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MIGRATE: Mobile Device Virtualisation Through State Transfer

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ABSTRACT Delegation of processing tasks to the network has moved from cloud-based schemes to edge computing solutions where nearby servers process requests in a timely manner. Virtualisation technologies have recently given data cloud and network providers the required flexibility to offer such on-demand resources. However, the maintenance of close computing resources presents a challenge when the served devices are on the move. In this case, if processing continuity is desired, a transference of processing resources and task state should be committed to maintain the service to end devices. The solution here presented, MIGRATE, proposes the concept of virtual mobile devices (vMDs) implemented as Virtual Functions (VxF) and acting as virtual representatives of physical processing devices. vMDs are instantiated at the edge of the access network, following a Multi-Access Edge Computing (MEC) approach, and move across different virtualisation domains. MIGRATE provides seamless and efficient transference of these software entities to follow the real location of mobile devices and continue supporting their physical counterparts. Software Defined Networks and Management and Operation functions are exploited to ''migrate'' vMDs to new virtualisation domains by forwarding data flows to the former domain until the new one is prepared, while a distributed data base avoids the transference of data. The solution has been deployed in a reference vehicular scenario at the Institute of Telecommunications Aveiro premises within the 5GINFIRE European project. In particular, the system has been evaluated under different virtualisation domains to study the operation of the migration approach in a vehicular monitoring scenario. The results validate the system from the application viewpoint with a Web monitoring tool, and the migration of the digital twin provided as VxF is analysed attending to the modification of data flows, indicating a seamless transition between virtualisation domains in a timely manner.

INDEX TERMS NFV, migration, mobility, computing offloading, 5G, multi-access edge computing, experimentation, data collection.

I. INTRODUCTION

A Advances in virtualisation of computing resources have been carried out within the area of Network Function Virtualisation (NFV). In parallel, during the last years, softwarisation has reached the management of networks and data flows, within the field of Software-Defined Networking (SDN). Using SDN it is possible to manage communication flows programmatically by acting on switching and routing devices in networks. Depending on flow peculiarities such as end points, type of traffic, protocol used or even quality of service (QoS) required, packets can be routed through different paths. This is particularly relevant when associated to NFV in wholly virtualised platforms, to host services elastically along

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the network path, from the access point to the datacenter. In these scenarios, resources assigned to "cloud" services can be adapted to the dynamic features of end-devices and clients.

Virtualisation of computing and network functions is a key advance of 5G, and it can be used to offload constrained devices from processing and data management tasks. Instantiating virtual substitutes for physical devices has been proved to be beneficial in terms of device access delay, reliability against wireless disconnections or data cache, as the SURROGATES proposal showed.[1] A way of exploiting Multi-access Edge Computing (MEC) capabilities of 5G is to maintain these virtual substitutes near or within the access network. However, a proper support of device mobility should be provided as it traverses access networks belonging to different administrative domains. In this case, virtual mobile nodes in the form of digital twins must be able to "migrate" to new edge virtualisation domains.

The MIGRATE proposal generalises the idea of virtual mobile devices (vMDs) and provides an efficient and novel solution for the migration of these software entities to follow the real location of mobile devices (MDs). This is carried out by using SDN and extended Management and Operation (MANO) functions. Many vertical industries may be identified as potential users of our proposal. Vehicular services are the first market that comes to mind. They are gaining great momentum again thanks to the low-latency and architectural flexibility provided by 5G and its closely-related networking virtualisation techniques such as SDN and NFV. In the previous SURROGATES project [1] some of these aspects were already considered. In that project, virtualisation of On-board Units (OBUs) was addressed with the aim of improving vehicle reachability in the case of connectivity issues as well as reducing response time. However, in SURROGATES, mobile scenarios in which the virtualized entity needs to be "migrated" from one domain to another was not studied. This novel feature paves the way for the development of a plethora of applications in other fields. A clear example is the development of intelligent and continuous spaces, in which a terminal device could seamlessly move across different scenarios e.g., home, office, recreational activities, etc., running auto-adaptable services and receiving customised information depending on its position and context. Wearables are another potential application use case, given their constrained processing and storage capacities.

Considering the previous constraints and limitations, the main contributions of this work are the following:

- Design and implementation of an SDN-powered solution for a state transfer approach for digital twins.
- Design and deployment of a novel end-to-end MANO architecture that enables the coordination of the different virtualisation domains of the system.
- Validation tests in real premises with a remote integration with a real vehicular scenario.
- Demonstration of the seamless transition between virtualisation domains.

[1] https://5ginfire.eu/surrogate/

The rest of the paper is organised as follows. Section II presents the most prominent related papers. The MIGRATE architecture and its operation are explained in Section III and Section IV, respectively. The implementation details for a reference vehicular scenario are given in Section V. Section VI shows and discusses the results obtained from the system after real evaluation. Finally, Section VII concludes the paper summarising the most important findings.

II. STATE OF THE ART

The MIGRATE proposal stands between the cloud and end device planes, by exploiting MEC in mobile scenarios. It is observed a growing interest in this area. The work in [2] identified the hot issues in MEC when facing mobile scenarios, which are divided into strategies to improve computing (application plane) and solutions to maintain connectivity mainly using SDN (routing plane).

There are several proposals in this line within the vehicular domain. A MEC layer implemented in drones as road-side units was presented in [3], but it is statically mapped on physical devices. The improvement implied by MEC for vehicle to vulnerable road user communications was evaluated in [4], using 4G simulation and observing up to 80% of latency reduction as compared with a cloud-based system. In [5], the MEC paradigm was used to improve the performance of a delay-tolerant network, by providing caching of messages for temporally disconnected vehicles. In [6], it was proposed a way to orchestrate computing and caching in vehicular scenarios between MEC and remote servers. In [7] a MEC layer was proposed to process information coming from vehicles implementing a vehicular social network, although the potential of NFV and MANO was not exploited to cope with the dynamism of the system. The same lack is found in [8], where a content delivery network used a MEC-based architecture to speed-up data sharing among vehicles. An interesting feature included in [9] is the combination of MEC and multiple Radio Access Networks (RAT), which is also considered in MIGRATE. Unfortunately, NFV flexibility was not exploited. This lack is covered in the works in [10], [11], focused also on vehicular applications, but without particularly dealing with the issue of moving resources.

SDN capabilities further improve network flexibility in dynamic scenarios. In [12], for instance, the authors present a system to adapt communication routes using edge computing and SDN for industrial Internet of Things (IoT) systems. A similar approach but focused on vehicular networks is presented in [13], paying special attention to the selection of diverse wireless RATs using SDN. MEC is used in [14] for both application and network planes, but it also considers the migration of virtual network functions (VNFs) along the network hierarchy according to the system load. The allocation and migration of VNFs is being widely studied using formal methods, as can be seen in [15]–[17] considering parameters such as the computing load and network performance.

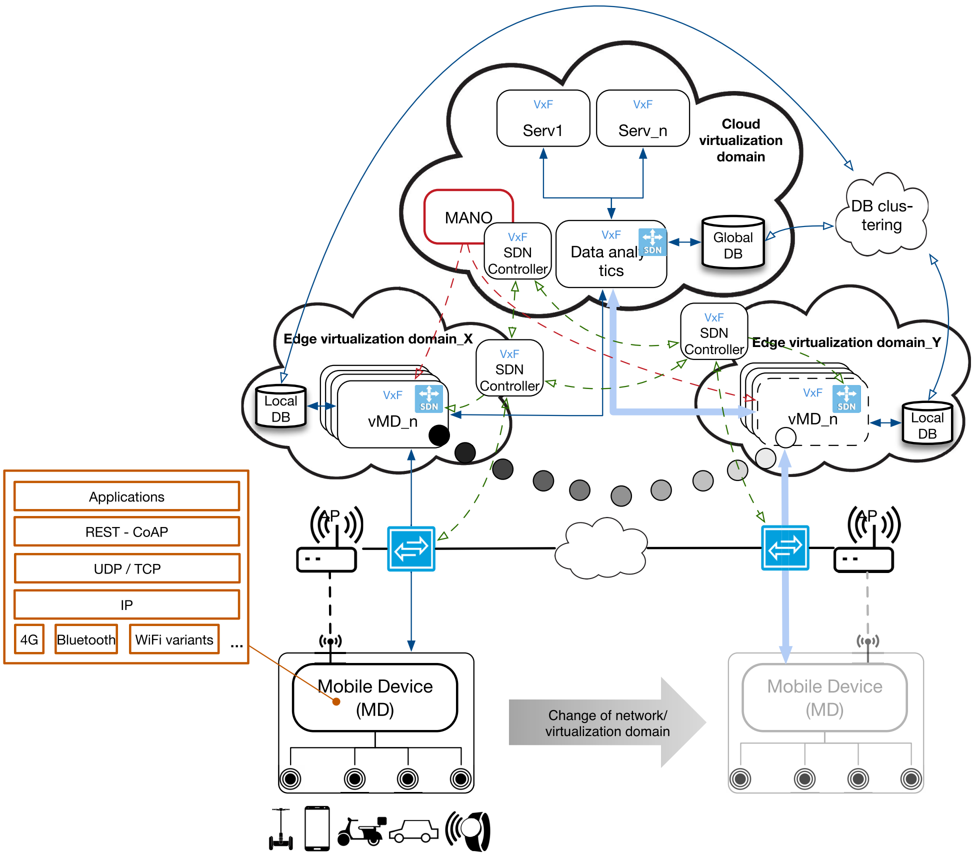

FIGURE 1. **Architecture of MIGRATE with main components and interconnections. The migration phase is illustrated with a shadowed MD appearing in a new edge virtualisation domain.**

These proposals distinguish between two different migration/scaling schemes: vertical, in which new instances of VNFs are started; and horizontal, when the NFV state is transferred to another VNF already prepared. The work in [18] proposes a solution to choose one or the other approach to meet application requirements, given that a vertical migration could imply significant cuts in the service. A solution to the loss of packets in the VNF migration process is given in [19] with SDN re-routing and minimising caching of messages addressed to the old VNF placement. However, a limited testbed is used to particularly evaluate the performance of the migration procedure using SDN, without involving the management of virtualisation resources with MANO capabilities. In [20] the migration of VNFs is dealt by using SDN to offer a better service of pure network functions, such as the case of a firewall, but this solution does not consider the issue of state transfer and the usage of general-purpose virtual functions (VxFs). The assurance of network capabilities and the seamless transference of data flows during migration is studied in [21], also through the extensive use of SDN and both simulating and presenting an experimental study case. The work in [22] does consider both SDN and NFV migration for generic computer resources, in this case dealing with the decision on starting the transference process once an overhead situation is detected, instead of considering the problem of attending the movement of constrained devices. The same problem is addressed in [23], but this time by using replicas of VNFs to speedup the migration once it is necessary. Although our experimental deployment involves a more general migration framework, it shares with this work the idea of using pools of VNFs that replicate already running virtual instances.

Being also a solution addressing MEC computation in mobile scenarios, MIGRATE bets on virtualising mobile devices as VxFs at the edge, in order to create always available "digital twins" where to offload intensive operations and save current and past state information. This presents a generic approach independent of any application domain, abstracting the access to the itinerant real device, which is subject to potential communication losses. MIGRATE proposes a horizontal migration scheme based on state transfer in which virtual mobile devices "follow" their physical counterparts across different access networks while providing MEC capabilities. These handovers are seamlessly provided by resource pre-fetching using MANO functions and route adaptation with SDN, while digital twin data is synchronised across the network by using a distributed database.

III. BASE ARCHITECTURE OF MIGRATE

As Fig. 1 shows, MDs are regular smart phones, wearable gadgets or embedded devices integrated in scooters, motorbikes or cars. They gather sensor data using light IoT protocols like Constrained Application Protocol (CoAP), and provide access to services of different nature. MIGRATE considers the dynamic creation of virtual functions (VxFs) in the form of vMD to cope with processing and data cache in a MEC fashion, given the energy and computing constraints of MDs. Data collected is then consumed by a data analytics function at a cloud virtualisation domain, which feeds final services. Upon the movement of MDs to a network point of attachment (access point - AP) that belongs to a different network virtualisation domain, it is necessary to maintain connectivity with its virtual counterpart. MIGRATE bets on instantiating new vMDs on demand, by using a base software platform that inherit the configuration parameters of the former vMD. To finally make operational the new vMD, data paths are updated using SDN functions, pointing monitoring and request messages to the new VxF. This is possible since the network entrance point to the virtualisation domains are SDN-capable switches. The transfer of data to a newly created vMD is deferred until it is checked to be ready in the new edge virtualisation domain.

The associated data base, which is provided as another VxF, maintains synchronised among the different network domains involved. A distributed data base approach has been followed in the solution, using a cluster-based data base management system. Hence, vMD data is synchronised among data base "copies" through the backbone network, which is expected to provide a high throughput.

Regarding the operation of SDN controllers, it can be seen in Fig. 1 that each virtualisation domain is envisioned with an SDN controller, deployed as a VxF as well for the sake of flexibility. It is worth noting that the migration solution is prepared to be used between sites physically located far away. Because of this, although the architecture is open to any SDN controller solution, it is understood that a multi-controller function would be appropriate to tackle potential reliability issues and bringing the controller near the switching functions to reduce signalisation delay [24]. It is important to note that a large deployment could involve many SDN switches managing a number of data flows, and a single SDN controller could be a bottle neck for the system. The concept design of MIGRATE considers as viable both flat [25] and hierarchical [26], [27] SDN multi-controller solutions; hence, both edge and cloud domains are initially provided with SDN controller functions.

Different 5G verticals involving mobile devices could benefit from the solution, such as the 5GPPP-identified automotive, smart city and health care, which in fact has presence within the 5GINFIRE ecosystem. A reference implementation of the solution has been developed within the 5GINFIRE project, including new software modules in the form of VxFs that will remain as facilities to be reused within the project lifetime and beyond.

As it is later detailed, a reference implementation of the system has been evaluated at Instituto de Telecomunicacoes in Aveiro (IT-Av) testbed [28], which involves a communications infrastructure for the evaluation of new services and applications for the vehicular vertical.

IV. OPERATION OF THE SOLUTION

A modular view of the different virtualised components of MIGRATE is given in Fig. 2 and Fig. 3. As a reference to show the operation of the solution, two edge and a cloud virtualisation domains are considered, using three different network services hosted by a Virtualised Infrastructure Manager (VIM). vMDs are deployed within the near edge virtualisation domains, in order to provide a MEC layer close to the MDs. The Local DB VxF allows vMDs to update data regarding MDs using a local access to the cluster-based database. Within the cloud virtualisation domain, the data analytics module is in charge of periodically collecting data from vMDs and apply Big Data algorithms. When no Big Data algorithms are used, this entity simply aggregates information. From the data analytics module, different services get the data collected and processed/aggregated. Additionally, both raw and processed data from vMDs are stored in the distributed database, which is accessible through the available DB VxF. Services are considered to be deployed also as VxFs in the cloud domain, hence consuming data from the Data analytics module. SDN controllers are kept synchronised using a multi-controller solution such a cluster-based distribution.

Signalling messages are depicted in red colour in Fig. 2 and these are REST packets over TCP. The blue ones indicate data requests and exchanges. Those messages traversing the wireless link between the MD and vMD are CoAP packets over UDP, while the rest are regular REST messages over TCP.

The operation showed in Fig. 2 first describes the registration of MDs in the system when it starts operating. This is necessary in order to assign a vMD instance to each physical MD. The process starts with a vMD solicitation from an MD, which is processed by the MD manager. The design of the solution considers here a communication with the MANO module in order to dynamically instantiate a new vMD for the physical MD. Once the vMD is allocated, the connection details are given to the physical MD, which can now start the data gathering process.

The behaviour of the system when a particular request must be sent to a MD from a cloud service is also illustrated in blue colour in Fig. 2. Here, it can be seen that there are three different indirection levels where requests can be solved, thanks to the multi-layer data processing scheme. In the first one the data request is processed by the data analytics module, which periodically receives information from MDs and process it in a global manner or, directly, aggregates all data collected. In this first level, data can be also accessed through the DB VxF. However, if the particular request from the service cannot be solved locally, it is then forwarded to the particular vMD representing a physical MD. For this to be done, the data analytics module needs to ask MD manager about the vMD "impersonating" the MD. Steps 8b and 9 in Fig. 2 are performed periodically, so it could not be needed

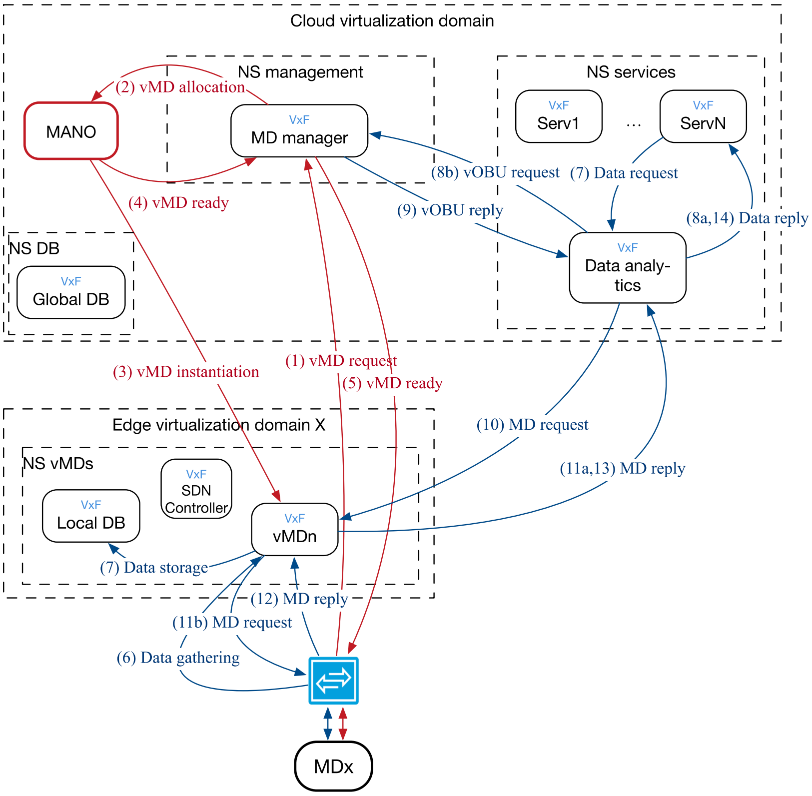

FIGURE 2. Registration of MDs to obtain its digital twin and illustration of the data path to access MD information.

at the time the request is made by the service. It is considered that most of the requests could be solved within the cloud virtualisation domain or the vMD but, if a particular data is required that is not stored in the platform, or if a real-time parameter is needed from MD, the request can be finally forwarder to the physical device.

The main advance of MIGRATE regards to the process of transferring MEC capabilities for MDs when they change the network domain they attach to. This is illustrated in Fig. 3. MD periodically reports data to the platform using an SDN switch as entry point to the wired network. The migration procedure starts at the switch, when it detects a packet arriving from the same mobile device address (layer two) to a new port, or when CoAP messages sent to the vMD come from a different IP source address (layer three). The solution is also prepared to add any other rule to detect the migration. The migration event is reported to the SDN controller present in the domain, which acts in two ways. First, it indicates a re-route action for this MD traffic towards its already running vMD. And, second, it warns the MANO function about a migration event, which prepares the new virtualisation domain to host a new vMD inheriting the behaviour of the former vMD. Once this is done by signalling with the VIM of the new domain, the SDN controller is notified to establish a new route in the SDN switch to send data packets through the new vMD within domain Y in Fig. 3.

The migration process guarantees that no data packets are lost due to the change of MEC capabilities from the source to the target virtualisation domain. Moreover, the process is transparent from any link or network mobility procedure, given that flexible matching rules can be established in SDN switches to identify the MD. If relevant data losses appear, they will be due to association and re-addressing mechanisms needed in the new network domain. As can be seen, since data is locally reported to a DB VxF implementing a cluster-based database, data coherence is assured if a proper database management system is used together with a high-performance network infrastructure. And, hence, data transfer is not needed in the migration, betting for a light state transfer approach using SDN and MANO capabilities.

Although it is not the main focus of the contribution, reliability issues have been considered in MIGRATE. Due to signalling with SDN controller and MANO use TCP, there is an inherent mechanism to deal with sporadic packet looses. However, under a fatal error in the network losing communication in any of the wireless or wired segments, the migration procedure is prepared to run a new MD registration if the system does not recover from too many losses after a timeout.

V. DEPLOYMENT OF THE SYSTEM

A. CORE MIGRATE PLATFORM

As introduced above, the MIGRATE solution has been deployed within the 5GINFIRE ecosystem in a reference automotive scenario, taking advantage of the IT-Av test-site capabilities [29], [30]. In its current state, the vehicular testbed consists of On-Board Units (OBUs), deployed

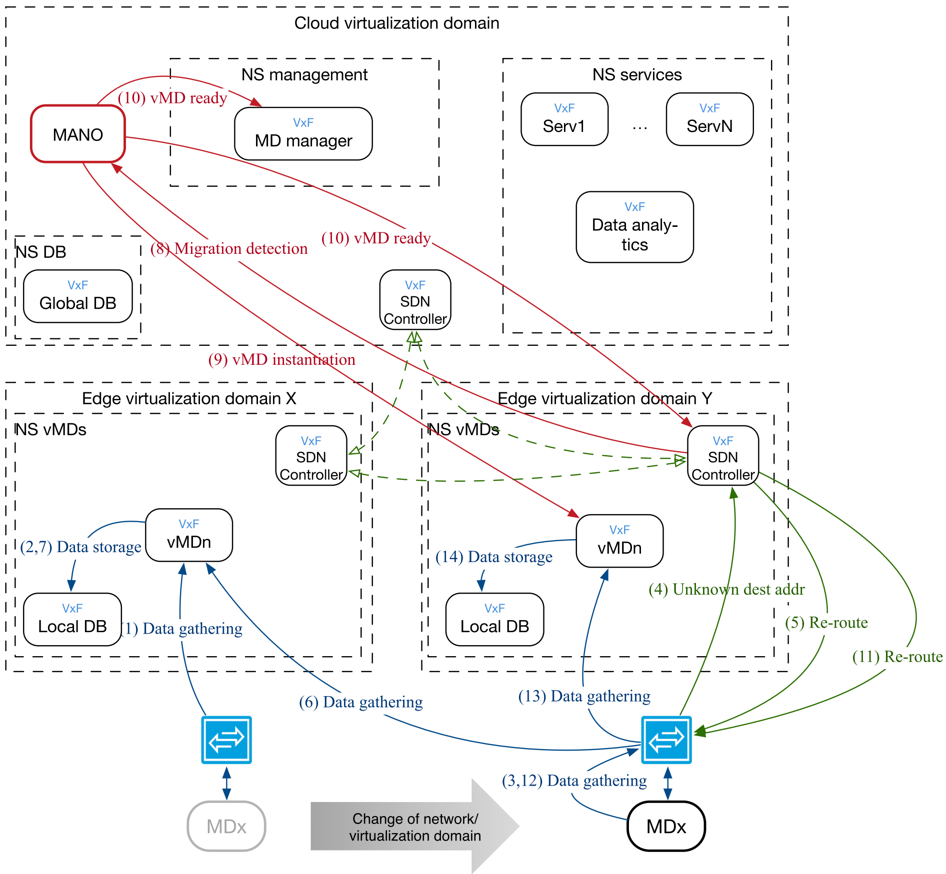

FIGURE 3. Migration procedure to transfer MEC capabilities to a new virtualisation domain, due to end device movement.

in vehicles, and Roadside Units (RSUs). The OBUs (and therefore the vehicles) are able to connect to each other using vehicular WiFi (i.e., IEEE 802.11 Outside the Context of a Basic Service Set (OCB)[2]), and with RSUs through vehicular/regular WiFi and cellular links, in a multi-homed scenario. The simultaneous connectivity between the OBU and the RSUs, through the available interfaces, is also possible, enabling the choice of the services to be transmitted through each technology. RSUs are connected through Ethernet to a central entity, responsible for coordinating the vehicles' handovers, and provide Internet connectivity through every RSU connection.

The testsite included a local virtualisation domain with Open Stack Ocata[3] acting as VIM, and mobile networking for vehicles using an extended version of Network-Based Proxy Mobile IPv6 for vehicular networks and multi-hop scenarios [31]. In order to test the migration approach, a new virtualisation domain has been set-up and registered within the 5GINFIRE MANO function, which has been deployed using Open Source MANO Release 5 (OSM).[4] OSM is located in the 5TONIC[5] testsite in Madrid, which acts as our cloud domain and is managed by Telefonica and Carlos III University. As can be seen in Fig. 4, an MD in the form of a Raspberry Pi is mounted in a car, which gains connectivity thanks to a Mobile Router (MR) with an IEEE 802.11 OCB transceiver. Two road-side units with OCB capabilities are connected with their corresponding virtualisation domains using a Pica 8 SDN switch. The edge domains are interconnected between them and with the cloud one using a virtual private network (VPN) connection over a fibre optic-based network, assuring high-performance data rate. The database management system used is Cassandra 3.11.4, and local clusters are located in the three domains. Ryu[6] is the chosen SDN controller, since it offers enough SDN functions for this particular deployment while simplifying the development of the proof of concept. A larger scenario would require an SDN solution with multi-controller capabilities such as ONOS.[7] Finally, a web-accessible service using Grafana has been developed to monitor vehicle data. This service can be reached through a 5GINFIRE gateway that creates a VPN for users registered in the platform.

Given the constrains imposed by the 5GINFIRE project, which assures a reliable service for a number of users and experiments as MIGRATE, OSM cannot be directly accessed

[2]IEEE 802.11 OCB technology was formerly known as IEEE 802.11p.
[3]https://www.openstack.org
[4]https://osm.etsi.org
[5]https://www.5tonic.org
[6]https://osrg.github.io/ryu/
[7]https://onosproject.org

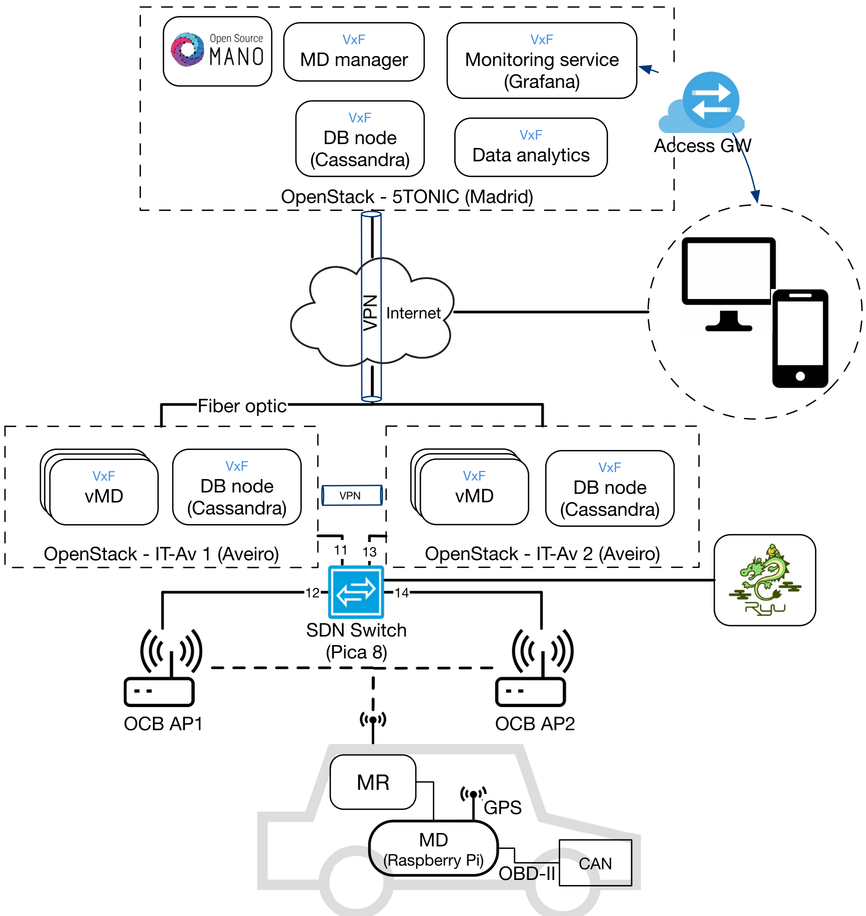

FIGURE 4. Deployment of MIGRATE in two reference 5GINFIRE testing infrastructures, involving two local (edge) clouds and a far one.

using its northbound interface. Hence, the assignment of vMDs for MDs is carried out by the MD manager using a pre-loaded pool of vMDs in each edge virtualisation domain. Due to this constraint, the deployment of the migration procedure, which also requires communications between the Ryu SDN controller and OSM, has been carried out assuming the instantiation of vMDs upon the detection of domain change. For the sake of simplicity in the deployment, the SDN controller has been installed locally, at IT-Av.

According to the components indicated in Fig. 4, the next VxFs have been deployed:

- vMD. This VxF is instantiated several times to cover the virtualisation needs of physical MDs. vMDs are deployed in the OpenStack domains of IT-Av automotive with the next resources assigned per instance: 2 CPUs, 1 GB RAM and 5 GB HD.
- DB node. This is a VxF running an instance of Cassandra in all domains and provided with 2 CPUs, 1 GB RAM and 5 GB HD.
- MD manager. This VxF has been deployed at 5TONIC premises, assigning the next resources: 2 CPUs, 2 GB RAM and 5 GB HD.
- Data analytics. Its global nature justifies its deployment in the central 5GINFIRE back-end at 5TONIC. The resources assigned are: 2 CPUs, 2 GB RAM and 10 GB HD.
- Monitoring service. A general VxF has been created as reference service to collect and show data from vehicles. The resources assigned are: 8 CPUs, 8 GB RAM and 40 GB HD.

All VxFs are provided with a base Debian 9 images, which reduces the overhead on portal interactions for the experimentation, and the software to be run on each instance is deployed and launched via Ansible scripts. This makes easier the configuration of each VxF at startup, at the same time an automatic downloading of the operating software is performed, connecting with our software repositories.

The MD Rasphberry Pi device is provided with a GPS chipset, and the physical MRs are MikroTik Router Boards 411U, provided by IT-Av. Data from vehicles are collected by the MDs using an OBD-II interface with the vehicle CAN bus. An OBDLink SX interface with USB connection is used.

B. DATA REPORTING

The monitoring middleware included in MDs has been implemented in Python, and it is in charge of periodically asking the OBD-II device for vehicle data. In the current implementation, all available OBD data records supported by

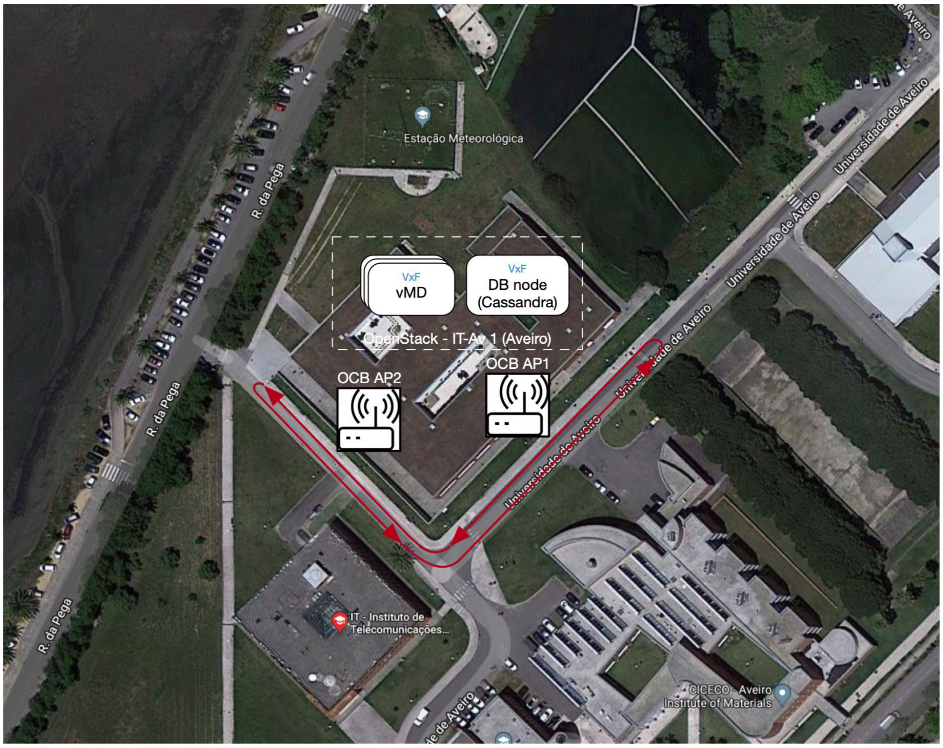

FIGURE 5. Scenario of the tests at IT-Av (University of Aveiro campus, Portugal).

the vehicle are collected and then sent using CoAP communication over UDP to the corresponding vMD. Signalling with MD manager is performed using regular REST over TCP, given that this exchange is expected to be performed only in the bootstrapping.

vMDs cache the last status values received from MDs and, in general, all operating parameters, acting as the physical one when it can resolve data requests. Hence, when MDs are unreachable due to mobility, vMDs act as digital twins of their physical counterparts.

In the data analytics module, all information collected and resulted from the Big Data algorithms are saved in the distributed data base. From here it is possible to provide current and past values of MDs.

C. VEHICLE MONITORING SERVICE

Regarding the service implemented in order to validate the whole platform, Grafana 5.2.4 is used in the VxF deployed in 5TONIC, Madrid. This software has been configured to periodically gather data from the data analytics VxF for each MD registered in the system, and show them using friendly plots. As shown in Fig. 4, it can be accessed through the Web, and Grafana adapts visualisation to the platform used to access the service. Due to security restrictions, this access is currently available by a VPN connection through a 5GINFIRE Access GW. In fact, an SSH tunnel has been setup over the 5TONIC VPN, by using a public address.

Data collected from vehicles through the MD depends on the OBD-II capabilities of the car, but the next parameters are usually available:

- GPS position, given by latitude and longitude, in degrees.
- Speed, in Km/h.
- Revolutions per minute (RPM).
- Engine temperature, in degrees.
- Air flow, in Kp.
- Warmups since a reset of status parameters in the vehicle.
- Engine type, diesel or gasoline.
- Distance covered since a reset, in Km.
- Intake pressure, in p.
- Position of the throttle, in %.
- Engine load, in %.
- Fuel consumption, in l/h (calculated using air flow).
- CO2 emissions (calculated using fuel consumption).

VI. TESTS

A. SCENARIO AND METHODOLOGY

With the aim of both validating the MIGRATE platform and analysing the operation of the migration procedure, the solution was tested under real driving conditions. This was done, as said above, using the vehicular testbed of IT-Av, after verifying in laboratory the good operation of all modules.

A Golf IV 1.9 TDI was used to carry out the tests. This vehicle, provided with the vehicular equipment previously described, was driven around the IT-Av premises at the University of Aveiro campus, as shown in Fig. 5. The OCB access points has been installed at different sides of the building, and the vehicle was driven next to them using the two

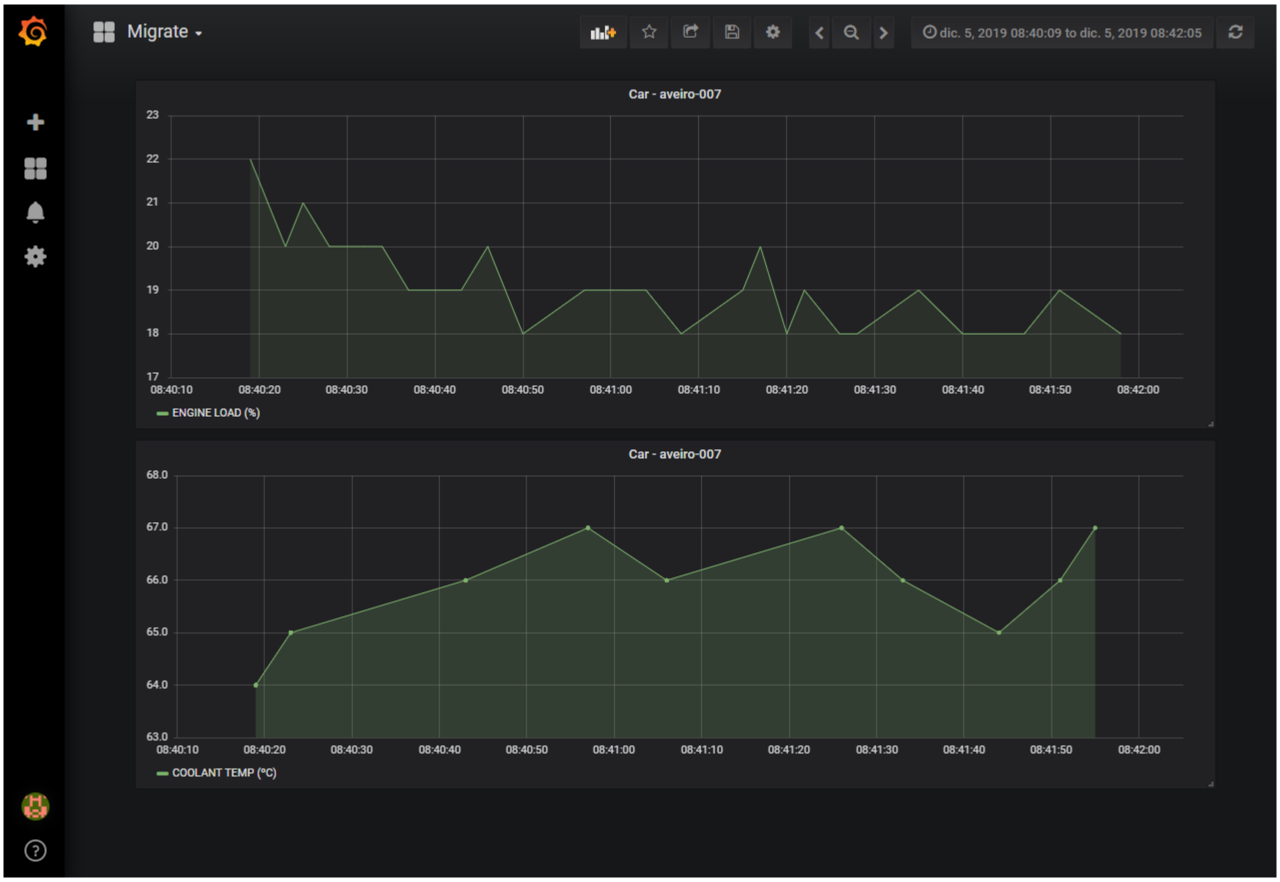

FIGURE 6. Validation of the overall proposal with the Grafana service.

roads available. Multiple rounds were performed to gather significant results.

The MD mounted in the vehicle has been provided with the monitoring software to access the OBD-II interface and report the data collected. It is in charge of registering with its virtual counterpart (vMD) and then continuously send data to it. This data flow is firstly locally processed and stored in the Cassandra DB, which is in charge of synchronising with the rest of DB clusters automatically, including the one setup in 5TONIC. In the tests performed, the data analytics module directly obtains vehicle data from the DB node available in 5TONIC and forwards it to the Grafana system, with no particular processing algorithm in this case. Hence, end users can finally check past and current status of the vehicle by accessing the Web interface of Grafana.

Given the two OCB APs available, when changing the network attachment point, the vMD used is migrated between the two available virtualisation domains. The two APs are connected with the same router, being part of the same network and, since no association is necessary with OCB, the tests have been done without considering layer two and layer three mobility. Hence, the analysis of the migration procedure is exclusively focused on the change of data flows.

B. SYSTEM VALIDATION

The good operation of the solution was checked initially with the Grafana web interface. Fig. 6 shows the results obtained in one of the test rounds performed. The plot panels are configurable, but in this view the vehicle engine load (upper) and coolant temperature (lower) are showed. It can be seen that the test was performed at very low speed, according to the engine load. It is worth to mention that the test duration for one of the rounds is about two minutes, enough to test the handover process while the data were collected. Approximately in the middle of the results shown in the plots, the vMD of the reference vehicle was migrated from the first virtualisation domain to the second one. This process is further analysed in the next part.

C. MIGRATION RESULTS

The results obtained in one of the testing rounds are plotted in Fig. 7 to showcase the operation of the migration approach. The plots are directly generated from the network analyser Wireshark, using the *pcap* trace file saved in both MD and vMDs. vMD1 belongs to the initial virtualisation domain (OpenStack - IT-Av 1 in Fig. 4), while vMD2 belongs to the destination domain (OpenStack - IT-Av 2 in Fig.4). As can be seen in the results, MD sends continuous

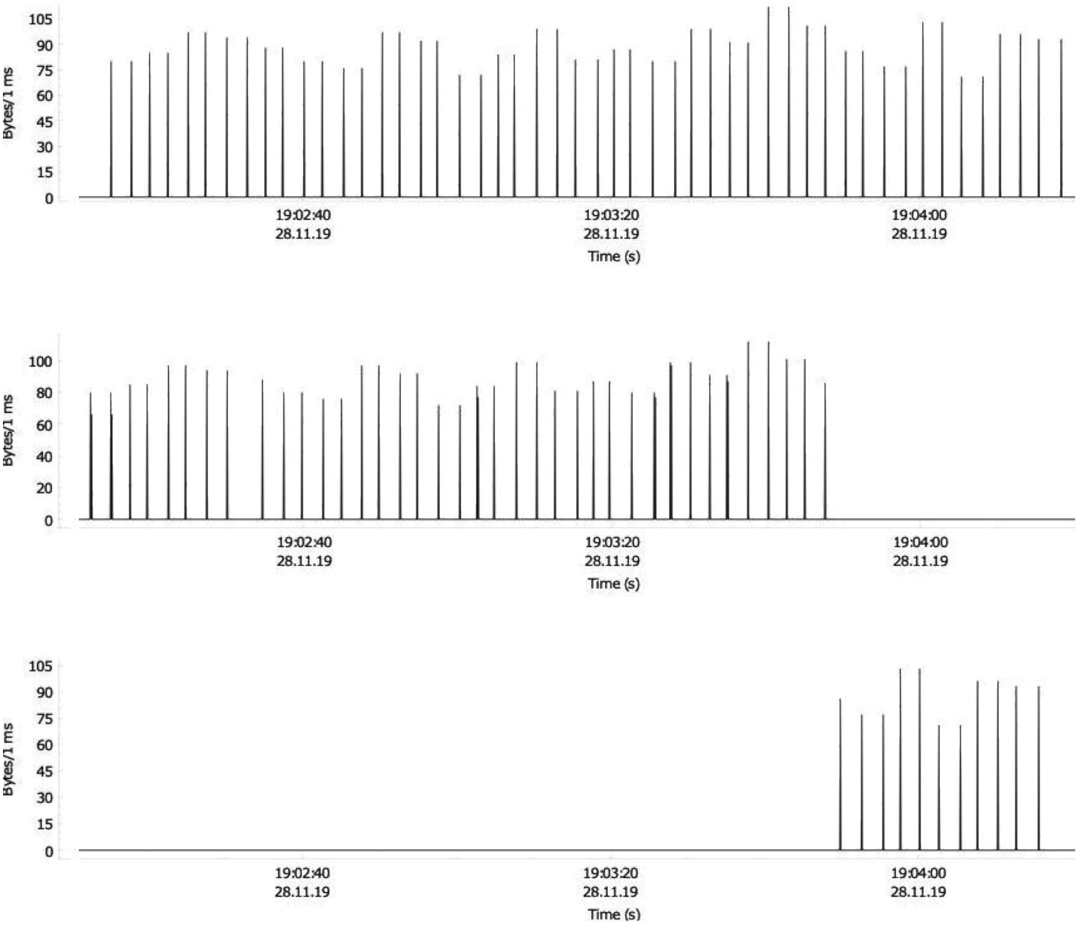

FIGURE 7. Data flow management in the migration process. From up to down, data flow from MD, data flow through vMD1 and data flow through vMD2.

monitoring data to the initial vMD1, considering a previous registration with MD manager. The vehicle maintains more time under the OCB AP1 coverage, due to the fact that initially it is stopped at the main road (see Fig. 5). Then, it moves and reaches the corner of the building. At this moment, the messages start to be received by OCB AP2, so a migration event is generated and the data flow is moved to vMD2. As can be seen in the plot, no data losses are recorded. In fact, in all the tests performed, no data losses have been perceived due to the migration solution.

With the aim of analysing in more detail the correct behaviour of the migration in the test, whose results are included in Fig. 7, we are going to check two key messages exchanged in the network. Listing 1 includes an OpenFlow packet captured in the SDN controller, which indicates the moment it detects the migration. From the information provided in Fig. 4, it can be seen that packets traversing the SDN switch from MD to vMD1 at the beginning of the test should arrive at port 12, and they are then forwarded to port 11. However, when MD moves under the coverage of RSU2, packets arrive at port 14 of the switch. Since the switch detects a packet addressed to vMD1 with a forwarding rule not specified, this event is reported to the SDN controller with the OpenFlow message included in Listing 1. As explained above, this launches the migration procedure, implying the usage of a new vMD instantiated within the new virtualisation domain. Until a new vMD is ready in the new virtualisation domain, the traffic is forwarded from port 14 to port 11, to reach the former vMD (vMD1).

Once the new vMD (vMD2 in OpenStack - IT-Av 2 in Fig. 4) is ready, the SDN controller is in charge of mandating the SDN switch to modify the route of packets and then forward data packets from MD to vMD2. Listing 2 includes an OpenFlow packet addressed to the switch with a route update message to change the forwarding rule for ports 14-11, with a new one with ports 14-13. All route updates in the switch must be done bidirectionally.

Attending to the time stamp of the OpenFlow message in Listing 1, it can be noticed that the migration indication is raised within the time frame the data traffic goes through vMD1 in Fig. 7. At this moment, the traffic continues arriving at vMD1, but from OCB AP2. Once the new mMD is ready,

```
Frame 619:
    Timestamp: 2019-11-28 19:02:32,360572 secs
    Lenght: 204 bytes (1632 bits)
Ethernet II:
    Src: Edgecore_98:e1:00 (b8:6a:97:98:e1:00),
    Dst: Raspberr_84:62:e2 (b8:27:eb:84:62:e2)
Internet Protocol Version 4:
    Src: 192.168.7.100,
    Dst: 192.168.7.90
Transmission Control Protocol:
    Src Port: 34510, Dst Port: 6633,
    Seq: 21957, Ack: 3185, Len: 138
OpenFlow 1.3
    Version: 1.3 (0x04)
    Type: OFPT_PACKET_IN (10)
    Reason: OFPR_NO_MATCH (0)
    Table ID: 0
    Match
        Type: OFPMT_OXM (1)
        OXM field
            Class: OFPXMC_OPENFLOW_BASIC (0x8000)
                OFPXMT_OFB_IN_PORT (0)
                    Value: 14
                OFPXMT_OFB_IN_PHY_PORT (1)
                    Value: 14
    Data
        Ethernet II:
            Src: Routerbo_b0:8a:84 (d4:ca:6d:b0:8a:84),
            Dst: fa:16:3e:ec:1f:0a (fa:16:3e:ec:1f:0a)
        Internet Protocol Version 4:
            Src: 192.168.6.98,
            Dst: 10.154.8.121
        User Datagram Protocol:
            Src Port: 42192, Dst Port: 12341
        Constrained Application Protocol, Confirmable,
                                        POST, MID:14173
            01.. .... = Version: 1
            ..00 .... = Type: Confirmable (0)
            .... 0010 = Token Length: 2
            Code: POST (2)
            Message ID: 14173
            Token: 706f
            Opt Name: #1: Uri-Path: vehicle
            Opt Name: #2: Uri-Path: GPS,HEADING,degrees
            End of options marker: 255
            [Response In: 637]
            [Uri-Path: /vehicle/GPS,HEADING,degrees]
            Payload: Payload Content-Format:
                        application/octet-stream
                        (no Content-Format),
                        Length: 1
        Data (10 bytes)
```

Listing 1. **OpenFlow message used to detect migration.**

the new route towards vMD2 is established at time 19:03:48, as can be seen in Listing 2 and Fig. 7.

The times obtained for each essential phase of the migration is shown in Fig.8, with a confidence interval of 95%. The messages marking the beginning/end of each phase are showed with the same numbering indicated in Fig. 3. The average time for the establishment of the back-up route from MD to the former vMD when the migration is detected is 1,543 ms. This comprises the delay of message (4) and message (5), plus the delay in the processing of the message in the SDN controller. The instantiating time of the new vMD is null in our testbed, since it is constrained by the lack of connectivity with OSM and the usage of a pre-loaded pool of vMDs. However, we have measured separately the time needed to start from scratch our vMD image, resulting in 41724,6 ms. This value is slightly increased by the signalisation time needed between the SDN controller in Aveiro and the OSM in Madrid, resulting a final value of 41739,942 ms.

```
Frame 1343:
    Timestamp: 2019-11-28 19:03:48,034696 secs
    Length: 234 bytes (1872 bits)
Ethernet II:
    Src: Raspberr_84:62:e2 (b8:27:eb:84:62:e2),
    Dst: Edgecore_98:e1:00 (b8:6a:97:98:e1:00)
Internet Protocol Version 4:
    Src: 192.168.7.90,
    Dst: 192.168.7.100
Transmission Control Protocol:
    Src Port: 6633, Dst Port: 34510,
    Seq: 6329, Ack: 50922, Len: 168
OpenFlow 1.3
    Version: 1.3 (0x04)
    Type: OFPT_FLOW_MOD (14)
    Transaction ID: 2986725846
    Match
        Type: OFPMT_OXM (1)
        OXM field
            Class: OFPXMC_OPENFLOW_BASIC (0x8000)
                OFPXMT_OFB_IN_PORT (0)
                    Value: 14
                OFPXMT_OFB_ETH_TYPE (5)
                    Value: IPv4 (0x0800)
                OFPXMT_OFB_IP_PROTO (10)
                    Value: UDP (17)
                OFPXMT_OFB_UDP_DST (16)
                    Value: 12341
```

Listing 2. **OpenFlow message updating the forwarding rule using the new vMD.**

Finally, when the SDN controller is notified of the readiness of the new vMD with message (10), the processing time plus the delay of the OpenFlow message (11) involve 0,785 ms.

It is clear from the results that most of the time required in the migration comes from instantiating the new VxF. It is important to note that new vMD can be instantiated in the order of 40 seconds because our solution considers data synchronisation through a distributed data base. This time could be further reduced by using light containers or even predicting migrations and pre-loading VxFs. Actually, our testbed already considers a pool of VxFs, which hides the instantiating time. Under this circumstance, an effective migration can be achieved in 2,328 ms, bearing in mind that the SDN controller is within the edge network. If the SDN controller were located at 5TONIC in Madrid, we have check that communication delay is bellow 8 ms, and an overall migration time of 24 ms could be obtained.

In our tests, no data packets are lost due to migration, since the SDN switch maintains in memory the packets to be forwarded while the new route is established between messages (4) and (5) in Fig. 8, which lasts 1,543 ms, as said. This way, packet looses could only appear under buffer overflow circumstances, which could only happen when the switch is managing huge data rates.

D. DISCUSSION OF RESULTS

It is difficult to find equivalent results in the literature, given the novelty of the field and the difficulties to create an experimental platform. Even if a real deployment is evaluated, it is not straightforward to compare results, given the differences in the set-up, ranging from simple networks in

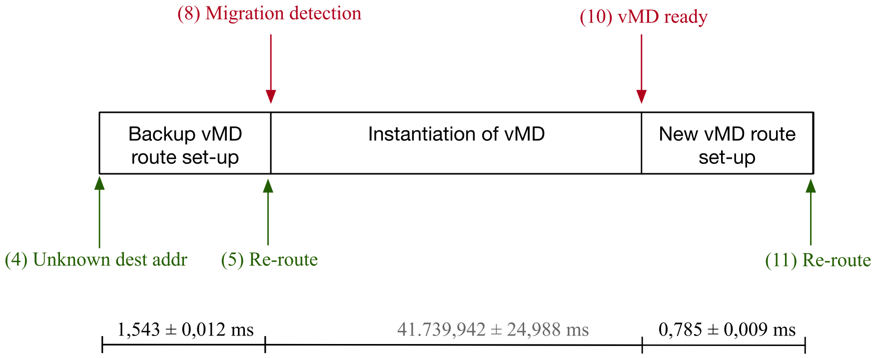

FIGURE 8. Time required for the migration in the testbed.

lab to complete infrastructures involving wide-area network delays.

Attending to the work cited in Section II, the ones most related to MIGRATE and including evaluations are cited next. In [17], [20], the authors are especially interested in the end-to-end delay when using edge resources instead of cloud services. MIGRATE is not focused on this, but on the migration procedure. However, our previous work in [1] does focuses on this, although with evident differences in the testbed, using a real deployment as compared with the simulations of [17]. When considering the work in [20], our results in [1] obtains greater differences when moving capabilities to the edge of the network, given the more realistic deployment used. In [21], the results are mainly addressed to check the number of SDN flow updates needed under migration conditions. The migration solutions presented in [22], [23] were evaluated under simulation to analyse the migration cost on the basis of an optimisation algorithm. The work in [18] does consider the VNF migration time using a set of simulations, indicating that an intelligent algorithm can reduce it by deciding between moving VNFs or re-instantiating the function. However, the times cannot be compared to our results, given that this work focuses on the time the system is out during the migration, and our solution focused on eliminating this issue by maintaining the old VNF until the new one is ready. In [19], the authors mainly focus on an SDN-based migration of traffic through different VNFs, attending to the reduction of packet buffering in the SDN controller. MIGRATE does not impose the controller the need to buffer packets during the handover, since packets are addressed towards the old VxF until the new one is ready; however, some reference numbers regarding the migration time can be found. It can be seen that migration times around 30 ms are obtained in experimental evaluations. These values are in the same range than our results when VxF are preloaded and the SDN controller is placed in a cloud domain, which have been estimated to be around 24 ms. However, when moving the SDN controller to the edge of the network, our numbers outperforms these results, obtaining a migration time of 2,328 ms.

VII. CONCLUSION

The work details the architecture of the MIGRATE platform, presenting a MANO and SDN-powered solution to implement a state transfer approach for digital twins that provides processing offloading capabilities to end devices on the move. In this way, mobile devices are able to maintain MEC services while changing to a new network domain with virtualisation capabilities. A transparent migration mechanism has been developed to maintain communication with a former virtual mobile device until a new one is prepared under the new domain, while data synchronisation is assured by using a cluster-based database.

The solution has been implemented and deployed in terms of both software and hardware, exploiting the IT-Av and 5TONIC capabilities within the EU project 5GINFIRE. A real vehicle has been equipped and driven to validate the solution, and the operation of the migration approach is analysed in detail, presenting reference performance values. The results show that a seamless migration between virtualisation (MEC) domains is achieved within the time frame between 2 ms and 24 ms, depending on the SDN controller location, by using a solution that is transparent for both mobile devices and services.

The work serves as reference for future lines in the areas of applying predictive algorithms to pre-load resources under mobility situations, or using light containers to diminish the VxF instantiating time. Nevertheless, a starting prominent line coming from MIGRATE is the creation of a distributing platform that automatically assign resources across different clouds in accordance with QoS requirements. This will come also with the integration of an SDN multi-controller solution and further investigation on east-west capabilities of MANO technologies such as OSM to even consider multiple orchestration services for very large deployments.

APPENDIX I. ABBREVIATIONS

The following abbreviations are used in this manuscript:

AP	Access Point
CoAP	Constrained Application Protocol

GPS	Global Positioning System
CPU	Central Processing Unit
HD	Hard Disk
OCB	Outside the Context of a Basic Service Set
IPv6	Internet Protocol version 6
IoT	Internet of Things
ITS	Intelligent Transportation Systems
MANO	Management and Orchestration
MD	Mobile Device
MEC	Multi-Access Edge Computing
MR	Mobile Router
NFV	Network Function Virtualization
OBD	On-Board Diagnosis
OSM	Open Source MANO
OBU	On-Board Unit
QoS	Quality of Service
RAM	Random Access Memory
REST	Representational State Transfer
RAT	Radio Access Network
RPM	Revolutions Per Minute
RSU	Roadside Unit
SDN	Software Defined Network
TCP	Transport Control Protocol
UDP	User Datagram Protocol
VIM	Virtualized Infrastructure Manager
VPN	Virtual Private Network
vMD	Virtual MD
VxF	Virtual Function
VNF	Virtualized Network Function

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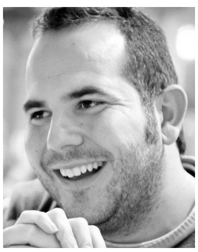

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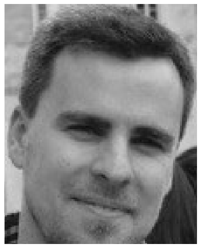

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