ORCHESTRA 2.0: Enhancing a multi-access solution to address 5G challenges

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***Abstract*—New challenges in communications are being raised as autonomous vehicles are gaining popularity. Higher data rates, connection reliability and real-time responses are challenges to be undertaken on the next years and, although they have been researched over the past decade, no solution that addresses all of them simultaneously has been widely accepted. In this paper, we reintroduce ORCHESTRA, an all-in-one solution to manage devices with multi-connectivity capabilities, while also enabling the use of techniques such as load balancing, seamless handovers and package duplication to address the challenges aforementioned. Furthermore, we also present a list of additions and improvements that would enable this solution to respond to the newest communication challenges.**

***Index Terms*—multi-connectivity, seamless handover, load-balancing, package duplication, autonomous vehicles, ORCHESTRA**

I. Introduction

Modern devices present themselves with multiple connectivity opportunities, such as Wi-Fi, 3G and 4G. Unfortunately, this heterogeneity is not always explored to its maximum potential. Devices are usually limited to the use of a single Radio Access Technology (RAT) at a time, especially because the different standards and protocols of each technology are not fully compatible with the ones from other technologies. Different technologies have, for example, different ways of encapsulating data frames, so they are ready to be transmitted over a suitable physical medium. This encapsulation is done in the Medium Access Control (MAC) layer, which is unique for each technology.

On top of that, new technologies, such as 5G, are arising and with them new communication challenges arise as well. Ultra-low latencies (≤ 4 ms), ultra reliability ($1-10^{-5}$ success rate), higher data rates ($\geq$ 100 Mbps) and the need to be always connected are examples of new requirements [1] that compose challenges like real-time communications, always-on and reliable connections and seamless handovers.

Every scenario has its own particular challenges. For example, Smart Highways demand seamless handovers and high reliability. Unmanned Aerial Vehicles (UAVs) use cases require reliable, always-on and high data rate connections. On the other hand, shipyard and maritime use cases do not always require high data rates (except for uses such as video and Augmented Reality (AR)), but need always-on stable and reliable connections. Figure 1 illustrates the different scenarios with their respective challenges while also showing that each scenario may use multiple different technologies.

This work was partly funded by the Helicus Aero Initiative – Scheduling, Connectivity & Security (HAI-SCS) project, co-founded by Imec, a research institute founded by the Flemish Government. Project partners are Helicus, skeyes, SABCA, Baloise, NSX, Orange, COSIC/KUL and IDLab/Imec, with project support from VLAIO.

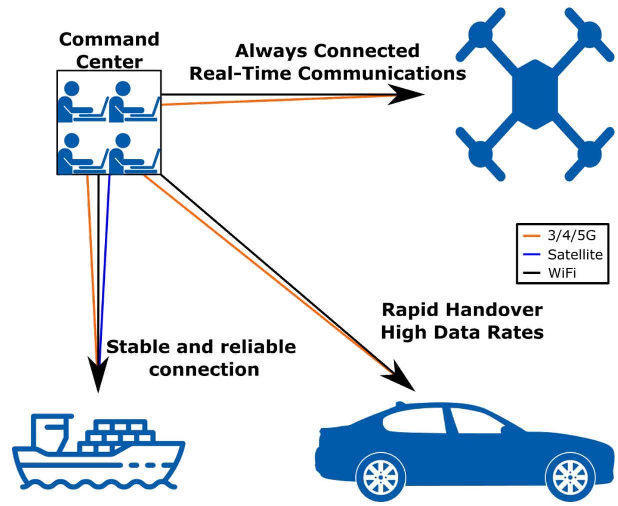

Fig. 1. Autonomous Vehicles scenarios, challenges and connectivity technologies.

Although challenges such as always-on connectivity, seamless handovers and maximization of data throughput have been individually researched over the past decade [2], [3], a solution that addresses several challenges simultaneously and that works on top of different technologies has not been widely accepted yet.

To address the challenges presented, ORCHESTRA was developed, by creating a new Virtual MAC (VMAC) layer that abstracts the different MAC layers of communication technologies, making them transparent to the network layer. By doing that, ORCHESTRA offers a single application-agnostic network interface that jointly manages the different lower layers in a seamless manner. In addition to the control of the different technologies, ORCHESTRA also introduces the possibility of combining them and adding different functionalities, such as Load Balancing, Seamless Handovers and Package Duplication.

Over the next sections of this paper we introduce the different aspects of an Autonomous vehicles scenario, where the previously challenges raised are constantly on display, and present ORCHESTRA as a promising all-in-one solution designed to fulfill the necessary requirements for these new types of communication. Finally, we also describe some of the required changes for ORCHESTRA to be used in these scenarios, such as the addition of new RATs in a modular manner, the shift of the management to the kernel level to reduce the packet processing latency, and the addition of network slicing support. These new features would allow ORCHESTRA to become a multi-RAT management system for a wide range of challenging 5G-envisioned vehicular use cases.

II. Autonomous vehicles scenarios

Smart Highways are becoming a reality and the usage of data to assist drivers in real-time about different events is one of its main features. But more than just information, driving assistance and autonomous driving are other elements to be looked at. Ensuring the security distances between cars, assisting cars to enter and exit the highway, interaction with signaling posts, other cars and even the internet are examples of actions taken in Smart Highways [4]. Therefore, the main concern is to make sure the information reaches the interested parties as fast and reliably as possible. So throughput and low latency are key aspects of communications in Smart Highways.

Regarding UAVs, the biggest concern is to ensure connectivity at all times. If that requirement is fulfilled, emergency measures are to take place in case something went wrong, like route reprogramming or even contact a control center in case of emergency landings. A second requirement is the existence of a high-speed and low latency connectivity in case real-time control is necessary.

Finally, logistics and navigation assistance are key points for autonomous ships. This allows for faster docking and undocking from ports and also to improve cargo loading logistics. For such case, a stable and ultra reliable connection is required.

The scenarios described above come with many different communications challenges. To start, different coverage areas and throughput of different technologies are directly related to the possibility of maintaining a stable connection while keeping high data rates.

Moreover, although horizontal handovers (intra-system) are well known and have mature studies and procedures on its execution, seamless vertical handovers (inter-system) are still not widely adopted, mainly due to the different addresses of the multiple interfaces. Once a vertical handover happens, all connections currently established need to be migrated from the old to the new system, which causes a temporary break in communications.

Another important challenge to be addressed is the underutilization of the total available throughput. The presence of multiple communication modems opens the possibility of combining the different technologies and maximizing the total data rate that one device can achieve.

Last, but not least, the ultra high levels of reliability required by some scenarios, like autonomous ships and shipyard logistics, can be achieved by the duplication of packages over different communication technologies. This ensures that all packages will arrive at the destination.

III. Architecture

The availability of multiple communication technologies in a device does not imply that the device will be always connected nor that a seamless handover might be triggered once better quality connectivity is available.

Mobile phones, for instance, have different interfaces for Wi-Fi, 3G and Long Term Evolution (LTE). But although they can be connected to their respective networks, if one of them fails, the connections established through this interface need to be reestablished on another one.

The architecture represented in Figure 2 depicts a device with multiple network interfaces connected to their respective networks, that usually do not reside in the same subnet space, which leads to a device having multiple addresses (identities) within one or more networks.

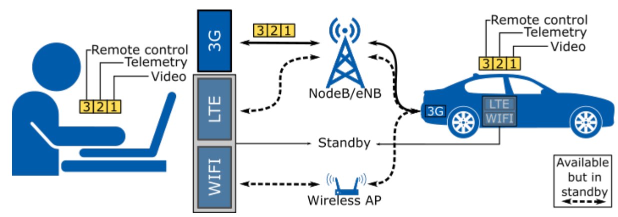

Fig. 2. Example Vertical Handover

The main issue of multiple addresses for one device in current technologies is that during communication a link is aware of only one address per device, meaning that if the connectivity of one interface is interrupted a new connection must be established using one of the other addresses available before restarting communications.

Regarding performance, the use of only one interface per connection limits the throughput of a device to the one of the used interface. By applying load balancing and interface bonding techniques, the throughput of different interfaces can be combined, making the best use of all available technologies.

A load-balancing architecture is represented in Figure 3.

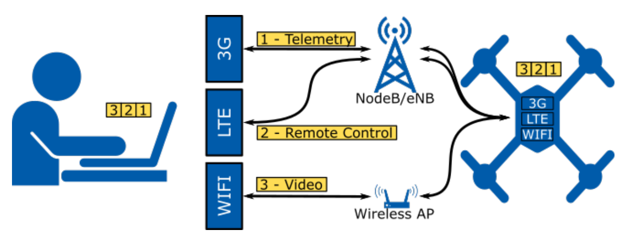

Fig. 3. Example Load-Balancing architecture.

Although this technique is widely available, it requires special networking equipment and also that all interfaces have addresses in the same network.

Some other software solutions were developed, like Multipatch TCP (MTCP) [5], but those are limited to specific protocols (Transmission Control Protocol (TCP)), which do not cover other protocols, such as User Datagram Protocol (UPD) or QUIC.

Finally, connection reliability is a big concern for any autonomous vehicle scenario, like the ones previously described in Section II. Current approaches, such as TCP, depend on Acknowledgement (ACK) and Negative-acknowledgement (NAK) messages to confirm that a given package has arrived or not and then trigger a retransmission in case of package loss. The ability to duplicate packages and sending them over different interfaces would add extra reliability to the connection, while avoiding retransmission delays. This is represented in Figure 4.

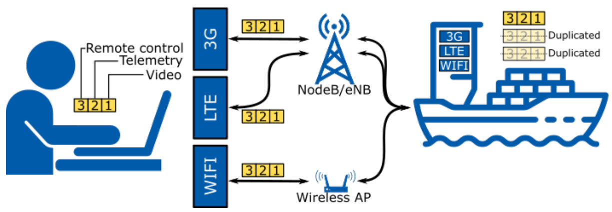

Fig. 4. Example Package Duplication.

This technique is not widely accepted, especially because it involves introducing duplicated packages in a network, which would reduce its available capacity and also consume processing power from devices, since they would require to filter the duplicated packages. But in highly unstable and unreliable environments, this is a way to ensure that mission critical packages will arrive at the destination.

IV. ORCHESTRA

To solve the problems mentioned before, ORCHESTRA is a tool that allows users and devices to seamlessly manage multiple communication technologies.

ORCHESTRA uses the concept of a VMAC to abstract different wireless technologies, such as Wi-Fi, 4G or LTE-MTC (LTE-M), providing inter-technology seamless handover, load balancing, or packet duplication. Some of these features are already present in current standards. For example IEEE 1905.1 [6] uses a hybrid MAC layer to enable seamless switching between several Local Area Network (LAN) and Wireless-LAN (WLAN) technologies. In the same way, MTCP introduces the concept of using multiple TCP connections over different technologies and combining them into one for the application layer. Finally, the 3GPP's approach [7] is to use tunnels to abstract the different available technologies (Wi-Fi, LTE, etc.) in a seamless manner for the application layer. However, ORCHESTRA is a combination of network-wide and packet-level control solution that allows the network to be fully programmable. A comparison between ORCHESTRA and such solutions is given in Table I.

	IEEE 1905.1	LTE-LWA	MPTCP	ORCHESTRA
Domain	LAN	LAN-Radio	Any	Any
Technology	Eth,WiFi	WiFi,LTE	All	All
Coordination	Global	Local	Peer to Peer	Global
Control Level	Flow-based	Flow-based	Packet-based	Packet-based
Transport	Any	Any	TCP	Any
Vertical Handover	No	Yes	Yes	Yes

TABLE I
COMPARISON OF ORCHESTRA WITH SIMILAR STATE-OF-THE-ART SOLUTIONS.

A. *Design and Implementation*

ORCHESTRA is based on the modular router Click [8] and it's based on two key components: A VMAC, to abstract the MAC interface of the different technologies, offering a unified interface to the upper layers of the network stack, and a centralized controller, to manage VMAC-enabled and legacy devices [9].

This solution can be used in different modes, according to the necessity of the scenario:

- Seamless handover: This mode keeps all but one interfaces in standby and them an interface change can be triggered automatically during link failures, as result of a decision made by a Machine Learning (ML) algorithm, or manually (see Figure 5);

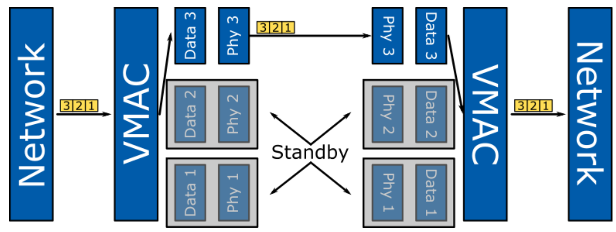

Fig. 5. Example Vertical Handover

- Load Balancing: distributing the network packets over the different interfaces to maximize their utilization and achieve better Quality-of-service (QoS) and Quality of Service (QoE) levels (see Figure 6). Here, ORCHESTRA's VMAC Layer is responsible to rearrange the received packages so that the final data is not corrupted;

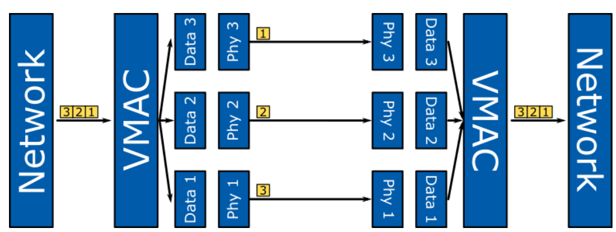

Fig. 6. Example Load Balancing architecture.

- Duplication: duplicating the packages across different interfaces for more reliable communications (see Figure 7. The duplication takes place in the VMAC layer of the source node, while the same layer of the destination is responsible to discard and/or rearrange the received duplicates, to ensure the integrity of the data.

B. *Challenges*

In terms of technologies, ORCHESTRA was developed to work with Ethernet, Wi-Fi and LTE connections. One new challenge imposed here is to add support for new technologies, like 5G and other IP-based RATs, like communications over the C-Band.

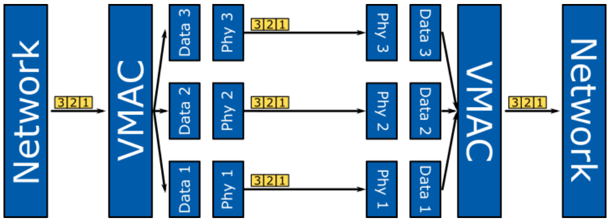

Fig. 7. Example Package Duplication.

Due to the way it was designed, ORCHESTRA's VMAC only works with all of its features on interfaces that are connected to the same network, which means that a scenario like the one described in Section II, where some of the interfaces are connected to different networks, would not make full use of the available features.

For 5G this could be done using Slicing techniques [10] to connect the devices directly to ORCHESTRA managed networks. For other RATs, adding Layer 2 (L2) tunneling on the connections that are on separate networks would have a similar effect, but without the need for the new slicing capabilities of the 5G.

C. Future improvements

Initially, ORCHESTRA targeted Wi-Fi and 4G connections. With the addition of 5G management, new features such as network slicing control will be added to this solution, making it more complete and capable of meeting higher network requirements.

Also, shifting the packet processing to a kernel level has the potential to increase performance by reducing the processing time. This improvement affects functionalities such as load balancing and package duplication.

Regarding seamless handovers, the addition of new ML algorithms that can predict the best moment to trigger handovers based on different Key Performance Indicators (KPIs), such as signal strength, connection delays and throughput, can further improve this functionality.

In terms of modularity, ORCHESTRA currently comes in one big package and all functionalities enabled by default, which makes it computationally costly. With this in mind, we also aim to make it more modular by better separating different functions into modules, thus making it possible to enable and disable features or modes, like complex decision-making algorithms and packaging reordering for load balancing. This can reduce packaging size while also specializing it, allowing for lower performance devices to execute our software with only essential features enabled.

V. Conclusions

In this work we have justified that the management of multiple networking technologies in a single device has many opportunities as well as many challenges still to be solved. Although many of the challenges presented in Section II have been studied over the past decade, no definitive solution has been widely adopted by neither industry nor research community.

The problem of one device with multiple addresses seems to be the most challenging one, requiring the device to have all interfaces to be connected to the same network. Load-balancing solutions already exist, but are usually connection oriented. And finally, package duplication solutions already are deployed in the real world, but are mostly related to broadcasting, where multiple devices are looking for the same data at the same time.

Previous works have shown that ORCHESTRA can offer a all-in-one solution for the challenges presented. In this work, we argue that ORCHESTRA can also, with slightly different approaches, offer a solution for the multiple addresses with its new VMAC layer while also offering the possibility for Load-balancing the data traffic with a smart package classifier. Finally, the VMAC layer can also be used to perform seamless handovers and package duplication, improving the reliability of the connection.

To conclude, the improvements envisioned for ORCHESTRA, such as 5G slicing management, kernel level package processing and the updates on existing functionalities like seamless handovers and load balancing, would make it a powerful solution for seamless multi-RAT management in 5G vehicular use cases.

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