Distributed Control Plane Optimization in SDN-Fog VANET

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***Abstract* — Vehicular Ad-hoc Networks (VANETs) migrate today towards emergent Internet of Vehicles (IoV), which promises advanced commercial and technical capabilities. IoV can be supported by other novel technologies like Cloud/Fog computing, Software Defined Networking (SDN) and Network Function Virtualization (NFV). However, a challenge in terms of cooperation is related to the distributed characteristic of IoV and logical centralization concept in SDN. A physically distributed SDN control plane could be a solution. This paper is a preliminary work proposing an IoV Fog-based architecture and a distributed SDN control plane. A specific problem is solved, to optimize the geographic placement of the SDN controllers based on multi-criteria optimization algorithms.**

Keywords — VANET; IoV; Software Defined Networking; Multi-criteria optimizations; Controller placement.

I. INTRODUCTION

The number of vehicles in the world has constantly increased, leading today to major traffic problems and associated events, including car accidents [1]. Specific technologies like *Dedicated Short-Range Communications* (DSRC) and architectural stacks like *Wireless Access in Vehicular Environments* (WAVE) have been developed for the emerging market of *Intelligent Transport System* (ITS) [1][2]. The specifications defined by IEEE802.11p and IEEE 1609 represent the most mature set of standards for DSRC/WAVE networks [2]. The traditional ITS has continuously evolved, including vehicular communication: vehicle to vehicle (V2V), vehicle to road (V2R), or more general vehicle to Infrastructure (V2I). These networks are denoted as *Vehicular Ad-hoc Networks* (VANETs). The basic components of a VANET are the *On-Board-Unit* (OBU) placed in the vehicle and *Road-Side–Unit* (RSU) placed on the roads. Naturally, VANETs have a distributed character both in data and control plane.

However, VANETs have limitations; despite their good potential to contribute in solving safety and traffic management problems with low operational cost, they did not attract a very high commercial interest [3]. The limitations are related to pure ad-hoc network architecture (in V2V case), unreliable Internet service, incompatibility with personal devices, non-cooperation with cloud computing, low accuracy of the services, and operational network dependency. Even for vehicular traffic management task, the current VANETs are not capable to meet the future needs. On the other hand, due to the high number of vehicles, the traffic congestion will increase significantly in coming years. It is estimated that a few minutes saved, experienced in the vehicular traffic, would globally produce revenues of tens of billions Euro per year by 2030 [4]. Therefore, extending the VANET architecture is indeed a must.

A novel and emergent solution to the above issues, is the *Internet of Vehicles* (IoV), which is seen as a global span network of a vehicle network [4][5]. At network edges, the IoV will be enabled by *Wireless/Radio Access Technologies* (WAT/RAT) interconnecting OBUs to RSUs, while traditional Internet and other heterogeneous networks will be used for wide area. The IoV can be considered as a special case of the *Internet of Things* [6], where the “things” are either vehicles or their subsystems. The IoV objectives include vehicles driving (this is a basic goal - in VANET), but also others - like vehicle traffic management in urban or country areas, automobile production, repair and vehicle insurance, road infrastructure construction and repair, logistics and transportation, etc. Generally, it is estimated that smart-cities systems will include a strong IoV component.

Several and recent strong technologies can contribute in a cooperating style to IoV development.

Cloud Computing (CC) offers services to large communities of users (processing power, storage, networking) Software/ Platform/ Infrastructure as-a-Service (SaaS/PaaS/IaaS/etc.) for a large variety of applications. However, CC relies on centralized computing resources grouped in large data centers, which is not fully suitable for some environments (e.g., mobile, vehicular, VANET, IoT), where real-time actions and fast system response are essential. Consequently, a new *Fog* or *Edge Computing* [7] has been recently proposed, to extend the CC paradigm, by bringing cloud-like services to the network edge, i.e., in the proximity of the users.

Software-defined networking (SDN) [8] separates the control plane (CPl) and data (forwarding) plane (DPl), thus enabling flexible and programmable external control of data flows through logical software entities, i.e., vendor-neutral controllers. This is a powerful approach, of high interest for operators and industry. The SDN centralized up-to-date logical view upon the network, facilitates a flexible network management, allowing on-the-fly modification of the network elements behavior.

The recently proposed *Network Function Virtualization* (NFV) [9], promises to highly increase the networks flexibility, by virtualizing many network functions and deploying them into software packages. Dedicated *Virtualized Network Functions* (VNF) can be defined, then dynamically created/destroyed, assembled and chained to implement legacy or novel services. NFV can cooperate with SDN in defining new flexible and powerful architectures. This approach is also attractive for IoV.

The large communities of users/terminal devices in IoT and IoV need powerful and scalable *Radio Access Technologies* (RAT). The 4G and the emergent 5G, based on cloud computing architectures (*Cloud Radio Access Network*- CRAN) are significant candidates for constructing the IoV access infrastructure [10][11].

While IoV is estimated to become a significant progress versus VANET, many IoV advanced features and integration with the above technologies (CC, SDN, NFV) can be seen, as well, as challenges and open research issues. In particular, applying SDN control in VANET/IoV has the challenge to harmonize centralization concept of the SDN control with the native distributed VANET character. A hierarchical control solution with several regional controllers can be considered.

This paper contains a preliminary effort, first, to define an SDN - distributed controlled IoV architecture. Then, an optimization is performed, by placing the SDN controllers in optimal locations, while following multiple criteria of interest in VANET. Such a multiple controller solution can also potentially solve the horizontal SDN scalability problems [12]. In the proposed architecture, the access points (RSUs or 3G/4G base stations) can be considered as SDN forwarder nodes. The SDN controllers can be co-located to some of these access points. The specific design problems are: *What is the optimal number and placement of the controllers? How to allocate the forwarder nodes to controllers?*

The controller placement problem is a NP-hard one [13]. Different solutions can be used, with specific optimization criteria, depending on the network context and scenarios. Frequently, several criteria are of interest, e.g.: (a) to maximize the *controller-forwarder* or *inter-controller communication* throughput, and/or reduce the latency of this communication; (b) limit the controller overload (load imbalance) by avoiding too many forwarders per controller; (c) find an optimum controllers' placement and forwarder-to-controller allocation, aiming to achieve a fast recovery after failures (controllers, links, nodes). Therefore, a multi-criteria algorithm should be naturally considered, capable to provide a global optimization.

The paper is organized as follows. Section II is an overview of related work. Section III introduces the SDN-based architecture of VANET. Section IV is dedicated to the SDN control plane optimization based on multi-criteria algorithms. Section V presents conclusions and future work.

II. SDN CONTROLLED VANET - RELATED WORK

This section shortly presents related work dedicated to VANET/IoV with SDN control.

Kaiwartya et. al. [4] presents an overview on IoV architectures, network model and challenges. The IoV includes an enriched set of vehicular communications in addition to V2V, V2R/V2I, i.e., *Vehicle-to-Personal* devices (V2P) and *Vehicle-to-Sensors* (V2S). Each IoV particular communication type can be enabled using a different WAT, e.g., IEEE WAVE for V2V and V2R, Wi-Fi and 4G/LTE for V2I, CarPlay/NCF (*Near Field Communications*) for V2P and Wi-Fi for V2S. The architecture can include vehicles and *Road Side Units* (RSU), but also other communication devices. Embedding such a large range of devices makes IoV more complex, (compared to VANET), but it has the important advantage to be strongly market oriented. The layered architectural stack includes a coordination layer at network level, where SDN/NFV technologies may be candidates. Horizontally, the architecture is a multiple-plane one in which a management plane can assure the overall management and orchestration of the assembly. The optimization of the control plane is not in the scope of this work.

Y. Lu et al. [14] shows that SDN, if applied to VANET, can provide flexibility, programmability and support for new services. An SDN-based VANET architecture and its operational mode to adapt SDN concepts to VANET environments are proposed. The architectural components are: SDN controller, SDN wireless nodes and SDN RSUs. The SDN controller is a single entity (logical central intelligence of the SDN based VANET) which performs the overall control of the system. The SDN wireless nodes are vehicles, seen as data plane elements (forwarders) under SDN control. The SDN RSUs are also treated as data plane elements, but stationary. Simulation is performed to demonstrate the benefits of the approach, while considering some specific use cases (e.g., routing). However, the variant of several SDN controllers is not considered.

A recent work [15] (K. Zeng et al.) proposes a general architecture comprising Cloud-RAN technology, to realize a soft-defined networking system, able to support the dynamic nature of future heterogeneous VANET functions and various applications. A multi-layer Cloud-RAN multi-domain architecture is introduced, where the resources can be exploited as needed for vehicle users. Virtualization (for flexibility) and hierarchical cloud computing (remote, local and micro clouds) are considered for structuring the system. The high-level design of a soft-defined HetVNET is presented in detail. A hierarchy (two levels) of SDN control is proposed (one primary controller and several secondary controllers exist; each of the latter controls a given service area). The problem of optimizing the placement of the secondary controller set is not treated.

Truong et al. [16] proposes a new promising VANET architecture called FSDN, which combines SDN and Fog computing; the latter additionally brings capabilities for delay-sensitive and location-awareness services. The solution covers V2V, V2I and Vehicle-to-Base Station communications. The SDN components are: *SDN Controller* (it controls the overall network behavior via *OpenFlow* – southbound interfaces; it also plays as Fog Orchestration and Resource Management for the Fog); *SDN Wireless Nodes* (vehicles acting as the end-users and forwarding elements, equipped with OBU); *SDN RSU* (controlled by the SDN Controller; it is also a Fog device); *SDN RSU Controller* (RSUC) (controlled by the SDN controller; at its turn it controls a cluster of RSUs connected to a RSUC through broadband connections before accessing to the SDN Controller). The RSUC can forward data, but also can store local road system information and perform emergency services. From Fog perspective RSUCs are fog devices); *Cellular Base Station* (BS) *(*these BSs perform traditional functions but they are SDN controlled via OpenFlow and are additionally capable to offer Fog services). The problem of distributed SDN control is not discussed in this paper.

Kai et al. [17] presents an overview of Fog – SDN computing for vehicular networks, considering several scenarios and issues. It is shown that a mixed architecture combining the SDN centralized control with edge cloud capabilities of Fog can be powerful and flexible enough to serve future needs of IoV. No optimization of the SDN control plane is treated.

In a recent study [18], the Fog idea is further extended by utilizing vehicles as infrastructures for communication and computation, named *Vehicular Fog Computing* (VFC). It uses a collaborative multitude of end-user clients or near-user edge devices, to carry out communication and computation, based on better utilization of individual communication and computational resources of each vehicle.

The problem of SDN controller placement is not quite new. It has been studied in various works [9][18-22], but only for fixed SDN-controlled networks, usually running single or multi-criteria optimization algorithms. The specific contribution in this paper is to apply such methodologies to the specific need and architecture of SDN-VANET networks where special optimization criteria can be defined.

III. SDN CONTROLLED VANET ARCHITECTURE

This section will introduce the architecture of an IoV heterogeneous network including SDN control and Fog capabilities. It is actually a modification and horizontal extension of the architecture proposed in [16].

The architectural elements considered are described below. The Data plane includes mobile units (vehicles) equipped with OBUs; advanced RSUs, which could have more resources (computing, storage) as to play also Fog role (F-RSU) and regular RSU like in traditional VANETs; base stations (BS) of WiMAX/3G/4G-LTE type.

Note that, given the Fog capabilities of some RSUs, it is useful to have a fixed network (it is a partial mesh) with broadband links interconnecting the RSUs. This will allow a cooperative RSUs functioning of the Fog infrastructure. From the SDN point of view, all the Data plane are (or could be seen as) forwarding nodes. The data plane can be geographically organized in several service areas, each one governed by a SDN controller.

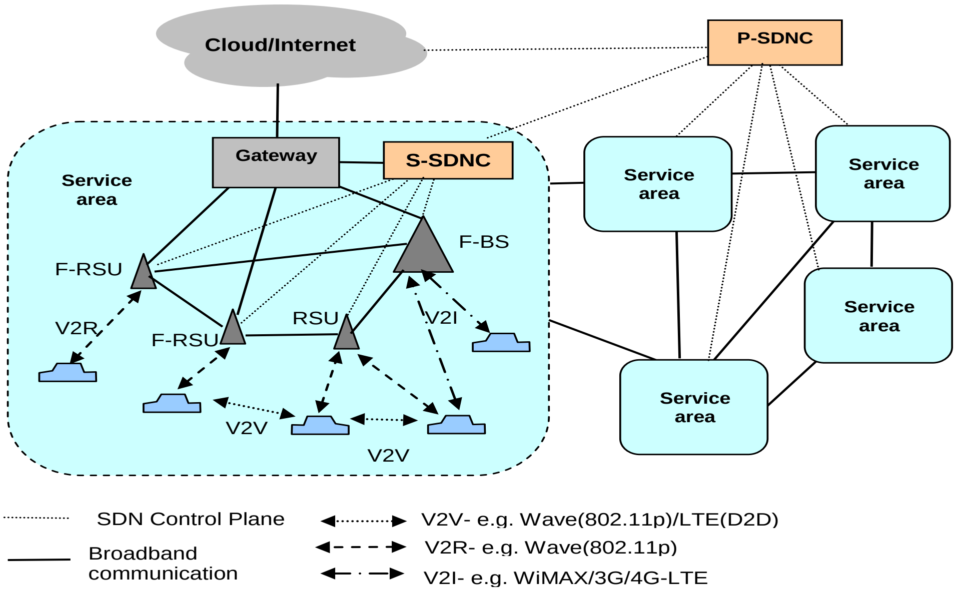

Figure 1. Generic IoV system architecture in study
F-BS - Fog-capable Base Station; F-RSU Fog-capable Remote Side Unit; P-SDNC- Primary SDN Controller;
S-SDNC Secondary-SDN Controller; D2D- device to device communication

The SDN Control plane is organized on two levels. The primary SDN controller (P-SDNC) is the central element controlling the behavior of the network as a whole. Several service areas can exist and the Control plane should cover all these. In a simplified approach, it is assumed that a regional secondary SDN controller (S-SDNC) exists in each area and it is responsible of its functioning. The S-SDNC can also contain the resource management function of the Fog infrastructure (see RSUC entity in the previous section).

The P-SDNC is logically connected to each S-SDNC via the Control plane overlay or physical links. For the sake of simplicity, Figure 1 does not detail the physical infrastructure supporting the Control plane communications. The south SDN interfaces between the controllers and the lower level can be supported by the OpenFlow protocol or a similar one.

IV. IOV SDN CONTROL PLANE OPTIMIZATION

This section develops a method to optimize the Control plane with regard of SDN controllers' placement.

A. *Problem statement*

The following assumptions are considered valid.

a. the whole access IoV geographic area is divided into several non-overlapping service areas.
b. each service area is covered by forwarders (RSUs and/or BSs) placed in fixed locations (the placement decision of the RSUs/BSs in some locations is out of scope of this study).
c. the network of forwarders in a service area can be represented by an abstract overlay graph whose properties are known by the optimization algorithm.
d. each service area can be controlled by one or, generally by several S-SDN controller(s) (the general case can provide a solution for a large service area with high number of RSUs).
e. the S-SDNCs will be co-located with some of the forwarders.
f. any SDNCs could be implemented as being 1-to-1 associated with a physical machine/node, or, several virtual controllers (based on NFV techniques) can exist in the same physical location. In the latter case the equivalent graph will have groups of nodes close together; however, the optimization solution would still work.

The optimization has two phases:

(1) given a set of criteria and a service area (region), what is the optimum placement of the S-SDNCs? This problem should be solved for each service area. The associated computation to run an algorithm can be performed in a centralized manner, e.g., in the P-SDNC.

(2) given the placement of the S-SDNCs and their equivalent higher level (overall) graph, what is the optimum placement of the unique P-SDNC, considering that it could be co-located to one node of this graph?

An early work of Heller et al. [13] has shown that the SDN controller placement problem is not new. If the metric is *latency*, then one gets the *facility or warehouse location problem* solved, e.g., by using *Mixed Integer Linear Program* (MILP) tools. Heller finds optimal solutions for realistic network instances, in failure-free scenarios, by analyzing the entire solution space, with off-line computations. Other studies [18–21] extended the approach, by considering several events like *controller* failures, *network links/paths/nodes* failures, controller *overload* (load imbalance), or *Inter-Controller Latency*, multi-path use cases, etc. The important thing is that the problem is a multi-criteria one, i.e., no unique solution is available satisfying all criteria.

Note that this work does not propose any new algorithms to optimize the controller placement for a given individual metric, but uses some previous multi-criteria overall optimization algorithm to obtain a trade-off solution in the novel IoV context.

B. *Examples of metrics used for optimization*

This sub-section is a very short presentation of a few typical metrics and optimization algorithms for controller placement. Several and more detailed examples are given in [23].

The network (of forwarders) in a service area is abstracted by an undirected graph G(V, E), where V,E are the sets of nodes and edges, respectively and n=|V| is the number of nodes. The edges weights represent an additive metric (e.g., *propagation latency*). The controllers will be co-located to some network nodes. Note that the number of controllers is much lower than the number of forwarders. After algorithm run, the controllers will be placed in some locations of forwarders. We denote a particular placement C_i of controllers, where $C_i \subseteq V$ and $|C_i| \leq |V|$. The number of controllers is limited to $|C_i| = k$ for any particular placement C_i. The set of all possible placements is denoted by $C = \{C_1, C_2 \ldots\}$

An example of a simple metric is d(v, c): *shortest path* distance from a forwarder node $v \in V$ to a controller $c \in V$. One can define, for a given placement C_i:

Worst_case_latency:

$$L_{wc} = \max_{v \in V} \min_{c \in C_i} d(v, c) \tag{1}$$

Average_latency:

$$L_{avg}(C_i) = \frac{1}{n} \sum_{v \in V} \min_{c \in Ci} d(v, c) \tag{2}$$

The algorithm should find a placement C_{opt}, where *either average latency* or *the worst case latency is minimized.*

Some comments are valuable to be given on this simple metric:

a. in IoV context, the latencies are dynamically changing, so the specific values used in (1) or (2) are actually some estimations (if static approach is applied) or otherwise they should be measured and averaged by a monitoring system and values delivered to the P-

SDNC. However, the process of obtaining the latency values is out of scope of this work.

b. the assignment of a RSU (seen as a SDN forwarder) to a given S-SDNC is based on selecting the closest S-SDNC to that RSU; so, there is no upper limit on the number of v nodes assigned to a controller; too many forwarders to be controlled by a given controller can exist, especially in large networks.
c. The placement solution does not consider any reliability features.

To solve the previous problem b., an additional criterion can be defined, i.e., to assure a good balance of the node-to-controller distribution. A metric *Ib(C_i)* will measure the degree of imbalance of a given placement C_i as the *difference between the maximum and minimum number of forwarders nodes assigned to a controller.*

$$Ib(C_i) = \{\max_{c \in C_i} n_c - \min_{c \in C_i} n_c\} \qquad (3)$$

where n_c is the number of RSUs assigned to a controller c. An *optimization* should find that *placement which minimizes the expression (3).*

Another criterion useful could be the estimated capacity (max. bandwidth) between each pair of nodes in the graph (let it be B) and in the equation (1) or (2) the latency could be replaced bay the value 1/B for each overlay link.

In a multi-controller SDN environment, the inter-controller latency (Icl) has impact on the response time for the inter-controller mutual updating. Therefore, this is an important metric. For a given placement C_i, the *Icl* can be given by the maximum latency between two controllers:

$$Icl(C_i) = \max d(c_k, c_n) \qquad (4)$$

Note that the attempt to minimize (4) will lead to a placement with controllers close to each other. However, this can increase the forwarder-to-controller distance (latency) given by (1) and (2). This is an example showing that a trade-off is necessary, *thus justifying the necessity to apply some multi-criteria optimization algorithms, e.g., like Pareto frontier - based ones* [22][23].

Various other metrics can be considered e.g., reliability-related, which consider node/link failures [20][21]. Other studies exploit the possible multiple paths between a forwarder node and a controller [22], hoping to reduce the frequency of controller-less events, in cases of failures of nodes/links. The goal in this case is to maximize connectivity between forwarding nodes and controller instances.

C. Overall optimization algorithm

Several optimization algorithms can be applied for the controller placement problem [13][19-22]. This paper uses a simple but powerful approach which is called multi-criteria decision algorithm (MCDA) [24] in a variant *reference level (RL) decision algorithm,* already used in [23] for a similar problem. The MCDA-RL selects the optimal solution based on normalized values of different criteria (metrics). Details on how to apply the MCDA-RL are given in the work [23]. Here, a similar approach is performed for the SDN controlled IoV.

The control plane optimization contains two phases, each composed of several steps which are described below.

Phase A. Optimization for S-SDNC controllers' placement.

a. The overall IoV geographic region (access part network) is conveniently divided in non-overlapping service areas, based on various criteria (commercial/ business, geographic, administrative, physical radio propagation criteria, vehicle traffic estimation data, etc.)
b. For each service area, the forwarder nodes (RSU, BS, gateway) placement is decided, based on criteria similar as in step a. An abstracted connectivity graph between RSUs should be derived. Note that not all RSUs should be considered as nodes in the abstract graph; usually the RSU-fog nodes or nodes having a minimum of resources (including electrical power) should be selected. Therefore, the branches of the graph might represent physical or overlay links. Some RSUs will be collocated with S-SDNCs.
c. The criteria of interest to be target of the MCDA-RL optimization are selected (e.g., controller-node latency, imbalance of a placement, inter-controller latency, etc.). These criteria will be mapped to the decision variables in MCDA-RL. If needed, the criteria can be assigned different priorities and the algorithm will consider them.
d. A reasonable number (heuristically decided) of S-SDNC controllers are supposed to be defined for each service area.
e. Repeat for each service area:

{e.1: For the parameters of interest, one should compute the *values of the metrics for all possible controller placements*, using specialized single-criterion algorithms and metrics like those defined in formulas like (1) - (4). This step will produce the set of candidate solutions (i.e., S-SDNC placement instances). This procedure could be time consuming (depending on network size) and therefore, could be performed off-line as suggested in [13].

e.2: Run the steps of the MCDA-RL (the details are shown in [23] and are not repeated here). The algorithm will provide as result the best trade-off solution (in Pareto [24] sense) for the S-SDNCs placement for this service area}.

Phase B. Optimization for P-SDNC controller placement.

Now the placement of the S-SDNCs is known; therefore, a connectivity graph linking the set of the S-SDNCs can be derived. Then the placement of the Primary SDNc should be computed in optimal sense by applying steps c. d. and e. of the Phase A.

D. *Numerical example*

A simple example illustrates the MCDA flexibility. Figure 2 shows a connectivity graph between RSUs, BS, etc., abstracted as vertices v_1, ..v_6. The numbers on the graph branches represent (generically) an additive metric (e.g., latency). Suppose that for this service area it is wanted to co-locate two S-SDNC controllers with some nodes v.

Suppose that for this network the metrics of interest and decision variables are on: d1: *Average latency* (1); d2: *worst latency (2)* (failure-free case); d3: *Inter-controller latency (4)*. We denote an S-SDNC controller with c_1 or c_2. The allocation of the forwarders to controller will be based in this example on shortest-path from forwarder to controller.

Several candidates for placement solutions can be considered, e.g.:

C_1= { [c_1_in_v_5 (v_5, v_2, v_4)], [c_2_in_v_6(v_6, v_1, v_3)]}
C_2= { [c_1_in_v_4 (v_4,v_2, v_5)], [c_2_in_v_6(v_6, v_1, v_3,)]}
C_3= { [c_1_in_v_5 (v_5, v_1, v_2, v_4)], [c_2_in_v_3(v_3, v_6)]}
C_4= { [c_1_in_v_3 (v_3,v_2)], [c_2_in_v_6(v_6, v_1, v_4, v_5,)]}

1. Case 1. The decision variables have equal priorities (p) i.e., p1=1, p2=1, p3=1. The values of the metrics are computed using equations (1), (2) and respectively (4) for each placement: C_1, ..C4. The final result after running MCDA is: *C_1 = the best placement.* In Figure 1, one can see that this placement is a good trade-off between node-controller latency and inter-controller latency.

2. Case 2. Different priorities are defined: p1=1, p2=0.5, p3=1, i.e., the worst case latency d2 has highest priority (lower value means higher priority). So, the solution minimizing the worst case controller-forwarder latency (this criterion has high priority) is searched by the MCDA. Finally, it is found after running MCDA, that *C_2= the best placement*. Figure 2 shows that worst case latency (node-controller) is minimized, however the inter-controller latency is in this case higher than in solution C_1.

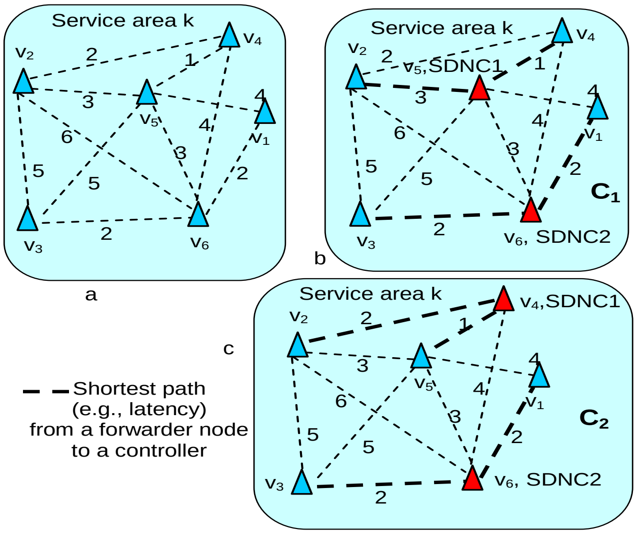

Figure 2. Numerical example of SDNC controller placement in an IoV service area

These examples prove how different network operator's policies can bias the algorithm results.

V. CONCLUSIONS AND FUTURE WORK

This paper presented a work in progress which proposed an IoV Fog-based architecture and a distributed SDN control plane. The architecture comprises RSUs, BS, geographically distributed in non-overlapping service areas which are interconnected. Some RSUs are advanced ones, having Fog capabilities. The whole infrastructure is controlled by a distributed SDN control plane.

The SDN control plane consists in several controllers organized on two hierarchical levels: a unique primary controller P-SDNC governing the assembly and several secondary S-SDNCs in the service areas. It is supposed that S-SDNCs could be collocated to some forwarder nodes (RSU, BS).

Then an optimization method is proposed for the geographic placement of the SDN controllers, by applying a multi-criteria optimization algorithms (MCDA). Some previously developed optimization algorithms have been used, but in a novel way adapted to IoV - SDN controlled context.

The optimization method proposed achieves an overall optimum (in Pareto frontier sense) and is very simple from implementation point of view. In particular, the MCDA-RL algorithm can produce a tradeoff (optimum) result, while considering several (weighted) criteria, part of them even being partially contradictory. The method is general and can be applied in various scenarios (including failure-free assumption ones or reliability – aware).

The computations could be performed offline, or even online (e.g., in the P-SDNC- which is naturally supposed in SDN technology to have knowledge upon its forwarding plane network). The S-SDNC placement algorithm could run in the P-SDNC, from time to time (or, event-triggered), especially if S-SDNCs are implemented as virtual machines in some forwarding network nodes, and the set of the active virtual machines should be re-defined. This approach will be for further study. Future work could deal with validation and simulation studies for large network environments (e.g., hundreds or more RSUs).

Future work will be done to apply the method proposed to other metrics, considering multi-path approach for forwarder-controller paths. Other area of investigation could consider the Fog node placement problem in the IoV access network, where similarity with the problem studied here can be found.

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