# Multi-technology Management of Heterogeneous Wireless Networks

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***Abstract*—Wireless networks are ubiquitous in today's world and consist of an ever-expanding number of heterogeneous consumer devices and communication technologies. Since these modern devices support the use of multiple communication technologies, efforts have been made to enable simultaneous usage and handovers between the different technologies for these devices. However, existing solutions are missing both the fine-grained control and intelligence to offer seamless inter-technology management and network optimizations. As a result, technologies operate in an isolated manner, network management is inefficient, and the requirements of users and modern applications are not being met. In contrast, in this dissertation, we introduce intelligent and dynamic multi-technology network management, abstracting the connectivity decisions from the user and application level. Different contributions are made: first of all, we introduce a framework for inter-technology management that enables, among others, seamless handovers and packet-based load balancing. Next, we propose different algorithms that can be deployed on top of the novel, or existing, management solutions to increase the network-wide throughput by providing more intelligent network configurations, taking into account mobility and real-time requirements. Finally, as management approaches rely on an accurate overview of the network state, we also consider the monitoring aspect and investigate the detection of traffic patterns in the radio spectrum.**

## I. Introduction

Recently, we have witnessed a tremendous increase in the utilization and availability of wireless networks and devices. The number of connected devices has reached 18 billion in 2017 and will only increase further [1]. Similarly, the heterogeneity and complexity of (wireless) networks are increasing as new technologies (e.g. IEEE 802.11ay and 802.11ax) are being released [2]. While this has enabled novel applications and services, it has also vastly increased the complexity and heterogeneity of the, mostly wireless, networks, as depicted in Figure 1. Furthermore, most modern devices are equipped with multiple communication technologies that can be employed to connect to the Internet or to communicate with other devices. As each of these devices, applications, and communication technologies has unique capabilities (e.g., bandwidth and range) and requirements (e.g., latency or power consumption), the management burden has drastically increased.

Current network management approaches often delegate decisions to the application layer, or even worse, to the user. As such, it is impossible to automatically react to dynamic network changes. In particular, we have identified the following problems: first, due to the design of the OSI stack, cooperation between different technologies is infeasible. Although this cooperation is needed to enable optimization features such as inter-technology handovers or load balancing [3]. Furthermore, due to the static management, devices typically decide for themselves to which connection point to connect or how to route their traffic. To counteract the resulting sub-optimal behavior and unfairly balanced network traffic and to automatically react to dynamic network events, there is a need for autonomous and real-time coordination across all the different of devices in the ever-growing wireless networks [3, 4]. Finally, the increasing availability of different, often neighboring, technologies and networks is causing spectrum scarcity and performance degradations [2, 5]. In order to have adaptive management systems that can efficiently and intelligently use spectral resources, these systems require access to accurate and real-time information on the state of the wireless spectrum.

In our work, we have made several contributions to the field of multi-technology management of heterogeneous wireless networks. We aim to solve the above-mentioned challenges in a fundamental manner, that is also adaptable and robust towards future evolutions within the field. Figure 2 illustrates how these contributions fit together. Our contributions are four-fold: first, we designed a multi-technology management framework called ORCHESTRA that enables features such as seamless inter-technology handovers or packet-based load balancing (Section IV-A). This framework can be deployed in all types of networks such as Local Area Networks (LANs) or backhaul networks as shown in Figure 2. On top of the ORCHESTRA framework, the second (Section IV-B) and third (Section IV-C) contributions provide the required intelligence to actually optimize the network. In particular, the proposed algorithms optimize the network-wide throughput, utilizing the underlying ORCHESTRA framework to acquire real-time monitoring information and roll-out network-wide policies. The bottom left area of Figure 2 visualizes a network, consisting of both wired and wireless technologies, that is managed by the algorithm of the second contribution. Similarly, the middle part of Figure 2 illustrates how contribution 3 allows managing a network consisting of mobile wireless devices. Finally, the fourth contribution (Section IV-D) allows wireless infrastructure devices to listen to the spectrum and identify traffic patterns of neighboring networks. This information can be shared via the management framework with the network management algorithms, for further exploitation and network optimization (e.g., smart spectrum management).

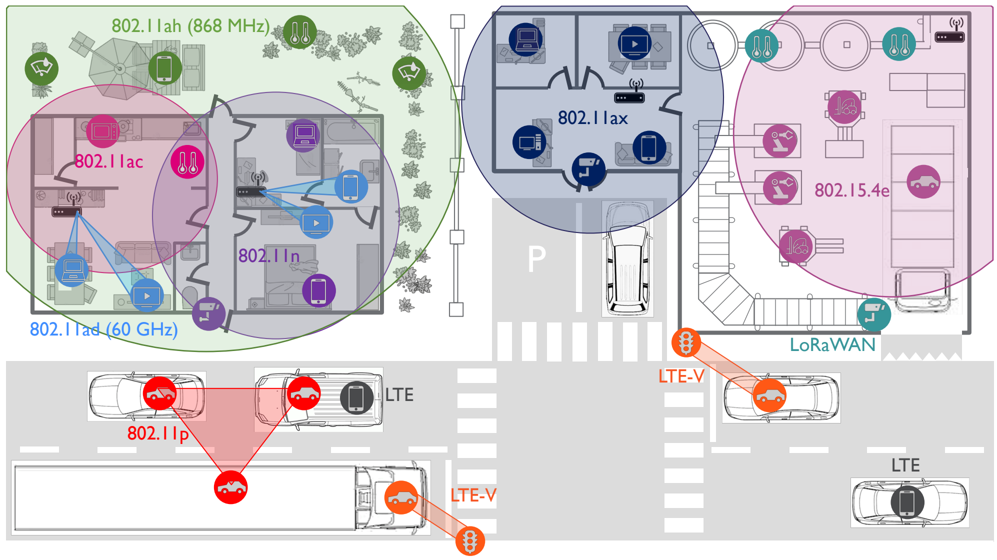


Fig. 1: The envisioned heterogeneous environment, consisting of a large variety of different networks, technologies, and devices.

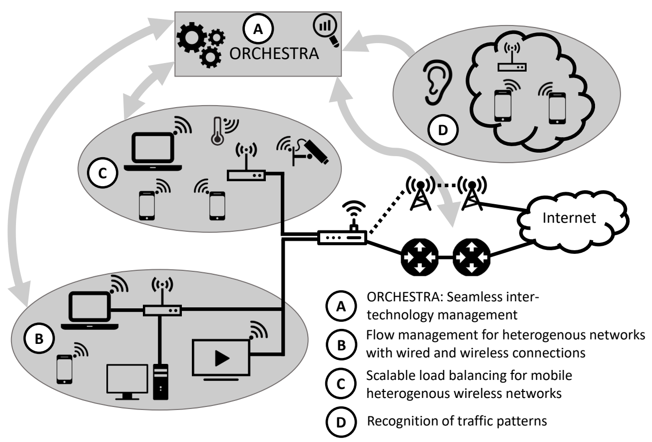


Fig. 2: Overview of how the different contribution fit together.

The remainder of this article is structured as follows. The concepts of multi-technology management, load balancing, and traffic recognition are discussed in Section II. Section III discusses the hypothesis and research questions we addressed in the dissertation, while Section IV presents our contributions. Finally, Section V highlights some future research directions.

## II. Background

### A. Multi-technology management and control

Several approaches have been proposed to facilitate inter-technology handovers and multi-technology load balancing, which are key features of intelligent and seamless inter-technology management. A key aspect in terms of user-friendliness and Quality of Service (QoS) is the abstraction from network connectivity, as users do not want to struggle with the low-level specifics of each network technology. To this extent, the IEEE 1905.1 standard introduced a hybrid MAC layer on top of the current data link layers to enable the transparent switching between several wired and wireless network technologies [4]. Similarly, the Multipath Transmission Control Protocol (MPTCP) standard offers multiple regular Transmission Control Protocol (TCP) connections (i.e., subflows) as one to the application layer. Under the hood, each subflow can follow different paths through the network [6]. Other solutions, such as 3GPP technologies, utilize tunnels to abstract away other technologies. Besides abstraction, and in contrast to MPTCP, the IEEE 1905.1 standard and Software-Defined Networking (SDN) solutions provide network-wide coordination through a centralized controller [7]. However, this is only done on a flow-level, while packet-level can more efficiently exploit the available network resources [4].

### B. Multi-technology load balancing

While these frameworks and standards introduce the features needed to enable handovers and load balancing, they are missing the intelligence to decide on the network-wide optimizations. To this extent, a number of approaches have been proposed in the field of LANs and cellular networks. The aim is to balance traffic flows or devices across different technologies, or within a single technology but across different connection points [4, 7, 8]. Popular approaches for the decision strategies are utility functions, linear programming, multiple attributes decision-making, Markov chains, and game theory. However, existing work mostly focuses on the development of theoretical models that assume detailed knowledge of flow throughput requirements and dynamic network conditions [4, 7, 8]. The specific nature of wireless networks (e.g., interference, link quality variability) and application or QoS parameters are also often ignored.

### C. Traffic recognition

The detection of traffic patterns in wireless radio signals can provide insights to increase the spectrum efficiency and to cope with neighboring networks. However, traditionally, traffic recognition takes place at higher layers of the network stack at gateways or routers in a (wired) network aiming to identify individual traffic streams or applications entering or exiting the controlled network environment [9]. The most popular method is Deep Packet Inspection (DPI). While this method is highly accurate, it requires a lot of computational power and is very privacy intrusive [9]. In the area of cognitive radios, the detection and classification of wireless radio signals has been studied to optimize spectrum usage [5]. The focus has mostly been on the recognition of modulation schemes and technologies, recently, using deep learning techniques.

## III. Hypothesis and research questions

The main objective of the thesis is to prove the validity of the following hypothesis: *Intelligent and dynamic inter-technology network management is needed to support the ever-evolving heterogeneous wireless networks.*

To validate the above hypothesis, the following research questions were addressed:

1) *How can we enable seamless inter-technology management transparent to all actors?* The problem of providing reliable and seamless inter-technology management exists in all kinds of different networks and devices. As such, a generally applicable solution requires transparency towards individual technologies, end-users and their applications, and the network itself (e.g., other devices). Furthermore, management operations such as inter-technology handovers should seamlessly take place with no noticeable impact on the user experience or application behavior. Note that also deployment efforts should be kept minimal, making sure that legacy operations or protocols are still maintained.
2) *Can intelligent inter-technology routing of traffic streams significantly improve network performance?* The intelligent routing of traffic flows is needed to cope with the stringent requirements of modern services and to more efficiently use the available resources. Such an approach should respond to dynamic events, such as link failures or fluctuating traffic demands, in a fast and adequate manner to minimize the loss of performance and experience. Furthermore, the demands of flows and the actual capacities of the technologies should be taken into account. The latter is especially important and more challenging for wireless connections and technologies.
3) *Can the impact of mobility and the growing number of devices and technologies be countered by introducing intelligent load balancing?* To account for mobility, algorithms should leverage at the same time different aspects, such as load, distance, mobility patterns, and resource demands in order to provide the best QoS possible by dividing devices and their traffic across various technologies and network paths. Since mobility patterns can vary often, the importance of a responsive approach grows even stronger. Furthermore, the complexity of this management puzzle scales within the scope of the ever-growing amounts of connected devices. To maintain responsiveness, the trade-off between scalability and optimality should be investigated.
4) *Can we detect traffic patterns of neighboring networks using spectral data?* To help network management solutions in coping with coexistence, advanced monitoring techniques are required. Based on spectral data it is already possible to detect interference of external sources like neighboring technologies or devices such as a microwave. However, existing traffic recognition approaches operate only on a packet-level. To construct a model that is capable of detecting these traffic patterns at the spectral level sufficient amounts of data are required. Furthermore, such a model needs to be robust in order to cope with the very dynamic wireless nature.

## IV. Contributions of the Dissertation

### A. ORCHESTRA: seamless multi-technology management

As the goal of this work is to provide more intelligent network management, a framework is required to enable the necessary features like inter-technology handovers. Since existing solutions fail to address this challenge fundamentally, we propose the ORCHESTRA framework that uses SDN principles and consists of two components: a Virtual MAC (VMAC) layer and a centralized controller [10, 11]. The fully transparent VMAC layer unifies the various underlying communication technologies per device, offering a single interface to the upper layers with a single IP address, as shown in Figure 3. With full control over underlying interfaces, the VMAC offers advanced features on a packet-level, like inter-technology handovers, duplication, and load balancing by using packet header matching rules. To ensure transparency to the upper layers as well, in particular, the transport layer, reordering and deduplication mechanisms are in place to process receiving packets at the VMAC layer.

While the VMAC allows for fine-grained Media Access Control (MAC)-level control inside individual devices, the ORCHESTRA controller is the heart of the proposed framework and enables multi-technology management and orchestration across the entire network. Following the SDN principle, the centralized controller maintains a global network overview by receiving detailed monitoring information from each VMAC and can in return propagate instructions (i.e., rule changes) to the different VMACs. Furthermore, there is support for gradual network-wide roll-out through the transparency towards standard (i.e., legacy) devices and the possibility to interact with existing (SDN) network controllers.

Moreover, we present the implementation of ORCHESTRA in a real-life prototype that supports the following communication technologies: Ethernet, IEEE 802.11 (Wi-Fi) (in both the 2.4 Ghz and 5 Ghz), and Long-Term Evolution (LTE) [11, 12]. An in-depth evaluation, using the prototype, demonstrates that the different features work as intended and offer the necessary seamless inter-technology management for both TCP and User Datagram Protocol (UDP) traffic, as such outperforming the default industry solution MPTCP.

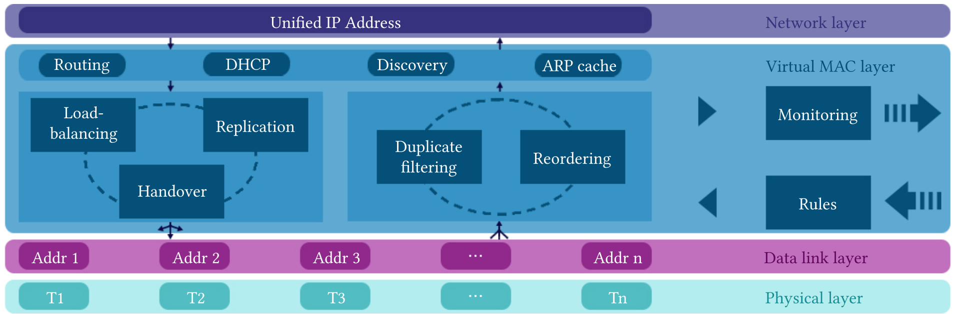

Fig. 3: Overview of the VMAC layer with its position in the OSI model, its buildings blocks, and its offered functionality.

### *B. Real-time flow management for heterogeneous networks with both wired and wireless connections*

To dynamically reroute traffic flows across different existing paths in the network, we present two Mixed Integer Linear Programming (MILP) formulations that aim to maximize the network-wide throughput [13, 14] In particular, we target environments with both wired and wireless links that can benefit from offloading between the different technologies. The first formulation calculates the optimal path configuration by taking into account individual traffic flows and TCP fairness mechanisms. The second algorithm does so by maximizing the throughput across all groups of interfering links or stations.

The flow management approach is constructed fully independent of the underlying network management tools (e.g., the previously introduced ORCHESTRA framework). The decision-making process is based only on real-time gathered monitoring data, allowing a fast response to dynamic network events, while also the specific nature of wireless networks (e.g., the impact of competing stations and the dynamic maximum capacity) is taken into account. Furthermore, we present a method to dynamically estimate the maximum capacity of wireless technologies, an approach that recently has been adopted by commercial Wi-Fi management solutions. Thorough evaluations, using the NS-3 simulator and a small-scale prototype, show that the presented approach can indeed improve the network performance by on average 20 % across a variety of scenarios. These evaluations include, besides static scenarios to prove the correctness, also more realistic dynamic scenarios with varying numbers of flows and link failures.

### *C. Scalable load balancing and flow management for mobile heterogeneous wireless networks*

Mobile devices need to perform multiple handovers, between different connection points or technologies, to remain connected to the Internet. Although our previous contribution provided the intelligence to dynamically reroute traffic and was able to capture the specific wireless context, the mobility of connected devices was not yet considered. To this extent, we present a novel a MILP formulation that optimizes both the path configuration and station associations within wireless networks to maximize the overall throughput [15].

To ensure real-time decision making, even for very large networks, we design two heuristic approaches [16]. First, we design a near-optimal two-step heuristic approach that splits the overall problem and optimally solves the problems of station association and traffic scheduling separately. As such, two different MILP formulations for the respective problems are solved after each other. Second, we present a greedy heuristic approach that also considers the problems of station association and traffic scheduling individually, after one another. These approaches operate fully independently of the underlying framework, based on only real-time monitoring information. As such, honoring the transparency properties stated previously. Furthermore, we propose a dynamic fingerprinting-based approach to capture the effect of mobility and distance on the maximum possible data rate per station. In other words, the approach takes into account the reduction in achievable data rate due to the decrease in Modulation and Coding Scheme (MCS) values and the increase in distance.

Overall, the load balancing is done by considering the traffic rates of the different flows, the distance between the devices and the connection points, the network load, and the maximum rates supported by the different devices and technologies. This contrasts to the default approaches, where devices tend to make connections based on the best Signal-to-noise Ratio (SNR), regardless of the network load or spectrum occupancy. Finally, using an NS-3 based framework, the three algorithms are evaluated across an extensive series of varying scenarios. We demonstrate a significant improvement of up to more than 100 %, in comparison to a static baseline where each device decides on its own. Moreover, a scalability analysis shows that a heuristic approach can provide a configuration in less than 3 s for networks up to 10000 devices, as shown in Figure 4.

### *D. Recognition of traffic patterns in the wireless spectrum*

Traditional traffic recognition approaches, such as DPI, operate on a packet-level and, typically, require that the capturing device is connected to the corresponding network. In contrast, we present a Machine Learning (ML) approach that is capable of detecting traffic patterns (e.g., interval occupancy, specific protocols, or rates) on spectral data of uncontrolled neighboring networks. To the best of our knowledge, the problem of detecting traffic patterns at the spectrum level has not been studied before. In particular, we present a Convolutional Neural Network (CNN) architecture that forms the basis for prediction models that can discriminate between

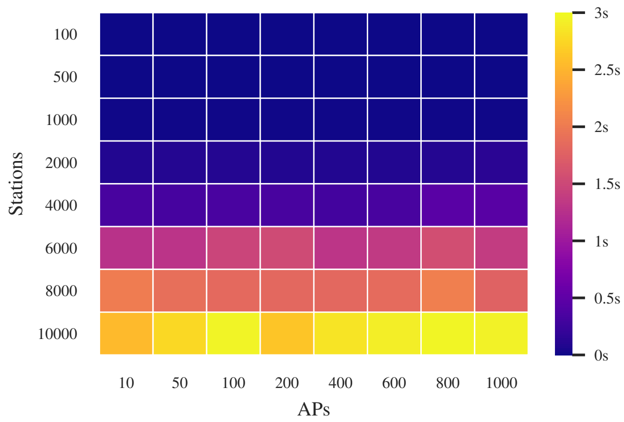


Fig. 4: Scalability of the heuristic approach

different transport protocols (TCP versus UDP), traffic patterns (constant versus 3 types of burst traffic with a duty cycle of, respectively, 25, 50, or 75 %), and transmission rates (100 Kbps, 1 Mbps, 10 Mbps, or 50 Mbps).

Following the successes of domain randomization in the area of robotics, we propose such an approach here where we can use large-scale synthetic generated data to train the models [17]. As such, allowing for more robust models that are capable of coping with the very dynamic and ever-changing nature of wireless environments. Therefore, we construct a framework that combines two state-of-the-art simulators, namely the NS-3 simulator and the Matlab toolbox, in order to generate large amounts of synthetic data to train the different aforementioned ML models. Furthermore, by using our proposed data generation framework, we generate two different datasets containing images that represent snapshots of the spectrum in either the time or time-frequency domain.

Our evaluation shows that all models, using both approaches, have an accuracy of more than 96 %, when being validated with a synthetic test dataset. However, the models trained with the dataset with images in the time-frequency domain, obtained after performing Short Time Fourier Transform (STFT), offer an even higher accuracy. To indicate the applicability of the domain randomization approach in a wireless context, we also present a validation with real-life data that shows, among others, that it is possible to detect different transmission rates with an accuracy of 86.9 %. Finally, a small-scale prototype setup is presented to demonstrate how the proposed models can be used in a real-life setting.

### E. Publications

The thesis is publicly available for download from [18]. The results of this research have been published in several journals and magazines: the contributions related to the ORCHESTRA framework have been published in IEEE TNSM [11] and Elsevier Computer Communications [12], while the contributions concerning the flow management and load balancing algorithms have published in IEEE TNSM [14] and Springer JNSM [16]. Furthermore, our work has also been published in the proceedings of well-known conferences and workshops in the community such as IEEE CNSM [10, 19, 20, 15], IEEE IM [13, 21], IEEE WoWMoM [22], and others [23, 24]. In summary, this Ph.D. resulted in 13 peer-reviewed publications of which 4 in journals and magazines.

### F. Collaborations

The results of our work have been performed in close collaboration with partners from both industry and academia. This work has been carried out in the context of 1 European project (Flexnet), and 1 Flemish project (SHIFT-TV) with project partners such as Nokia, Technicolor, Proximus, and OpenTelly. Furthermore, this work was partly funded by imec, a research institute founded by the Flemish Government.

## V. Future Perspectives

The research presented in this work has introduced several important new research directions. First, while the proposed ORCHESTRA framework has shown its potential and feasibility in networks with Ethernet, Wi-Fi, and LTE technologies, we did assume that all of these technologies could be controlled. Additional research should investigate the corporation of the framework with non-controlled technologies or networks. Furthermore, the performance of the framework under the presence of different technologies should also be explored.

Second, the evaluation of the different algorithms proposed, have shown that the proposed approaches succeed in increasing network-wide throughput. Future work could consider other criteria as well, such as energy consumption, latency, or different QoS classes. Energy consumption can, for instance, be taken into account through the offloading of all traffic flows from a specific connection or technology. Additionally, taking into account different QoS classes can, among others, allow the assignment of the required bandwidth to priority flows. Furthermore, one of the novelties of the algorithms proposed in this dissertation is that the decisions are based strictly on real-time monitoring information. This can further be advance by not only making decisions based on the live state of the network but also consider predictions of the future state of the network. For instance, using ML techniques.

Third, we have successfully explored the possibility of detecting traffic patterns directly at the level of the wireless spectrum. However, because of the difference in accuracy between the validation with synthetic and real-life data, there is room for improvement. This can, for instance, be done by using a part of the real-life datasets to retrain the models. It is also possible to generate additional training data based on the real-life data captures, using Generative Adversarial Networks (GANs). Another option would be to investigate the performance of semi-supervised learning methods that can better cope with unseen data. Furthermore, more complex scenarios with multiple flows and transmitters should be considered.

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