A Novel Path Computing Framework under QoX Constraints Based on N&PV Functions Embedding

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***Abstract*—Network function virtualization (NFV) and software-defined networking (SDN) represent new paradigms in networking. In this paper, we extend the concept of NFV to include the functions associated to the physical objects of Internet of Things and name it as network and physical functions virtualization (N&PV). We propose a novel path computing framework under QoX constraints based on such N&PV functions embedding and the paths algebra. This novel framework is assessed by means of three use cases and its potential and flexibility are demonstrated.**

***Keywords*–network functions virtualization; software defined network; paths algebra; QoX constraints.**

I. Introduction

According to [1], software-defined networking (SDN) emphasizes the role of software in running networks through the introduction of an abstraction for the data forwarding plane and, by doing so, separates it from the control plane. This separation allows faster innovation cycles at both planes as experience has already shown.

According to [2], network function virtualization (NFV) is a powerful emerging technique with widespread applicability. Among the NFV high-level objectives we mention: (i) improved capital efficiencies compared with dedicated hardware implementations; (ii) improved flexibility in assigning VNFs to hardware.

In this paper, we extend the concept of NFV to include the functions associated to the physical objects of Internet of Things and name it as network and physical function virtualization (N&PFV). The path computation problem is addressed, under a wide range of quality constraints: service (QoS), network economics (QoNE), energy (QoEn), resilience (QoR), grade of service (GoS), transport (QoT), information (QoI).

The main contribution is the proposal of a novel path computing framework under QoX (where X represents S, NE, En, etc.) constraints based on such N&PV functions embedding and the paths algebra. The framework is assessed by three study cases and its usefulness and flexibility are demonstrated.

This paper is organized in the following way: Section I defines and introduces the goals and problems analyzed in this work. In Section II, the related works are described and the main contributions of this paper are highlighted. In Section III, an architecture is proposed following the RFC 7426. In Section IV, the procedures used in this work to identify and to select candidate paths are explained, and a fitness equation defined to provide an optimization criterion. In Section V, three use cases are presented to validate the proposed architecture and path selection procedures. Section VI summarizes the results and concludes the paper.

II. Related work

To reduce costs and improve network management, the industry has recently introduced NFV; an initative that is being standardized by the European Telecommunications Standards Institute (ETSI) in a joint effort that includes the world's major service providers and network equipment manufacteres [3] [4]. The main goal of NFV is to go one step beyond standard information technology (IT) vir-

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tualization in order to consolidate all the current network functions onto high volume servers, switches and storage that can be located anywhere in the network (commodity hardware). Services are deployed by chaining a set of Virtual Network Functions (VNFs) in the commodity hardware. In this way, functionality can be decoupled from location, allowing software to be located at the most appropriate places. As a consequence, services can be deployed sharing hardware resources that can concurrently execute more than one functionality, reducing network operators' capital expenditures (CAPEX) and operating expense (OPEX). A comprehensive survey on NFV can be found in [5].

SDN is an emerging paradigm that proposes to separate network's control plane from the underlying routers and switches (data plane), promoting network control centralization, and introducing the network programmability. The separation of concerns introduced between the definition of network policies, their implementation in switching hardware, and the forwarding of traffic, is key to the desired flexibility: by breaking the network control problem into tractable pieces, SDN makes it easier to create and introduce new abstractions in networking, simplifying network management and facilitating network evolution. A comprehensive survey on SDN can be found in [6].

The implementation of NFV is being defined in consonance with the SDN paradigm. In fact, the management support for the fifth generation of mobile networks is being conceived as a collaborative implementation of SDN and NFV [7] [8]. Currently, the open standardization of SDN is being performed by the Open Networking Foundation (ONF) [9]. However, the Internet Engineering Task Force (IETF) is currently working in the official standardization of SDN and its control protocol Open Flow (OF) [1] [10]. Inside the Internet Research Task Force (IRTF), a research group is also working on SDN since 2013 [11]. With regard to NFV, the main standardization is being done by ETSI, specifically, the NFV cluster is currently producing the standard documents [3].

This paper proposes a path computing framework under QoX constraints. In this framework, a path computation element (PCE) is in charge of computing optimal solutions to either the routing problem with regard to technical and economic objectives, or the resource allocation problem in NFV or network virtualization environments.

With regard to resource allocation in future internet architectures, there are two widely recognized problems: The virtual network embedding (VNE) problem has been tackled in the last years by the research community [12]. Also, the resource allocation problem in NFV has been recently tackled by several approaches [13]–[17].

The main contribution of this paper, besides the definition of an architecture for inter-domain SDN and NFV, is the proposal of a novel path computing framework under QoX constraints based on such N&PV functions embedding and the paths algebra [18]. The framework is assessed by three study cases and its usefulness and flexibility are demonstrated.

III. Proposed architecture

The purpose of this work is to propose an architecture to deploy N&PV functions. There are no restrictions concerning the N&PV functions to be considered. Any of the functions proposed by ETSI in [2] are of interest and PCE as described in [19] as well.

Figure 1 shows a possible SDN implementation of N&PV functions among different autonomous systems, that has the following characteristics: (i) each autonomous system has its own SDN controller. The controller communicates with the switching elements using the OF protocol (represented in grey in the figure); (ii) the controllers gather statistics of the underlying substrate network (represented in black in the figure), process the information and publish in the shared database; (iii) the shared database can be accessed by all controllers (represented in blue in the figure). It can be either a centralized or distributed database physically hosted in the cloud; (iv) the controllers form a logical full connected network (represented in red in the figure).

In this work, we adopt the SDN architecture and terminology as proposed in [1]. Accordingly, this proposal focus on two planes, namely: Control Plane (CP) - the collection of functions responsible for controlling one or more network devices; (ii) Application Plane - the collection of applications and services that program network behavior.

The controllers shown in Figure 1 are entities of the CP and the PCE is the main N&PFV function considered in this work and is an entity of the

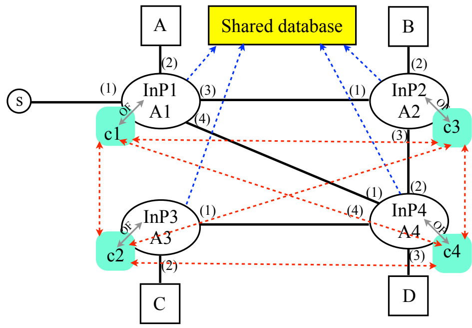


Figure 1. SDN implementation of N&PV functions among different autonomous systems.

application plane. There is also a clear distinction between the infrastructure provider (InP) that owns, controls and publishes the statistics about its infrastructure in the shared database, and the service provider (SP) that access the shared database and using the PCE running in the application plane identifies and selects the routes that maximize its technical and economic objectives.

IV. PATH IDENTIFICATION AND SELECTION

The concepts of paths algebra, developed in [18] and extended to solve the VNE problem [12] are used in this work.

The paths algebra uses $\mathbf{M}$ as the set of m adopted routing metrics and $\mathbf{F}$ as the set of k metrics combination functions.

A synthesis $\overline{S}[.]$ is a set of binary operations applied on the values of the links combined-metrics along a path to obtain a resulting value that characterizes this path as far as the constraint imposed by the combined-metrics is concerned. The syntheses are restricted to the following set: $\{\text{add}(), \text{mult}(), \max(), \min()\}$.

A path α is worse or less optimized than a path β, if $\overline{S}[\alpha] \preceq_{ML} \overline{S}[\beta]$, where $\preceq_{ML}$ stands for multidimensional lexical ordering. For example, we may have $\preceq_{ML} = \{\geq, \leq\}$, that is translated by the following ordering relations: (i) $S_1[\alpha] \preceq S_1[\beta] \Rightarrow S_1[\alpha] \geq S_1[\beta]$; (ii) $S_2[\alpha] \preceq S_2[\beta] \Rightarrow S_2[\alpha] \leq S_2[\beta]$.

Table I presents the parameters, syntheses and ordering relations to be used to achieve different QoX objectives.

TABLE I. QOX PARAMETERS, SYNTHESES AND ORDERING RELATIONS.

QoX	Parameter	Synthesis	Ordering ($\preceq$)
QoS	Delay (d_i)	$\sum d_i$	$\geq$
	Jitter (j_i)	$\sqrt{\sum j_i^2}$	$\geq$
	Packet Loss Rate (plr_i)	$1-\prod(1-plr_i)$	$\geq$
QoNE	Cost / Revenue (cr_i)	$1 - n + \sum_{i=1}^{n} cr_i$	$\geq$
QoEn	Energy ($en_i = A_i + B_i \times BW_i$)	$\sum en_i$	$\geq$
QoR	Availability (av_i)	$\prod av_i$	$\leq$
GoS	VNR accept. perc. (vnr_i)	$\prod vnr_i$	$\leq$
QoT	Bit error rate (ber_i)	$\sum ber_i$	$\geq$
QoI	Belief and plausability (bel_i and pl_i) [20], [21]	Not applicable	$\leq$

In Table I, n is either the number of links of a path or the number of autonomous systems traversed by the chosen path.

A. Fitness equation

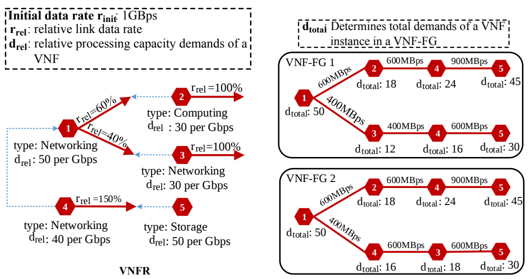
Let $X_i(p) =< x_d, x_j, x_t, x_p >$ be a vector in which each element represents the end-to-end delay, jitter, throughput and packet loss rate of flow f_i when using path p respectively. The problem is to find a path p from source node to destination node for each flow, such that $x_d \leq w_d$ and $x_j \leq w_j$ and $x_t \geq w_t$ and $x_p \leq w_p$ for each flow f_i.

Consider a path p. Its QoS(p) may be evaluated by means of a fitness value FIT(p) given by (1) in which $H(n) = 0$ if $n < 0$ or $H(n) = 1$ if $n \geq 0$, and α, β, γ and δ are the weight factors of the QoS parameters, that only depend on the application, and $\alpha + \beta + \gamma + \delta = 1$.

The fitness equation has to be defined according to the application / service and the objective to be optimized.

The paths algebra framework associated to the fitness equation provides a powerful and flexible tool to optimize multidimensional InP and SP objectives, and it can be fully implemented by the proposed architecture.

$$\text{FIT}(p) = \left[\alpha\frac{w_d - x_d}{w_d} + \beta\frac{w_j - x_j}{w_j} + \gamma\frac{x_t - w_t}{w_t} + \delta\frac{w_p - x_p}{w_p}\right] \times H\left(\frac{w_d - x_d}{w_d}\right) \times H\left(\frac{w_j - x_j}{w_j}\right) \times H\left(\frac{x_t - w_t}{w_t}\right) \times H\left(\frac{w_p - x_p}{w_p}\right) \quad (1)$$



(a) VNF Request

(b) VNF Forwarding Graphs

Figure 2. NFV-RA: Chaining Composition

V. Proof of concept scenarios evaluation

In this section, we describe three scenarios and show how the proposed architecture and implementation strategy allows to achieve the envisaged objectives. All scenarios share a common denominator, namely: employment of N&PFV paradigm, implemented within a paths algebra framework by the proposed SDN architecture shown in Figure 1.

A. *VNF chaining*

The VNF chain composition and embedding is the main resource allocation challenge in NFV, commonly called NFV-RA [14]. The objective of a NFV-RA algorithm is to embed a set of VNF embedding requests (VNFRs) on top of a shared SN infrastructure in an efficient way. The algorithm has to consider placement constraints and dependencies between VNFs. Figure 2 shows a possible solution of the chain composition problem, depicting a VNFR and two possible chainings of its VNF instances.

VNFs can split the traffic flow. In Figure 2a, this is depicted as links leaving the VNFs: if a VNF has more than one link, the traffic flow is split into several subsequent sub-flows. For each link, the relative traffic (r_{rel}) rate is defined. For instance, for a deep packet inspection VNF separating incoming data into two streams (for example, TCP and non-TCP traffic), it can be specified that 60% of the incoming traffic is forwarded to a VNF 2 and 40% to VNF 3 (cf. VNF 1, 2, and 3 in Figure 2a).

Depending on the ordering of the VNFs, bandwidth demands of the network flow changes. The ordering of VNFs is flexible, but has to consider dependencies between VNFs. Based on the dependencies, valid chaining options of VNFRs are derived. Figure 2b depicts two possible chaining options for the VNFR shown in Figure 2a) where d_{total} is the demand per node depending on the incoming traffic load. For each VNF, one or more VNF instances are created: this is due to the fact that in some scenarios, if the network flow is split, traffic has still to be processed by the same types of VNFs, even if traffic is not routed through the same VNF instances (in Figure 2b, both chains require two instances of VNF 4).

Once a valid chain is chosen (for instance, VNF-FG 1), the subsequent challenge is to allocate it in the substrate network with regard to a predefined optimization criterion. Each VNF specifies whether it needs to be placed on a storage/networking/computing node. Hosting capabilities of substrate nodes and links are limited, the amount of required processing capacities is specified for handling the network flow. For example, a VNF performing video encoding should always be embedded on top of a computing node and demands 500MHz of CPU processing capacities to encode 100MBit/s. The amount of required capacities depends on the amount of data handled by that VNF instance (see Figure 3).

This problem is an extension of the VNE problem. The difference is that the node mapping shall consider the type availabilities in each substrate node. To map the VNFs, existing VNE approaches may be used [22]. The mapping of the virtual links can be made using the paths algebra framework in the proposed architecture.

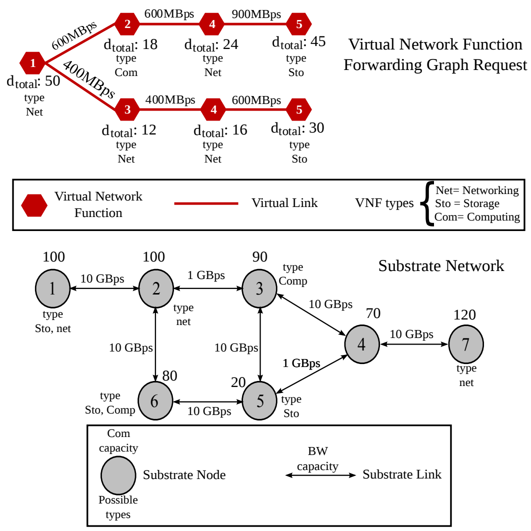


Figure 3. VNF-FGE Scenario

B. Optimization-of-QoEn-and-Qos

In this section, QoEn and QoS aware path computing will be considered to show how paths can be provided to allocate a set of NFVs performing functions over the data plane, regarding QoS guarantees (bit rate, delay, delay jitter and losses) while energy consumption is optimized. Figure 4 shows a network topology that is used in this use case.

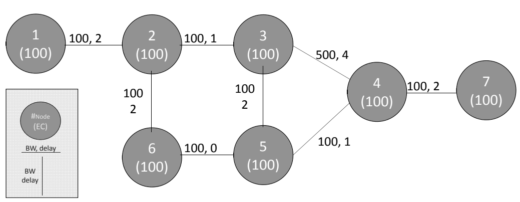


Figure 4. Network topology for the QoEn and QoS scenario.

The energy consumption model considered here is an on-off model. We also assume that services can be shifted (moved to other servers) and consolidated (some servers can be switched off to save energy). In this situation, the cost of shifting services must be considered, since energy is required to move service from one server to another. A fitness equation can be defined in this use case including all these elements. The procedure to search paths follows 2 basic steps: (i) concerning QoS, search all paths meeting the demanded QoS; (ii) select the paths minimizing the energy consumption. At this stage, shifting and consolidation can be considered, for those paths where QoS can be still guaranteed. Metrics considered include the following: energy consumption, revenue (the resource of the service allocated), cost (the total amount of resources consumed to get a certain revenue), acceptance ratio (the ratio of accepted services) and cost / revenue.

Let's consider simple demands from nodes 1 to 7, 2 to 4 and 6 to 3, all demanding bit rate 30 and maximum end-to-end delay < 20. In these conditions, the best allocation will be (1, 2, 3, 4, 7) for 1 to 7, (2, 3, 4) for 2 to 4 and (6, 5, 3) for 6 to 3. In the case 6 to 3, the path (6, 2, 3) is also possible but delay is larger. So, with no shifting and consolidation, the remaining resources after the best allocation is shown in Figure 5.

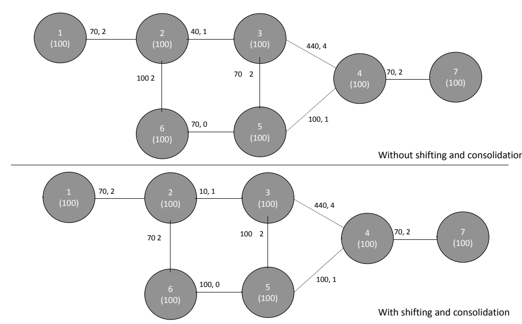


Figure 5. Remaining resources without and with shifting and consolidation.

The metrics are the following: acceptance ratio = 100%, energy consumption = 7 (7 nodes on), cost = 30 x 4 links + 30 x 2 links + 30 x 2 links = 240, revenue = 30 x 3 demands = 90, cost / revenue = 240 / 90 = 2.67.

Let's activate now shifting and consolidation: load in node 5 will be moved to node 2, and node 5 will be switched off. In this situation, all the metrics remain the same but the energy consumption is reduced from 7 to 6.

So, the benefits of searching paths by means of specialized NFVs and deciding using shifting and consolidation mechanisms in order to manage QoEn while meeting QoS are proved.

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C. Optimization of QoNE and QoR

Figure 6 shows a network topology used to evaluate a QoNE and QoR scenario.

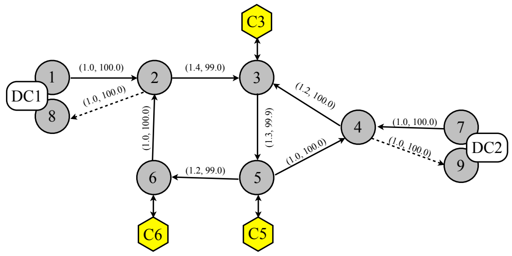

Figure 6. Network topology used in the evaluation of a QoNE and QoR scenario.

In the figure, (i) each gray node represents an autonomous system and is identified by a number; (ii) there are 7 autonomous systems in the network. The autonomous systems 1 and 7 are split in two just to avoid the use of bi-directional links; (iii) the autonomous systems 1 and 7 give access to the data centers DC1 and DC2, respectively; (iv) each autonomous system has its own SDN controller and publishes its reachability, performance and business related information in the shared database. This is represented by the vectors on top of each arc meaning the cost/revenue and availability, respectively.

1) Scenario description: A SP wants to access to provide Big Data processing services to Internet of Things (IoT) customers identified as C3, C5 and C6. Due to the nature of their critical applications related to healthcare, they want to establish an SLA in which the QoR and QoNE are assured.

2) QoNE and QoR fitness evaluation: From the information available in the shared database, the SP built the adjacency (A), availability (Av) and cost/revenue (C/R) matrices. The available routes to the data centers DC1 and DC2 for each customer found using the paths algebra framework are: (i) customer in AS3 – (3, 5, 6, 2, 8 = DC1), (DC1 = 1, 2, 3), (3, 5, 4, 9 = DC2), (DC2 = 7, 4, 3); (ii) customer in AS5 – (5, 6, 2, 8 = DC1), (DC1 = 1, 2, 3, 5), (5, 4, 9 = DC2), (DC2 = 7, 4, 3, 5); (iii) customer in AS6 – (6, 2, 8 = DC1), (DC1 = 1, 2, 3, 5, 6), (6, 2, 3, 5, 4, 9 = DC2), (DC2 = 7, 4, 3, 5, 6).

Using the synthesis equations given in Table I for QoNE and QoR the availability and cost / revenue figures for different situations can be evaluated.

The evaluation of QoNE depends on the adopted price models. The simulations were run considering $90 \leq av \leq 100$ and $2.5 \leq p \leq 4.0$, where av and p represent availability and price respectively. We adopted three prices models in which the price depends on the network availability: a linear model that may be considered as a reference and the other two represent less (first quadratic) and more (second quadratic) aggressive price policies. The prices are given in arbitrary monetary units.

The QoNE is evaluated by the fitness equation $\text{FIT} = \alpha \frac{g - g_l}{g_l} + \beta \frac{av - av_l}{av_l}$ that considers the normalized gain g and availability av as variables. The normalized gain g is given by $g = \frac{p - cr}{cr}$ where cr is the C/R offered by InP. $\alpha = \beta = 0.5$ are weighting factors, $g_l = 0.2$ and $av_l = 97\%$ are the minimum acceptable values for the normalized gain and availability, respectively.

The results are given in terms of normalized fitness defined as $||\text{FIT}|| = \frac{\text{FIT}}{\max(|\text{FIT}|)}$.

Table II summarizes the normalized fitness results for the proposed scenario.

TABLE II. NORMALIZED FITNESS FIGURES TO ACCESS DC1 AND DC2.

Access to DC1					
			Price model		
Customer in AS	Availab.	C/R	Linear FIT	1st q. FIT	2nd q. FIT
3	97.91	1.9	0.20	0.15	0.25
5	97.91	1.9	0.20	0.15	0.25
6	97.91	1.9	0.20	0.15	0.25
Access to DC1 and DC2					
3	97.81	2.4	0.10	0.05	0.12
5	97.81	2.4	0.10	0.05	0.12
6	95.77	3.3	< 0	< 0	<0

At high levels of network availability the price models are equivalent, where for medium or low network availability levels the difference in price models may represent going from profit to deficit. From the end user point of view, it is clear that the network availability is his/her guarantee to pay a fair price for the service. Otherwise, high prices

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will be practiced to protect the gains of the SP. If the SP offers access to only one data center, it always achieves a positive fitness and can use the price models to increase either the attractiveness of its service by lowering the prices or its gains by increasing the price. If it offers simultaneous access to both data centers for a same customer, there is no policy that may provide positive gains for the price models adopted in this study.

D. Discussion of results

The study cases presented in the preceding sections aim at optimizing different objectives, employ linear and non-linear variables, and deal with technical and economical constraints. All the cases are solved using the same mathematical framework: the paths algebra. It has been proved that the paths algebra provides an harmonized and coherent environment to accommodate a complete and diverse set of objectives and is a powerful way to implement services policies.

To the best of our knowledge, there are no equivalent published results that we could compare to. The results available int the literature are, in general, restricted to single autonomous systems, linear variables and the technical and economical aspects are treated separately.

VI. Conclusions and Future Work

In this work, a novel path computing framework under QoX constraints based on N&PV functions embedding was proposed. It relies on virtual PCEs running in the application plane of an SDN architecture and on the controllers that can configure the switching elements across multiple autonomous systems. Path identification and selection employs the powerful paths algebra framework enhanced by a fitness function that is defined according to the application/service and objectives of the SP. The framework was assessed by three study cases and its usefulness and flexibility was demonstrated.

As future works, we intend to adapt the algorithms of VNE to solve the VNF chaining problem and evaluate the overall performance simulating different topologies under different QoX constraints.

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