Spectrum Coordination for Disaggregated Ultra Dense Heterogeneous 5G Networks

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***Abstract*—Cloud-RAN paves the way for flexible network management and control in the upcoming 5G and beyond networks. The base station disaggregation in different functional elements facilitates the incorporation of heterogeneous technologies in the user access network (e.g. 5G-NR, LTE, WiFi). Network densification and integration of heterogeneous technologies enables larger network capacity through the aggregation of multiple links, thus assisting the transition from the existing network infrastructure to innovative 5G networks. Nevertheless, as Ultra-Dense Heterogeneous Networks may operate in the same wireless spectrum, their performance potential may be hindered through the operation in overlapping frequencies. Thus, efficient coordination is required between the involved heterogeneous technologies. In this work, we consider a disaggregated base station setup, based on the current standards for 5G-NR, with capabilities to incorporate heterogeneous technologies for serving the UEs. We develop signalling between the heterogeneous Distributed Units and the Central Unit, and apply a spectrum coordination algorithm for optimal use of the wireless spectrum. We use OpenAirInterface as our development platform, and evaluate our results in a real testbed setup.**

***Index Terms*—5G Disaggregated base stations, Cloud-RAN, spectrum coordination, OpenAirInterface, testbed evaluation**

I. Introduction

The incorporation of heterogeneous technologies at the end-user access has the potential to increase the overall offered network capacity, and allow operators to further expand their coverage through low cost solutions, such as WiFi. This integration of heterogeneous technologies to the traditional cellular infrastructure has been approached through different manners in the past [1] in two manners: 1) by offloading the cellular traffic to WiFi networks, and 2) by aggregating these networks from either the Core Network side or the base station side and offering multiple seamless connections to the serviced User Equipment (UE). As a matter of fact, traffic offloaded to hotspots or femtocells has surpassed the overall traffic transmitted to the Internet compared to traditional base station units [2], highlighting this paradigm shift from traditional macro-cell based setups to ultra-dense heterogeneous networks.

The 5th Generation of mobile networks (5G) is expected to boost existing network flexibility in terms of management and control of the edge access nodes, through the disaggregation of the base station units and their instantiation in the Cloud. Via Cloud based Radio Access Networks (Cloud-RAN), base stations can be instantiated on the fly in an area, based on the demand that is perceived by the operator. Several points of disaggregating the base station stack have been proposed in literature, yet the scheme that is currently standardized for the 5G New Radio interface (5G-NR) regards the disaggregation of the base stations between the higher Layer 2 of the cellular network stack, between the Packet Data Convergence Protocol (PDCP) and the Radio Link Control (RLC) layers. In this split, Cloud-located unit as annotated as a Central Unit (CU) and the radio elements as Distributed Units (DUs) [3]. CUs incorporate the functionality of the layers from the PDCP layer and upwards, whereas DUs the functionality of the RLC layer and downwards. The selection of this point of splitting the stack is of major importance: it allows the incorporation of other lower layer splits inside the DU, thus transforming the CU-DU link as a Midhaul interface, whereas it allows several technologies to be aggregated through a signal point at the base station level inside the PDCP layer. Similar aggregation of technologies took place for the legacy LTE technology as well, with the incorporation of the LTE-WiFi Aggregation Adaptation Protocol (LWAAP) [4]. In the context of 5G-NR, the technologies that can be aggregated regard 5G-NR, legacy LTE and WiFi, as shown in Figure 1. This is the architecture also that we consider for this paper.

As the deployments of different technologies in an area become denser, the available wireless spectrum crucial for their performance becomes more scarce. Especially when considering heterogeneous technologies in the RAN, efficient coordination is required in order to achieve spectral efficiency in a given area. In this work, we deal with the proposed CU/DU split of the base station stack, integrated with non-3GPP technologies, based on our prior contributions in [5]. In such a setup, our contributions are the following:

- To provide new signalling in order to collect usage statistics of the heterogeneous technologies that are available in the area.
- To introduce and apply algorithms handling the spectral overlap of the different RANs, in order to efficiently place the different cells in the available frequency space.
- To experimentally evaluate the added functionality, demonstrate and prove its efficiency.

We use the OpenAirInterface (OAI) platform [6] as our development platform, and we evaluate our algorithms under real network settings in a testbed setup. Our results showcase efficient allocation of the under-study networks within a single congested wireless band. The remaining of the paper is organized as follows: Section II is providing some former background and motivation for our work. Section III provides

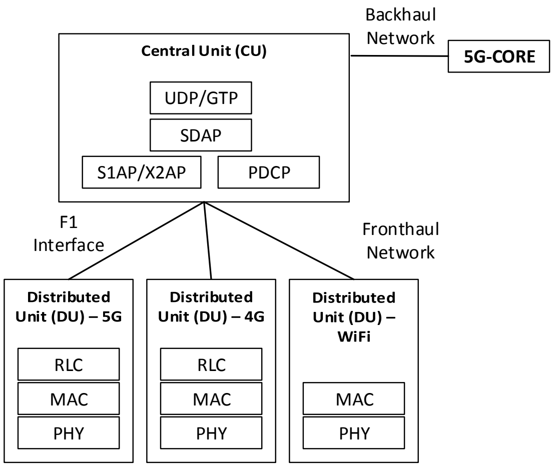


Fig. 1. Disaggregated Base Station architecture according to the 5G-NR specification for F1AP [3]; multiple heterogeneous and legacy DUs can be managed through a single CU instance, located at an Edge data-center.

information on the system setup, relevant signalling used for collecting network statistics and the development of algorithms supporting the coordination of the disaggregated distributed units. Section IV presents our experimentation platform and topology used for our experiments. Section V showcases our experimental findings, whereas in Section VI we conclude our work.

II. Related Work

Base station disaggregation has been an extensively investigated topic in relevant literature, as the realization of Cloud-RANs may potentially yield several benefits for both network operators and users. Works [7] and [8] indicate possible points of disaggregation of the base station and analyze the benefits from the operator‘s point of view. However, these works assume a high-throughput low-latency fronthaul link between the disaggregated base station components. Similar splits have been in higher layers of the base station stack, which can be efficiently served through a packetized fronthaul interface, with lower demands for latency and capacity. The disaggregation of base stations between the PDCP and RLC layers has been included in the 3GPP standardization of 5G New Radio (NR), through the introduction of the F1 Application Protocol (F1AP) [3]. The F1AP is the protocol for the packetized intercommunication between the Central Units (CUs) integrating PDCP and above layers, and the Distributed Units (DUs) of the network. F1AP has two variations: F1-U for transferring the user plane traffic over tunnels through the GPRS Tunneling Protocol (GTP), and F1-C for the control plane traffic, running over SCTP. From the CU point of view, the connections that can be maintained with the DUs is $1 : n$, meaning that each CU may control multiple DUs, whereas from the DU point of view is $1 : 1$, meaning that each DU can be controlled by a single CU.

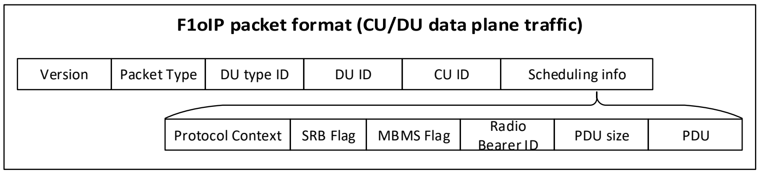
In the proposed architecture for disaggregated Cloud-RANs, support for heterogeneous DUs has been incorporated, as shown in Figure 1. The point of disaggregation is very convenient, as one of the PDCP roles in the mobile networking stack is to manage and rearrange the independent RLC entities. Thus, it may be used for the subsequent management of DUs corresponding to different technologies, enabling higher network capacity and network selection policies even on a per-packet basis, as shown in [9]. Incorporation of heterogeneous technologies on the mobile networking stack was included in the 4G protocol standards as well. Through the introduction of the Xw interface, the PDCP instance of a LTE base station is able to communicate with WLAN based cell deployments, towards expanding the network capacity and utilizing the unlicensed bands [4]. This process is known as LTE-WLAN Aggregation (LWA) and uses the LWAAP protocol for the intercommunication and signalling of the different components.

Nevertheless, aggregation of multiple heterogeneous links within a single area may entail performance degradation in the cases of overlapping spectrum usage. This is mainly an issue for WiFi-like technologies that use the CSMA/CA mechanism for accessing the wireless medium, and hence apart from interference they are subject to contention with other neighbouring cells operating in the same spectral area. Hence, an efficient coordination mechanism for the different technologies used to provide data services to the users is needed. In [10], the authors argue the applicability of different coordination mechanisms for including heterogeneous networks in the enhanced Intercell Interference Coordination (e-ICIC) mechanism that LTE networks may implement. Similarly, in [11] authors observe the coexistence between WiFi and LTE within the same spectrum, paved by the suggestions for enabling LTE to opportunistically access the unlicensed bands in order to increase the channel capacity [12]. The authors introduce through eICIC a novel coordination scheme as a coexistence solution.

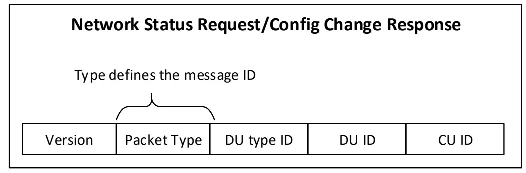
In this work, we build on top of a real Cloud-RAN setup, in order to introduce coordination functions for heterogeneous technologies. We use the OpenAirInterface [6] platform for our developments, and make use of the extensions to the platform [5] that introduce heterogeneous wireless technologies to the RAN, controlled by a single point located at the CU side of the base station. The implementation makes use of dedicated signalling between the CU and heterogeneous DUs, introduced as F1-over-IP (F1oIP) due to its resemblance with the F1AP protocol. We extend the scheme to introduce new signalling between the DUs and the CU, in order to retrieve the appropriate RAN configuration settings and conclude on the optimal use of spectrum in an area. The following section details the developed signalling between the CU and DUs.

III. System Architecture

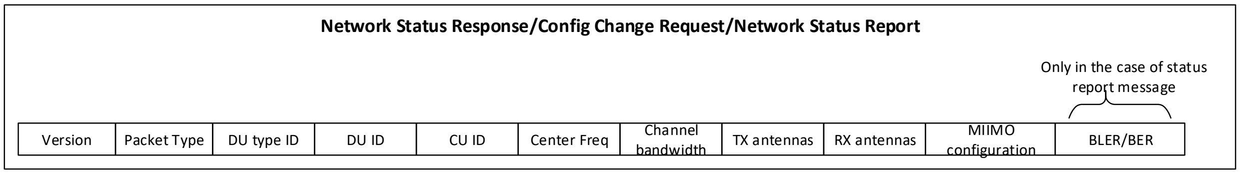
In this section we detail the existing signalling between the disaggregated heterogeneous base stations, and the extensions to support the heterogeneous cell coordination in terms of spectrum. We use as our starting point the F1oIP implementation for the disaggregation of base stations as CUs and DUs, detailed in [5], and extend it accordingly in order to enable the spectrum coordination between the heterogeneous entities of the network. The implementation is introducing a new signalling mode between the PDCP and RLC layers, resembling the F1AP standardized interface for



(a) Packet format for data plane traffic exchanged between CU and DUs



(b) Network status request (CU to DU) and config change response (DU to CU) message format.



(c) Network status response/report (DU to CU) and config change request (CU to DU) packet format

Fig. 2. Message format exchanged between the CU and DUs regarding data plane traffic and spectrum coordination messages.

the communication between CUs and DUs. Originally, F1AP is handling data plane packets over GTP tunnels, established for each served UE of the system. The F1oIP implementation is using UDP/TCP interfaces in order to exchange the traffic between the CUs and DUs, including also some signalling information on the packet headers that is ordinarily exchanged between the PDCP and RLC layers (e.g. DRB/SRB allocation, frame/subframe scheduling, protocol context, etc.). The following sections initially describe the new packet format introduced with the F1oIP messaging mechanism and the roles of the CUs and DUs, and later on we introduce the new messages for facilitating the coordination.

A. Disaggregated base station communication

According to 5G-NR specifications, the disaggregated functionality of the 5G base stations shall address several technologies. To this aim, the proposed standardized split option by 3GPP resides in the high layer 2 of the OSI stack, between PDCP and RLC. As this split option has more slack limitations on the latency and throughput over the fronthaul [13], different technologies can be used in the wireless part of the DU. Target network access technologies offered by the DUs are 5G-NR, LTE, WiFi and their evolution.

We use as a starting point the implementation of F1oIP, which handles the communication between the CU and heterogeneous DUs of the system. In this implementation, each packet exchanged over the fronthaul interface is bearing on its header scheduling information to be used by the lower layers, according to Figure 2a. Based on this information, the packet is assigned to the respective transport channels of RLC and is then left to MAC layer for scheduling its transmission over the air. For the case of non-cellular DUs, the respective information is not handled from the respective DU software. For example, in the case of a WiFi DU, the F1oIP header information related to the scheduling of the packet is ignored. For the UL case, the reverse process takes place before transmitting the packet to the CU. This means that the DU is assigning new PDCP sequence numbers and creates the respective the header in order for the packet to be handled at the CU side.

B. Coordination Messages

In order to enable central management of the heterogeneous DUs, we introduce some new signalling messages used for exchanging the capabilities and network configuration between the CU and DUs of the network. To this aim, we implement a second communication channel between the CU and DUs, apart from the data channel, that is exchanging this type of messages. The messages that we introduce are:

- The **Network Status Request** message, sent by the CU and requesting from a single DU about its current RAN configuration. The message format is shown in Figure 2b.
- The **Network Status Response** message, sent by the DU responding to a Network Status Request message. The format of the message is shown in Figure 2c and includes the configuration on the center frequency, channel bandwidth used, number of antennas used, and MIMO configuration.
- The **Configuration Change Request** message, sent from the CU after the coordination algorithm has taken place and has concluded on the new spectrum allocation of the network. The message format is the same with the Network Status Response message.
- The **Configuration Change Response** message, sent from the DUs of the network as an acknowledgement that the new configuration advertised to the DU has been applied to the RAN.
- The **Network Status Report** message, sent periodically by the DUs to their managing CU as a keep-alive message. The message contains similar fields as the Network Status Response message, but contains also information on the error rates that are perceived over the network from the DU side. Hence, reception of such a message where a DU is reporting several losses over the network may trigger the spectrum coordination algorithm at the CU side.

In order to enable the exchange of these messages, a respective agent message has been written on the DU side in charge of synthesizing and parsing these messages, and issuing the appropriate commands. As we target the coordination of WiFi based DUs, complementary to the cellular

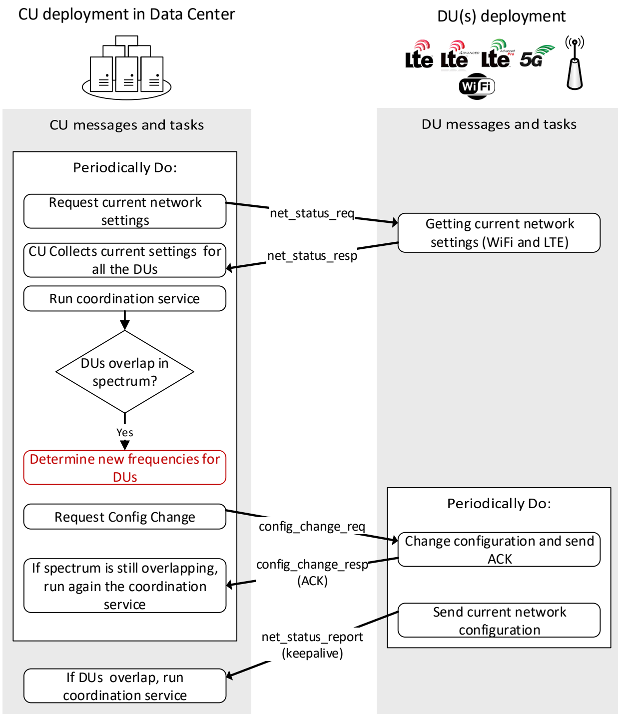


Fig. 3. Signalling and process developed for coordinating heterogeneous DUs managed from a single CU. The coordination function takes place at the CU side and the new configurations are transmitted to the DUs.

based DUs (5G-NR and LTE), we make use of the Channel Switch Announcement (CSA) feature that WiFi incorporates for imminent channel changes. This allows us to reconfigure the cell and the associated channels, based on the information of dedicated WiFi messages indicating a channel switch after a number of milliseconds.

C. Coordination Service and Algorithms

Based on the above messages, the coordination service for the heterogeneous DUs is summarized in Figure 3. The coordination system is based on the client - server model, with the server side being located at the DU side of the communication channels. Upon system startup, the CU that has information of the managing DUs, sets up this coordination communication channel with all the DUs and starts to periodically query all the DUs for their current wireless configuration. Upon the reception of such a message, all the DUs respond with their settings. Once the CU has the information collected from all the DUs, checks whether there is any overlap in the frequencies. If so, an algorithm determining the new frequencies is executed, and *configuration_change_request* messages are sent to the DUs.

It is worth to mention that the requests may include new configurations for the antenna configuration of the DU, the placement of the secondary channel in the case of an IEEE 802.11ac/n access point, and even the configuration of the channel bandwidth using the methods indicated in [14]. The algorithm that is running on the CU is distinguishing two different types of coordination: 1) coordination for heterogeneous technologies, e.g. in the case of an LTE DU operating in unlicensed spectrum [12] in the same frequency spectrum as a WiFi DU, and 2) in the case of homogeneous technologies,

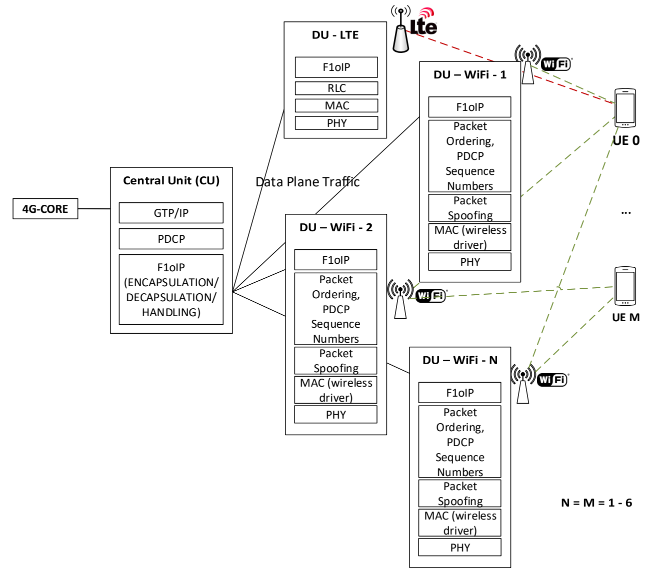


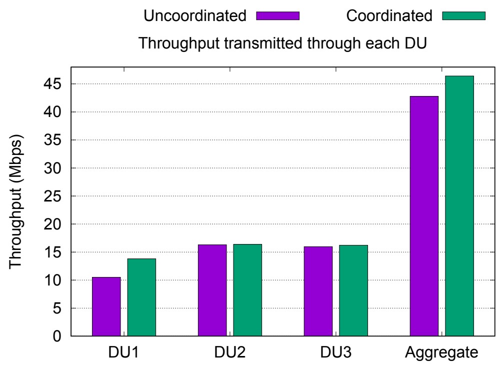
Fig. 4. Experimental setup used for evaluating our scheme

e.g. only LTE/5G-NR or only WiFi. For the former case, we use the incentives that are provided in [15], where the authors examine the coexistence of LTE and WiFi cells. Based on their conclusions, in the case of overlapping or partially overlapping configurations, we move all the WiFi traffic by at least 2.5MHz away from the cellular traffic, in order to mitigate any performance issues. For the case of homogeneous cells, we use the approach highlighted in [16], which uses a graph coloring approach to determine the WiFi cells that are operating in an area. Our algorithm begins with examining the case of heterogeneous technologies overlapping spectrum, and then subsequently checks for any homogeneous technologies overlapping case. This processes are taking place within the red colored process at the CU, indicated in Figure 3.

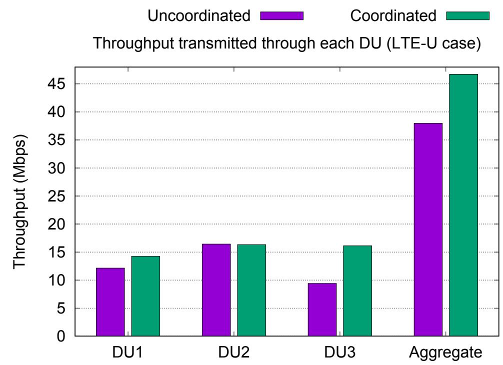
IV. Testbed Setup

As our development platform for the described functionality we have been using the OpenAirInterface [6] platform, which provides a software based full stack implementation of contemporary cellular networks. We evaluate the framework in the NITOS testbed, an open and remotely accessible infrastructure located in University of Thessaly, in Greece [17]. NITOS is offering a wide selection of resources, spanning from commercial LTE to open source WiFi and several Software Defined Radio devices, used to setup our experimentation system. Figure 4 presents our experimental setup, with the F1oIP framework [5] being setup at all the WiFi and LTE DUs of the system. Although the OpenAirInterface platform currently supports both LTE and 5G-NR, the developments in the latter technology only span the physical layer. Hence, our experiments are solely limited to LTE and WiFi DUs.

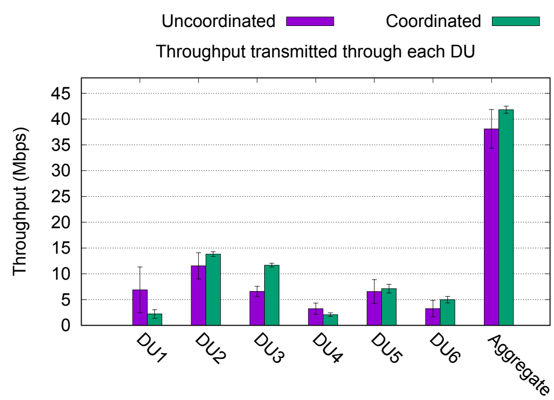
For the development of the respective messaging scheme, we used Google's Protocol Buffers Library. The *protobuf* library allows us to create the messages in different languages, using the same message definitions. Hence, the implementation of the WiFi DU agent is a Python based, with two different parts; one for receiving the data plane messages from the CU



(a) Throughput achieved over each DU for 3 WiFi DUs



(b) Throughput achieved over each DU for 3 WiFi DUs coexisting with an LTE cell



(c) Throughput achieved over each DU for 6 WiFi DUs

Fig. 5. Experimental results for 3 - 6 WiFi DUs within the same band: Overall throughput exchanged over each DU is depicted

side, and injecting them to the WiFi network or receiving them and packaging them accordingly to send them to the CU, and a second part in charge of collecting the statistics and exchanging the coordination related messages with the DU.

The topology used for our experimentation process is given in Figure 4. As the split for OpenAirInterface regards only the data plane operation of the platform CU and LTE DU are collocated on the same service. However, we emulate the disaggregated type of behavior by injecting delay between the network interfaces that are used for the F1oIP communication between the CU and DU, in the range of 0,250ms. The delay that we inject is done with the *netem* application and is equal to the mean delay that we measure over the interface between the CU and the WiFi DU. The number of WiFi DUs is ranging from 1 to 20, thus creating a highly dense heterogeneous network consisting of WiFi and LTE devices. Since none of the nodes is able to bear more than four heterogeneous technologies for setting it up as the receiving UE, we employ different nodes for the WiFi based UEs. By using the extensions built in [5], we inject traffic from the Core Network side an the CU is broadcasting this information to all the DUs in our system, thus creating a highly contention system. We use the *iperf* application to saturate the network with UDP traffic, and measure the delivered traffic at each node (throughput) over each DU. The following section presents our experimental findings for ranging the number of different DUs in the network.

V. System Evaluation

In this section, we provide a proof-of-concept evaluation of our scheme. We organize our experiments in the following manner: 1) initially we conduct experiments using the 2.4GHz band, and place a contending LTE-U cell within the band and 2) subsequently we place up to 6 different WiFi DUs within the same band, that create an environment high in contention and interference. The depicted results are averaged from 10 different experiment runs in the testbed.

For the first set of experiments, we use three different WiFi DUs and an LTE DU. We compare our algorithm with the default process that is running at the WiFi driver of the DU for auto selecting the transmission channel. Figure 5a shows our results. For the uncoordinated case (each WiFi driver selects its own channel), all the WiFi DUs are selecting their transmission channel to be one of the non-overlapping WiFi channels in the band (channels 1, 6 and 11). For most of the cases that the experiment was executed, two DUs were automatically switched to operate in the same channel, thus suffering from contention. Our CU co-ordinated case is assigning channels in the similar manner, but also takes into account the current allocation of other DUs in the same area, and thus is assigning different channels to them. This solution suffers from interference, but in the case of low numbers of DUs in the area this problem is mitigated. This is reflected in the measured aggregate throughput, where our coordinated solution is achieving more than 10% higher overall throughput.

Figures 5b shows the case where at channel 6 of the band we setup an LTE DU to operate. For this case, our solution is able to retrieve the setup of the LTE DU and coordinate all the WiFi DUs to organize in a manner that they are under no destructive interference from the LTE cell. For such a case, and for the 3 WiFi DUs that we used, we see that the aggregate throughput is enhanced by almost 20%.

Figure 5c depicts our results when using up to 6 different WiFi DUs, located within the same frequency band in overlapping frequencies. We observe that the auto select channel feature results in higher throughput being delivered over some DUs, but the measured values present high deviations between different experiment runs. It is indicative that DU1 and DU4 manage to deliver through different experiment runs constantly lower throughput, however the deviation in the provided measurements is very low. The lower throughput is imposed due to the interference created by all the other DUs operating in overlapping channels. Nevertheless, the coordination algorithm is able to deliver higher aggregate throughput over the setup and with lower deviations from the mean values across different experiment runs. The provided evaluation showcases experiments where the DUs are reorganized only in terms of spectrum. However, the developed protocol allows the organization based on the physical characteristics of the DUs (e.g. number of antennas, placing secondary channels, etc.) and a more sophisticated algorithm may yield better results.

VI. Conclusion

In this work, we presented a protocol for the coordination of DUs in ultra-dense heterogeneous network setups. We detailed the developed signalling over the OpenAirInterface platform for the communication between a single CU and multiple heterogeneous DUs, and applied an algorithm for the selection of the optimal operating frequencies as a proof-of-concept experiment. Our experiments targeted the highly congested 2.4 GHz band, and employed WiFi operating DUs. The results denote that the coordination may be used to efficiently provide higher overall capacity, while showing lower throughput volatility for different experiment rounds.

In the future we foresee the further development of spectrum coordination algorithms from the CU point of view. As the developed protocol is allowing the collection of physical interface characteristics in the CU side, more sophisticated algorithms can be developed that allow the reconfiguration of the DUs regarding the number of antennas, transmission power, etc. Moreover, we will seek to investigate how the allocation of clients at each DU may be perceived at the CU side and introduce signalling for the allocation of the clients to DUs that can serve them based on the overall energy efficiency of the deployed infrastructure.

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