Orchestration of Heterogeneous Wireless Networks: State of the Art and Remaining Challenges

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Abstract

Wireless devices have a plethora of technologies at their disposal to connect to the Internet and other services. Management and control of each technology are traditionally isolated, and coordination between technologies is nearly non-existent. This isolation leads to poor resource usage, which in turn reduces performance and service guarantees. To satisfy growing user demands, we need to leverage the different service guarantees offered by each technology. Additionally, we need to improve orchestration between technologies to increase performance and flexibility while offering a more extensive range of service guarantees and maximizing resource utilization across networks and users. In this work, we present the general challenges one encounters when managing heterogeneous wireless networks. We argue that the primary challenge is the heterogeneity itself, the number of different devices and technologies, the different service requirements, and the increasing complexity as a consequence. However, technology abstraction can overcome these challenges. We provide an overview of state of the art commercial and scientific solutions and show their strengths and weaknesses. Based on this, we discuss the current status and what future challenges still await to provide full seamless heterogeneous wireless network management.

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1. Introduction

Today's devices, such as phones, wireless access points (APs), sensors, and other machines, are often equipped with multiple networking technologies to enable them always to stay connected. This connectivity allows users to use a plethora of Internet and other services through technologies like Digital Subscriber Line (DSL), Long-Term Evolution (LTE), or IEEE 802.11 with even more technologies in the future such as IEEE 802.11ax/ay or 5G solutions [1, 2, 3]. We expect this trend to continue, with a further increase in available technologies. From this follow two scenarios: i) technologies cover similar scenarios but do not share spectrum, such as LTE and IEEE 802.11 bring Internet access to users, ii) technologies cover different scenarios but share the spectrum, such as IEEE 802.11 and Bluetooth. Currently, technologies are isolated, and applications or the operating system takes care of technology selection. This isolation leads to inefficient use of each technology; for example, one technology is congested while another has plenty of free resources. To truly achieve the high bandwidth and low latency requirements of today's services, orchestration across technologies needs to be in place. Only a holistic approach allows optimizing the performance of services in these heterogeneous networks.

Heterogeneous wireless management also becomes increasingly important for new technologies, such as 5G. The usable spectrum is extended, and different frequencies cover different scenarios. For example, lower frequencies can be used for long-range connections, especially in rural areas, while high frequencies can be used for smaller cells to achieve high throughput and keep cell interference at a minimum. Similarly, IEEE 802.11ad/ay, which supports the 60 GHz spectrum, handovers between higher and lower frequencies are necessary and need to happen instantaneously. This handover requires precise monitoring and management to utilize all available spectrum fully. Improved utilization includes three cases. First, increasing reliability by duplicating packets over multiple technologies and therefore maximizing the chance of a packet arriving. Second, improving throughput by splitting a traffic flow among several technologies and achieving higher bandwidths than a single technology can provide. Third, keeping latency low by handing over flows to the technology that can provide the lowest available latency. Additionally, clients can be assigned to the technology that suits their needs the best, and the overall resource use can be maximized and therefore costs saved.

This paper aims to provide a broad overview that includes the newest commercial and research solutions besides established ones. In contrast to existing surveys on this topic, we consider coordination throughout the complete network stack and do not focus on specific networks or network architectures [4, 5, 6, 7, 8, 9, 10], specific use cases [11, 12, 13], specific methods [14, 15, 16], or specific paradigms [17, 18, 19]. Additionally, we provide an overview of research algorithms that address resource optimization in heterogeneous networks by use of load balancing as well as a short overview of coexistence schemes.

We first present a generic architecture of components and services that are found in heterogeneous networks in Section 2. This architecture will serve as a basis for comparing existing solutions in Section 3. Analyzing existing solutions and their features will give a good understanding of the differences in their approach, as well as the advantages and disadvantages they bring. In Section 4 follows a discussion of the different solutions. Section 5 gives a short overview of coexistence schemes, and Section 6 gives an overview of load balancing algorithms that can be employed in small and large-scale networks. We will explore the remaining open challenges in Section 7 and conclude in Section 8.

2. Architecture of multi-modal heterogeneous networks

In this section, we discuss the different actors and building blocks of heterogeneous networks and their functionalities.

As illustrated in Figure 1, any network consists of several interconnected nodes. A node can, among others, represent a consumer device (e.g., smart-

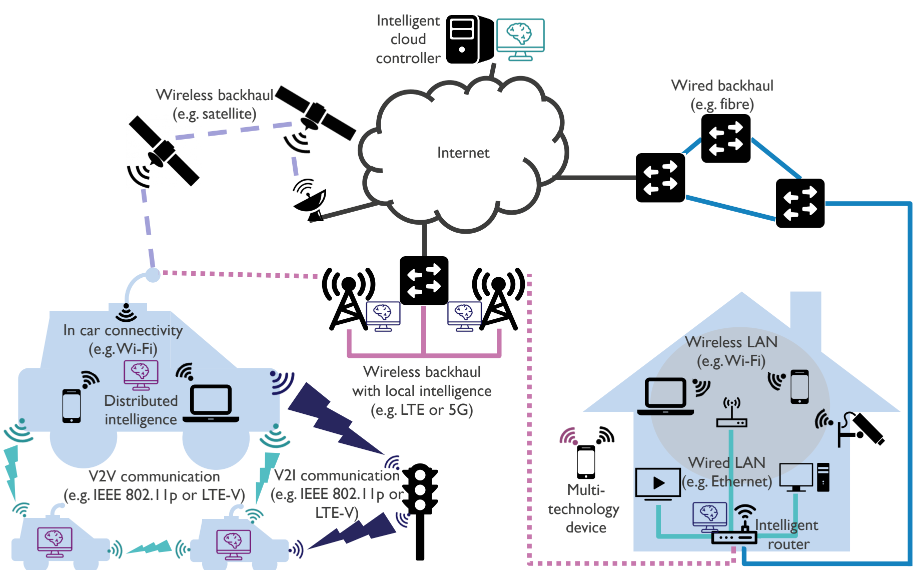

Figure 1: Representation of a subset of different heterogeneous networks and their interconnections

phone, sensor) or an infrastructure device (e.g., an AP or base station). These nodes can be connected to one or multiple neighboring nodes, can be part of one or more networks, and can be positioned within or at the border of a network. Such nodes are, respectively, called intermediate and edge nodes. Nowadays, nodes, especially edge nodes, are often equipped with multiple communication technologies. This multi-technology support is, for instance, the case in the area of vehicular networks where two competing standards have been developed: IEEE 802.11p (the base for the IEEE 1609 and European ITS-G5 standard) and

LTE-Vehicular (LTE-V) [20, 21]. As depicted in Figure 1, communication using both technologies will occur between vehicles and (road-side) infrastructure and between vehicles mutually. The intelligence for managing the network and its devices can be fully distributed (the devices decide themselves), placed centralized on a controller, or in the cloud. Furthermore, these nodes are interconnected by using wired or wireless technologies. Especially for the management of wireless technologies and environments, significant challenges remain.

The management burden has increased as the heterogeneity among nodes and technologies expands. On a node level, different applications are running on different hardware with varying demands (e.g., low power consumption or high throughput) and capabilities (e.g., supported technologies and functionalities). Similarly, because of the diversification of technologies, each technology has its unique properties (e.g., capacity, range, power consumption). This diversification leads us to four main problems that need to be solved:

- **There is no multipath routing support across technologies.** Each technology handles packet forwarding and receiving individually. Features, such as load balancing and packet duplication can therefore not be employed.

- **Seamless vertical handovers of traffic flows** (across technologies, compared to horizontal handovers, which are within a technology) **are not possible.** Instead, the connection drops until an upper layer switches to another technology. This switch can take up to several seconds, which is too high for real-time applications.

- **Spectrum coordination between technologies does not exist** and can severely degrade performance [22, 23]. If the spectrum is shared efficiently, throughput can increase and latency decrease. While spectrum coexistence schemes exist, they usually make use of a framework that supports the technologies in question to apply the scheme (e.g., Tan et al. [24]). Otherwise, acceptance by industry and deployment are difficult. Current frameworks either support only limited technologies or require significant change to devices to enable the functionality. Additionally, technologies may require changes to support coexistence schemes. We provide an overview of such schemes in Section 5.

- The **lack of coordinated management** between technologies enables the previous problems and decreases overall performance in the network. Performance can be increased, and costs decreased by centralizing the control of all technologies.

This management problem is present in all kinds of heterogeneous networks and use cases. For instance, in Local Area Networks (LANs), where different high-end consumer devices (e.g., smartphones, smart-TVs, and laptops) compete for the available bandwidth of different technologies such as Ethernet, IEEE 802.11, and Bluetooth. The second example of a challenging heterogeneous use case is providing connectivity for smart vehicles like self-driving cars, as depicted in Figure 1. These vehicles require reliable communication with infrastructure (e.g., road-side units) or other vehicles (V2V communication) to function correctly. Furthermore, these vehicles should also provide connectivity for their passengers. Once again, different technologies are available, such as IEEE 802.11, LTE, IEEE 802.11p, LTE-V, or satellite communication. Other relevant scenarios are, amongst others, wireless community networks, industry 4.0 environments, or smart cities.

3. Standards and frameworks for heterogeneous networks

There have been many efforts related to both vertical handovers and multi-technology load balancing. First of all, we individually highlight the most relevant existing standards and frameworks. Afterward, we position the different solutions next to each other and provide a comparison in Table 1.

3.1. Media Independent Handover (IEEE 802.21)

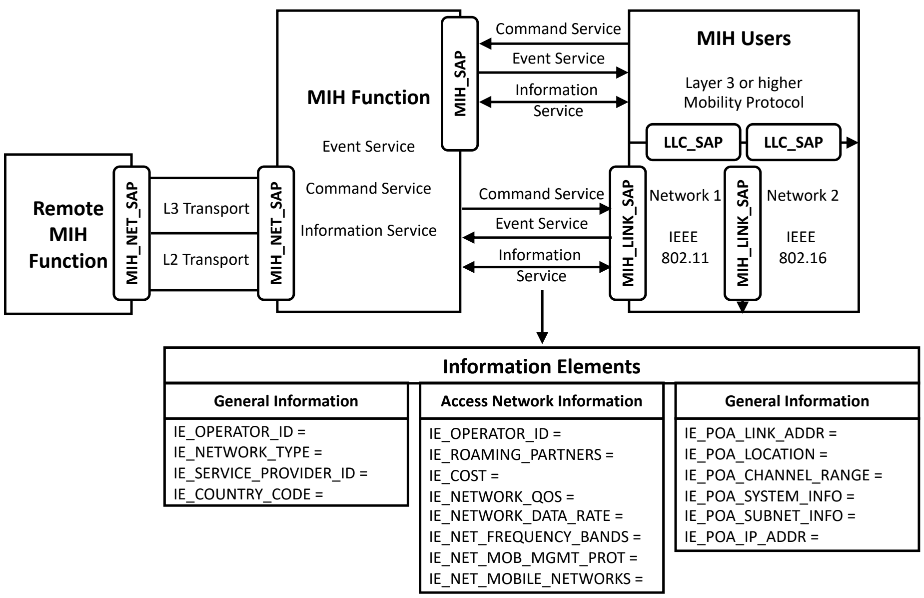

Figure 2: The architecture of IEEE 802.21 depicting all included functionality. [25]

Handover mechanisms have been defined or proposed for roaming across APs or base stations within single technologies such as IEEE 802.11, IEEE 802.16 or 3G/4G [26, 27, 28, 29, 30]. To offer similar seamless mobility across those different networks (in particular LAN-WAN), and to speed up mobile IP handovers, the Media Independent Handover (MIH) standard was proposed in 2009 [31, 32, 33]. Figure 2 shows the general architecture of IEEE 802.21.. This standard allows for the continuation of IP sessions across different technologies and networks by the introduction of the exchange of inter-layer messages through the MIH Function (MIHF). This function is located between layer 2 and layer 3 of the corresponding wireless technology. It can use various Internet Protocol (IP) based protocols, including Session Initiation Protocol (SIP) and Mobile IP, to facilitate handovers. Communication between MIHFs of different wireless technologies is managed by event notifications, commands, and information services. An event notification can include a warning about dropping signal quality, while a command can be used to initiate a handover between technologies. Information services are used to exchange information between higher and lower layers as well as the MIHF.

However, this requires adaptations to the underlying technology. Additionally, not only end-devices but edge nodes as well need to support this standard. For centralized management, intermediate network nodes, which do not have a wireless connection, that implement MIHF are necessary as well. While the focus is on handovers between on the one hand IEEE 802.11 and Worldwide Interoperability for Microwave Access (WiMAX), and, on the other hand, WiMAX and LTE, it is extendable to other technologies [31, 32]. Currently, IEEE 802.21 is being used in Mobile IPv6 to facilitate handovers [34].

The standard was heavily reworked in 2012 and 2017 with more focus on security and support for Internet of Things (IoT) networks as well as edge and fog computing [35, 36]. It also includes new technologies that only support downlink traffic, like typical broadcasting networks. As the standard does not give any guarantees for handover times, many authors tried to improve handovers times as summarized by Ghahfarokhi and Movahhedinia [37]. Additional research includes implementation and actual deployment, extending the standard to support a broader range of commands, and handover strategies to improve user experience [37, 38, 39].

3.2. IEEE 1905.1

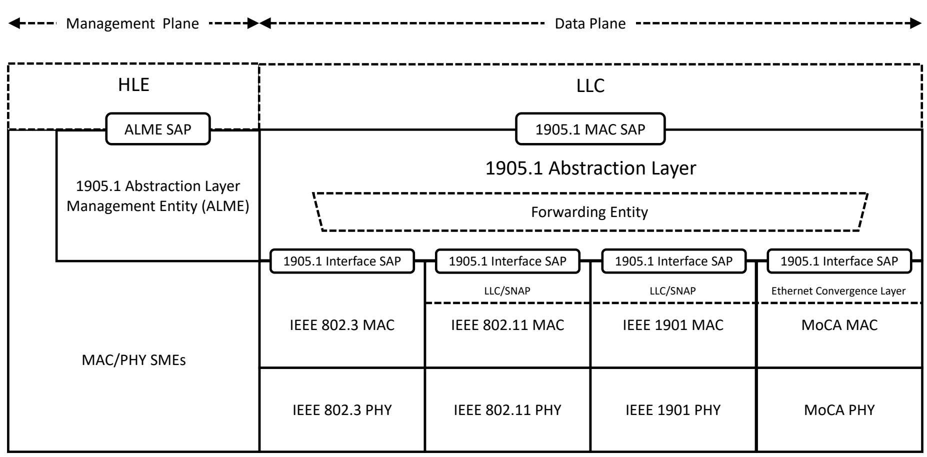

Figure 3: The abstraction layer of IEEE 1905.1 [40].

The IEEE 1905.1 standard from 2013 also tries to address the inter-technology handover and management problems, especially in LANs [40]. As can be seen in Figure 3, IEEE 1905.1 compliant devices have an abstract layer hiding the underlying diversity in supported technologies (i.e., Ethernet, IEEE 802.11, Powerline HomePlug, and Multimedia over Coax (MoCA)). This abstract layer is key regarding user-friendliness and Quality of Service (QoS), as users do not want to struggle with the low-level specifics of each network technology [41, 42, 43]. It allows for easy installation of new devices as it is, in essence, plug-and-play. Both users and service providers benefit. It is also compatible with legacy hardware. A unique virtual Medium Access Control (MAC) address is required to represent each device on the network. This unique virtual address is used to detect IEEE 1905.1 enabled neighbors and communicate with them to create topology information and link metrics.

Management of the abstract layer can be done through the Abstraction Layer Management Entity (ALME) service access point, which serves as a point of contact to higher layers. Besides topology and link metrics, it also offers a way to set flow forwarding rules based on MAC addresses. These packet header matching rules can be used to transparently handover flows and to load balance different flows across the different interfaces. While products exist that support this standard (e.g., Qualcomm Hy-Fi), the standard was never widely adopted by industry. Research interest is limited to, for example, applying and making use of the standard in a framework for network management [44].

3.3. *ORCHESTRA - Virtual MAC layer*

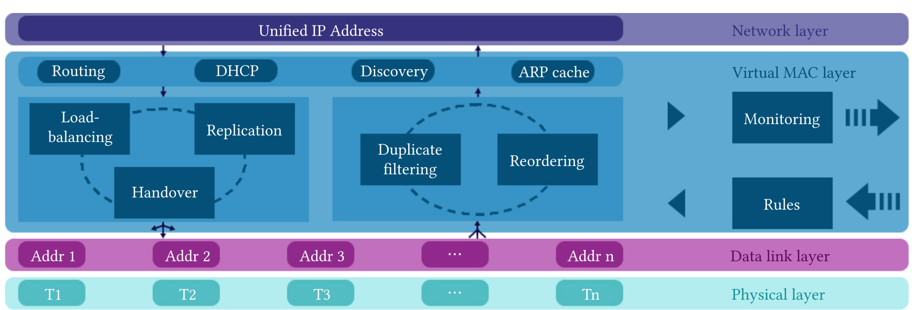

Figure 4: The abstraction layer of ORCHESTRA [45].

The ORCHESTRA framework was proposed to solve the challenge of transport protocol and technology independent management with packet-level control [46, 45, 47]. The framework consists of two parts: a Virtual MAC (VMAC) which can be implemented on all types of network nodes and a centralized controller. The VMAC allows to abstract network access by introducing a virtual layer between data link layers of different technologies and the network layer, therefore being able to offer a single virtual data link layer to the network layer with a unified IP address. With full control over the data link layers, the VMAC offers advanced services on a packet-level, like handovers, duplication, and load balancing by using packet header matching rules. Handovers are performed by changing the outgoing interface for a specific flow of packets, while duplication is done by sending all packets out over several available interfaces.

Similarly, load balancing is conducted through weights that balance packets across different interfaces. Packets are reordered, and possible duplicates are filtered out at the receiving VMAC to cope with possible different latency characteristics across links. Furthermore, the central controller maintains a global real-time view over the network by gathering monitoring statistics from all VMACs and can send commands to each VMAC instance to update rules. The controller allows the deployment of algorithm and intelligence to perform network optimization [46, 45, 47]. Furthermore, the ORCHESTRA controller can communicate (e.g., via Netconf or OpenFlow (OF)) with existing Software-Defined Networking (SDN) controllers to manage legacy devices without a VMAC and can be distributed to allow scalability in ever-growing networks.

The advanced functionality of ORCHESTRA can not only be used by end devices, but it can also be used in wireless backhaul networks. These networks are part of the core network and replace wires where it is either expensive or not feasible to deploy wires. Primarily the load balancing functionality can be used to achieve high throughput.

3.4. SDN-based solutions

The well-known paradigm of SDN can also be transferred from the wired domain to the wireless domain. The splitting of control and data plane allows better management of large deployments by abstracting difficulties, such as handovers, in wireless networks. SDN was mainly deployed in IEEE 802.11 networks, as they had the most need for better management. Much of the decision-making process was either concentrated on the AP or client, which led to wasted resources. Most of the solutions presented in this section follow a similar principle of abstracting functionalities of IEEE 802.11 and centralizing them in a controller. However, each solution has its specific approach and adjustments.

3.4.1. SDN@Home

Alternatives for an abstract MAC layer have been recently proposed that bring SDN into LANs, such as SDN@Home [49, 50]. SDN@Home transforms the gateway into an SDN controller which is ultimately controlled by a network administrator. In addition to SDN in wired networks, the gateway does not only configure forwarding tables, but also takes wireless network conditions into account, such as radio configuration, mobility, and interference. There is no need though for specialized hardware such as Software Defined Radios (SDRs). A programmable MAC engine allows for the configuration of wireless devices without modifying the underlying physical hardware [51]. The channel, transmission power, priority, and other parameters can be modified. While this approach allows using legacy hardware, it still requires modification on a software level to enable modification of parameters.

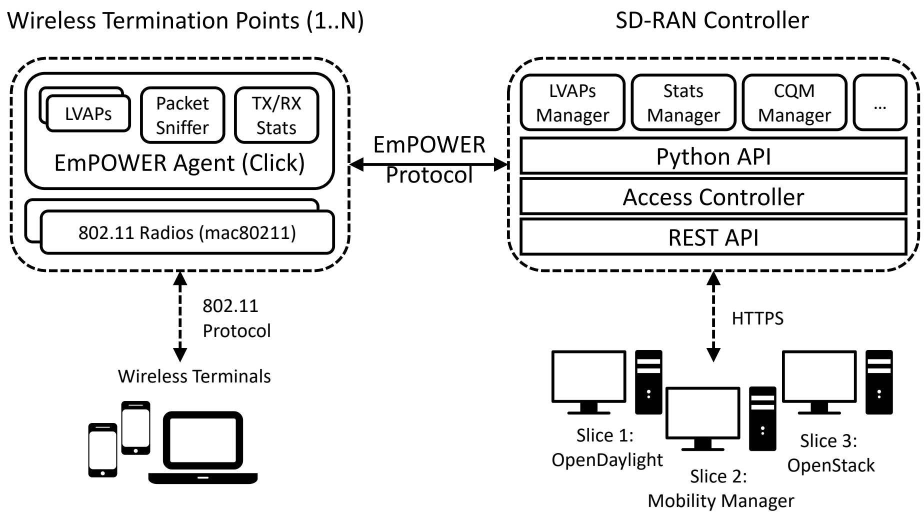

Figure 5: The 5G-EmPOWER architecture as an example of SDN in wireless networks [48].

3.4.2. ODIN

In order to make (dense) wireless networks more manageable and increase IEEE 802.11 experience and QoS, ODIN is proposed as one of the first wireless SDN controllers [52, 53, 52, 54]. Essential in its design is the introduction of the Light Virtual AP (LVAP) abstraction, as an addition to the default virtualization of APs. This concept virtualizes the association state and separates this from the physical AP. Stations will now connect to their unique LVAP instead of the underlying physical AP. This abstraction allows for the seamless mobility of stations as these stations will remain associated, and only the corresponding LVAPs are transferred to other physical APs. The ODIN architecture consists of two parts: the ODIN master (i.e., controller) and the ODIN agent running on the physical APs (using OpenWRT). The ODIN master is implemented on top of the Floodlight OF controller, supporting full OF capabilities, and maintains a global view over the network, including the status of APs, stations, and OF switches.

3.4.3. 5G-EmPOWER

A more recent wireless SDN contribution is the 5G-EmPOWER networking framework [1] [48, 54, 55]. It is inspired by and builds further on top of the principles of the previously mentioned ODIN framework. In particular, 5G-EmPOWER also uses the principle of LVAP in order to manage the mobility of stations. However, compared to ODIN, it extends the programmability of the network through either several Python interfaces or a REST API and offers an

[1]https://5g-empower.io/

increased amount of Virtualized Network Functions (VNFs) [48, 55]. As such offering increased control and insight in the available resources in the network (e.g., available bandwidth or load per physical AP). Currently, its focus is on the following control aspects: wireless clients' state management, resource allocation, network monitoring, and network reconfiguration [48]. Finally, it is vital to highlight that the offered functionalities are not only available for IEEE 802.11 networks but that there is also support for cellular networks and devices [48, 55].

3.4.4. Wi-5

Within the context of the European Horizon 2020 program, the Wi-5 project focuses on managing IEEE 802.11 APs more efficiently [56]. Instead of deploying more hardware, it aims at evolving APs into more intelligent network nodes, which enables inter-provider cooperation and seamless user experience. Instead of letting APs decide on their own, they exist in a framework with a centralized controller. The controller then tries to minimize interference and maximize throughput between different AP deployments. Further, it allows seamless handovers between providers and therefore, a better user experience. Additionally, QoS management and Network Function Virtualization (NFV) is employed to enable low latency or high throughput services. It also intends to reduce operational cost by reducing the management cost of each service provider.

Research in the Wi-5 project covers a wide spectrum to achieve the goals of the project. It ranges from flow optimization of small packets [57], over frame aggregation to support either lower latency or higher throughput [58], to being more flexible in moving wireless clients [59].

3.5. LTE-U/LTE-LAA

The ever-growing bandwidth and traffic speed demands have urged the 3GPP community to explore the wireless spectrum outside of the traditional licensed 3G/4G bands. In order to offload traffic, the use of unlicensed spectrum (i.e., LTE Licensed Assisted Access (LTE-LAA)/LTE-Unlicensed (LTE-U)) has been proposed [60, 61, 62, 63, 64, 65, 66]. Both proposals define the use of LTE in unlicensed spectrum, specifically the 5 GHz band. LTE-U was defined outside the 3GPP standardization body first. Afterward, it was standardized in the 3GPP release 12. In this version, downlink traffic could be offloaded to the unlicensed spectrum, while the licensed spectrum was still used for uplink traffic. To speed up the launch of the technology, mainly in countries such as the United States and China, no Listen-Before-Talk (LBT) protocol was specified. The lack of such a protocol led to researching the effect of LTE on IEEE 802.11 and vice versa [22, 23, 67]. The common conclusion is that LTE transmissions can heavily affect IEEE 802.11 performance, while this effect is very minimal the other way around. Unlicensed spectrum also allows for other types of services, such as device-to-device communication [68].

The complications led to a more refined version with a mandatory LBT protocol with Energy Detection (ED) [69]. It also employs a so-called freeze period, where LTE leaves free airtime that IEEE 802.11 can use. While the specification in 3GPP release 13 only allows for downlink traffic in the unlicensed spectrum, besides dynamic channel selection, the extended version of 3GPP release 14 allows for uplink traffic in the unlicensed spectrum as well. LTE-LAA with LBT leads to better coexistence than LTE-U, and with the mandatory LBT, it can also be used worldwide [66, 70]. The throughput per AP while using LTE-LAA as coexistence can even be increased compared to IEEE 802.11 sharing spectrum with other IEEE 802.11 devices.

3.6. MulteFire

Based on LTE-LAA, but specified outside of the 3GPP standardization body, MulteFire, specified by the MulteFire Alliance in version 1.0 in 2017, aims to fill the market for small cells and local deployment [71, 72]. It supports an LBT protocol, as well as private deployments and mainly works in unlicensed and shared spectrum. Contrary to standard LTE deployments, no service provider is necessary, but it can be connected to a public network as a neutral host. Deployment and operation work similar to IEEE 802.11, where a company can manage its own network. The use of the LTE protocol promises similar advantages of a centralized scheduled network with voice and data services alike.

3.7. LWA

In addition to specifying LTE in unlicensed spectrum, 3GPP also defines the use of IEEE 802.11 in combination with LTE [74, 75, 73]. LTE-Wireless Local Area Network (WLAN) Aggregation (LWA), first presented in 3GPP release 13, proposes the use of an IEEE 802.11 AP over which LTE traffic is encapsulated in the standard IEEE 802.11 MAC frame. This combination requires either that there is a physical integration of an IEEE 802.11 AP into an Evolved Node B (eNB), or that the AP is externally connected through a network interface. The LWA approach introduces fewer coexistence issues than LTE-U or LTE-LAA, and no hardware changes are required on the infrastructure, except support for the new interface, which can be done in software [76]. From a user perspective, both LTE and IEEE 802.11 are used seamlessly as mobile traffic flows are tunneled over the IEEE 802.11 connection and can be handed over between both technologies. The main focus of research for LWA lies in achieving high performance and low latency handovers. Therefore, research is mainly done to decrease the overhead of handovers and schedule them properly, reducing the handover time in both cases [77, 78].

3.8. 5G New Radio

In light of the ongoing roll-out of 5G technologies, the 3GPP community has announced Release 15 in 2018. This release, also informally called 5G phase 1, introduced the first 5G standards that specify, among others, the New Radio (NR) idea [79, 80]. NR is a novel radio interface that eventually will replace the existing 3G / 4G technologies, and as such, also the LWA, LTE-LAA, and LTE-U technologies.

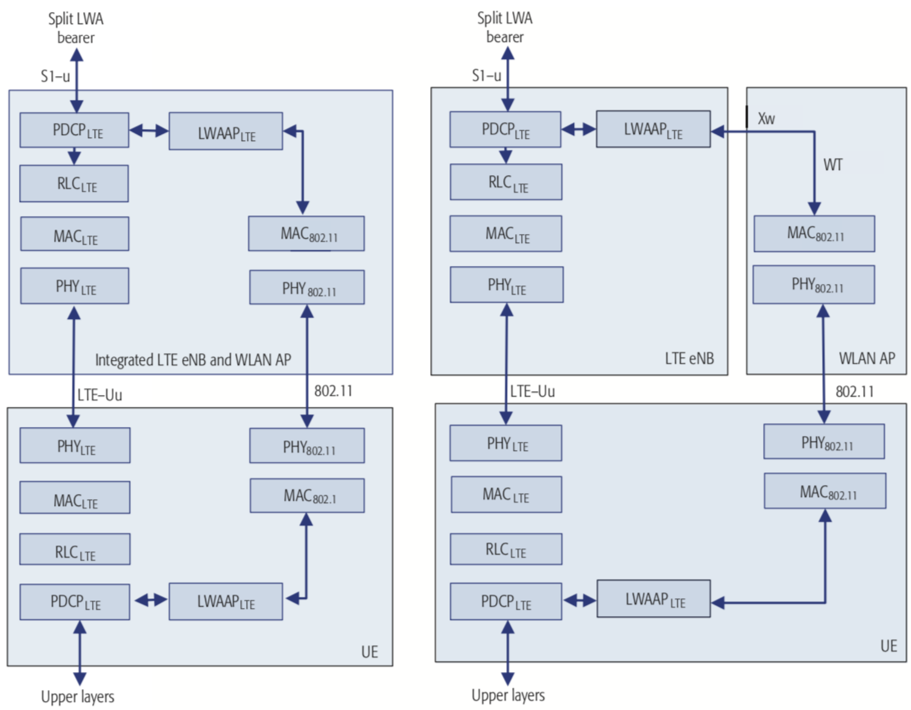

Figure 6: The LWA architecture providing the options of an integrated access point or an external one [73].

In contrast to these previous technologies, NR will support from the start operation in all frequencies from below 1 GHz up to 52.6 GHz [80]. Key in this will be the support for the frequencies above 6 GHz, introducing millimeter-wave (mmWave) communications to 5G, in order to find free spectrum to support massive bandwidth and high throughput requirements [79]. mmWave communications rely on beams between multiple directed antennas and Multiple-input and Multiple-output (MIMO) to offer Gigabit connections. However, critical elements are, among others, beamforming and the interworking (e.g., handovers) between the higher and lower frequencies [79, 80]. Such features are currently still under (further) development.

3.9. MPTCP

In order to maximize resource usage and increase redundancy in multi-technology networks, MPTCP has been proposed. This Transmission Control Protocol (TCP) extension offers multiple regular TCP connections (denoted as sub-flows) as one to an application while allowing each sub-flow to follow different paths through the network [82]. A scheduler can thus divide or duplicate application data across these sub-flows, based on the ever-changing network characteristics (e.g., increased RTT), to attain a higher throughput or increased

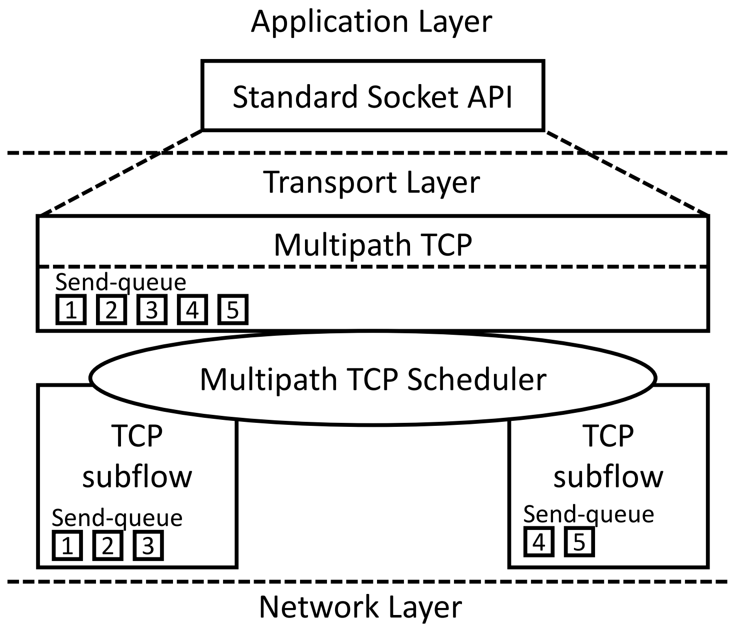

Figure 7: The Multipath Transmission Control Protocol (MPTCP) architecture [81].

reliability [81]. Additionally, one sub-flow could be kept idle and only used when the main sub-flow is broken. In this case, the fallback sub-flow is already established, meaning the handover can occur very quickly and fully transparent to upper layers.

While MPTCP aims at improving QoS and network resource utilization, it focuses only on the alternative paths between two hosts and not network-wide optimization [83]. It can also have degraded performance if the receive buffer is too low or if the network paths are heterogeneous [84, 85, 86, 87]. In both cases, the available throughput drops. MPTCP is actively used on a large scale in Android and iOS devices (e.g., by Siri) [88, 89]. Furthermore, telecom operators are using MPTCP to split traffic across both wired and wireless backbone networks (called hybrid access networks). This type of use is, in particular, the case for DSL and LTE solutions, to circumvent the limited capacity of DSL wires (also known as DSL-LTE bonding). This technology is, for instance, commercially available as Hybrid Access Solution [2].

3.10. Application layer and operating system based solutions

While the previous focus lay on lower layer solutions, the application layer also offers solutions for inter-technology or intra-technology handovers. The Border Gateway Protocol (BGP) offers a decentralized routing protocol based

[2] https://www.tessares.net/

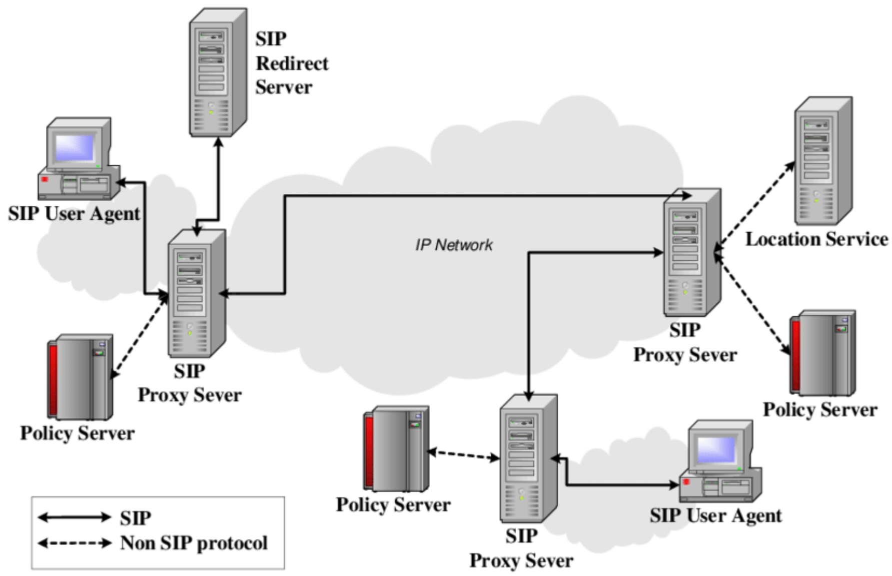

Figure 8: The SIP architecture as an example of application-based solutions [90].

on TCP [91, 92]. Each routing device opens a TCP port and listens, as well as sends, keep-alive messages, which show which links are alive and which not. While BGP is most famous for its use in the routing of the Internet, it can be used in smaller independent networks as well, which makes it also suitable for wireless networks. It is not directly usable for seamless handovers; however, it can help in identifying multiple routes that traffic can take. SIP, on the other hand, with its extension, focuses on Session Mobility [93, 94, 95]. Each device is registered at a registrar which manages current reachability of the device through its identifier. When the network or technology changes, the devices updates its IP address with its registrar, which in turn forwards it to registrars of currently connected devices. This mechanism allows for fast handovers, but there is a short downtime until the IP address is updated. SIP is currently used by Voice over LTE (VoLTE) to allow for voice calls over the mobile data connection.

Operating systems continue technology integration as well, especially in the mobile market segment. By monitoring IEEE 802.11 and LTE parameters, iOS from version 12 on can near seamlessly hand over connections between technologies. This behavior is mainly achieved by reacting early on and preferring the more stable technology.

3.11. Low power based technologies

The IoT promises billions of wireless devices for monitoring, information gathering, and low power wireless communication. Many technologies offer this functionality. They range from low throughput of hundreds of bytes per second with long-range (e.g. LoRa [96], Sigfox [97], and NB-IoT [98]) to high throughput of hundreds of kilobytes per second but shorter ranges (e.g. IEEE 802.15.4g [99], IEEE 802.11ah [100], and DASH7 [101]). Similar to other technologies, these also operate independently from each other.

Current solutions to provide unified management are mostly limited to research with a limited number of products available for select technologies like Wizzilab's D7A::LoRa::SigFox gateway [3]. The European Telecommunications Standards Institute (ETSI) defined a machine-to-machine (M2M) service layer which abstracts the technology on the service layer and therefore allows interoperability [102]. In research, there are mainly two approaches to manage different technologies. The first is based on SDN, web services utilizing REST, and Constrained Application Protocol (CoAP) [103, 104]. While the second is based on a multimodal approach that focuses on integrating multiple technologies into the same hardware [105, 106]. In both cases, energy efficiency is the most pressing concern, which results in lightweight solutions that require little power to operate. The first approach allows for simplified management by using established methods to manage the network. The second approach is capable of reducing deployment costs while also further reducing energy requirements due to singular hardware.

Table 1: Feature comparison of existing and upcoming solutions.

Features		**Technologies**
Network domain	LAN	IEEE 1905.1, SDN@Home, ODIN, 5G-EmPOWER
	LAN-WAN	IEEE 802.21, Wi-5, MulteFire, LTE-LWA
	Any	ORCHESTRA, LTE-U/LAA, 5G New Radio, BGP, SIP
Intelligence	Yes	IEEE 1905.1, ORCHESTRA, SDN@Home, ODIN, 5G-EmPOWER, Wi-5, LTE-U/LAA, MulteFire, LTE-LWA, 5G New Radio
	No	IEEE 802.21, MPTCP, BGP, SIP
Coordination	None	IEEE 802.21
	Local	SDN@Home, ODIN, 5G-EmPOWER, MulteFire, LTE-LWA, MPTCP, BGP, SIP
	Global	IEEE 1905.1, ORCHESTRA, Wi-5, LTE-U/LAA, 5G New Radio

[3] http://wizzilab.com/

Table 1: Feature comparison of existing and upcoming solutions.

Features		Technologies
Control-level	Flow-based	IEEE 802.21, IEEE 1905.1, SDN@Home, ODIN, 5G-EmPOWER, Wi-5, LTE-U/LAA, MulteFire, LTE-LWA, 5G New Radio, BGP, SIP
	Packet-based	ORCHESTRA, MPTCP
Transport protocols	Any	IEEE 802.21, IEEE 1905.1, ORCHESTRA, SDN@Home, ODIN, 5G-EmPOWER, Wi-5, LTE-U/LAA, MulteFire, LTE-LWA, 5G New Radio, BGP, SIP
	TCP	MPTCP
Vertical handovers	Yes	IEEE 802.21, IEEE 1905.1, ORCHESTRA, Wi-5, LTE-LWA, MPTCP, SIP
	No	SDN@Home, ODIN, 5G-EmPOWER, LTE-U/LAA, MulteFire, 5G New Radio, BGP
Load balance single flow	Yes	ORCHESTRA, MPTCP
	No	IEEE 802.21, IEEE 1905.1, SDN@Home, ODIN, 5G-EmPOWER, Wi-5, LTE-U/LAA, MulteFire, LTE-LWA, 5G New Radio, BGP, SIP
Packet duplication	Yes	ORCHESTRA, MPTCP
	No	IEEE 802.21, IEEE 1905.1, SDN@Home, ODIN, 5G-EmPOWER, Wi-5, LTE-U/LAA, MulteFire, LTE-LWA, 5G New Radio, BGP, SIP
Client changes required	Yes	IEEE 802.21, IEEE 1905.1, ORCHESTRA, SDN@Home, MPTCP
	No	ODIN, 5G-EmPOWER, Wi-5, LTE-U/LAA, MulteFire, LTE-LWA, 5G New Radio, BGP, SIP
Infrastructure changes required	Yes	IEEE 802.21, IEEE 1905.1, ORCHESTRA, SDN@Home, MPTCP, ODIN, 5G-EmPOWER, Wi-5, LTE-U/LAA, MulteFire, LTE-LWA, 5G New Radio
	No	BGP, SIP

4. Discussion

The number of already available solutions shows the complexity in managing heterogeneous environments, but also the effort already invested in the domain.

However, the solutions differ from each other in terms of supported technologies, use of shared frequency bands, and scenarios in which they are employed. Following, we will categorize and explain each solution, while showing when they are beneficial and when to avoid them.

4.1. Technology support

First, we will discuss the supported technologies. Here we have three subcategories: single technology support, multiple technologies, but limited to specific ones, and multiple technologies without any limitation.

Single technology support is present in all SDN solutions, such as SDN@Home, 5G-EmPOWER, ODIN, and Wi-5. They only support IEEE 802.11, with partially experimental support for LTE for 5G-EmPOWER. However, also 3GPP based solutions, such as LTE-U/LTE-LAA, MulteFire, and NR, only support a single technology. In this case, we can even group them as IEEE 802.11-based and 4G/5G-based solutions. All of these solutions were defined with a single use case and specific network domain in mind, where the solutions fit perfectly. In the case of IEEE 802.11, this would be LANs, which are often deployed by private users themselves as a cheap way of connecting wireless devices first to the local network and second to the Internet. In the case of 4G/5G, these are mobile networks, which are deployed by a service provider, which scale well and serve millions of users at the same time. Except for MulteFire, which aims to provide an IEEE 802.11 type of experience, but based on LTE technology. While the specialization is a clear benefit, the disadvantage for IEEE 802.11 technologies is the lack of management, which SDN based solutions try to overcome. A shortcoming for 3GPP solutions, like LTE, is the protocol design. It was built for a single solution to work exclusively in the spectrum. With the move to the unlicensed spectrum, coexistence is needed, which increases the management overhead or decreases the performance as LBT is needed.

The next group contains solutions that support multiple technologies, but also define with which technologies they are compatible. In this category, we find solutions such as IEEE 802.21, IEEE 1905.1, and LWA. The first two are mainly compatible with other IEEE technology and are limited to LANs, mostly for home, industrial, or office use. Both require significant change to the hardware but are legacy compatible. While LWA only requires changes to the infrastructure side, it is limited to LTE and IEEE 802.11. A further limitation is the direct use of IEEE 802.11, in which LTE is encapsulated. This direct use means that no centralized scheduling is available anymore, and the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol of IEEE 802.11 is used to gain access to the medium which results in more effort for guaranteeing service requirements. While specific support results in less management complexity, and it is, therefore, easier to manage the technologies in parallel, it also limits the capabilities of the solution. Especially in the wireless domain, it is useful to not only share spectrum but use technologies, that operate in entirely different frequency bands, therefore avoiding interference.

The last group of solutions support any technology and are therefore arbitrarily usable. This group consists of technologies like ORCHESTRA, MPTCP, BGP, and SIP as well as operating systems, although operating systems do support less in advanced functionality, such as handovers, and their reaction times are usually higher than a more specialized solution. ORCHESTRA is positioned between the MAC and network layer and uses an abstract virtual layer, similar to IEEE 1905.1, but without the additional virtual MAC address. All other solutions are either on the network layer or higher. This placement can both have benefits and shortcomings. Lower layer support generally has more fine-grained control over each technology but requires changes to the network device. If the support is on the network layer or above, it is easier to support it. This is usually done by an application, or in the case of MPTCP by a kernel implementation. The shortcoming though is a reduced amount of control, which can result in lower response times to changing network conditions.

4.2. Frequency use and cooperation

The technologies of all solutions, one way or another, can make use of different spectrum or need to share spectrum with another solution or technology. We can further distinguish between several groups. One group includes solutions that do not have any direct access to technologies and are therefore limited. Another group consists of solutions that have single technology support but use multiple spectrum bands for this technology. The last group coexists between different technologies in the same or different spectra by managing multiple technologies.

All higher-layer solutions are in the first group as they do not have direct control over the technologies. This group includes MPTCP, BGP, SIP, and any operating system level solution. While indirect monitoring of the underlying link via collected data on a higher level is still possible, interference avoidance or cooperation is not, as there is no direct information about other wireless networks. This lack of information makes coordination with other technologies, to optimize throughput or latency, complicated as the behavior of other technologies needs to be derived from indirect monitoring information. While coordination is difficult, the benefit is the ease of use and the small amount of change that these technologies require.

Another group consists of solutions that only support one technology and are therefore limited to the frequency spectrum of that technology. The members of this group are SDN@Home, ODIN, 5G-EmPOWER, Wi-5, MulteFire, LTE-U/LTE-LAA, and NR. Half of these technologies were not designed with coexistence support for other technologies in mind, but the requirement to use an LBT protocol, as they only work in unlicensed spectrum, gives them indirect support. This support mostly derives from the possibility that anybody can deploy its wireless network. One notable exception is LTE-U, which does not have an LBT protocol and therefore can cause severe performance degradation for other technologies. NR, LTE-LAA, and MulteFire, which is based on LTE-LAA, all support an LBT protocol for unlicensed spectrum, mitigating the negative impact on other technologies.

In many cases, the use of additional spectrum in another frequency band is due to contention in the current frequency band of the technology. IEEE 802.11

went from 2.4 GHz to 5 GHz, and 60 GHz while 3GPP technologies currently range from sub-GHz bands up to millimeter wave. The use of additional spectrum allows for more throughput, but it also makes management significantly more complex as characteristics of different spectrum as well as devices with different capabilities need to be considered.

The last group is capable of technology coexistence management, mainly because the management layers of these solutions have access to multiple technologies and their low-level monitoring information and can decide on their behavior. This group is comprised out of IEEE 802.21, IEEE 1905.1, ORCHESTRA, and LWA. All of these solutions support at least two technologies, either by trying to abstract the technology itself (IEEE 802.21, IEEE 1905.1, ORCHESTRA) or by integrating it into an existing technology (LWA). While this facilitates easier management as all information and control over each technology is available, it usually comes at the cost of requiring modification of devices. This group is the only one that does support more advanced functionality like load balancing, duplication, and handovers between technologies. However, the necessary change of devices is a significant obstacle to overcome as it requires hardware vendors to implement those changes in their software stacks and drivers. Currently, the need does not seem big enough to tackle this issue, as IEEE 802.21 and IEEE 1905.1 were not widely adopted by industry in the years since they were released.

4.3. Scalability and management

Scalability is an important aspect, and many solutions were defined with a specific scenario or scale in mind. However, many technologies evolved and are covering more scenarios, partially ones that were not present when the technology was initially defined. We categorize the solutions into two groups, small to medium scale and large scale solutions. This grouping is not a straightforward categorization, though, and there is room for discussion.

The first group, solutions that are small to medium scale, include IEEE 802.21, IEEE 1905.1, SDN@Home, ODIN, 5G-EmPOWER, MulteFire, and MPTCP. It is no surprise that many solutions based on IEEE technologies are present here because initially, most of those technologies were designed for small scale deployments, such as at home or an office with single APs. The scalability of those solutions is mainly derived from centralizing management components, such as association and client placement in IEEE 802.11, as formerly, there was not much management involved. This is the case for SDN as with SDN@Home, ODIN, and 5G-EmPOWER, where functionality is moved from APs to the central controller, allowing the controller to make decisions. Controllers can then be distributed to allow further scaling. Similar, the transmission range of these solutions is limited, which makes it harder to scale to large deployments, but throughput can be very high. MulteFire, on the other hand, uses a technology that was mainly developed for large scale deployments with centralized management already in mind. This background makes it easier to scale down and support smaller deployments, such as industry and manufacturing sites, but with all the benefits of a centralized solution. MPTCP can be seen as separate of both as it is an end-to-end solution with no centralized or decentralized management and limited scalability due to flows interfering with each other and possibly degrading performance [83]. While this makes it useful for private and professional users, and their specific performance needs, the possible negative influence of other TCP flows reduces possible scalability [83]. While the scalability is limited, the setup of these solutions is comparatively easy compared to large scale solutions.

Large scale solutions include ORCHESTRA, Wi-5, LTE-U/LTE-LAA, LWA, NR, BGP, and SIP either due to design, controller distribution, or federation. Except for Wi-5, all solutions were developed with such a scenario in mind and have tools to facilitate scalability. LTE and NR, as well as previous technologies like Universal Mobile Telecommunications System (UMTS) and Global System for Mobile Communications (GSM), need to scale from cities to countries, to multi-national cooperative networks. The use of unlicensed spectrum or another technology (LWA) merely extends the available spectrum, which offers different transmission ranges due to the physical limits of the spectrum. For larger deployments, this would require more APs. However, the scale of the solution itself is determined by the architecture. Wi-5, on the other hand, tries to scale a specific technology to a large scale, that was previously intended for small to medium scale deployments. It achieves this by federating a multitude of smaller networks into one big network, therefore allowing arbitrary scaling. While BGP achieves scalability by decentralizing the management task, SIP centralizes management in the registrar but scales with distribution of the registrar. ORCHESTRA does use centralized management as well with the capability to distribute controllers to scale an arbitrarily large network. The cost in many cases for being easily scalable to any size involves a centralized management platform that is in itself scalable, but complex to handle and therefore only larger organizations tend to use these solutions.

4.4. Conclusion

Depending on the use case, different solutions can be recommended. For a large scale network, where a single entity, like an Internet provider, manages the network and requires a significant amount of spectrum, LTE-U/LTE-LAA and NR are recommended solutions. Especially if an LTE network already exists and needs to be extended. If the deployment is smaller, for example, in an office or industry environment, then SDN solutions or MulteFire, depending on the requirements are an appropriate solution. For home networks, as complexity needs to be kept at a minimum, automatic SDN solutions like SDN@Home are more suitable. If changes on devices can be made, ORCHESTRA or similar solutions that are based on a virtual MAC layer can be recommended as arbitrary technologies can be used and managed together. If there is limited or no control over the network infrastructure, solutions such as SIP have the advantage.

While for specific areas, one or more solutions are a suitable choice, there are also many open problems. None of the presented solutions can be recommended as a universal solution. This problem has different reasons:

- **Technology support is lacking** in many solutions. Already a variety of wireless technologies exists, and more are bound to be deployed in the future. However, standardized solutions, like LWA or Wi-5, focus only on a tiny subset of available solutions. This small focus will lead to either fragmented solutions or no support at all for specific technologies.

- **Client modification is necessary** to support advanced functionality. Both ORCHESTRA and MPTCP offer load balancing, duplication, and handovers but need client modifications as a modified kernel or virtual MAC layer.

- **Adoption** by providers and vendors **is essential** for the success of a solution. Only LWA, MPTCP, and VoLTE have an industry-wide adoption, but all have limitations.

- **Interference between technologies**, also new technologies, **is** increasingly **a problem**. Currently, no scheduling across technologies exists, and technologies in the same spectrum will degrade each other's performance. Two networks from different providers will have similar issues.

5. Coexistence of technologies

While frameworks and standards for technology coordination allow for the best performance, other work concentrates on coexistence between technologies - either based on an existing framework like LTE-LAA or as a standalone implementation. In recent years, with the introduction of LTE-U and LTE-LAA, the focus lay on the two most used wireless network technologies for high throughput, LTE and IEEE 802.11 in the unlicensed spectrum. The introduction of LTE in the unlicensed band can have a significant performance impact on IEEE 802.11 networks, which requires adjustments to how LTE works in the unlicensed band or other coexistence mechanisms [23, 22]. Zimmo et al. show that it does not need frequency separation between both technologies, but the virtualization of the time domain allows for improving the performance on both technologies [107]. The authors solve the problem by proposing two throughput optimizations, one for each technology, and combine it with a scheduling algorithm that assigns different slot ratios. Another approach that aims for coexistence between LTE and IEEE 802.11 optimizes QoS parameters by considering user association and resource allocation as a singular problem [24]. By adjusting power allocation, transmission time, and subcarrier assignment for LTE, fairness can be kept for IEEE 802.11 users. Wu et al. propose a device-to-device (D2D) communication scheme in unlicensed spectrum with LTE-Direct, based on LTE-U, that offers protective fairness for IEEE 802.11 to scale cellular networks [68]. They propose to use an LBT protocol in combination with interference avoidance routing to optimize to achieve the highest performance while avoiding interference. Another study discusses different deployment scenarios and compares existing coexistence schemes for LTE and IEEE 802.11 with and without LBT [65]. They lead from LTE-U, over LTE-LAA to LWA, which offers the possibility to aggregate both technologies. A similar study and discussion are provided by Chen et al. about LTE in the unlicensed band [108]. It discusses many parameters, challenges, and enablers, combined with a wide variety of current research to enable coexistence between both technologies. Mukherjee et al. show that the introduction of LTE-LAA already shows significant improvements over LTE-U by introducing an LBT protocol for LTE [66]. IEEE 802.11 can achieve performance nearly equivalent to normal conditions.

Naik et al. extend the coexistence discussion in the 5 GHz spectrum by additional technologies like radar, Dedicated Short-Range Communications (DSRC), and Vehicle-To-Everything (V2X), especially Cellular-V2X (C-V2X) showing that coexistence problems exist outside of the focus of LTE and IEEE 802.11 technologies [109]. IEEE 802.15.4, for example, besides different implementations of the same standard, needs to coexist with IEEE 802.11 in the 2.4 GHz spectrum [14, 110]. Yang et al. provide an overview of different coexistence schemes and highlight that IEEE 802.15.4 is at a disadvantage because the transmission power is significantly lower than of IEEE 802.11 technologies. Natarajan et al. extend this by adding Bluetooth Low Energy (BLE) to the comparison finding that IEEE 802.15.4 impacts BLE more than vice versa and that BLE is more resilient to IEEE 802.11 interference than IEEE 802.15.4 [111]. These findings are confirmed by Silva et al. and Kalaa et al. testing BLE and IEEE 802.11, although they propose to improve coexistence by cooperation mechanisms [112, 113]. Another area for low power technologies is Wireless Body Area Network (WBAN) for example. Barsocchi and Potortì and Hayajneh et al. provide an overview of different technologies in use and their challenge of coexistence, especially when reliability and fault tolerance, for medical applications, is of utmost importance [114, 115].

The domain of cognitive radio provides a more radical approach towards technology coexistence. Instead of adjusting current technologies and their mechanisms, wireless communication is redesigned from scratch, with an architecture that has coexistence and support for multiple technologies in mind. Intelligent spectrum occupancy detection and spectrum use decisions in combination with different performance protocols allow for more flexibility in designing wireless devices [116]. De Domenico et al. provide an overview of different MAC strategies that can be employed and also provides a classification for those strategies [117]. It is important, though to consider real-life scenarios as imperfect conditions in real environments can have a significant impact on performance [118]. The applicable area for cognitive radios is broad. For example, it allows for flexible and reliable communication smart grids [119].

6. Heterogeneous network optimization algorithms

The solutions mentioned in the previous section define features and, to a varying degree, enable multi-technology network management through advanced functionality, such as handovers or load balancing. Many of the solutions can utilize management intelligence and algorithms to optimize network performance by selecting suitable paths for flows and load balance the load of

APs and base stations or across technologies. We will discuss both forms of load balancing, within one technology across multiple endpoints and with multiple technologies and one endpoint for each technology, in this section and elaborate on current research in this area.

We will distinguish between two application scenarios, LANs, as a part of the previously presented solutions focuses more on local networks, and more extensive, mobile networks.

6.1. Load balancing in local area networks

Load balancing different links of a device, may they be wired or wireless, to cope with increased traffic has been proposed in several contributions. Sahaly and Christin propose a per-flow decentralized load balancing technique as part of a framework for heterogeneous home networks [120]. This technique distributes incoming flows reactively on available links. It has a shortcoming though as it only takes local parameters per device into account and there is no real-life implementation available, only a theoretical description. Macone et al. present a per-packet load balancing algorithm instead of a per-flow technique [41]. In theory, it can exploit network resources more efficiently and provides better results. However, if TCP is used as the transmission protocol, per-packet load balancing can result in packets arriving out of order and therefore, unnecessary retransmissions. In real-life systems, this results in throughput fluctuations. Additionally, the algorithm runs on a centralized gateway and assumes full instantaneous knowledge of network resources and conditions. In contrast, De Schepper et al. present an algorithm that does not need full knowledge of the network, but can dynamically optimize the network based on QoS requirements towards a global maximum throughput [121]. While Ethernet and IEEE 802.11 were used, it can be extended to other technologies as well. Another approach for dynamic environments with multiple technologies achieves up to 100 % throughput improvement, depending on the scenario, by using a mathematical formulation and a heuristic to achieve scalability [122]. While the algorithm itself is technology independent, it requires technology-dependent parameters, such as global throughput degradation with an increasing number of stations, as input, but an approximation of those is sufficient.

Oddi et al. propose another decentralized load balancing technique that is specifically designed for heterogeneous wireless access networks [123]. A multi-connection layer is used to cope with the drawbacks of per-packet based load balancing if TCP is used as a transport protocol. The algorithm itself is based on the Wardrop equilibrium. It does not take into account that users do not have dedicated wireless network resources, but that they are subject to contention, interference, and competition. Determining the actual available bandwidth on links can have a significant impact on load balancing flows in a wireless network, especially with the time-varying capacity of IEEE 802.11 and power line communication [124]. With IoT technologies in mind, optimizing for energy efficiency is an essential aspect of load balancing as well. Bouchet et al. and Kortebi and Bouchet show that QoS can be provided while reducing energy consumption and therefore increasing the operation time of wireless nodes. However, the assumption is that the energy model is known in advance. Real-time measurements are not used.

Besides approaches that focus on load balancing across different technologies, research has also been conducted towards load balancing across different infrastructure devices within a single technology. The most popular application is load balancing clients in an IEEE 802.11 network across multiple APs. One way to tackle the problem is through game theory and mathematical programming formulations [127, 128, 129]. For instance, Yen et al. show that a Nash equilibrium exists, and overall fairness and bandwidth are improved, in a game where stations greedily select an AP purely to maximize their achievable throughput [127]. Malanchini et al. propose a more general game setup that also takes the resources of different operators into account while using mathematical programming to solve the game optimally [128]. Similarly, a linear programming formulation, taking into account the differences among the bandwidth demand of the different stations, has also been proposed [129]. Coronado et al. present a station association approach that utilizes channel selection for APs first to minimize interference and collisions [130].

6.2. Load balancing in mobile and large-scale networks

Research for management algorithms, especially load balancing, in mobile and large-scale networks, proposes mostly technology-specific techniques, similar to how the previously presented solutions are mostly technology-specific [131]. More specifically, the technologies are mostly limited to two, either between LTE and IEEE 802.11 (Wi-Fi) or between Wi-Fi and WiMAX. Most commonly, decisions are made centrally on the base station, with the option to use a separate controller. A popular metric to use for load balancing policies is the number of connected devices that a base station currently supports. Other decision strategies have been proposed as well, which include using utility functions, multiple attributes decision making, Markov chains, and game theory [131, 132, 133, 134]. Coucheney et al. provide a fully distributed solution based on the Nash equilibrium [135]. This solution supports fair station assignments across Wi-Fi and WiMAX. Another approach by Ye et al. proposes a distributed dual decomposition-based algorithm, relaxing physical constraints, to provide a near-optimal solution for an optimal logarithmic utility maximization problem for equal resource allocation [136]. Harutyunyan et al. realize traffic-aware load balancing across LTE and Wi-Fi networks by using an Integer Linear Programming (ILP) formulation [137]. Mishra and Mathur give an overview of LTE load balancing between normal cells and explain the differences between two types of load balancing, active and idle [138]. In the first one, the base station is aware of users. In the second one, the base station is not aware of users but can adjust its cell reselection parameters to cope with it. The authors also explain the importance of handovers as without it QoS for users would be impacted. Most classical load balancing algorithms will not work in a mobile environment, but for example, an approach based on game theory is promising [139]. The importance of handovers is also highlighted in an overview by Zhang and Dai, which shows that significant work has been done on handovers and mobility prediction [140]. It is based on a Markov chain, neural networks, Bayesian networks, or data mining. Another approach is combining load balancing algorithms and handover parameter optimization into one algorithm as decision parameters overlap [141]. This combination, compared to using multiple single algorithms, can reduce computation time and achieve better results. Gbenga-Ilori and Sezgin provide a load balancing approach combined with coexistence for LTE and IEEE 802.1111 as one model, which consists of two submodels that solve different problems. The first uses game theory to model the data rate gain for the mobile network, while the second is based on a Markovian model that optimizes spectrum utilization. The proposal of NR for 5G networks has sparked new research to enable handovers and load balancing for millimeter wave communications [79, 80]. While for example, a user association scheme based on mixed integer nonlinear programming was proposed by Alizadeh and Vu, further research and optimizations are needed within this area [143, 79].

The presented and other approaches have the downside of only taking a limited number of parameters into account [133, 144]. The most popular parameters are the Received Signal Strength Indicator (RSSI) and Signal To Noise Ratio (SNR), which can not fully map the complexity of the wireless domain. The limited number of parameters leads to several open issues [145, 133, 134]. More generic management techniques are missing but should be feasible with some of the previously presented frameworks. Mobility and multi-criteria decision functions are an essential aspect, but currently, the amount of parameters included in research is limited. The focus on supporting different QoS classes is rudimentary, similar to the support for asymmetric characteristics of downlink and uplink traffic. As current proposals mainly focus on access networks, the capacity of backhaul links might be overlooked and can cause bottlenecks.

7. Open challenges

We have seen and discussed various solutions that try to tackle the problem of managing heterogeneous wireless networks. For specific scenarios, solutions can be recommended, but for a full heterogeneous wireless network management solution, all have shortcomings. May it be in technology support, performance, adoption rate, or support of different transport protocols. Therefore, to indeed solve the issue at hand, several challenges need to be overcome. Following, we will outline them and also offer possible solutions.

7.1. Technology integration

The most straightforward challenge is the integration of current and upcoming technologies, which includes low power solutions as well. As networks and devices are evolving, this also includes domains that rely on machine-to-machine communication instead of user interaction, like industry 4.0 and sensor networks. In most cases, the devices for these networks are limited in resources like energy and computing power. However, also the supported network protocols are adjusted, which means that packets are as compressed as possible to reduce the time needed for transmission and therefore save power [105].

The most natural and most straightforward solution, in this case, is an abstraction layer. Not only can any current technology be integrated, but future technologies and their management can be included via a software update. For low power devices, a minimal abstraction layer could be used that implements only the subset of essential functionality that is needed for those low power devices which is demonstrated by Hoebeke et al. [106]. However, we can see that a standard across multiple standardization bodies is complicated. IEEE 802.21 and IEEE 1905.1 both only include technologies from the IEEE standardization body. A more sophisticated solution is the way that 3GPP follows with LWA, integrating a solution from a different standardization body into its solution, one technology at a time. While this gives a standardized solution with multiple technologies, it is a time-consuming process, and technologies might emerge too fast for standardization to keep up. An abstraction layer would solve that. Any vendor can implement it if the protocol between the abstraction layer and controller is standardized, similar to how OpenFlow is standardized and used.

7.2. Load balancing latency management

While advanced functionality such as load balancing can significantly increase throughput, it also provides challenges if the used technologies have significantly different performance properties. Especially latency can be problematic for TCP streams. To properly work in such a scenario, the packets of a TCP stream need to be reordered, as they likely arrive out of order, before the TCP stack. Otherwise, if the time between packets becomes too long, TCP will consider the packet lost and throttle the throughput. On the other hand, if the time between packets is too short, TCP might interpret this as better channel conditions and will try to increase the throughput. If this short interval between packets is a rare occurrence, it will hurt the throughput as TCP will throttle down immediately afterward. While MPTCP offers such functionality, it is heavily dependent on the scheduler to achieve such properties, and in most cases, the weights of the stream cannot be adjusted, but are defined by the scheduler. As MPTCP also does not offer centralized management, optimal network management is difficult.

A more generalized approach is needed that takes reordering and flow normalization, or more precisely, packet arrival normalization towards the transport layer, into account. While history-based normalization is an option, it can also be error-prone because of TCP's dynamic behavior. A predictive approach, based on machine learning, is more promising as the future packet arrival rate can be predicted and the forwarding towards the transport layer adjusted.

7.3. Technology coexistence

As usable spectrum is limited, but the need for bandwidth continuously increases, and the improvement of technologies is not enough, spectrum sharing will become critical in the future for new solutions. While single technologies already crowd today's wireless spectrum, the current and future use of multiple technologies in the same spectrum requires coexistence mechanisms so that all technologies get their share of airtime without negatively affecting other technologies. One negative example is LTE-U and IEEE 802.11, where the first significantly impacts the performance of the latter [22, 23]. In a heterogeneous environment, packet scheduling cannot be performed on only one technology anymore but needs to be done cross-technology to avoid interference.

There are multiple solutions to this problem. On the one hand, packet scheduling across technologies can be achieved by higher layer functionality that does not require a change to the technology. This solution would require a centralized management and scheduling platform and the implementation of such higher layer functionality, for example, in the form of an abstraction layer. On the other hand, following the trend of physical and MAC layer integration, technologies can be integrated into one platform that might even make use of a single radio chip for multiple technologies. This integration allows more freedom and cost savings in terms of hardware, but it requires further development for a suitable platform.

7.4. Intelligent global network management

The number of future connected devices is continuously increasing, and with it rises the diversity and complexity of different service requirements. This increase in combination with the integration of technologies and enabling advanced functionality leads to the need for intelligent network management to adequately provide connectivity as a service to every user. Additional complexity is added by the need for fast reactions on a device level in case of connectivity loss in the form of a fast recovery. Neighboring networks also affect the performance and need to be considered in managing airtime and transmission schedules.

Currently employed SDN and NFV architectures need to be extended to not only focus on centralized network management but include a hybrid mode as well, that allows for devices taking autonomous actions, for example in the case of connection loss to achieve this level of management. This architecture assumes a certain intelligence on devices as well as mechanisms for fast recovery in case of sudden connection loss to allow seamless connectivity in all conditions. Coexistence between neighboring networks and technologies can be achieved in several ways besides exploring new frequencies in the wireless spectrum. Networks and solutions can add a coexistence protocol that allows communication between neighboring networks and aligning scheduling schemes so that collisions do not waste possible transmission time. Another option would be predicting the behavior of neighboring networks, with machine learning techniques, for example, and adjusting the behavior of the network and transmission so that as little airtime as possible is wasted. While this will not yield optimal results, in light of the current development of competing wireless network technologies, this seems the more likely solution.

8. Summary

Heterogeneous networks require the integration of many technologies to work together to achieve better coordination and thus, higher performance. This cooperation is challenging as each technology uses isolated management while central management is needed. We presented many solutions in this survey that try to tackle the existing problems. However, none of them offers a straightforward solution that can easily be implemented in today's wireless networks. They either lack support for technologies, intelligent management, or are not readily accepted or implemented by industry. Therefore, several challenges remain. Only fulfilling the four defined challenges of technology integration will allow full integration of arbitrary technologies, enable advanced functionality, and provide abstractions to higher layers, services, and users. These challenges are load balancing latency management, technology coexistence, and intelligent global network management. Intelligent management, in combination with enabled advanced and precise functionality, will lay the foundation of true continuous connectivity for machine-to-machine communication as well as users. This connectivity will allow a new wealth of services and applications to rise and enrich the industry and consumer markets alike.

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