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Efficient Virtual Evolved Packet Core Deployment Across Multiple Cloud Domains

Miloud Bagaa*, Tarik Taleb*, Abdelquodouss Laghrissi* and Adlen Ksentini§

* Communications and Networking Department, Aalto University, Finland.
§ Communication systems, EURECOM, Sophia-Antipolis, France.

Emails: miloud.bagaa@aalto.fi, talebtarik@ieee.org, abdelquodouss.laghrissi@aalto.fi, adlen.ksentini@eurecom.fr

Abstract—Many ongoing research activities relevant to 5G mobile systems concern the virtualization of the Evolved Packet Core (EPC) elements aiming for system scalability, elasticity, flexibility, and cost-efficiency. Virtual Evolved Packet Core (vEPC) will principally rely on some key technologies, such as Network Function Virtualization (NFV), Software Defined Networking (SDN) and Cloud Computing, for enabling the concept of Mobile Carrier Cloud. The key idea beneath this concept, known also as EPC as a Service (EPCaaS), consists in deploying virtual instances (i.e., Virtual Machines or Containers) of key core network functions (i.e., Virtual Network Functions - VNF), such as the Mobility Management Entity (MME), Serving Gateway (SGW), and Packet Data Network gateway (PGW) over a federated cloud. In this vein, an efficient VNF placement algorithm is highly needed to sustain the Quality of Service (QoS) while reducing the deployment cost. Our contribution, in this paper, is to devise an algorithm that derives the optimal number and locations of the deployment cost. Our contribution, in this paper, is to devise an algorithm that derives the optimal number and locations of VM instances to instantiate and their placement over a federated cloud to create a vEPC for a specific traffic pattern. Let $\vartheta$ denote a VNF, whereby a set of different $\vartheta$s would compose the vEPC network service. Formally, $\vartheta$ can be one of the following network elements: HSS, MME, SGW or PGW. The proposed solution, dubbed virtual-EPC, derives the optimal number and location of VM instances of each VNF $\vartheta$ (i.e., HSS, MME, SGW and PGW). The virtual-EPC solution consists in placing the instantiated VNFs in the federated cloud, i.e. indicating on which cloud network instance (i.e., HSS, MME, SGW and PGW). The virtual-EPC solution consists in placing the instantiated VNFs in the federated cloud, i.e. indicating on which cloud network instance (i.e., $\mathcal{C}$) should run. Here, we formulate the problem using Coalition Formation Game. Unlike the existing solutions, which assume that $\mathcal{C}$’s belong to the same cloud operator, in this work, we relax this constraint by allowing that $\mathcal{C}$’s could belong to different cloud providers. The proposed placement algorithm considers the different $\mathcal{C}$’s as players and assumes that it is better for them to cooperate by building coalitions rather than not cooperate. Indeed, a $\mathcal{C}$ would decide to participate in a coalition (i.e., the creation of a set of instances of a VNF $\vartheta$) only if its profit is improved. The profit of a $\mathcal{C}$ refers to the difference between the price that the mobile operator is willing to pay and the cost needed to handle the traffic generated from different Tracking Areas (TAs) associated to this $\mathcal{C}$.

The remainder of this paper is organized in the following fashion. Section II presents some related research work. The network model and problem formulation are covered in Section III. The proposed VNF placement strategy is introduced in Section IV. Section V evaluates the performance of the different optimization solutions envisioned in this paper. The paper concludes in Section VI.

II. RELATED WORK

The concept of carrier cloud (i.e., vEPC) assists in achieving elasticity, flexibility, and significant reduction in the operational cost of the overall network system. Indeed, using NFV and general-purpose hardware in $\mathcal{C}$’s to run network functions helps in dynamically scaling up/down the network according to the demands of users for resources and can largely reduce the cost. NFV aims at offering diverse network services using network functions implemented in the format...
of a software, deployable in an on-demand and elastic manner on the cloud. In return of its numerous advantages, vEPC introduces some important challenges, mainly related to the placement of the telco-specific VNFs (i.e., MME, PGW, and SGW) over a federated cloud to ensure an optimal connectivity for users and simultaneously reduce the deployment cost.

More recently, new research work has emerged, proposing algorithms for the placement of vEPC’s VNFs. In [14], the authors proposed a VNF placement method, particularly for placing mobility-anchor gateways (i.e., SGW) over a federated cloud so that the frequency of SGW relocation occurrences is minimized. The aim of this work was to conduct an efficient planning of Service Areas (SAs) retrieving a trade-off between minimizing the UE handoff between SAs, and minimizing the number of created instances of the virtual SGWs. In [15], the focus was on the VNF placement and instantiation of another mobile network functionality, namely a VNF that would be deployed to build a vEPC. Formally, the set of VNFDs that would be deployed to build a vEPC is defined as

\[ \Phi = \{ \text{MME, HSS, SGW, PGW} \} \]

Moreover, these research works assume that MME keeps record of the locations of UEs in idle mode at a TA granularity [17], [19]. As per Release 8 of the 3GPP mobile network specifications, S1-MME and S1-U interfaces are changed by the S1-Flex interface that allows each TA to be served by multiple MMEs and SGWs within a pool area. The set of TAs, served by the same MME/SGW node, forms an MME/SGW pool/service area, respectively. Formally, a MME pool area is defined as a set of TAs where a UE may be served without the need to change the serving MME. MME pool areas may overlap with each other [20]. On the other side, SGW service area is also defined as a set of TAs where a UE does need to change its SGW while moving within the same service area. SGW Service Areas (i.e., SA) may also overlap with each other. Knowing that the traffic generated by UEs (i.e., at both control and data plane levels) could be aggregated at the TA level, the first part of the virtual-EPC framework consists in devising algorithms that compute the optimal number of instances to deploy for each VNF \( \vartheta \) (i.e., HSS, MME, SGW or PGW) to handle the expected mobile traffic. In addition, the algorithms should associate each TA with its respective MME/SGW pool.

A VNF that would be deployed to build a vEPC. Formally, \( \vartheta \) can be MME, HSS, SGW, or PGW.

\[ T \] is the time in discrete format, where each element \( t \in T \) represents the occurrence time of one or multiple events.

\[ \Phi_{A,B} \] is an array that shows the number of cumulative events \( x \in \Upsilon \) that would be removed if TAs \( A \) and \( B \) are served by the same instance of VNF during \( T \). For each \( t \in T \), \( \Phi_{A,B}[t] \) represents the number of cumulative events \( x \in \Upsilon \) that would be removed if TAs \( A \) and \( B \) are served by the same instance of VNF during the time \( t \).

\[ \Gamma_{A} \] is an array that shows the number of cumulative events \( x \in \Upsilon \) initiated from TA \( A \) during \( T \). For each \( t \in T \), \( \Gamma_{A}[t] \) represents the number of cumulative events \( x \in \Upsilon \) initiated from TA \( A \) during the time \( t \).

\[ \mathcal{L}^{\Upsilon} \] is the set of flavors in \( \Upsilon \).
IV. VIRTUAL-EPC MECHANISM

In this section, we present the basic concept of the coalitional game and the different mechanisms used for instantiating vEPCs. In what follows, the VNF $\vartheta$ of vEPC will be instantiated one by one using coalitional game mechanism. Let $v(S)$ denote the characteristic function of the coalitional game, which is defined as follows:

$$v(S) = \begin{cases} 0 & \text{If } |S| = 0 \text{ or QoS is not ensured.} \\ P_{\vartheta} - \theta_{\vartheta} & \text{Otherwise} \end{cases}$$  \hfill (1)

where $P_{\vartheta}$ is the price that the operator is willing to pay for deploying VNF $\vartheta$, whereas $\theta_{\vartheta}$ is the price for deploying $\vartheta$ in variant $\mathcal{CN}$.

A. Coalitional game for building one vEPC instance

In this paper, the type of coalitional games used belongs to the coalitional formation game which aims to form the different coalitions, such that the profit of the different players $(\mathcal{CN})$ is increased. The coalition formation would be defined according to the gain and the cost from the cooperation. Many ways are proposed in the literature to share the profit $v(S)$ among the different players $(\mathcal{CN})$ in the same coalition $S$. The shapely value [22] is used in the literature to fairly share the profit among the different players. An easy way to share the profit among different players is the use of an equal-sharing method. Due to the simplicity of its implementation, this method is widely used in the literature [22]. In this paper, we also use the equal-sharing method to define the payoff of different players in the coalition. However, any other method (i.e., shapely value or nucleolus) can be also used in our framework with a slight modification. Based on the above-mentioned remark, the payoff of each player $\mathcal{CN}$ in a coalition $S$ is defined as follows:

$$\Pi_S(\mathcal{CN}) = \frac{v(S)}{|S|}$$  \hfill (2)

In what follows, we define the two main rules for the coalitional formation game [23]: the merge and split. We define two comparison relations $\succsim_m$ and $\succsim_s$ for the merge and split, respectively. Note that $\mathcal{CN}$s are selfish as each of them aims to increase its payoff without caring about the other players. The merge $\succsim_m$ and split $\succsim_s$ relations are defined as follows:

$$C_m \succsim_m C_s \Leftrightarrow \{ (\forall S \in C_s, \forall \mathcal{CN} \in S : \Pi_{C_m}(\mathcal{CN}) \geq \Pi_{C_s}(\mathcal{CN})) \wedge (\exists S' \in C_s, \exists \mathcal{CN} \in S' : \Pi_{C_m}(\mathcal{CN}) > \Pi_{C_s}(\mathcal{CN})) \}$$  \hfill (3)

$$C_s \succsim_m C_m \Leftrightarrow \{ \exists S \in C_s : (\forall \mathcal{CN} \in S : \Pi_{C_m}(\mathcal{CN}) \geq \Pi_{C_m}(\mathcal{CN}) \wedge \exists \mathcal{CN} \in S : \Pi_{C_s}(\mathcal{CN}) > \Pi_{C_m}(\mathcal{CN})) \}$$  \hfill (4)

We consider two coalitions $S_1$ and $S_2$, where $S_1 \cap S_2 = \emptyset$. Based on (3), $S_1$ and $S_2$ would be merged into $S_m = \{ S_1, S_2 \}$ iff the following conditions are fulfilled:

1) The two following conditions are correct:
   a) $\forall \mathcal{CN} \in S_1 : \Pi_{S_m}(\mathcal{CN}) \geq \Pi_{S_1}(\mathcal{CN})$
   b) $\forall \mathcal{CN} \in S_2 : \Pi_{S_m}(\mathcal{CN}) \geq \Pi_{S_2}(\mathcal{CN})$

2) One of the following conditions is correct:
   a) $\exists \mathcal{CN} \in S_1 : \Pi_{S_m}(\mathcal{CN}) > \Pi_{S_1}(\mathcal{CN})$
   b) $\exists \mathcal{CN} \in S_2 : \Pi_{S_m}(\mathcal{CN}) > \Pi_{S_2}(\mathcal{CN})$

The $\text{instanceVNF}(\vartheta, \Gamma, \Phi)$ function will merge two coalitions $S_1$ and $S_2$ iff at least the profit of one player in this coalition will increase while the profit of all the other players will remain unaffected. For the split mechanism, a coalition $S_m = \{ S_1, S_2 \}$ will split into two coalitions $S_1$ and $S_2$, iff the conditions in (4) are met. $S_1$ (resp., $S_2$) will split from $S_m$, iff at least one player in $S_1$ (resp., $S_2$) enhances its payoff while the payoffs of the other players in $S_1$ (resp., $S_2$) are not affected. Formally, $S_m = \{ S_1, S_2 \}$ will split into two coalitions $S_1$ and $S_2$ iff one of the following conditions are fulfilled:

1) The two following conditions are correct:
   a) $\forall \mathcal{CN} \in S_1 : \Pi_{S_1}(\mathcal{CN}) \geq \Pi_{S_m}(\mathcal{CN})$
   b) $\exists \mathcal{CN} \in S_1 : \Pi_{S_1}(\mathcal{CN}) > \Pi_{S_m}(\mathcal{CN})$

2) The two following conditions are correct:
   a) $\forall \mathcal{CN} \in S_2 : \Pi_{S_2}(\mathcal{CN}) \geq \Pi_{S_m}(\mathcal{CN})$
   b) $\exists \mathcal{CN} \in S_2 : \Pi_{S_2}(\mathcal{CN}) > \Pi_{S_m}(\mathcal{CN})$

The $\text{instanceVNF}(\vartheta, \Gamma, \Phi)$ function that uses coalitional game to deploy the instances
Algorithm 1 instanceVNF(ϑ, Γ, Φ)

Input:
ϑ: A component of vEPC.
Γ: The number of cumulative events.
Φ: The number of cumulative events would be omitted.

1: Ξ = \{DC_1, DC_2, ..., DC_{|Ξ|}\}
2: visited = \emptyset;
3: while True do
4:   stop = True
5:   for all S ∈ Ξ do
6:       if S ⊈ Ψ then
7:           Ψ[S] = v(S)
8:       end if
9:   end for
10: // Merging process
11: for all S_i, S_j ∈ combinations(Ξ, 2) \ visited do
12:   visited = visited ∪ {(S_i, S_j)}
13:   if |S_i ∪ S_j| /∈ Ψ then
14:      Ψ[S_i ∪ S_j] = v(S_i ∪ S_j)
15:     end if
16: // Using Ψ the values of Π_{S_i}, Π_{S_j} and Π_{S_i ∪ S_j} are computed
17:     if |S_i ∪ S_j| /∈ m \{S_i, S_j\} then
18:       Ξ = Ξ ∖ \{S_i, S_j\}; Ξ = Ξ ∖ \{S_i \cup S_j\}; Ξ = Ξ ∪ \{S_i, S_j\};
19:       stop = False;
20:       break;
21:     end if
22: end for
23: // Split process
24: for all S ∈ Ξ ∧ |S| > 1 do
25:   break = False;
26:   for all \{(S_i, S_j)\} ∊ S ∧ S_i ∪ S_j = S ∧ S_i ∩ S_j = \emptyset do
27:     if S_i ∉ Ψ then
28:       Ψ[S_i] = v(S_i)
29:     end if
30:     if S_j ∉ Ψ then
31:       Ψ[S_j] = v(S_j)
32:     end if
33:   end for
34: // Using Ψ the values of Π_{S_i}, Π_{S_j} and Π_S are computed
35:     if |S| /∈ m \{S_i, S_j\} then
36:       Ξ = Ξ ∖ \{S\}; Ξ = Ξ ∖ \{S \cup S_i\}; Ξ = Ξ ∪ \{S_i \cup S_j\};
37:       break = False;
38:     end if
39:   break;
40: end for
41: if break = False then
42:   break;
43: end if
44: end for
45: if stop = True then
46:   break;
47: end if
48: end while
49: return Ξ;

of ϑ across different CN’s. In this function, we assume that the QoS desired for a TA A can be assured by every CN. Algorithm 1 is used to explain the general functionality of instanceVNF(ϑ, Γ, Φ).

The function instanceVNF(ϑ, Γ, Φ) first starts by forming a collection Ξ by putting every player CN in a separate coalition (Algorithm 1: Line 1). Then, a variable visited is initialized by \emptyset (Algorithm 1: Line 2). The variable visited is used to keep track of every pair of coalitions which was already visited for the merge. Every visited pair of coalitions will be put in the set visited. Then, a while loop is executed where the merge and split processes are executed repetitively until achieving the ID_p-stable collection (Algorithm 1: Lines 3–44).

In instanceVNF(ϑ, Γ, Φ), the merge and split processes are executed one after the other. In other words, only one merge (Algorithm 1: Lines 10–20) would be executed, and then only one split (Algorithm 1: Lines 21–40) would be executed until achieving the ID_p-stable collection. In the merging process, every pair of coalitions S_i and S_j, which are not yet visited, are tested if they can be merged or not (Algorithm 1: Line 10). These pairs of coalitions are put in the vector visited to prevent redundancy checks (Algorithm 1: Line 11). To prevent the computation of the function v(.) twice, the value of v(S_i ∪ S_j) will be put in the vector Ψ (Algorithm 1: Lines 12–14). If the merging condition \{(S_i, S_j) \supset_m \{S_i, S_j\}\} is verified, we merge these coalitions in the same coalition, and then exit the merging process to execute the split process (Algorithm 1: Lines 15–19). Otherwise, another pair of coalitions which was not visited yet, will be tested. Meanwhile, in the split process, we will consider every coalition S that has more than one player CN (Algorithm 1: Line 21). We try to split every two sub-coalitions S_i and S_j of S that satisfy the following conditions: i) S_i ∪ S_j = S; ii) S_i ∩ S_j = \emptyset (Algorithm 1: Line 23). The partitioning of the coalition S is done through the partitioning of an integer into two parts [21]. For example, the coalition \{CN_1, CN_2, CN_3\} can be presented with a number 7 (i.e., 111), whereas the coalitions \{CN_1, CN_3\} and \{CN_2\} would be presented with the numbers 5 (i.e., 101) and 2 (i.e., 010), respectively. Enumerating all the possible two sub-coalitions of S that satisfy the condition in Algorithm 1: Line 23 is equivalent to finding all the two numbers whereby the sum of these numbers equals to the number that represents S. Using the same approach, the redundancy in the computation of v(.) is also prevented in the split process (Algorithm 1: Lines 24–29). Then, the function instanceVNF(ϑ, Γ, Φ) splits S if it is better for the collection Ξ (Algorithm 1: Lines 30–35). If one split succeeds, we exit the split process and re-initiate the merge process. Note that the variable stop will be set to false if only one merge or one split is carried out, and then the algorithm keeps repeating the loop (Algorithm 1: Lines 3–44) until achieving the ID_p-stable collection. Then, no further merge or split processes will be carried out. Later, for the VNF ϑ, the coalition C is selected from the collection Ξ that has the highest payoff value. Then, the VNF ϑ will be instantiated in C.
V. SIMULATION RESULTS

In this section, we evaluate the performance of the proposed scheme to instantiate vEPC instances over a federated cloud of CNs. The proposed algorithm is evaluated in terms of the following metrics:

- Payoff of individual CN: is defined as the average value of individual payoffs for each player in the selected coalitions of different instances of each VNF \( \vartheta \);
- Number of merge and split: is defined as the average number of merge and split operations needed to deploy each VNF \( \vartheta \). This metric shows the complexity of the underlying scheme virtual-EPC;
- Number of CNs in the selected coalition: is defined as the average number of players in the selected coalition for each instance of each VNF \( \vartheta \).

The algorithms are evaluated using the python programming language and an extended package for graph theory called networkx [24]. We implement the proposed virtual-EPC scheme using IBM ILOG CPLEX version 12.6.1, using the branch-and-bound method to solve the optimization problems. We used historical data from real-life mobile operator network to evaluate the different solutions; i.e., the different events generated in the network, such as the attach or detach operation of a UE, the executed procedure and the number of generated messages. In the simulation results, each plotted point represents the average of 10 executions. The plots are presented with 95% confidence interval. The different algorithms are evaluated by varying the number of TAs and the number of CNs. We conduct two sets of experiments. Firstly, we vary the number of TAs and fix the number of CNs to 15. In the second scenario, we vary the number of CNs while fixing the number of TAs to 50. The value of \( P \) – the price that a vEPC operator is willing to pay – is set proportional to the number of TAs in the network.

Fig. 1 shows the performance of the proposed solution for a varying number of TAs. Fig. 1(a) depicts the impact of the number of TAs on individual payoffs of each CN. We clearly observe that an increase in the number of TAs has a positive impact on the individual payoffs. For 100 TAs, the proposed virtual-EPC solution achieves an individual payoff of 140000. Indeed, the proposed virtual-EPC solution succeeds in forming the optimal coalition for each instance among all the players \( \text{CNs} \), which reduces the cost and hence increases the profit of each player in the selected coalition. In Fig. 1(b), we notice that the number of involved \( \text{CNs} \) increases proportionally with the number of TAs in the network; from which we conclude that the proposed virtual-EPC solution uses the average number of \( \text{CNs} \) to form vEPC instances. On the other hand, we observe from Fig. 1(c) that the number of merge and split operations in the proposed solution does not exceed 20. This means that the proposed solution converges to the optimal solution within reasonable time. From this figure, we also observe that the number of TAs has a negative impact on the number of merge and split operations.

Fig. 2 depicts the performance of virtual-EPC for varying numbers of players \( \text{CNs} \). In Fig. 2(a), we illustrate the evaluation of individual payoff of each \( \text{CN} \). From this figure, we remark that an increase in the number of players has a positive impact on the individual payoff of each player in the selected coalitions formed by the proposed solution. The proposed virtual-EPC solution selects the coalitions in an efficient way, such that the profit of the players is increased as much as possible. Fig. 2(b) shows that the number of \( \text{CNs} \) in the selected coalitions increases proportionally with the number of \( \text{CNs} \) in the network. The higher the number of \( \text{CNs} \) in the network is, the higher the likelihood to select them in the best coalition becomes. Fig. 2(c) shows that the number of merge and split operations in the proposed solution increases proportionally with the number of players \( \text{CNs} \). An increase in the number of players leads to an increase in the number of possible combinations, which intuitively has a negative impact on the number of merge and split operations. Finally, we observe from this figure that the number of merge and split operations still does not exceed 25; meaning that the proposed solution would converge to the optimal solution within reasonable time.

VI. CONCLUSION

The upcoming 5G mobile system will be based on the concept of carrier cloud to facilitate the upgrade for other
next generation mobile systems. In this paper, we proposed an efficient VNF placement algorithm that aims to sustain the Quality of Service (QoS) while reducing the deployment cost. The developed framework aims for building virtual EPC instances as a Service (EPCaaS). The aim of this framework is the placement of VNF of virtual EPC in an efficient way over a federated $CN$. To achieve the desired objectives, an algorithm was proposed that uses coalitional game to place the VNF instances across different $CN$’s, such that the QoS is ensured and the profit of each $CN$ is maximized. The simulation results demonstrate the efficiency of the proposed framework. The obtained results clearly indicate the advantages of the proposed algorithm in ensuring QoS given a fixed cost for vEPC deployment, while maximizing the profits of cloud operators.

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Fig. 2. The performance evaluation of virtual-EPC for varying numbers of $CN$'s.