Applying NFV and SDN to LTE Mobile Core Gateways; The Functions Placement Problem

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ABSTRACT

With the rapid growth of user data, service innovation, and the persistent necessity to reduce costs, today's mobile operators are faced with severe challenges. In networking, two new concepts have emerged aiming at cost reduction, increase of network scalability and service flexibility, namely Network Functions Virtualization (NFV) and Software Defined Networking (SDN). NFV proposes to run the mobile network functions as software instances on commodity servers or datacenters (DC), while SDN supports a decomposition of the mobile network into control-plane and data-plane functions. Whereas these new concepts are considered as very promising drivers to design cost efficient mobile network architectures, limited attention has been drawn to the network load and infringed data-plane delay imposed by introducing NFV or SDN. We argue that within a widely-spanned mobile network, there is in fact a high potential to combine both concepts. Taking load and delay into account, there will be areas of the mobile network rather benefiting from an NFV deployment with all functions virtualized, while for other areas, an SDN deployment with functions decomposition is more advantageous. We refer to this problem as the functions placement problem. We propose a model that resolves the functions placement and aims at minimizing the transport network load overhead against several parameters such as data-plane delay, number of potential datacenters and SDN control overhead. We illustrate our proposed concept along with a concrete use case example.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design

Keywords

NFV; SDN; Datacenters; LTE Mobile Core Gateways

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1. INTRODUCTION

The mobile cellular network has recently seen a rapid development, in particular with the introduction of the 4th generation LTE network. Today's mobile cellular networks are capable of offering higher data rates, integrating more services and guaranteeing a higher user experience. However, this development means also that the volume of data to be transported within a mobile network is increasing as well. In addition, market competition requires faster service deployment and elasticity in changing the service criteria to cope with the market dynamics. All of these points cause a drastic reduction in the operators revenues and consequently result in a need for Total Cost of Ownership (TCO) reduction, to be able to keep a revenue margin [1]. Two concepts are in the focus of research and development at the moment.

Network Functions Virtualization (NFV) [2] proposes the operation of the mobile network functions as software instances on commodity hardware or datacenters (DC). This deployment brings several advantages with respect to network scalability, load optimization or energy savings. The possibility of incremental functional additions without the need to install or acquire specialized equipment is definitely of huge value. In addition, a mobile network becomes more dynamic as virtualized platforms support a rapid instantiation, tearing down or dynamic allocation of resources. Therefore, it is expected that NFV would have an impact on the desired cost reduction in today's mobile networks.

Meanwhile, Software Defined Networking (SDN) [3] has been considered as a complementary deployment concept for mobile networks. SDN introduces what we call Network Functions Decomposition (NFD), where control-plane functions are appended to a logically centralized controller that could be deployed in a datacenter platform, while data-plane functions are realized by SDN networking elements at the transport network. The advantages of having an SDN-based mobile network include programmability and thus flexibility to steer the data traffic on run-time basis and tailor the data flows inside the network. This leads to an improved service quality and user experience in addition to potential cost savings through a dynamic optimized network operation.

Whereas introducing NFV to the mobile network has lots of advantages as previously mentioned, it also requires transporting the whole network data traffic to the operator's datacenters which imposes additional load on the transport network. Furthermore, an additional data-plane delay is expected, which requires a thorough planning of the datacenters location within the mobile network. In the same way, introducing SDN adds an extra control-plane which is not present in the standard architecture, that similarly imposes additional transport network load overhead, depending on the SDN control volume. In order to investigate such additional overhead, we focus on the two main functions of the LTE mobile core network which involve both control and data-plane functions; the Serving Gateway (SGW) and PDN Gateway (PGW). Our main aim is to investigate the influence of virtualizing or decomposing those two central functions on the data-plane delay as well as the transport network load, since the transport load reflects network costs.

Related Work Introducing functions virtualization and SDN to mobile networks has been the focus of recent research work, triggered by the NFV initiative and wide adoption of SDN. There are studies discussing the architectural aspects of migrating the mobile functions to a datacenter, as in [4] which highlights the advantages and use-cases of virtualized mobile functions. [5] propose the utilization of a datacenter platform to offload the mobile core traffic. Regarding SDN, we have presented in [6], an analysis of different mobile functions deployment architectures in addition to their realization through SDN. Conceptual architectures and use-cases of an SDN-based mobile core have been additionally discussed in [7]. While the authors in [8] have concluded to the need for enhanced SDN networking elements. [9] proposed the use of middleboxes to provide flexibility and policy enforcement in the mobile core via SDN. Nevertheless, it can be seen that early investigations were concerned with the architecture design, where most proposals focus on one concept only, either virtualization or SDN.

The objective of this paper is to define, model and solve the problem of applying virtualization, SDN decomposition or a combination of both concepts on the mobile core gateways. In other words, for each mobile core gateway, this problem resolves whether to virtualize and migrate all gateways functions to a datacenter or decompose this gateway as a controller residing in a datacenter and a networking element at the transport network, we call this the functions placement problem. It also addresses the optimal placement of the datacenters, which host the virtualized gateways as well the SDN controllers. The controllers placement problem has been previously addressed in [10] and [11], which focused on minimizing the SDN control delay and resilience provisioning, receptively. In our study, the optimal functions placement aims at minimizing the network load and satisfying the data-plane delay budget. Note that this novel problem could also be adapted to other network functions.

2. MOBILE CORE GATEWAYS RE-DESIGN

In this section, we discuss the functions allocation for both virtualized or SDN decomposed deployments in addition to the required transport network elements. In our previous work [6], we have presented a thorough analysis and classification of the main SGW and PGW functions. We have grouped the classified functions into two main categories as follows: (1) Control-plane functions, as for example LTE signaling or resources allocation (2) Data-plane functions, such as GTP Tunneling, or additional functions required at the PGW only such as QoS enforcement or charging.

2.1 Virtualized Gateway

Applying the concept of NFV to the current gateway architecture shown in Figure 1(a) results in moving the control-plane (GW-c) and data-plane (GW-u) functions to an operator's datacenter as shown in Figure 1(b). In this case, an off-the-shelf network element (NE) would be used to direct the data traffic from the transport network to the intended datacenter. All further processing would be done by the virtualized gateway instance. Note that the network element could be either a typical transport switching element or otherwise a standard SDN network element, in case flexible data flow handling between the transport network and datacenters is desired and beneficial for the operator.

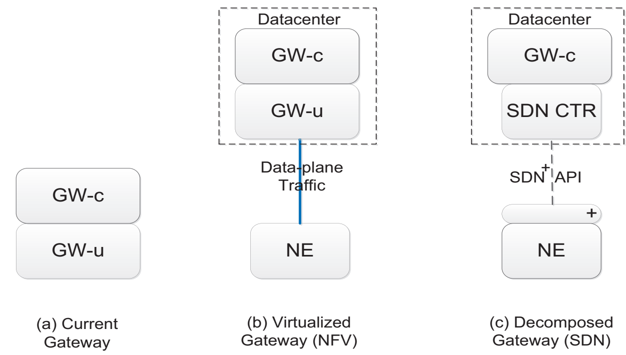

Figure 1: Mobile core gateways re-design

2.2 SDN Decomposed Gateway

An SDN decomposed gateway is illustrated in Figure 1(c), SDN controllers are extended with control-plane gateway functions as for example LTE signaling, and hosted within operator deployed datacenters. In this case, enhanced SDN network elements are needed which we call "SDN NE+", where the "+" resembles the previously mentioned data-plane gateway functions such as GTP tunneling or charging which cannot be realized with current SDN network elements. In addition, an extended SDN API that should be adopted by the operator to program and control those features. In this case, the data traffic is kept at the transport network while only SDN control is flowing between the datacenter and the transport NE+.

3. PROCESSING DELAY MEASUREMENT

The data-plane traffic delay within the mobile core, i.e. traffic forwarded through the gateways between the access network and IP domains, could be simply defined as the sum of packet propagation delay T_{prop} on each link in addition to the packet processing delay T_{proc} at each node a packet traverses. The propagation delays depend on the link distances and transport technology between the gateways which we cover in our model in Section 4. In this section we aim at providing a quantitative comparison between the fully virtualized and SDN decomposed gateways by measuring the data-plane packet processing delays.

For our measurement, the first step was to develop prototype implementations, abstracted versions from the 3GPP standard, of the previously classified SGW and PGW functions, most importantly the GTP packet processing function. For the virtualized gateway, we have developed a GTP packet processor in java. The virtualized gateway has been hosted on one of our server nodes and was allocated 20 Intel(R) Xeon(R) CPU E5-2690 v2 @ 3.00GHz virtual CPU cores with 128 GB RAM.

Table 1: Mean packet processing delay

no. of Tunnels	10	100	1 K	10 K
bits/sec	1 M	10 M	100 M	1 G
packets/sec	83	830	8.3 K	83 K
Virtualized GW T_{proc}	62 μs	83 μs	109 μs	132 μs
Decomposed GW T_{proc}	15 μs	15 μs	15 μs	15 μs

Regarding the SDN decomposed gateway evaluation, the SDN NE+ has been realized using an NEC PF5420 OpenFlow switch from our SDN testbed, running OF 1.3 firmware [12] and supporting a rate of 1 Gbps per physical port. It should be noted that since GTP headers are not included in the OF match fields specification, we have emulated the NE+ packet processing as header bits modification using OF Modify action. Additionally, the open source java floodlight controller [13] has been modified and extended to represent the gateway's control-plane.

Our measurement setup consisted of a measurement PC with a 4 ports DAG card which has a time stamping precision in *nanoseconds*. Network taps were used to capture the traffic and forward duplicate copies to the measurement PC which then calculates the packet processing delay. The taps were directly connected within a small vicinity to the SDN switch and the server node running the software packet processor, to eliminate any propagation delay.

The packet processing delay, of both the virtualized software function and SDN networking element, has been measured against different values of data rate, number of packets per second and number of established tunnels. Each measurement run lasted for a duration of 10*seconds*. The mean delay is calculated for each run, where the overall mean, shown in Table 1, is calculated within 95% confidence and at least 100 runs. A fixed packet size was considered of 1500 Bytes. Note that the SDN signaling or tunnel establishment delay is not considered in this case as the main focus is packet processing delays. Hence, delay measurements are triggered after all tunnels are established.

The decomposed gateway, emulated by an SDN switch, shows a stable processing delay of 15μs over the range of parameters. It can be seen that the virtualized gateway, running in software, experiences higher processing delays compared to the decomposed gateway with a maximum of 132μs in case of 1 Gbps line rate. This is in line with common observations in switch design where packet processing in hardware is typically faster than software processing, certainly dependent on the available resources.

4. PROBLEM FORMULATION

In this section, we formulate a model that evaluates the different gateway deployments in a mobile core network, where the aforementioned processing delay measurements are taken as input parameters. As previously discussed in Section 2, considering the core gateway as a network function, it could be either virtualized and moved to a datacenter where the gateway is replaced with a switching NE which steers the traffic towards the datacenter. Alternatively, the gateway function could be decomposed between an enhanced SDN NE+ and an extended controller which is hosted by a datacenter. In our study, we target a first step migration scenario, so we keep the gateways' geographical locations unchanged. Additionally, we assume that datacenters would be placed in a location where the operator has already an existing site to reduce the floor space cost i.e the datacenter is placed in a location where an operator has a gateway.

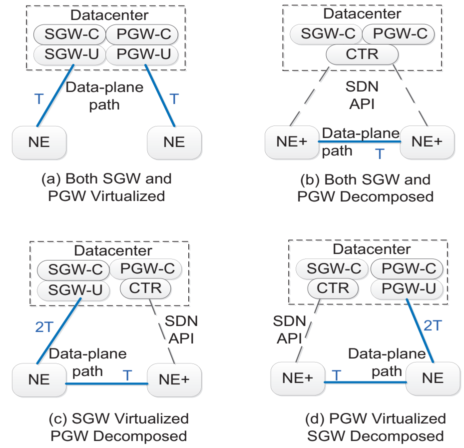

Figure 2: Alternative paths for data-plane demand between SGW and PGW, demand volume = T

The problem is formulated as a path-flow model considering transport data-plane demands between SGWs and PGWs. For each demand, there are four possible paths depending on the SGW and PGW functions placement in addition to the datacenter location, as shown in Figure 2. Hence, for each traffic demand, the selected path results in the SGW and PGW functions placement and datacenter location. Demands are considered to be uniform, bi-directional and non-splittable. We define the total load as the sum of the data-plane traffic or SDN control traffic on each link multiplied by its length, over all links. The problem's objective is to determine each gateway function placement and datacenter location, which minimizes the total transport network load:

$$\min \sum_{c \in C} \sum_{d \in D} \sum_{p \in P} \delta_{c,p,d} N_{c,p,d} \tag{1}$$

where the set C includes all possible locations of the K datacenters. $\delta_{c,p,d}$ is a binary variable which denotes that a path p is chosen for demand d, with the location of datacenter c. The parameter $N_{c,p,d}$ is pre-calculated load resulted from a combination of datacenter location, path and demand. The constraints are given by:

$$\sum_{c \in C} \delta_c = K \tag{2}$$

$$\sum_{p \in P} \delta_{c,p,d} \leq \delta_c \quad \forall d \in D, c \in C \tag{3}$$

$$\sum_{c \in C} \sum_{p \in P} \delta_{c,p,d} = 1 \quad \forall d \in D \tag{4}$$

$$\sum_{p \in P} \delta_{c,p,d} L_{c,p,d} \leq L_{budget} \quad \forall d \in D, c \in C \tag{5}$$

where (2) ensures that K datacenters are chosen, a binary variable δ_c denotes each selected datacenter c. (3) reflects that if a datacenter c is chosen, a path p for demand d could be chosen using this datacenter c. In case of K selected datacenters, only one path using one datacenter for each demand is chosen, guaranteed by (4). Finally, (5) ensures that the chosen path satisfies the data-plane delay budget where parameter $L_{c,p,d}$ is pre-calculated latency resulted from a combination of datacenter location, path and demand.

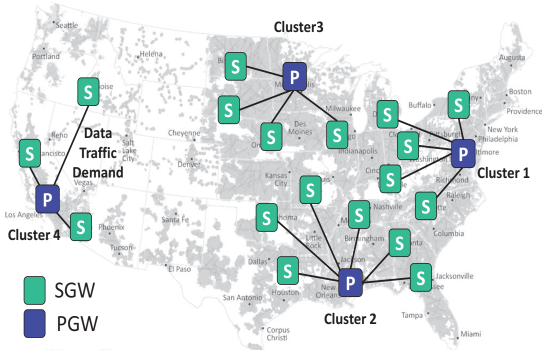

Figure 3: Presumed core gateways topology based on LTE coverage map in [15]

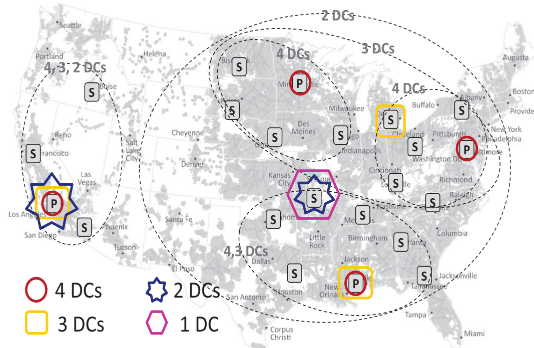

Figure 4: Datacenters location at K = 4, 3, 2, 1

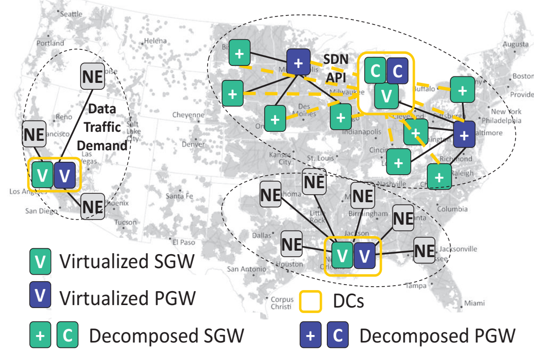

Figure 5: Functions placement at 3 datacenters with SDN control of 10% under 5.3 ms delay budget

5. RESULTS AND EVALUATION

For simulation, a java framework was developed and we used Gurobi [14] as the optimization problem solver. It is known that it is quite difficult to set hands on a real deployment topology of an operator's mobile core. Therefore, we presumed a core gateways topology for the US as shown in Figure 3, based on LTE coverage map in [15]. The topology consists of 4 clusters with 4 PGWs and 18 SGWs, resulting in 18 demands in total. A fully meshed infrastructure is assumed to be available between the the gateways i.e. a link could be established from any gateway to any other.

The data-plane delay budget is defined for the different SGW-PGW interface realizations, either going through the datacenter or between NE+ equipment. Each datacenter hosts the virtualized gateways and the control functions of the decomposed gateways i.e extended SDN controller, respectively. The processing delay input is taken from our previous measurement as a relative average of 10 μs for the decomposed gateway transport element (NE+) and 100 μs for the virtualized gateway transport element (NE). An underlying optical transport network has been considered which results in propagation delays depending on the distances between the functions' location. So far, constraints on the datacenter available resources or restricted locations are not considered. However, these are important factors that we would consider for future work.

There are two sources of traffic that comprise the network load depending on the functions placement. First is the data traffic to be transported between the SGW and PGW. Second, SDN control traffic that is added in case of decomposed deployment. This SDN control volume is pretty much dependent on the protocol adopted by the operator and the customization added to implement the mobile core functions as for example tunneling or charging. The SDN control volume depends on the LTE signaling that an operator sees within its core network as well. Hence, we have investigated the impact of having different SDN control profiles and we denote it as a percentage of the data volume transported for each gateway. For example, an SDN control profile of 10% means SDN loads the link from the datacenter to the gateway NE+ by a volume that is one tenth the data volume transported by such gateway. It would be the task of the operator to identify the SDN control volume in its network.

The optimization problem is a deterministic problem, therefore multiple runs are not needed. The network load $N_{c,p,d}$ and path latency $L_{c,p,d}$ were pre-calculated for all possible combinations of datacenter, path and demand, which decreases the complexity and makes the run time quite fast i.e. in the resolution of *milliseconds* per iteration.

5.1 Full Virtualized Deployment

The maximum propagation delay between an SGW and its respective PGW in the presumed core topology is $5.128ms$, Figure 3 in cluster 4 between Idaho and Los Angeles. Considering an additional processing delay of $100\mu s$, the data-plane delay budget has been set to $5.3ms$. First question; *how many datacenters are needed to fully virtualize all gateways and move them to datacenters for this given topology under the* $5.3ms$ *data-plane delay budget?*

The problem's solution determines that at least 4 datacenters are required to support a full migration to virtualized gateways under a data-plane delay budget of $5.3ms$, where a datacenter is located at the PGW of each cluster as shown in Figure 4. The total network load of the original presumed gateway topology has been calculated to be used as a reference for the load overhead. In this case, the total network load with 4 datacenters is equal to the total network load in the original presumed gateway topology. In such tree structure at each cluster, placing the gateway functions at the tree root node would diminish any extra traffic transport overhead. It has also been noted that with a fewer number of datacenters, it is infeasible to fully virtualize all gateways under such data-plane delay constraint.

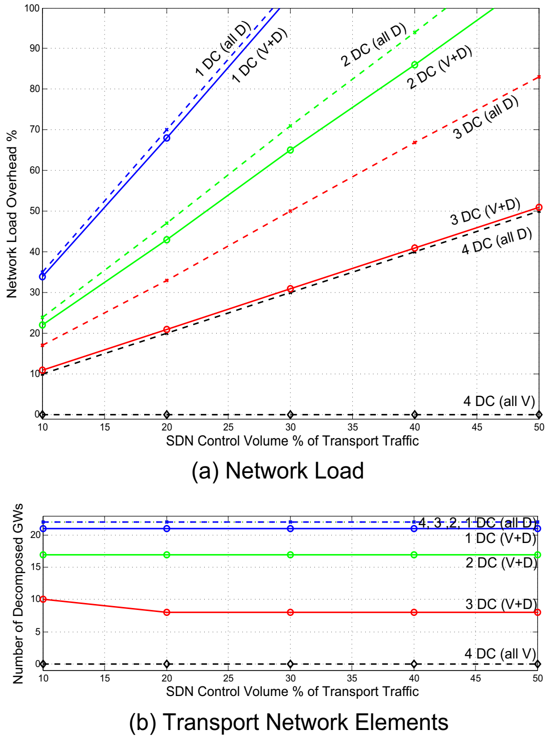

Figure 6: Data-plane delay budget of 5.3 ms

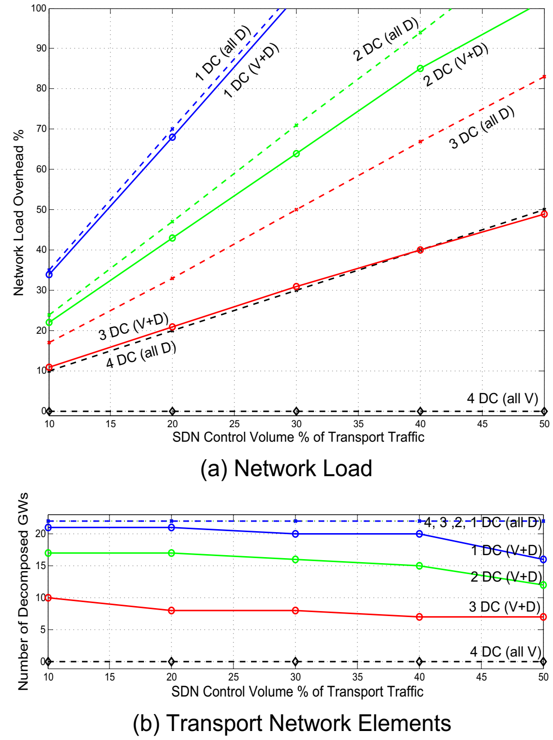

Figure 7: Data-plane delay budget of 10 ms

5.2 Virtualized and Decomposed Deployments Combination

Another conclusion that can be drawn from the above results is that, if we want to operate less than four datacenters in this given topology and under a strict delay budget, decomposed gateways are needed to keep a subset of the data traffic at the transport network . Hence, we solve again our functions placement problem with the possibility of having virtualized or decomposed gateways, which minimizes the total network load under the same data-plane delay budget of $5.3ms$. The resulting datacenter placement with the respective network partitioning is illustrated in Figure 4, ranging from 3 to 1 available datacenters. A snapshot of the functions placement with a combined virtualized and decomposed deployment is shown in Figure 5, having 3 datacenters and SDN control volume of 10% under $5.3ms$ delay budget. We also solve the problem for a full decomposed gateway deployment, i.e. all gateways are decomposed, to have a comparison with the combined virtualized and decomposed gateway deployment. The total network load of the original presumed core topology is considered as a reference for the load overhead.

5.2.1 *Network Load Overhead*

It is shown in Figure 6(a) that the number of datacenters represents an important factor in determining the network load overhead as the total network load increases significantly in case fewer datacenters are deployed. For instance, at a 10% SDN control volume, the combined virtualized and decomposed gateways deployment with 3, 2 and 1 datacenters show 11%, 21% and 34% load overhead, respectively. A single datacenter is showing a significant load overhead with a steeper incline as the SDN control volume increases, doubling the traffic inside the core network at an SDN control volume of 29%. This is due to the extra SDN control-plane and the high number of NE+ needed shown at Figure 6(b) for a single datacenter.

Figure 6(a) shows also that with the considered topology and input parameters, a combined virtualized and decomposed gateway deployment outperforms the deployment with only decomposed gateways in all cases of K datacenters, concerning network load overhead. Furthermore, the load overhead resulted by a combined deployment using 3 datacenters approaches the full decomposed gateways deployment using 4 datacenters.

Additionally, the network load overhead gap observed between the combined deployment and the full decomposed deployment is seen to be closing down as the number of available datacenters decreases. This could be explained by Figure 6(b) which shows that the number of needed decomposed gateways is increasing while fewer datacenters are used, approaching a full decomposed deployment. In case of a single datacenter, 21 out of 22 gateways are decomposed.

5.2.2 *Functions Placement*

Figure 6(b) shows that the number of decomposed gateways, realized by SDN NE+ at the transport network, increases significantly with the availability of fewer datacenters. This is to avoid the extra delays of transporting the traffic through the datacenter under such data-plane delay budget of $5.3ms$. For instance at an SDN control volume of 10%, if an operator decides to deploy a combination of virtualized and decomposed gateways using 3 datacenters instead of a full virtualized deployment with 4 datacenters, 45% of the transport network elements are required to be decomposed gateways or enhanced SDN NE+. In this case, a cost analysis is essential for the operator to evaluate the cost difference between the deployment of a datacenter or deploying enhanced transport network elements.

Regarding datacenters placement, it is observed that each datacenter is placed in a central location towards the respective transport network elements within its selected network partition, as in the case of 3 datacenters and SDN control volume of 10%, shown in Figure 5. The centrality of each datacenter in its respective network partition is an indication for the transport network load balancing and the responsiveness of the SDN control as well.

5.3 Delay Budget Relaxation

In the previous subsection, the gateway functions have been placed under a strict data-plane delay budget of $5.3ms$. We solve the problem again yet after relaxing the data-plane delay budget to $10ms$ to observe the impact of relaxing the data-plane delay constraint on particularly the functions placement and total network load. Note that higher delay budgets could be tolerated by some services, yet nowadays mobile networks attempt to offer less delays to improve the user satisfaction.

For a full virtualized gateways deployment, it is still infeasible with fewer than 4 datacenters, which again points out to the necessity of a combined virtualized and decomposed deployment for the case of using less than 4 datacenters.

The network load overhead after relaxing the delay-budget to $10ms$ is quite comparable to $5.3ms$, shown in Figure 7(a). However, with a higher data-plane delay tolerated, it is affordable to deploy more virtualized gateways in case the SDN control volume increases, to keep a minimum network load, as illustrated in Figure 7(b).

6. CONCLUSION

In this paper, we discuss alternative deployments for mobile core network gateways, namely fully virtualized gateways hosted in a datacenter and decomposed gateways based on SDN. We analyze possible placements of virtualized gateways or decomposed gateway functions with respect to delay and imposed network load. We call this the network functions placement problem. As a basis, we provide a packet processing delay measurement for our virtualized and decomposed gateway implementation. For fully virtualized gateways, the processing delay results in a maximum of $132\mu s$ compared to $15\mu s$ in case of decomposed gateways.

As a solution to the functions placement problem, we provide a model that minimizes the network load, comprised of transport data-plane in addition to SDN control if decomposed gateways are present, for a certain data-plane delay budget. We consider the proposed model to be a solid tool for mobile operators to plan the migration of mobile core gateways to NFV or SDN.

For an exemplary gateway deployment in a US network, the problem has been solved against different number of available datacenters, delay-budgets and SDN control volume. In this setting, four datacenters are required to support a full virtualized gateways deployment. If less than four datacenters are available, a combined deployment of fully virtualized gateways and decomposed gateway functions is most suitable with respect to network load overhead and delay constraints.

Outlook For future work, further constraints to the functions placement problem could be included, which consider the available resources at each datacenter or the transport network links available bandwidth. Additionally, non-uniform traffic patterns in the mobile core could be adopted, which are based for example on user population density. The formulated problem could also be extended to incorporate other mobile network functions such as the MME.

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