Adaptive Virtual Infrastructure Planning over Interconnected IT and Optical Network Resources using Evolutionary Game Theory

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Abstract—This paper focuses on integrated optical network and IT infrastructures in support of the Future Internet and its new emerging applications. In this context, the concept of virtualization of the physical infrastructure is proposed and the process of virtual infrastructure planning is discussed. A novel optimization scheme suitable to adaptively plan virtual infrastructures employing evolutionary game theory is presented and compared to conventional centralized approaches. Our evolutionary game theory modelling results clearly show, that given sufficient time to learn the status of the underlying physical topology the virtual infrastructures planned have similar performance to those generated through traditional global optimization approaches such as integer linear programming.

Index Terms—Virtual Infrastructure Planning, Evolutionary Game theory, replicator dynamics, Optical Networks

I. INTRODUCTION

Distributed computing systems able to support a large variety of existing and upcoming applications, in accordance to the cloud computing paradigm, have gained increased popularity over the past decade. Existing distributed applications as well as new emerging applications such as UHD IPTV, 3D gaming, virtual worlds require large scale computer networks interconnecting specific IT resources that maybe geographically distributed and remote. Best Effort Internet appears to be insufficient to support the specific requirements of these high performance applications. In response to this need optical networking is offering a very high capacity transport with increased dynamicity and flexibility through recent technology advancements including dynamic control planes, elastic technologies etc. In this context, architectures that facilitate the provision of “Optical Network and IT resources” for end-to-end service delivery, according to the Infrastructure as a Service (IaaS) framework provide a very promising solution [1]. To facilitate and maximize the benefit of such an infrastructure, in terms of both efficient resource utilization and creation of new business opportunities that suit well the nature and characteristics of the Future Internet, virtualization of the underlying physical infrastructure has been proposed [1]. In this framework, Virtual Infrastructure (VI) planning and VI provisioning play a key role.

This paper is focusing on the problem of VI planning over one or more interconnected Physical Infrastructures (PIs) comprising both network and IT resources. More specifically, the introduction of VIs facilitates sharing of physical resources among various virtual operators, introducing a new business model that enables new exploitation opportunities for the underlying physical infrastructures.

In the existing literature planning and re-planning of the VIs are performed through conventional centralized service planning and re-planning algorithms [2]. However these may be limited when trying to address the increasing scalability and flexibility required by the dynamic service-oriented network and computing infrastructures. Therefore there is a need to implement disruptive approaches that support VI planning and re-planning utilizing online optimization mechanisms that will introduce an increased level of intelligence. This type of approach will allow VI providers (VIPs) to provision their own services and optimize their performance selfishly, i.e. without considering their impact on the overall network. A suitable approach would be to let the VIPs learn empirically how to construct their own virtual topologies during the game according to the evolutionary game theory (EGT) [3].

This paper studies the virtualization of infrastructures comprising optical network and IT resources. For the first time, an optimization scheme suitable to adaptively plan and re-plan VIs employing EGT is proposed, described and compared to conventional centralized approaches. Our EGT modeling results clearly indicate, that given sufficient time required to learn the status of the underlying physical topology the planned VIs have similar performance to those generated through traditional global optimization approaches such as integer linear programming (ILP).

II. CENTRALIZED VI PLANNING ALGORITHMS

In centralized approaches that are exclusively used for planning purposes to date, decisions are taken by a single controller based on an overall optimization criterion. Usually, these types of algorithms are formulated using ILP, Mixed ILP and Non-Linear Programming techniques ([2],[4]-[6]). For example, assuming that for each $VI_i$, $i = 1, 2, \ldots, I$, there is...
a set of demands $d_1, d_2, \ldots, d_i$, to be served by a set of IT servers $s$, $s = 1, 2, \ldots, S$, the resulting network configuration is optimized by minimizing the following cost function:

$$\text{Minimize } F = \sum_g C_g(u_g) + \sum_s C_s(u_s)$$  \hspace{1cm} (1)

where $C_g(u_g)$ denotes the total cost for installing and operating capacity $u_g$ of link $g$ of the PI and $C_s(u_s)$ the total cost (CapEx and OpEx) for processing demands $u_s$ on server $s$. At the same time, the following set of constraints should be satisfied:

1) Every demand has to be processed at a single IT server.

   By introducing the binary variable $a_{ds}$, that takes value equal to 1 when demand $d$ that is handled by $VI_i$ is assigned to server $s$; 0 otherwise, this constraint may be expressed as follows:

$$\sum_s a_{ds} = 1, \hspace{0.5cm} d \in D_i, \hspace{0.5cm} i \in I.$$  \hspace{1cm} (2)

This allocation policy reduces the complexity of implementation and increases the reliability of the resulting VI.

2) The planned VIs must have sufficient optical link capacity for all demands to be transported to their destinations. Assuming that $h_d$, $d \in D_i$ is the traffic volume for demand $d$ of $VI_i$ and $P_{ds}$ the candidate path list for the lightpaths required to support demand $d$ at server $s$, the following demand constraints should be satisfied by the VI:

$$\sum_s a_{ds} w_{dps} = h_d, \hspace{0.5cm} d \in D_i, i \in I, p \in P_{ds}$$  \hspace{1cm} (3)

where $w_{dps}$ is the the non-negative number of wavelengths allocated to path $p$ realizing demand $d$ at server $s$. Furthermore, the required capacity of each link $e_i$, $e_i = 1, 2, \ldots, E_i$, of the $VI_i$, denoted by $c_{e_i}$, is determined by summing up the lightpaths that transverse link $e_i$. This is described by the following equation:

$$\sum_d \sum_p \pi_{eps} w_{dps} \leq c_{e_i}, \hspace{0.5cm} d \in D_i$$  \hspace{1cm} (4)

where $\pi_{eps}$ is a binary variable taking value equal to 1 if link $e$ belongs to path $p$ realizing demand $d$ at server $s$.

3) The capacity of each link in the VI should be realized by specific PI resources. This constraint is formulated according to Equations (3), (4). For further details on this issue the reader is referred to [5].

4) The planned VI must have adequate IT server resources such as CPU, memory, disk storage to support all requested services.

In general the centralized VI planning approach, that has been already presented, is used to provide globally optimal solutions, however, it suffers by several limitations that maybe incompatible with the vision of the future internet e.g.:

1) they require global and up-to-date knowledge of the underlying physical infrastructure both in the IT and the optical network domain,

2) they need accurate estimation of the traffic demands for each VIP,

3) they require significant processing power to address the severe scalability issues that arise when trying to solve large scale optimization problems that involve a large number of decision variables and constraints.

To address these issues a fully distributed algorithm with low processing cost and high speed of convergence is proposed in the following section that achieves performance similar to the globally optimal.

### III. DYNAMIC VI PLANNING

In contrast to the previous model where the VI planning process is carried out by a centralized authority, a more reasonable assumption would be to let each VIP to identify its optimal topology selfishly. This process can be appropriately modelled by evolutionary game theory. Specifically, VIPS are competing in an oligopolistic setting where each VIP tries to minimize its total costs and therefore, increase its revenues. Thus, information regarding the traffic demands per VIP is not commonly known to all VIPS. Furthermore, for simplicity, the granularity of demands is the wavelength and the IT locations (demand destinations) at which the services will be handled, are not specified and are of no importance to the services themselves. Therefore, the demand destinations for each VI will be identified through a dynamic optimization process.

In the distributed VI planning scheme with limited information, initially, all VIPS select randomly the virtual links as well as their mapping to the physical layer paths that realize their demands at an IT server. As every VIP wishes to minimize its own overall operational cost, it reconsiders periodically its planning strategy by randomly sampling different IT servers and VI to PI mapping strategies. Then, it compares the corresponding operational cost with its own. When a lower value is found, the VIP adopts the new virtual topology; otherwise, the current virtual infrastructure remains unchanged. The pricing model that is adopted in this work assumes that the fixed operational costs of the integrated network and IT infrastructures are shared equally among VIPS that exploit the same resources, while variable operating costs (energy consumption of network and IT resources per wavelength) are charged on a pay as you go basis.

The corresponding evolution of the capacity for each virtual link follows the well known replicator dynamics model ([7], [8]). One of the basic elements of replicator dynamics is the rate at which the VIPS revise their strategy. This rate depends on several factors including the operational cost of the current virtual infrastructure, the VI to PI mapping process, whether demands are satisfied or not etc.

For simplicity the COST 239 [9] reference topology presented in Fig.1 (lower layer) is assumed, where two VIs, generate information that must be transmitted to one of the available IT servers. The set of all available paths (strategies) connecting the source nodes and the IT servers $s$ is denoted by $P_{d,s}$ where $P_{d,s}$ is the set of paths realizing demand $d_i$ of $VI_i$, $i = 1, 2$, at one of the IT servers $s$ in the
S3 is related to the energy cost for using network or IT resources. Formulation energy efficiency is the main objective, IT server processing constraints. Since in the current problem assumption under the traffic conservation, network capacity and to the IT servers with the minimum end-to-end energy con-

\[
\dot{x}_{dps} = \sum_{d \in D_j} \sum_{p \in P_{ds}} u_x y_{dps} - \sum_{d \in D_i} \sum_{p \in P_{ds}} \sum_{d_i, p, \in P_{d_i}} x_{d_i, p, s} u_x y_{d_i, p, s} + x_{dps}, \quad p \in P_{ds}, \; d \in D_i, \; s \in S \tag{5}
\]

\[
\dot{y}_{dps} = \sum_{d \in D_j} \sum_{p \in P_{ds}} u_y x_{dps} - \sum_{d \in D_i} \sum_{p \in P_{ds}} \sum_{d_i, p, \in P_{d_i}} y_{d_i, p, s} u_y x_{d_i, p, s} + y_{dps}, \quad p \in P_{ds}, \; d \in D_j, \; s \in S \tag{6}
\]

The traffic volume of demand \( d \) is accommodated by \( h_d = \sum_p w_{d,p} \), \( p \in P_{d,s} \), wavelengths. The normalized capacity of the path \( p \) realizing demands \( d \) of VI_i and VI_j at server \( s \) is denoted by \( x_{dps} = \frac{w_{dps}}{h_d} (d \in D_i) \) and \( y_{dps} = \frac{w_{dps}}{h_d} (d \in D_j) \), respectively. Then, \( x_{dps} \) and \( y_{dps} \) are collected for each demand \( d \) in the vectors \( x_{dps} \) and \( y_{dps} \). The expected payoffs of \( VI_i \), \( VI_j \) for realizing their set of demands \( d_i, d_j \) when the mapping strategies \( P_{d_i, s}, P_{d_j, s} \) have been selected are \( u_x \) and \( u_y \) respectively. The evolution of the normalized capacity of the path \( p \) realizing demands \( d \) of \( VI_i \) is described via the multi-population replicator equations [10] through Equation (5) while for \( VI_j \) through Equation (6).

At the same time, the following demand constraints should satisfied

\[
\sum_s \sum_p x_{dps} = 1 \quad \text{and} \quad x_{dps} \geq 0, \quad d \in D_i \tag{7}
\]

\[
\sum_s \sum_p y_{dps} = 1 \quad \text{and} \quad y_{dps} \geq 0, \quad d \in D_j \tag{8}
\]

The objective is for each demand to identify the capacity vectors \( x_{d, s}, y_{d, s} \) that route information via the paths \( p_d \in P_{d, s} \) to the IT servers with the minimum end-to-end energy consumption under the traffic conservation, network capacity and IT server processing constraints. Since in the current problem formulation energy efficiency is the main objective, \( u_x \) and \( u_y \) is related to the energy cost for using network or IT resources. Details concerning the energy consumption model adopted in this paper may be found in [11].

Finally, the stability of the proposed adaptive energy minimized service provisioning algorithm is examined. To achieve this, initially the critical points of the system are determined by setting Equations (5)-(6) equal to zero and then solving the resulting system of algebraic equations. The stability of the critical points is then examined using the Lyapunov’s first (or indirect) method. It is proved that if the total demands per VIP do not exceed the capacity of an IT server, then the VI planning strategy that reserves capacity that realizes demands through the shortest paths to a single IT server is evolutionary stable. Otherwise, if the capacity of the closest to the sources IT server cannot accommodate all the traffic, a part of the demands will be served by the closest to the sources IT server, while the rest will be served by the second, third, etc next closer IT server.

IV. NUMERICAL RESULTS AND DISCUSSIONS

To investigate the effectiveness of the proposed VI design scheme, the architecture illustrated in Fig.1 is considered: the lower layer depicts the PI and the layer above depicts the VIs. The effectiveness in this case is examined in terms of the energy efficiency of the designed infrastructure taking into consideration the energy consumption of both the optical network and the IT resources. As already stated in this study
Fig. 2. Comparison of evolutionary planning scheme with two different centralized approaches in terms of infrastructure total power consumption.

Fig. 3. Evolution of capacity reservation in IT servers from the two VIs.

Fig. 4. Phase space of the evolutionary optimization VI Planning scheme: All information generated from VI1 is served by IT #1.

Fig. 5. Impact of the number of VIs on the speed of convergence (sampling periods).

The COST239 European topology has been used, in which randomly selected nodes generate demands to be served by two IT servers. Furthermore, we assume a single fiber per link, 40 wavelengths per fiber, and wavelength channels of 10Gb/s each. The power consumption models that are adopted in the numerical results are similar to those described in [2]. In Fig.1 it is also observed that during the first stages of the evolutionary planning algorithm, each VI consists of 6 virtual links and 5 virtual nodes. However, after few sampling periods all demands from the two VIs are forwarded to a single IT server.

Fig.2 illustrates the total power consumption of the infrastructure (optical network and IT resources) when applying the conventional centralized ILP approach optimizing for energy or distance between sources and IT servers and the proposed evolutionary approach. It is assumed that all source nodes generate traffic demands equal to 20 wavelengths. Due to the global knowledge in the centralized approach, the decisions are made instantly at time 0 and exhibit globally optimum performance. On the other hand, distributed adaptive algorithms learn from the environment and eventually achieve convergence to the optimal solution.

Fig.3 depicts the evolution of the normalized capacity that is reserved in the two IT servers as well as the speed of convergence. It is observed that after 30 sampling periods all traffic that is generated by the two VIs is served by a single IT server. The corresponding phase diagram of the nonlinear dynamic system describing the evolution of population shares on IT server 1 is plotted in Fig.4. It is observed that the problem has a unique stability point corresponding to the situation for which all information is routed to IT server 1, while IT server 2 is switched off.

Finally, the scalability of the proposed evolutionary planning scheme is investigated in Fig.5, where it’s speed of convergence is plotted as a function of the number of VIs. It is observed that for up to 4 VIs less than 100 sampling periods are required for the proposed model to converge to the optimal solution.

V. CONCLUSIONS

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