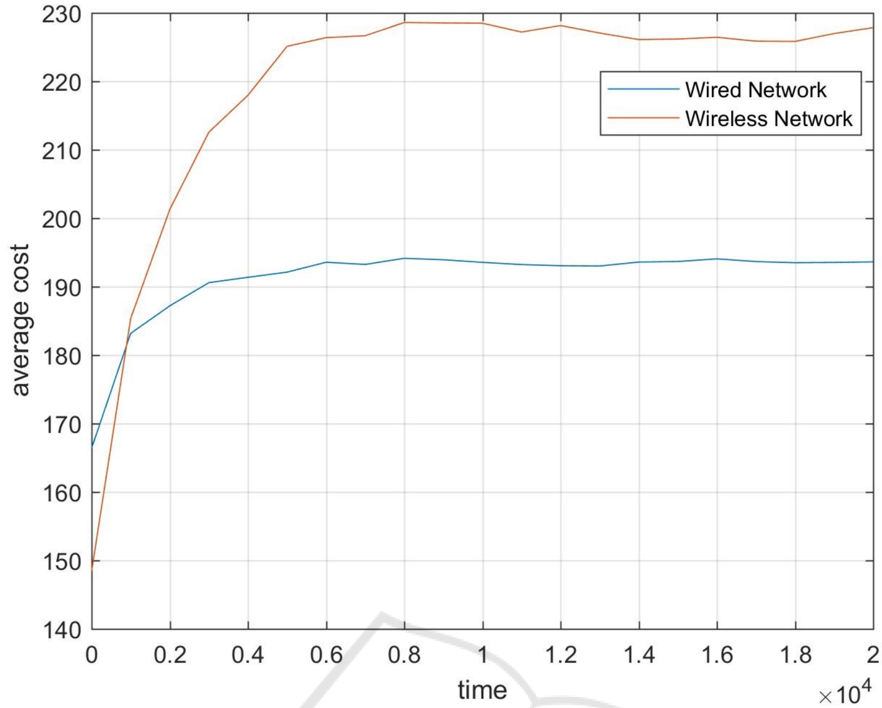

Figure 1: Average Cost in a Wired (With Basic Model) and Wireless Network (With Extended Model), 'BT Europe' Topology.

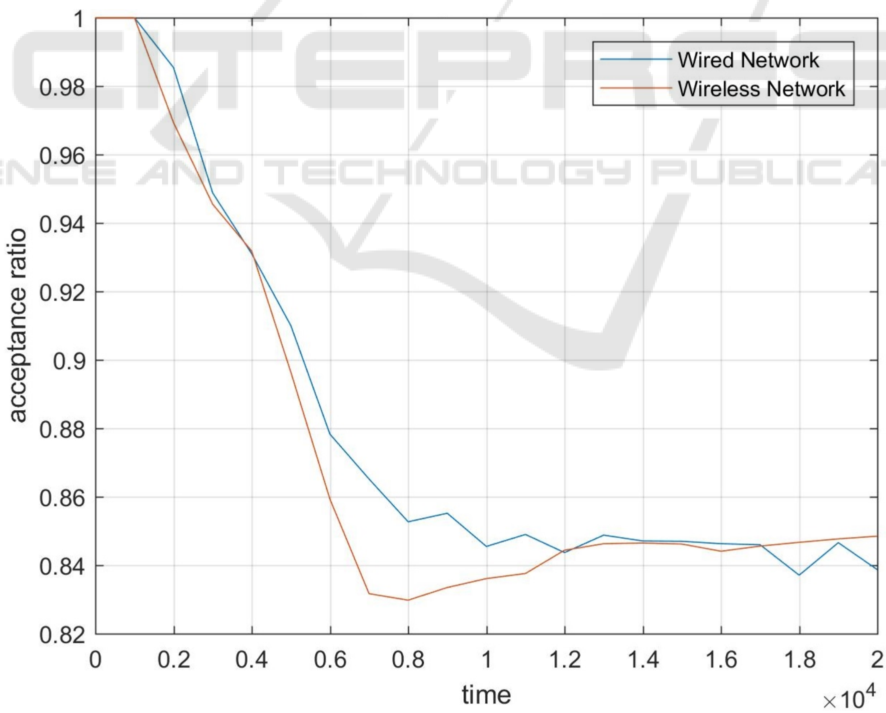

Figure 2: Acceptance Ratio in a Wired (With Basic Model) and Wireless Network (With Extended Model), 'BT Europe' Topology.

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The parameter values were inspired by (Sahhaf et al., 2015). Processing, memory and storage capacity of the nodes and bandwidth of the links are numbers uniformly distributed between 100 and 150 in both network scenarios. The flows arrive over time following a Poisson process with an average rate of four flows per 100 time units. Each flow has a lifetime, exponentially distributed with an average of $\mu = 1000$ time units and is accompanied by a Service Graph, defining the required NFs and their interconnection to handle this flow. The number of NFs for each of the requests is a number uniformly distributed between 2 and 10. The computation, memory and storage unit demands of each NF follows a uniform distribution between 1 and 20. The bandwidth requirement of each link is between 1 and 50 units, uniformly distributed.

4.2 Measurement Metrics

We used different metrics in order to compare the results and observe the impact of the wireless network's characteristics in the NFEP.

- Average cost: average of the units of computation, memory, and storage used for the deployed service requests that are not expired.
- Acceptance ratio: The total number of accepted requests divided by the total number of requests.
- Number of physical links used to deploy SGs: It shows us over how many nodes the NFs have been deployed in the wired and wireless network.

4.3 Results

In this section, we discuss the results of the modeling for wired and wireless networks. For the basic model, we used the 'BT Europe' topology from the Internet Topology Zoo (Knight, 2010). This topology has been chosen to be able to compare the results to (Sahhaf et al., 2015). The rest of the results are based on random wireless topologies that have been generated as discussed above. In these topologies, we kept the density of the nodes constant as the number of the nodes increases. The program ran for 20000 seconds in order to reach a steady state where the curves flatten off after initial settling due to the initially unloaded network. Fig. 1 shows the average cost of deploying requests over time in the wired and wireless network. As was expected, the interference model has caused higher bandwidth usage and higher average cost for placing the NFs. Higher BW usage in the wireless network lowers the number of requests that can be placed in the network and reduces the acceptance ratio. The low reduction of the acceptance ratio in Fig. 2 is due to the fact that, for the chosen arrival rate of the requests and requested resources, most of the SCs can be placed in one or two nodes. Which limits the impact of interference in the acceptance ratio. The next set of figures shows the result by running the basic and extended optimization model for the randomly generated topologies. Fig. 3 shows the average cost for different-sized wired and wireless networks. Fig. 3 demonstrate clearly that increasing the number of the nodes can decrease the average cost. This is mainly due to the fact that the optimization method tends to minimize the resource usage for each SG; therefore, it chooses a placement that has fewer physical links involved. This is confirmed by the next figure. Increasing the number of nodes will increase the possibility to use fewer physical links and consequently lower the average cost. This is why the decrease in the wireless networks is higher than the wired one. We measured the number of assigned links for each accepted SG and also the number of the virtual links that were requested for each SG in the network. Fig. 4 shows the results of a 20 node wireless network with random topology. We can see that the majority of SG requests is placed completely in one node, very few placements involve multiple nodes. This is true even though the number of virtual links of the SGs ranges from 1 to 9. Fig. 4 and 5 show that there can be a trade-off between a number of the nodes and BW usage in the network. Increasing the number of nodes increases (overall) resources such as memory, CPU, and storage. While this increases the overall costs for deploying the network, it reduces the average cost of deploying SGs.

Fig. 5 shows the results from a scenario where we increased the node's computation, memory and storage by 50 units. In this scenario, we kept the number of the nodes constant (20 nodes) and increased the available resources in each node. It can be seen that, as the nodes' resources are increased, the average deployment cost dropped in both the wireless and wired network. However, the decrease is higher in the wireless network case. This again shows a trade-off between lowering the cost of the deployment of NFs by using less bandwidth and increasing the cost of the network by increasing the available resources of the nodes. We compared the cost reduction in Fig. 6. This figure shows the cost reduction (in number of units) when we increase the nodes' resources. As we can see, the number of units saved is much higher in the wireless network. The cost added by increasing the available resources in each node is 150 processing, memory and storage units. This is a one-time cost and for the network of 20 nodes, it will be 3000 units. We can see that this increase leads to a large cost reduction over time. It can also be seen that by increasing the available resources the average cost for the wired and wireless networks becomes close to each other.

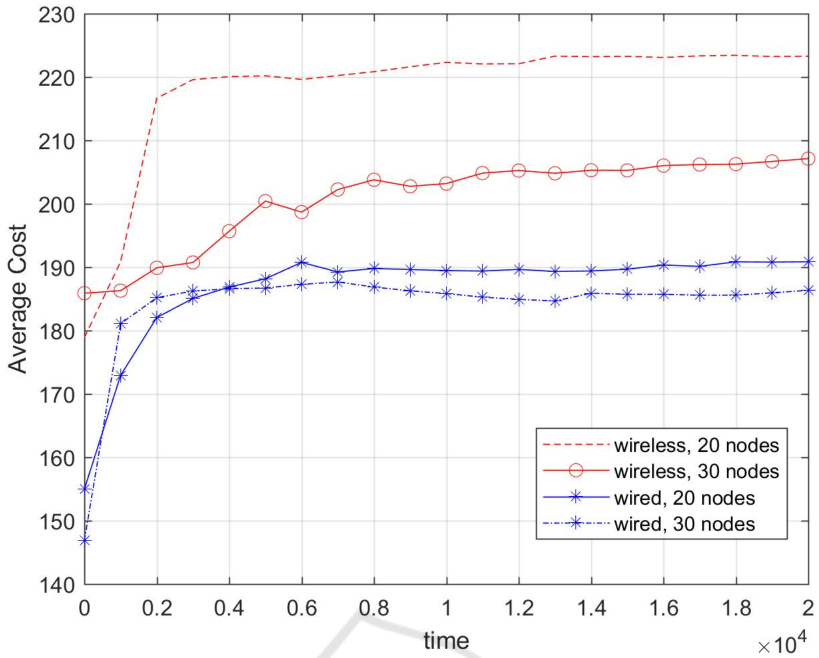

Figure 3: Average Cost in Wireless(With The Extended Model) and Wired Networks(With The Basic Model) with Increasing Number of Nodes.

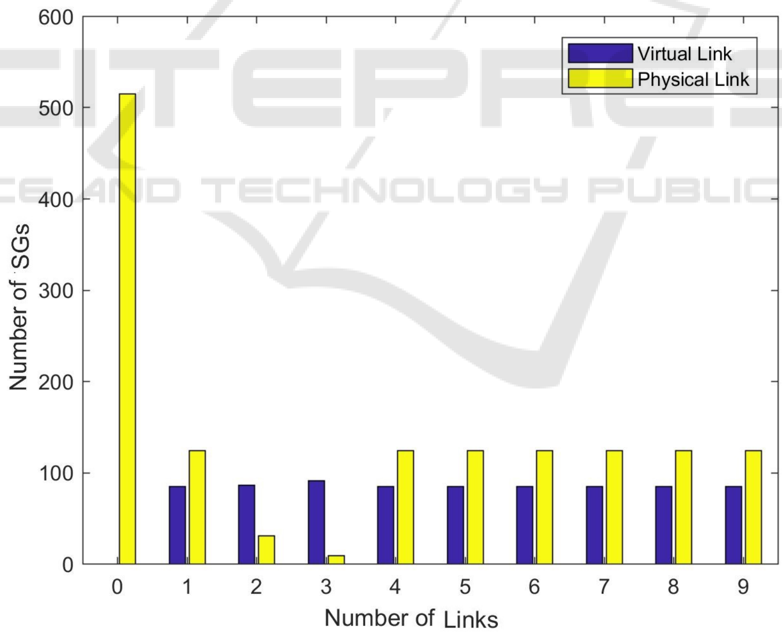

Figure 4: Number of Physical Links and Number of Virtual Links in the SG's Requests (20 Nodes, Random Topology).

5 CONCLUSIONS

Placing NFs in a multi-hop wireless network can be more challenging as there is more BW scarcity: wireless links interfere with and therefore reduce the available BW of links in their vicinity. This challenge can affect the NF placement in comparison to wired networks. In this paper, we extend an existing optimization method for a wired network and consider the characteristics of the wireless network. The basic and extended optimization model are applied to the topology reported in (Sahhaf et al., 2015) to compare

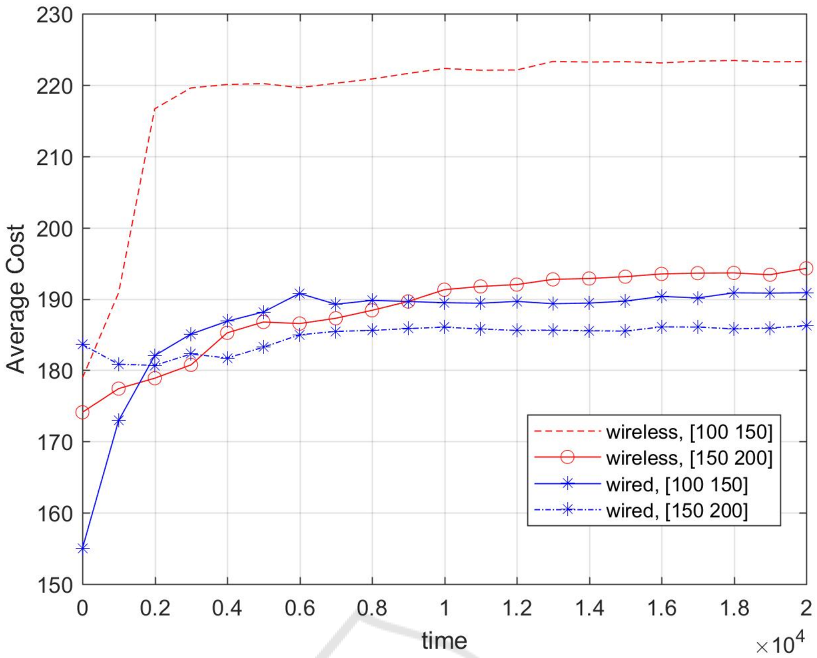

Figure 5: Average Cost in Wireless(with The Extended Model) and Wired Networks(with The Basic Model) with Increasing Available Nodal Resources.

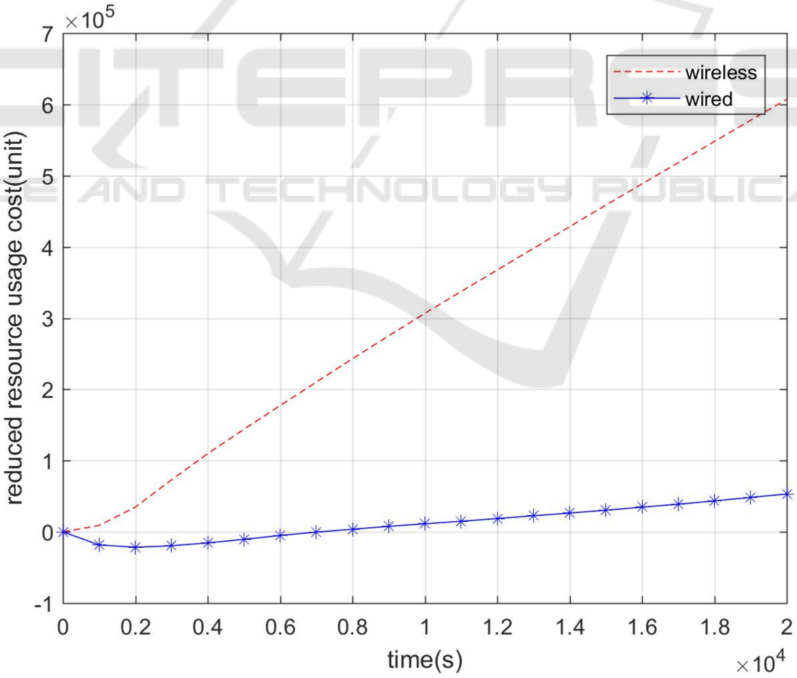

Figure 6: Cost Savings by Increasing Nodal Resources in Wired(with The Basic Model) and Wireless Network(with The Extended Model) (20 Nodes, Random Topology).

the average cost and acceptance ratio. As expected, the wireless interference caused higher BW usage and slightly lowered the acceptance ratio in the wireless network as shown during the time period of 400 seconds to 1200 seconds. The basic and extended optimization model were also applied to randomly generated wireless network topologies with multiple sizes to compare the average cost, acceptance ratio and the number of the physical links and virtual links used to deploy SGs.

We learned from the results that the interference model in wireless networks causes an increase in the average cost. Our results show that the bandwidth usage has a major impact on the placement of NFs. BW is the only factor that can be reduced by using fewer links for the deployment of SGs and that is the main reason the optimization method tends to place the NFs in fewer nodes. We show that increasing the available resources of the nodes or increasing the number of nodes increases the acceptance ratio and reduces the average cost. However, this also increases the deployment cost of the network. This trade-off is more obvious in the wireless network as the BW usage is higher than the wired one. It can be deduced from Fig. 5 and 6 that in the wireless network increasing the available resources has the potential to result in large cost savings.

Extending the experiments already performed in this paper, future work will be devoted to including more features of a wireless network in the NFEP. It will be interesting to include the characteristics of the multi-hop wireless networks such as the traffic pattern, the mobility, and nodes in the optimization method. On the other hand, the optimization problem can be more specific about the NF types to explore how they will affect the traffic rate and consequently the BW usage.

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