WIBACK: A SDN ENABLED WIRELESS BACK-HAUL NETWORK ARCHITECTURE FOR FUTURE 5G NETWORKS

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Abstract

Recently both academic and industry worlds have started to define the successor of Long Term Evolution (LTE), so-called 5G networks, which will most likely appear by the end of the decade. It is widely accepted that those 5G networks will have to deal with significantly more challenging requirements in terms of provided bandwidth, latency and supported services. This will lead to not only modifications in the access segment and parts of core networks, but will trigger changes throughout the whole network, including the Back-haul segment. In this work we present our vision of a 5G Back-haul network and identify the associated challenges. We then describe our Wireless Back-haul (WiBACK) architecture, which implements Software Defined Network (SDN) concepts and further extends them into the wireless domain. Finally we present a brief overview of our evaluation results.

1 Introduction

It is widely accepted that future 5G networks, which are expected by the end of the decade, have to cope with a huge variety of existing and novel services and applications, such as cloud-based applications, ultra-HD television and online conferencing, Machine-Type-Communication (MTC) as well as augmented reality [1]. First and foremost, this leads to a tremendous increase in the required capacity [2] for future networks. Besides that, 5G networks also need to provide high reliability and very low latency in order to support those novel applications and allow for a good Quality-of-Experience (QoE) perceived by the user. Precisely, 5G networks are supposed to provide 10x higher throughput per User Terminal (UT) and 1000x more traffic in the Back-haul network connecting the Base Stations (BSs) [3], while reducing the service level latency to 5ms and maintaining a reliability of 99.999% [4].

A lot of effort is made to investigate novel technologies and mechanisms for the access networks, such as mmWave, ultra dense deployments or massive multiple-input and multiple-output (MIMO), in order to cope with the aforementioned requirements, yet the implications on the Back-haul segment of the network are often silently ignored. However, the increasing number of cells, each supporting a significantly higher throughput, needs to be adequately connected to transport the traffic to the core segment and eventually the Internet.

In existing 4G networks this is usually not an issue, since Evolved Node Bs (eNodeBs) are either connected with a high speed wired connection, e.g. optical fiber, or with a high capacity micro-wave link so that the Back-haul network typically does not present a bottleneck. With the advent of network densification and small cells, which are deployed at non-conventional locations, more complex Back-haul network structures relying often on heterogeneous wireless technologies will appear. For example, cells might be located on traffic lights, distributed in- and outdoor on large campuses, etc., where a wired infrastructure and high capacity line of sight (LOS) microwave links are either impractical or too costly to deploy everywhere. Instead, more cost-effective wireless connections might be used, most likely even in a multihop fashion. Hence, an over-provisioned Back-haul network, as it is the usual case in 4G networks, becomes rather the exception and capacity constraints will occur. In order to moderate those, intelligent and self-organizing Back-haul techniques are required, which utilize the available spectrum most effectively by avoiding interferences with each other and the Radio Access Network (RAN).

Moreover, in order to provide sufficient bandwidth virtually everywhere including rural and remote areas, satellite overlay networks will be used in future 5G networks. Satellite networks are expected to evolve tremendously in recent years into a terrabit per second communication system, yielding to a significant decrease in costs per bit [5]. They are primed for broadcast and multicast type of services covering large areas and are therefore particularly suited to provide additional capacity wherever it is needed.

In this paper we present our WiBACK technology, which provides a self-managing, Quality-of-Service (QoS)-aware network management architecture supporting heterogeneous technologies. WiBACK is the outcome of several research projects, such as CARMEN [6] and Solarmesh [7], that is continuously being extended and adopted to new requirements of future networks and services. While in previous publications, e.g. [8]–[10], we have already presented various key building blocks of WiBACK, in this work we present the holistic WiBACK architecture in the context of future 5G networks and their requirements.

The remainder of the paper is structured as follows: First we present our vision of future 5G Back-haul networks in detail and identify the challenges associated with them. Afterwards, we review the related work before we present our WiBACK architecture. Finally we briefly present our evaluation results followed by a conclusion and an outlook on the future work.

2 5G Back-haul vision and challenges

Figure 1 depicts our vision of an exemplary future Back-haul network: Base stations, i.e. eNodeBs++, the 5G equivalent of an eNodeB, which are providing access to UTs, are connected via a Back-haul network, utilizing heterogeneous technologies, with the core network and eventually with the Internet. The terrestrial Back-haul network relies upon optical fiber, microwave but also other wireless network technologies to establish connections among the nodes within the Back-haul , the core network and the RAN. It is complemented with an additional satellite overlay network, i.e. some of the eNodeBs++ as well as some intermediate nodes in the Back-haul are equipped with bi-directional satellite equipment [1]. Even individual households are connected via a terrestrial and an additional satellite connection. The counterpart of those nodes in the satellite domain is a ring of hub stations connected to the core network.

The RAN is potentially much denser compared to current 4G networks and consists of cells of different sizes, i.e. ranging from macro to femto cells. As already mentioned, this significantly higher amount of cells also impacts the Back-haul network. On the one hand it needs to deal with a tremendous increase in traffic, and on the other hand it faces cells deployed in unconventional locations, where technical or economical constraints often lead to the usage of various wireless technologies providing a flexible, more cost-efficient and, thus, more suitable solution. This explicitly includes technologies such as Wireless Local Area Network (WLAN), mmWave or TV Whitespaces (TVWS) technologies, which either operate in unlicensed bands or on frequencies that might have a prioritised primary user.

However, the usage of such frequency bands imposes numerous challenges on the spectrum management components of a network. Since multiple operators share the same frequencies, interferences might occur more frequently. Hence, the networks also need to be more flexible and more dynamic to cope with these changing wireless channel conditions and the resulting changing capacity. Moreover, it is expected that in future denser networks, the configuration of the network devices is expected to take place autonomously by the network itself, without the need of an administrator to e.g. manually assign frequencies [11]. This is further complicated by the heterogeneity of devices, since devices of different technologies are typically also controlled differently. For example, satellite modems, WLAN or mmWave devices have different means of control and different parameters to configure.

At the same time, emerging SDN concepts are becoming popular and frequently used in today's operator networks, which highly increases the flexibility and programmability of networks. This trend of softwarisation of networks is continued and extended from pure flow controlling to holistic control and configuration of networks and their resources, e.g. radio spectrum. This encompasses controlling physical layer parameters of the interfaces of a network device, such as port speed or duplex configuration.

Even though in wired networks the amount of interface parameters that can be configured is rather limited and given that wired networks nowadays tend to rely on Ethernet technologies in all parts [12], which have matured auto-negotiation means, configuring interface parameters similar to the flow controlling seems not necessary, this changes once wireless technologies come into play. Wireless network interfaces has a significantly higher amount of parameters, which need to be configured properly in order to establish network links. Examples of these parameters are the used frequency, transmission power or Modulation and Coding Scheme (MCS). Furthermore, different wireless technologies have different sets and means to configure interface parameters, even though the actual parameter might be the same. For example the frequency of an IEEE 802.11 WLAN interface is configured entirely different than on a DVB-S2/RCS2 satellite modem in terms of commands and primitives. Hence, an open and standardised interface allowing for a holistic network management is important.

Given this vision and trends in 5G Back-haul networks, several new challenges arise or become much more important compared to current Back-haul structures in 4G networks. Those can be classified into lower and higher layer challenges. The lower layer challenges are primarily important for wireless connections and encompasses the configuration of links in terms of frequency, MCS, Transmission power (TX-Power), etc. in order to minimize interferences and spectrum usage while optimizing the available capacity on each link. This Spectrum Management also includes dealing with exploiting temporarily free frequencies, i.e. secondary usage of spectrum, as well as configuration of beamforming antennae in order to decide which node can 'talk' to which other node.

In contrast to that, the higher layer challenges are focusing on capacity planing and traffic engineering issues. Since in 5G networks capacity constraints might occur virtually everywhere in both RAN and Back-haul network while the latency demands

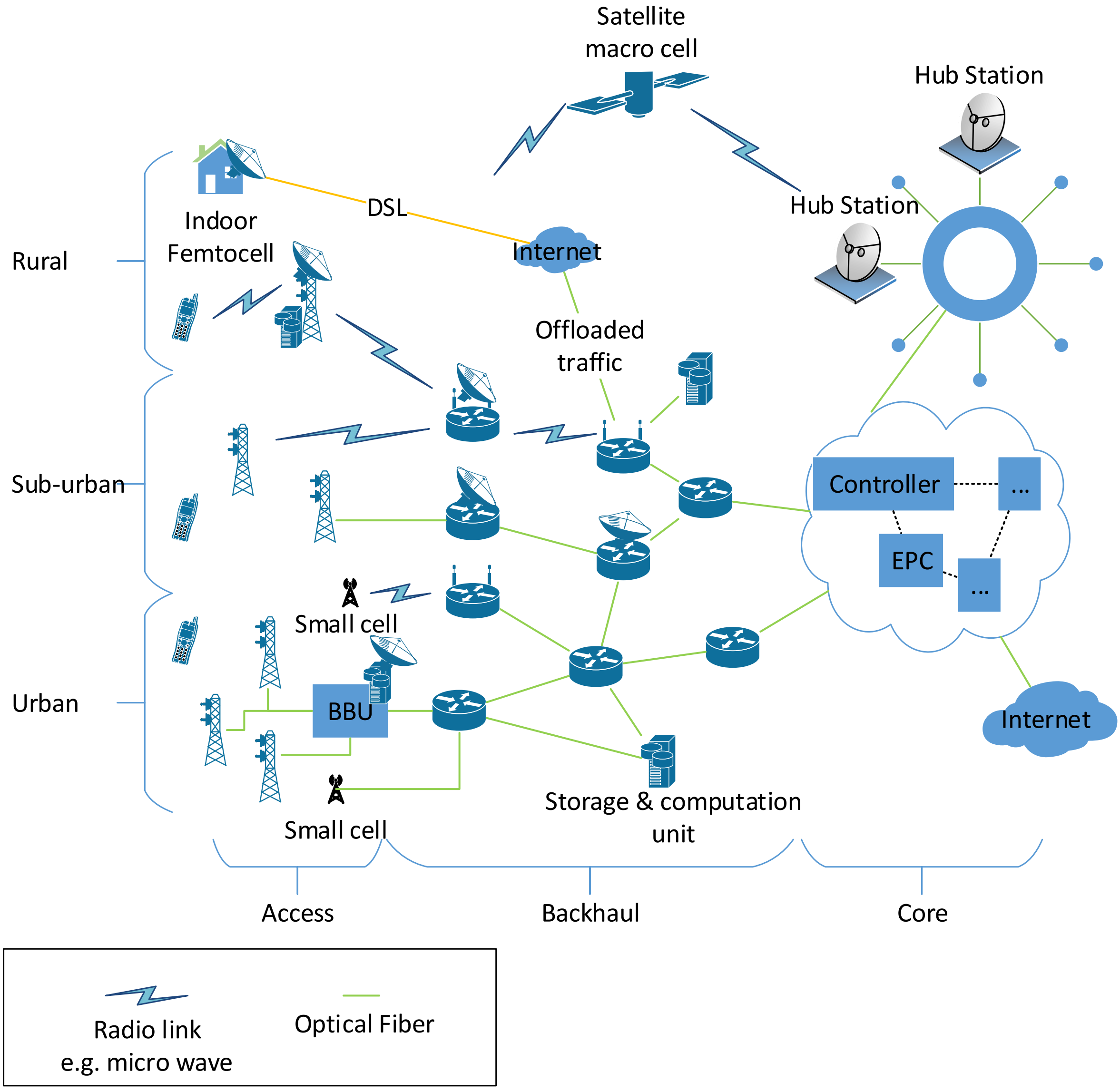

Figure 1: Example of a 5G Back-haul network

increase, the routing processes will become highly complex. Current routing protocols, such as Open Shortest Path First (OSPF) [13] or Border Gateway Protocol (BGP) [14], usually operate in a decentralised manner and are a monolithic block performing multiple tasks. These include the following: First, detecting the network topology and forming a network graph. Second, calculating least cost path for each (IP) destination and populating the routing table of a router running the routing protocol and finally, monitoring the network in order to react on e.g. link failures. However, in very heterogeneous (5G) Back-haul environments, in particular if satellite networks are included, these features are not sufficient anymore. For instance, since satellite networks can usually bridge long distances, the amount of hops required to reach a certain destination from a source might be small compared to terrestrial links. This leads to a routing decision in favor of the satellite, without taking into account the comparatively high delay on satellite connections, which causes problems for real-time and interactive services. Instead, intelligent traffic engineering exploiting the advantages of SDN is required, which considers both the traffic's QoS demands as well as the capabilities and properties of the potential links in order to avoid congestions and a bad QoE perceived by the user. This includes a potentially centralised dynamic capacity management, which has a global view on the network and incorporates feedback from monitoring and spectrum management, in order to immediately or even proactively detecting problems.

Furthermore, the Back-haul network might be equipped with additional storage capabilities, i.e. caches, or even computational units. This is required to bring content and services closer to the user in order to achieve the demanded low latency. Thus, the Back-haul network needs to become highly flexible in terms of traffic controlling, capacity management as well as radio management and therefore heavily rely on novel SDN, Network Function Visualization (NFV) and cloud concepts [15].

3 Related work

Besides the higher amount of data 5G networks need to support, one of the main characteristic is flexibility to quickly adapt to emerging application and services [16]. This includes first and foremost, a more complex traffic management, which will evolve from a source-to-destination traffic routing to a context-aware traffic controlling. It is widely acknowledged that existing SDN concepts, which allow for a programmable data plane, are able to provide this flexibility required to quickly adapt to changing protocol and emerging services.

It is generally believed that already established and emerging SDN approaches increase the flexibility of networks and enable novel concepts to address the aforementioned challenges. With the advent of SDN [17] a paradigm change in networking architecture has started, shifting from monolithic network devices, which combines control-, monitoring-, management- and data-forwarding functions in a single entity, towards a clear separation of control- and data planes. That is, the decision making processes, such as routing of traffic, firewalling, spanning-tree protocols, etc., are clearly separated from the pure data forwarding methods. This allows for a more flexible network management, since the control functions can be run centralised. [18] presents further details on the differences between traditional networking and SDN.

SDN enabled networks are characterized mainly by two things, namely the decoupling of control- and data-plane, and programmability [19]. Figure 2 shows the general SDN architecture [19]. On the lowest layer, the infrastructure layer, the actual data forwarding devices are located. Their main task is to perform any kind or packet processing based on the rules the SDN-controller, which is located in the middle layer, provides. The functionality provided by the controller is often referred to as Network Operation System (NetOS). The most commonly used protocol between the SDN controller and the devices on the infrastructure layer is currently OpenFlow [20]. This interface is also often referred to as Southbound interface. It is used to push rules to the infrastructure layer, to request monitoring information and statistics or to transmit packets, for which none of the rules apply to, back to the controller. Furthermore, the control layer provides an application programming interface (API), the so-called Northbound interface, to the application layer, which contains so-called network applications. An application might be something simple such as a centralised Dynamic Host Configuration Protocol (DHCP) server or more complex services like parental control for certain UTs or seamless mobility. It should be noted that so far there is no standardised Northbound interface.

While most of the existing SDN related work is focusing on wired environments, recently the advantages of SDN have been also recognized in the wireless world, particularly in the Back-haul segments of the network. As described in [21], given the more complex control- and management plane for wireless devices, introducing SDN concepts here can bring even more advantages than for the wired world.

However, to the best of the authors' knowledge there is no single architecture for SDN in the wireless domain, which we refer to as Software Defined Wireless Network (SDWN), that covers all potential use cases, starting from controlling regular WLAN Access Points(APs) to managing large-scale wireless Back-haul network, all of which require a specific set of features. Thus, a standardized Northbound interface for SDWN is very unlikely to be defined.

Moreover, most of the work related to SDWN is focusing on the actual data forwarding or higher layer control functions, such as handover or network access selection, which is only one aspect of the 5G requirements. The existing work is lacking the unified control of the actual radio interfaces, which enables flexibility in spectrum and capacity management as well.

4 WiBACK Architecture

After analysing the technology of the Back-haul segment in 5G networks and evaluating the related work, we now present our WiBACK approach, which addresses the aforementioned challenges. As we described in [22], WiBACK aims at providing a holistic cross-layer solution for wireless Back-haul networks. It implements the concepts of SDN for data forwarding and also includes extensions compared with typical SDN to control wireless interfaces in a technology agnostic manner. Thus, the WiBACK architecture can be seen as a realisation of SDWN.

Figure 3 gives an overview of the general WiBACK architecture. The key parts of WiBACK are located in the control layer and enable the operation of a wireless Back-haul network. Hence, WiBACK can be seen as a NetOS that manages and controls a (wireless) Back-haul network. Accordingly, WiBACK provides a simple Northbound interface allowing applications to request capacity with certain Service Level Agreement (SLA) between arbitrary points in the network. An application, for example, can be a 5G enabled evolved Packet Core (EPC)++ responsible for controlling the RAN. That is, if (guaranteed) bearers with a certain bandwidth and QoS Class of Identifier (QCI) are established between a UT and the core network through the Back-haul segment, the underlying network needs to be able to fulfil the QoS level associated with the bearer. While in current Back-haul

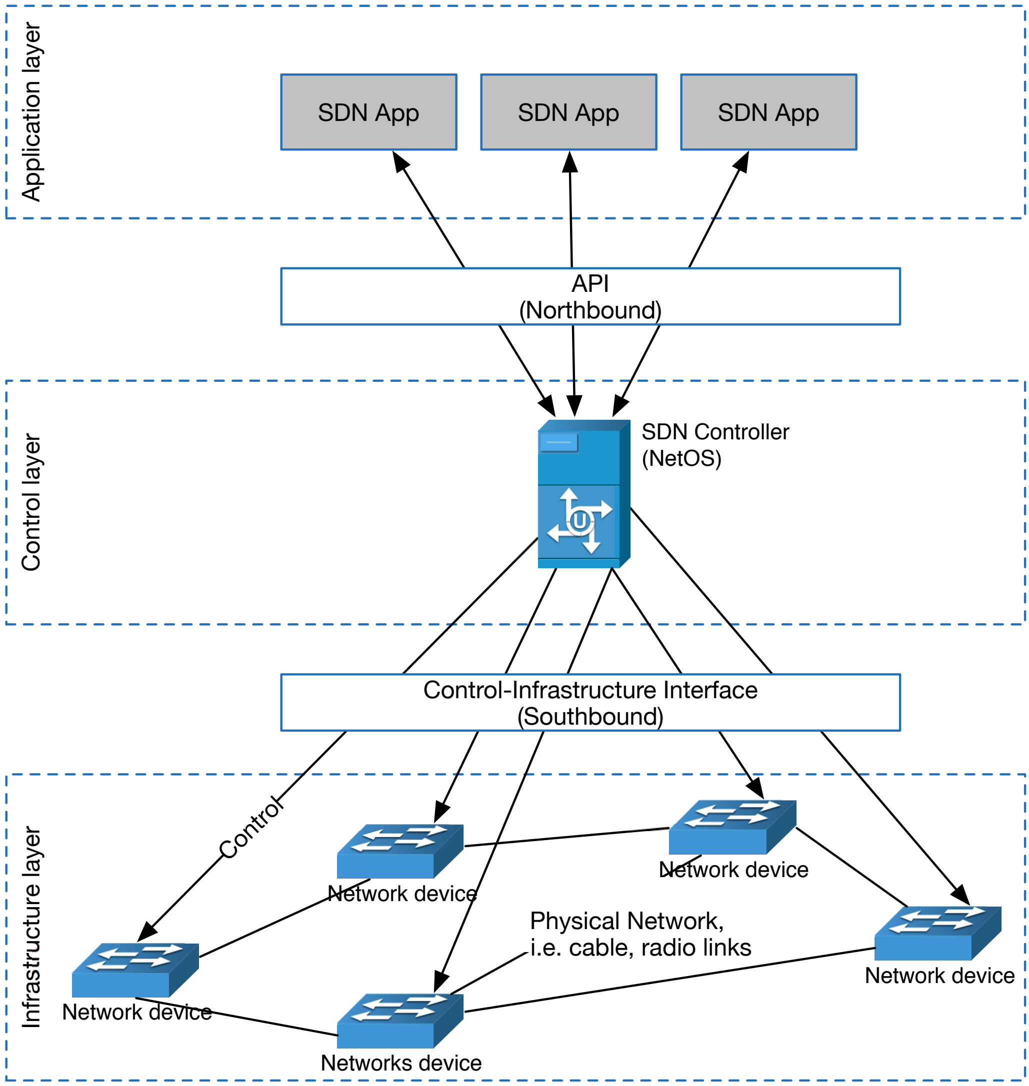

Figure 2: SDN architecture

networks this is typically not an issue due to over-provisioning of network resources, in future 5G networks this will change as we described in Section 2. Hence, a tighter integration between the EPC or other application and the network is required. In order to allow for unified control of heterogeneous network elements, of which future Back-haul networks very likely consist of, we have defined a Unified Technology Interface (UTI), which extends the typical Southbound interface with a set of commands and events allowing the controller to also program the lower layer (PHY and MAC) parameters.
In the following sections we describe the different layers and their functions in details.

4.1 Infrastructure layer

One of the main drivers of SDN is to have simplified data forwarding devices on the infrastructure layer, which solely perform packet forwarding based on rules from one or multiple flow tables. By having an open and standardised interface to push packet handling rules into these flow tables, this significantly eases the interchangeability of network devices and control planes from different vendors [23].
As discussed in [24] it is worthwhile to also abstract and standardise the configuration of physical layer parameters of the interfaces of a network device in similar manner in order to make the technology specifics transparent to network management, particularity in a heterogeneous environment. In order to do that, WiBACK defines a UTI, which is a generic set of commands and events that extends a typical SDN Southbound interface to allow for configuration and monitoring of lower layer interface parameters. Its functionality includes, but is not limited to, configuring cell membership, spectrum scanning or TX-Power

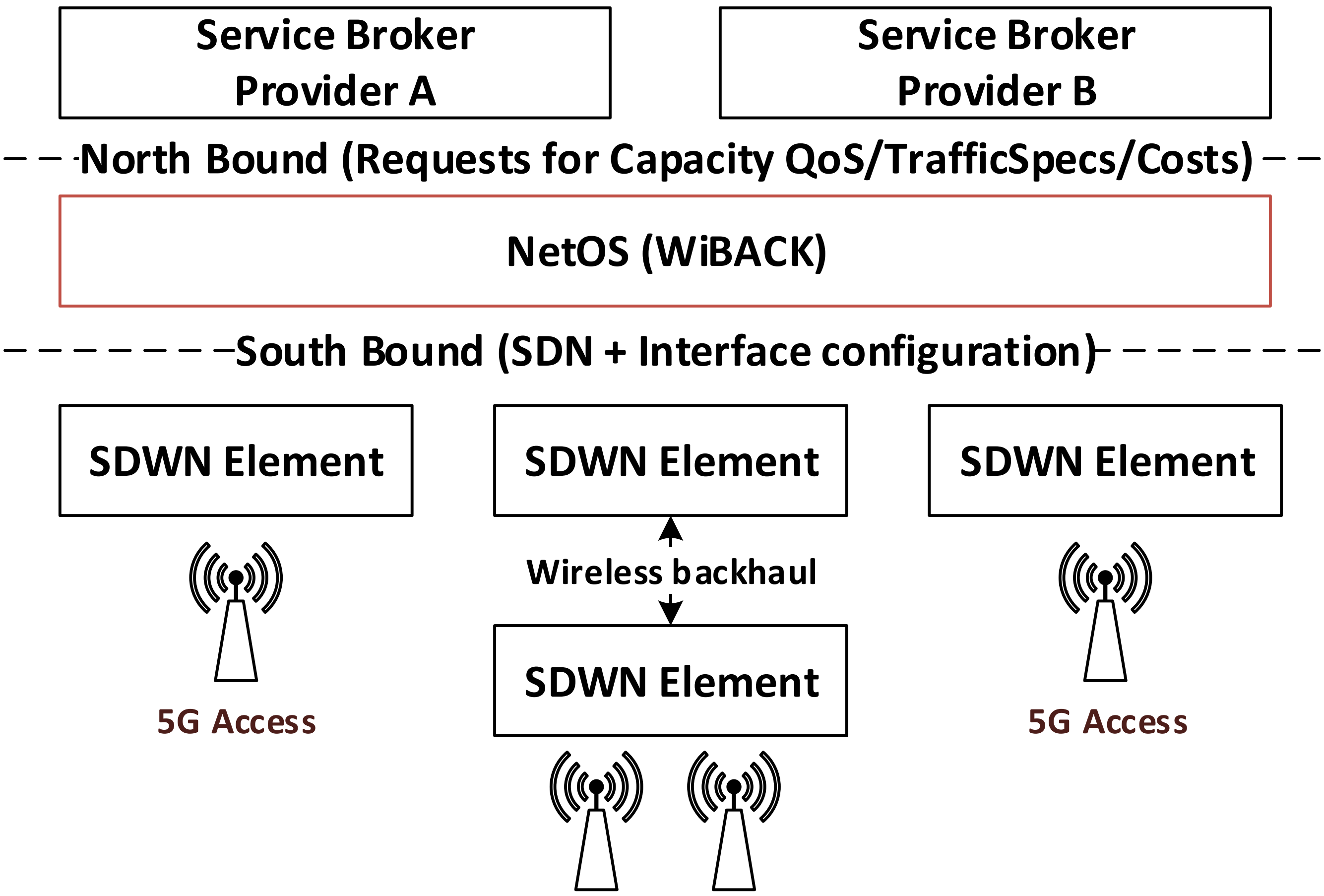

Figure 3: WiBACK architecture

regulatory management and other actions frequently required in carrier-grade wireless Back-haul networks, regardless of the used technology.

For each technology, the commands and events provided by the UTI to the control layer need to be mapped to technology specific primitives on each network device. For instance, the UTI `scan` command, which performs a neighbourhood scanning, is mapped onto a `MLME-SCAN.request` for IEEE 802.11 WLAN. Hence, it is intended that the UTI is designed generically so that it can be standardised and implemented in future devices. Following the SDN idea, this allows for managing not only data flows but devices and their interfaces holistically, regardless of the technology or the vendor.

Figure 4 gives an overview of the infrastructure layer and highlights the enhancements compared to a typical SDN architecture. Similar to SDN-enabled devices, the WiBACK data forwarding also relies on one or multiple flow tables, which contain the packet handling instructions. However, in contrast to a typical SDN network element, within a WiBACK network device interfaces are abstracted by the UTI. Hence, they can be controlled in a standardised manner by network management entities in the control layer. This allows the WiBACK controller to perform networks operations, such as centralised frequency assignments or topology forming, as we describe in section 4-B. With respect to the envisioned future 5G Back-haul networks, it is important to note that the UTI provides a standardised interface for controlling heterogeneous, multi-technology network devices that might occur frequently in those networks, as we explained in section 2. This, in turn, enables further softwarisation and programmability of networks, which becomes essential with the increased number of network devices.

We present a more detailed description of the abstract UTI in [25], including a definition of the abstract messages being exchanged between the network devices and the controller and also discuss the underlying signalling mechanisms.

4.2 Control layer and Northbound interface

The heart of WiBACK is the WiBACK controller sitting in the control layer of the SDN architecture. It acts as a typical SDN controller but is designed having the Back-haul scenario presented in Section 2 in mind. Thus, its primary task is to control and to supervise the network and the data forwarding behaviour of the network devices, i.e. it provides a proper configuration

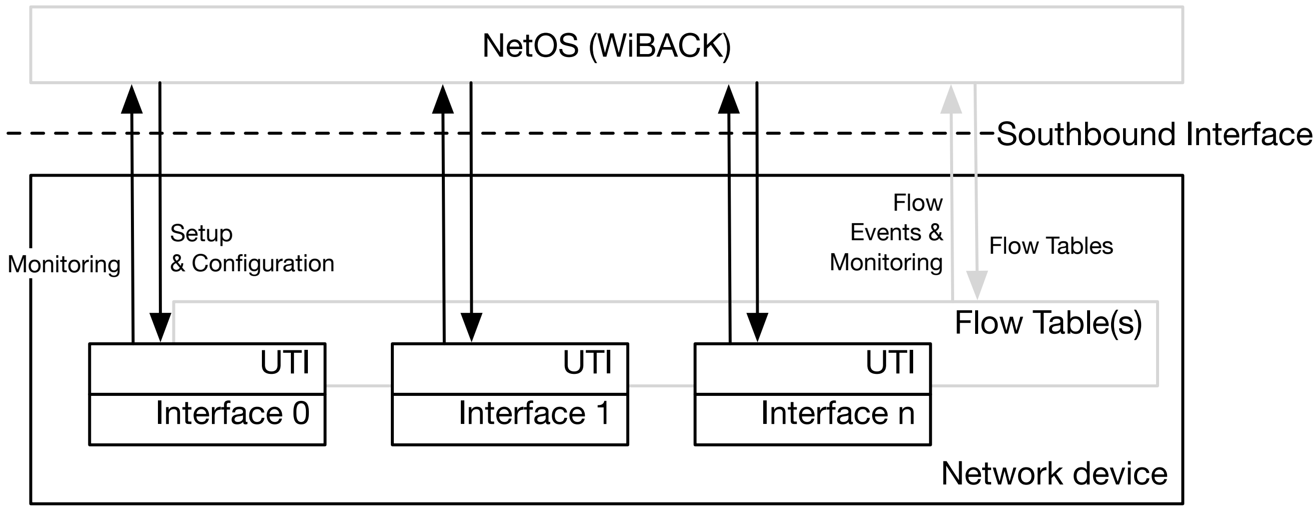

Figure 4: WiBACK extended infrastructure layer

of the flow tables of the network devices. However, due to its designated use case, the WiBACK controller also performs two other main task, namely configuring and maintaining the topology of the Back-haul network as well as allocating capacity upon request. While the first is usually not a challenge in wired networks, since the topology is defined by the existing cables, it becomes more complex once wireless links are considered due to the additional configuration dimensions of MCS, frequency and channel bandwidth, as well as the heterogeneity of technologies. Moreover, since WiBACK aims predominantly at controlling and managing wireless links, the capacity allocation becomes more complicated compared to networks, which solely rely on wired technologies. The main reason for this is the more volatile link conditions in wireless networks, particularly if unlicensed bands are used, leading to changing capacities in the network, which makes it more challenging to allocate them properly to individual service flows. It becomes clear that in scenarios as considered in this work, network capacity and flow management cannot be performed independent of the spectrum and lower layer management, as often done in many SDN approaches.

Figure 5 presents an overview of the WiBACK control layer. As can be seen, the WiBACK controller consists of two main modules, namely the Capacity Management Module and the Spectrum Management Module, which are interacting with each other while operating at different time scales. The Capacity Management Module might (re-)allocate resources in the order of seconds, while the Spectrum Management Module (re-)assignments might take minutes to administer, and are therefore triggered less frequently.

The main goal of the Spectrum Management module is to gain a global view on the physical network topology. In order to do this, it utilizes the generic command set provided by the UTI, e.g. it highly relies on the aforementioned `scan` command to identify which interface on which network device is physically able to communicate with which other interfaces of another device. That is, it identifies which interfaces are of the same technology, can be tuned on the same frequency and are in communication range of each other. This information is stored in the so-called Physical Topology Database. Moreover, the raw ambient spectrum usage is also assessed, where supported by the underlying hardware. Based on this global knowledge the Spectrum Management Module centrally assigns optimized frequencies and channel bandwidths to interfaces in order to minimize interferences within the network and with other networks.

By performing this task, it selects out of the physically possible connections the most optimal links and creates the actual topology of the network used to forward the data, which we refer to as Logical Topology. Again, thanks to the UTI the algorithms assigning the interface parameters can work technology independently and use a standardised way to set up and configure the different interfaces. As we explain in more detail in [26], the Spectrum Management module tries to form the Logical Topology in a way that it consists only of point-to-point links between nodes, avoiding point-to-multipoint connections wherever possible. While this might increase the hop count, it increases the capacity on each link and allows for the usage of more directional antennas. It should be noted that the Spectrum Management Module runs not solely once a new network device joins the network but continuously in order to react on events in the network, such as new interferences, link failures or decrease in signal quality. By utilizing well-defined UTI messages the interfaces of the network devices can be closely monitored and the Physical Topology is constantly being updated.

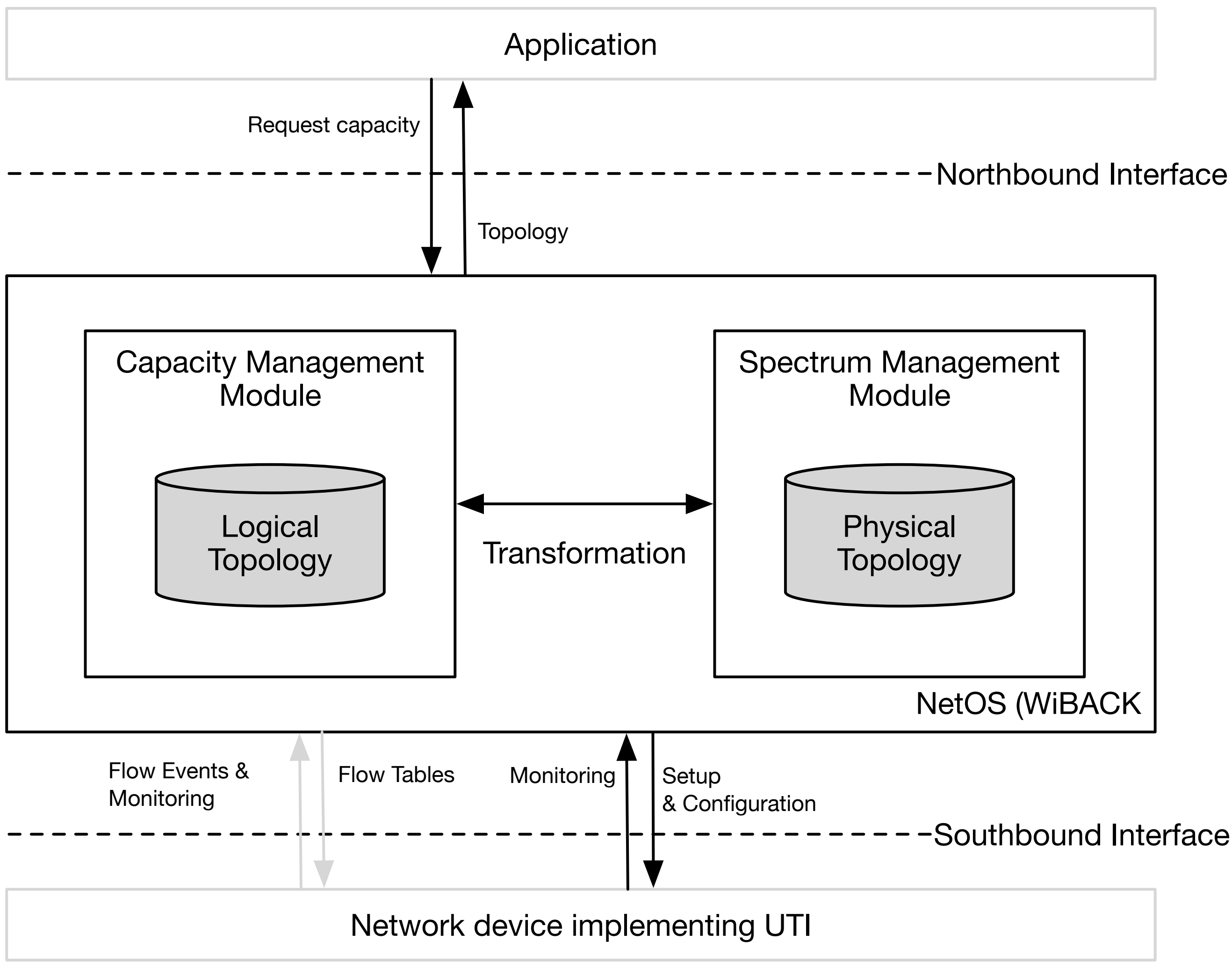

Figure 5: WiBACK Control Layer

The Logical Topology is used by the Capacity Management Module, which acts as a *Slave* towards the Spectrum Management Module. It also operates centralised, following the SDN approach and performs the task of path calculation and resource, i.e. capacity, allocation. While the Physical Topology contains physical layer link characteristics, i.e. used MCS, channel bandwidth and frequency, the Logical Topology provides more abstract link characteristics, such as available capacity in bits per second or average link latency. Hence, the Capacity Management Module can perform its task on a logical resource level ignoring the physical layer aspects.

The complete transition process from the Physical Topology to the Logical Topology is shown in Figure 6. In the first phase, the Spectrum Management Module identifies all possible communication paths, as described above, by using the UTI. The corresponding UTI primitive reports among other parameter the Received Signal Strength (RSSI) for each link. Based on this, frequencies and channel bandwidths are assigned to the most optimal subset of links in the next phase. Afterwards, the most suitable MCS is determined and, if possible, the transmission power is reduced to further reduce the interferences. Once this phase has been finished, the actual available capacity on each link in bits per second is calculated based on the parameters configured in the previous phases [9] . Moreover, jitter and latencies values are determined as well by using the proper UTI monitoring primitives. This completes the Logical Topology on which the Capacity Management Module operates.

The Capacity Management Module itself is based on the concept of a centralised stateful Path Computation Element (PCE) [27]. For each link, the stateful Capacity Management module keeps track of the available resources as well as the currently allocated resources incl. possible *overbooking* allowances. We have provided a more detailed discussion on management of the available capacity in WiBACK in [28].

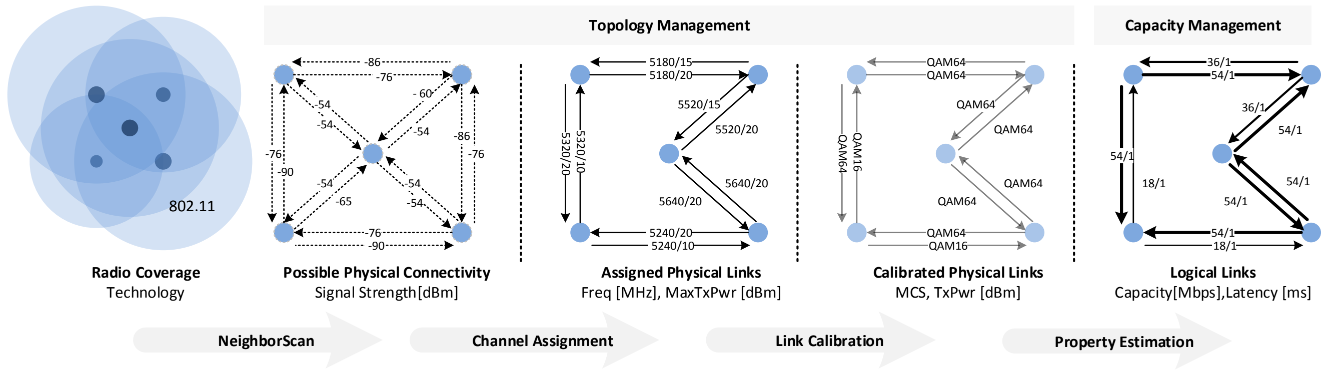

Figure 6: WiBACK Topology transition [9]

Capacity is allocated based upon request from an application via the Northbound interface. Our Northbound interface has been designed having the Back-haul scenario in mind and might therefore not cover all potential use cases for SDWN, since a universal Northbound API seems not useful, given the huge field of applications [23].

By using the Extensible Markup Language (XML)-based interface an application can retrieve the current network topology from the WiBACK Controller and can request capacity between two arbitrary nodes. Such a request might also contain explicit SLA requirements in terms of maximum latency, jitter, packet loss ratio or overbooking allowances if not only best-effort (BE) traffic should be transported. Upon reception of a request the Capacity Management Module validates it and checks if it can be admitted taking into account the requested bandwidth and other QoS parameters. Failure or success message of the request execution is sent back to the application.

If the request can be admitted and sufficient resources are available in the network the Capacity Management Module updates the Flow Tables on each network device along the calculated path. In order to provide traffic separation and reduce the switching overhead, WiBACK utilises Multi Protocol Label Switching (MPLS). That is, ingress network devices add an additional MPLS header to the incoming data packets based on the Flow Tables, which is removed at the egress network device. Hence, except for the ingress and egress devices, the Flow Tables on each network device only need to contain rules to properly switch the MPLS packets. This process essentially establishes an MPLS Label-Switched Path (LSP) in the network. Such an MPLS LSP, a so-called pipe, is associated with the requested QoS requirements. It should be noted that a pipe is meant to be a traffic aggregate to transport more than just a single flow. Moreover, the Capacity Management Module is also responsible for monitoring the established pipes and for evaluating and possibly reacting to end-to-end QoS violations signalled via the UTI by a network device. In such a case, if possible, a fail-over to a backup pipe might be triggered using the MPLS Fast Reroute (FRR) feature.

As can be seen, the WiBACK controller operating jointly with the UTI extensions on the infrastructure layer tremendously simplifies the lower layer network management. Given our vision of 5G networks, as explained in section 2, the WiBACK approach fosters the autonomous spectrum management of networks. Since in future Back-haul networks on one hand wireless connections will be used more frequently, and on the other hand due to the rare spectrum, frequencies will be no longer used exclusively by a single operator, which will lead to reconfiguration and adaptation of the network and interfaces, this feature is essential.

4.3 Boot strapping

Of particular interest for the aforementioned (wireless) Back-haul use case is the bootstrap phase when nodes are trying to (re-)join the network, e.g. due to power failures or when new nodes are being installed. As mentioned in Section 2, in 5G Back-haul networks it is expected that nodes are working autonomously with no or only limited amount of configuration and interaction with an administrator required. Furthermore, current SDN approaches also expect an always existing, pre-configured connection between the network devices and the SDN controller. In a data-centre environment exclusively utilising wired networks this expectation might seem valid. However, in networks which consists of nodes having only wireless connections that might be multiple hops away from the controller, this expectation can become difficult to realise with reasonable management overhead, since the wireless channels as well as the packet forwarding need to be configured properly. This applies not solely to the node joining the network but most likely also on intermediate nodes on the path from the new node to the controller. Moreover, it can easily lead to a chicken-and-egg problem, if the nodes are entirely configured centralised by a controller but the communication

with the controller has not yet been established.
Given that, we introduce a Bootstrap module on each network device, as depicted in Figure 7. This module acts like a minimalistic WiBACK controller. It also utilizes the UTI and updates the Flow Tables on a network device as a regular WiBACK controller. However, its only task is to initiate connectivity to one adjacent node, which is already connected to the network, in order to establish communication between the new node and the actual WiBACK controller. Once this connection is established the Bootstrap module stops and the Spectrum and Capacity Management Modules of the controller takes over until the connection is lost unintentionally. Hence, a connection between the WiBACK controller and a network device is always (re-)established, if the node is in communication range.
The Bootstrap Module utilises the UTI scan command on each interface of the network device in order to detect potential neighbouring nodes. If neighbouring network devices are within communication range it selects the most suitable one based on RSSI and tries to establish communication. This process solely relies on local knowledge of the network device. As soon as the connection is established, the controller might re-evaluate the network topology, based on its global knowledge, and might request the network device to connect to the network via a different connection. A detailed description of the bootstrapping mechanism can be found in [26].

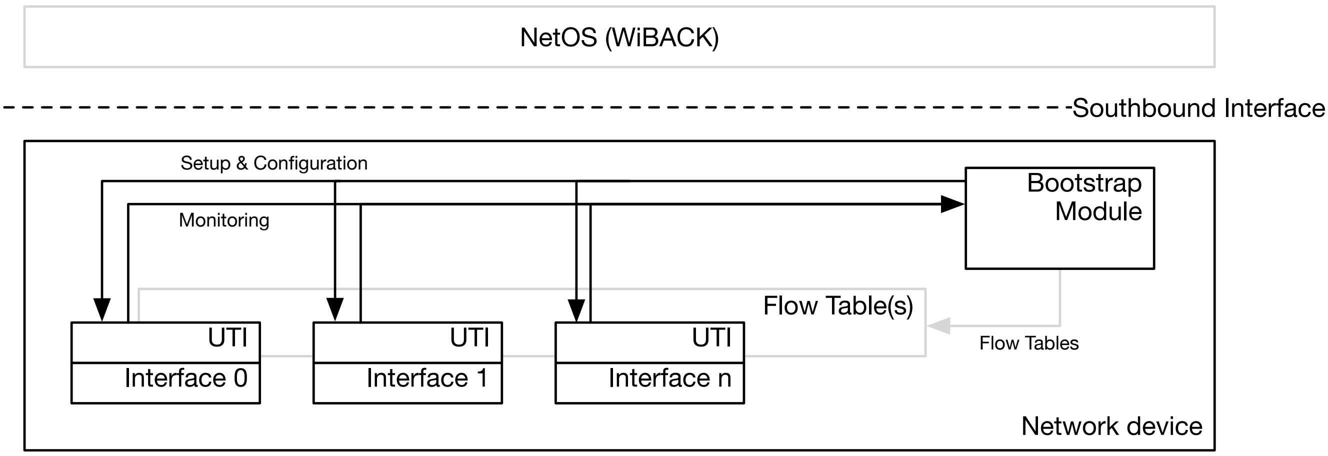

Figure 7: WiBACK Bootstrap Module

4.4 Differentiation from other architectures

Besides the WiBACK/SDN architecture other network architectures exists, which have a partially overlapping scope. The most prominent ones are typically LTE and Long Term Evolution Advanced (LTE-A) and a combination of Internet Protocol (IP), MPLS, PCE and Resource Reservation Protocol (RSVP) used jointly to perform Traffic Engineering (TE).
While 3rd Generation Partnership Project (3GPP) LTE and LTE-A standards define both the actual core as well as the RAN, i.e. EPC and the eNodeB, highly detailed, for the actual Back-haul network, which interconnects the core with RAN, they rely on regular IP routing and the underlying network technology to provide a sufficient quality of service. In fact, [29] defines no limitation on the used network technology. Given that, WiBACK and existing 3GPP LTE and LTE-A architectures do not compete but complement each other, since an LTE network relies upon a self-managed, stable and reliable Back-haul network. Hence, an EPC can be seen as a application requesting capacity between two arbitrary network devices in a WiBACK network.
Furthermore, in current operator networks a combination of IP, MPLS and RSVP is used [30]–[33]. The Internet Engineering Task Force (IETF) has also standardised the so-called PCE architecture [27], which allows to offload from the network devices the computational intensive path calculation processes onto a centralised controller. Network devices, which act as Path Computation Clients (PCCs), can request a PCE to calculate a path, which is then implemented in the network by e.g using RSVP. This functionality is similar to the Capacity Management Module in WiBACK. However, while the IP/MPLS/PCE/RSVP approach is solely focusing on managing the data path, WiBACK is able to perform also the Spectrum Management and to configure the radio interfaces of the networking devices properly, which is entirely out of scope of the first. Furthermore, the Spectrum Management Module results are fed back into the Capacity Management Module, so that the latter can operate on more accurate values and, more importantly, can better utilise links with dynamically changing conditions.

5 Evaluation results

All core components of the presented WiBACK architecture have been implemented from scratch in C++ using our Simple and Extensible Network Framework (SENF) [34] library. They have been tested on a local test-bed [35] consisting of real network devices, which are mainly utilising IEEE 802.11 WLAN, DVB-S2 satellite and 700MHz radio equipment and are evaluated in a number of pilot installations in Europe and Africa, e.g. [36] and [37].

Numerous test results have been published in separate publication [8], [22], [26], [38], [39]. All of which validate and evaluate aspects of the architecture presented in section 4 or individual component of it, i.e. the Spectrum and Capacity Management modules.

The Spectrum Management Module of the WiBACK Controller has been evaluated in [26]. The results show that the Spectrum Management Module can properly configure densely and sparsely populated topologies of network devices with up to 10 hops. Moreover, validation performed in [8] shows that the Spectrum Management can even cope with sub-optimal link conditions. The total time to required by the discovery process is within the theoretical bounds and mainly depends on the maximum hop distance between the WiBACK controller and the farthermost network device managed by the controller.

One aspect of the necessity of having a Spectrum Management Module when operating in unlicensed bands with multi-channel radios is shown in Figure 8, which depicts measurement results from IEEE 802.11 wireless link in the Fraunhofer campus testbed formed by two network devices that are a few hundred meters apart from each other. The figure shows the results of the channel assigning process. In order to select the most appropriate and least interfered channel each of the network devices scans the available frequencies in order to avoid transmitting on already used channels. The dashed and the dotted graphs present the result from the scanning process on each of the two network devices. Due to the distance of both network devices, these signal levels of other network devices, i.e. the interference levels, are not identical but differ heavily. In a typical network one of the two nodes, the master node, selects a least used frequency arbitrarily based on its local knowledge, without taking into account the interference level of the remote network device. Thus, the 5.62GHz channel might be selected, even though the remote network device has detected a higher noise level, indicating another transmitter on this channel, which might lead to decreased performance. In contrast to that, the Spectrum Management Module in the WiBACK controller utilises the UTI to request the channel scan results of both network devices in order to generate the enveloped graph. This solid graph in Figure 8 basically aggregates the scan results of both network devices. Based on this global knowledge in selects and assigns 5.7GHz instead, which has less interferences and therefore might perform better.

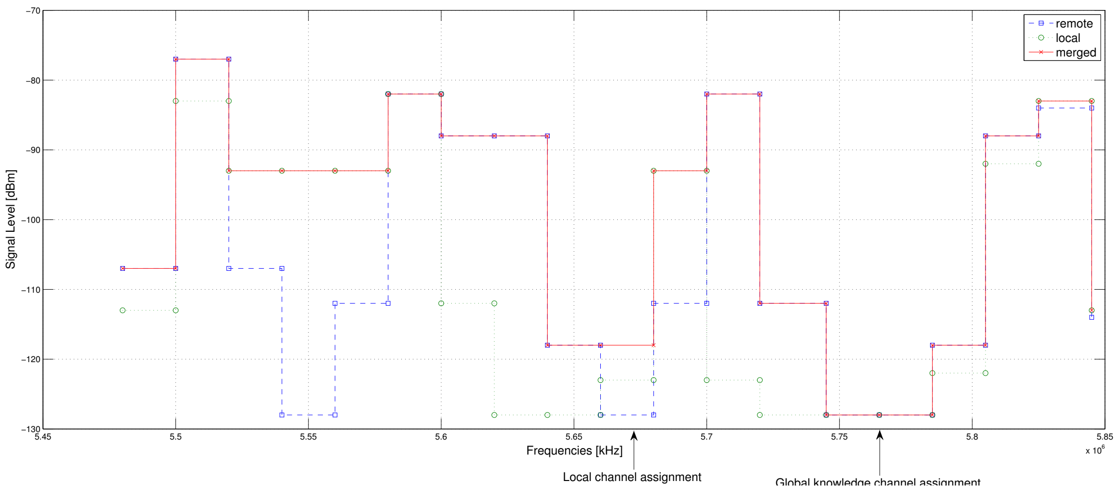

Figure 8: Example of WiBACK Spectrum Management

Furthermore, [38] presents an approach to realise the integration of Global System for Mobile (GSM) nano-cells into a Back-haul network managed by a WiBACK controller. Even in high load situation the network still behaves predictable and is able to prioritise the voice traffic.

In [39] we have particularly validated the Capacity Management and TE functions of WiBACK. Extensive measurements have shown that QoS assurances can be guaranteed while fairness and predictability in traffic handling are met.

Finally, in [22] we have evaluated a WiBACK deployment in Hennef, Germany. In this work it has been shown that Spectrum and Capacity Management collaborate properly to allow for a cost-efficient but QoS-enabled and carrier-grade Back-haul network solution.

6 Conclusions and future work

We have presented our vision of future Back-haul networks in a 5G environment and the challenges that need to be solved in order to cope with requirements of future services and their associated traffic volumes and pattern. We acknowledge that future networks need to be highly flexible and, thus, should follow the SDN concepts and extend them even further to also control (wireless) interfaces to become a SDWN. Furthermore, we have presented our WiBACK architecture, and have shown that it can already be seen as a SDWN implementation for wireless Back-haul networks.

Since WiBACK provides a smart and flexible Back-haul network it is able to cope with the requirements of 5G Back-haul networks arising from extreme network densification. Moreover, its ability to integrate heterogeneous technologies, including satellite networks, makes it particularly suitable to provide ubiquitous Back-haul connectivity, especially in rural and remote areas, which is extremely important as fast and reliable connectivity is the basic prerequisite for a smarter environment.

Fture work will focus on a close integration with the EPC and other potential applications for our SDWN controller. Moreover, we will focus on implementing and testing the UTI with emerging technologies, such as millimetre wave (mmW) or high frequency radio technologies operating at 28GHz or 60 GHz. Moreover, the applicability of the UTI approach and the SDN concepts for further use cases will be analysed. For example, a centralised Dynamic Frequency Selection (DFS) function is being discussed. DFS is mandatory in most countries when certain 5 GHz frequencies are being used, in order to avoid interferences with existing radar system. If a network device detects a radar it has to vacate the channel. In such a case the UTI and WiBACK's Spectrum Management Module enables a more controlled reaction in case of the presence of a radar, which helps to avoid network failures.

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