Enabling Distributed Spectral Awareness for Disaggregated 5G Ultra-Dense HetNets

Kostas Chounos[†], Nikos Makris[†⋆], Thanasis Korakis[†⋆]
[†] *Department of Electrical and Computer Engineering, University of Thessaly, Greece*
[⋆] *Centre for Research and Technology Hellas, CERTH, Greece*
{hounos, nimakris, korakis}uth.gr

***Abstract*—Future wireless infrastructures will have to deal with significantly higher loads of data, produced by applications demanding higher capacity with lower latency for the exchanged information. 5G networks are expected to resolve these problems, by bringing in advanced flexibility of deployment through the Cloud-RAN concept, and new air interfaces. Dense Heterogeneous Networks will also assist in the smooth transition to a holistic approach for managing the wireless network, especially through their integration at the base station level. Nevertheless, networks operating under a very tight spectral environment, with limited spectrum resources, need to be aware of their expected performance in order to optimally decide their operating frequency. In this work, we consider a disaggregated heterogeneous base station, complying with the Cloud-RAN concept, and integrate spectral aware non-3GPP access (WiFi) to the base station. We use multi-technology links to serve the end users, through two different paths: an LTE and a WiFi. The WiFi units are able to automatically discover their operating frequency ensuring efficient data delivery to the end users. We integrate all our contributions in a framework and deploy it over a real testbed. Our experimental results illustrate enhanced performance for the non-3GPP access of the network, delivering more than 5 times better throughput for high interference scenarios.**

***Index Terms*—5G, Next Generation Networking, Cloud-RAN, Spectral Efficiency, self organizing DUs**

I. Introduction

As the unprecedented demand for continuous wireless connectivity is increasing exponentially, the existing infrastructures are proved inadequate to handle the exchanged data loads efficiently. Recent studies [1] have shown that the request for wireless data will double up in the near future, a burden that the infrastructure providers will have to cope with. Typically, the increased demand for wireless applications is overtaken through the extension of existing infrastructures. However, the advent of 5G technologies proposes a novel architecture, through the cloudification of parts of base stations (Cloud-RAN) and the integration of heterogeneous technologies in the cell, as a means to minimize the CAPEX and OPEX costs. In such architecture, all the available heterogeneous radio technologies for serving a client can be aggregated at the cloud, as a means of increasing the overall wireless capacity, needed by novel data-hungry user applications.

Dense Heterogeneous Networks (HetNets) are formed through the integration of smaller scale solutions (e.g. femto-/pico-cells) complementary to the existing macro- and meso-scale base station deployments. These deployments offer efficient data offloading to users within a specific region, and relieve the macro-scale network from the burden of serving the end users at a significantly larger geographical area. The inevitable steer to smaller cells is more than essential in order to ensure a smooth transition to 5G networks, of which they will be an integral characteristic. Nevertheless, the dense deployment of heterogeneous cells, which may operate within the same frequency band, mandate the efficient coordination of the wireless technologies. The harmonic coexistence of several existing wireless protocols mainly operating in sub-6GHz bands (5G-NR, LTE-A, WiFi) is needed for providing increased coverage and capacity for densely populated areas.

Nonetheless, severe performance challenges can be produced through the sharp raise of wireless terminals within densely populated urban environments. More specifically, the unlicensed (ISM) bands can be referred as a typical example of uncoordinated and excessively used spectrum portion, mainly from non-3GPP technologies. Therefore, a large variety of wireless devices including the widely adopted IEEE 802.11 (WiFi), already face degraded performance due to the heavy transmission contention. As expected, these great fluctuations on wireless channel conditions may arise the obvious question: *How can such over-congested protocols eliminate the degraded performance and efficiently participate in the future 5G heterogeneous architectures?*

5G networks bring architectural advancements as well, thus creating fertile ground for the efficient coordination of HetNets. Through the introduction of the Cloud-RAN concept, part of the base station can be executed in the cloud, thus allowing several time critical applications for coordination such as eICIC [2] to take place. In this work, we consider a heterogeneous technology Cloud-RAN based on our prior efforts in [3], and introduce network driven intelligence for the coordination of the distributed Radio Access Networks (RANs) and the users associated in the formed cells. We consider the disaggregation of the base stations according to the 3GPP Option-2 split [4], between the Packet Data Convergence Protocol (PDCP) and the Radio Link Control (RLC) layer of the base station stack, according to the recent 5G New Radio (NR) specifications [5]. The two formed units are the Central Unit (CU), incorporating the processes of PDCP and upper layers, as well as the interface with the core network, and the Distributed Unit (DU) incorporating the RLC, MAC and PHY. The DUs in the 5G architecture may be heterogeneous, as a means to offer expanded capacity to the end-users through legacy technologies (LTE, WiFi). As a matter of fact, WiFi aggregation to the RAN level is expected to be dealt with the NR releases beyond Rel. 16. In this work, we adopt the prototype in [3] and further extend it in order to operate as an autonomic spectral aware base station for the WiFi managed part of the network as follows:

- *Real-time self organized Wi-Fi DUs:* Based on the autonomic channel reconfiguration of each DU, our framework achieves efficient spectrum utilization and load balancing for the over-congested ISM bands. This increases directly the total achieved throughput that can be served from all the DU candidates and any other external interference sources.
- *UE association decisions:* Each UE may associate with a DU in a given region, based on the decisions that it concludes on the expected performance over the network. These decisions are based on information about the wireless spectrum utilization, contrary to off-the-shelf received signal strength based metrics.
- *Extensive testbed experimentation:* We experiment with the developed solution over a real testbed, and under different external interference settings.

II. Related Work

Alongside with the deployment of 5G networks, a rapid increase of smaller and denser networks (DenseNets) is expected. Several research approaches have been proposed in order to deal with the expected disaffects of the dense operation of the networks. Primarily, multiple works propose general architecture designs for ultra dense and small-cell networking [6]–[9], either through the formation of similar technology and different scale setups, or using heterogeneous technologies for small cell access. Regarding the former, off-the-shelf solutions exist in the 3GPP specifications, like for example the InterCell Interference Control (ICIC) and enhanced ICIC (eICIC). Through the utilization of Almost Blank Subframes (ABS), the femto-cells are instructed to operate for certain timeslots, without receiving any interference from the macro-cell. Nevertheless, their application in real-world deployments needs low-latency links between the base stations, which is not feasible for monolithic base stations at legacy setups. Regarding the latter, cautious decisions should be taken at all HetNet's tiers for maximizing UE's performance and thus a lot research interest focuses on the coexistence of cellular with non-3GPP technologies (e.g. WiFi). Works [10]–[13] are indicative of such setups, primarily focusing on the coexistence of LTE and WiFi within the same region and selecting the technology through which each UE shall be served.

Nevertheless, the advent of 5G technologies brings in new features for increasing the flexibility in network deployment, instantiation, maintenance and operation. The RAN cloudification [14] creates fertile ground for the real world application of operations that formerly where not possible due to stringent latency requirements, like the eICIC [2]. HetNets are expected to play a complementary role to fixed network infrastructure, through their integration in the RAN. Similar efforts existed in the legacy LTE technology as well, through the introduction of the LTE-WLAN Aggregation Adaptation Protocol (LWAAP) [15]. In such setups, non-3GPP technologies (e.g. WiFi) are integrated and controlled from the operator cell, as a means to access new spectrum towards enhancing the end-user's Quality of Experience (QoE). As such technologies usually access unlicensed spectrum, they suffer from contention and external interference, which leads to performance degradation.

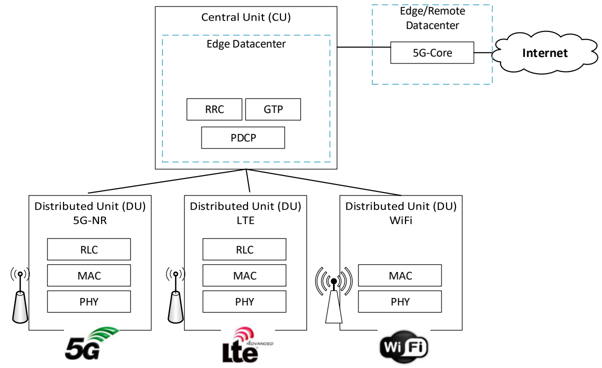


Fig. 1: Disaggregated Heterogeneous Cloud-RAN architecture for 5G: Each component is added to the network as a new DU, suppoting even heterogeneous access technologies, converging at the same CU in the Cloud.

Unlike straightforward resource allocation schemes given in base station centric protocols like LTE, the IEEE 802.11 standard employs a more opportunistic technique based on carrier's sense and multiple access (CSMA-CA). However, uncoordinated existence of densely deployed Access Points (APs) in the limited overlapping WiFi channels, undoubtedly leads to degraded performance for the network. In this context, we propose a novel distributed framework in which overall spectral awareness is enabled at both heterogeneous base station deployments and UE's sides. We adopt a disaggregated base station setup, complying with the Cloud-RAN concept, and augment it with non-3GPP technologies as a means to maximize the overall capacity of the network. We disaggregate the base station based on the recent specifications for 5G-NR [5], and create two entities; the Central Unit (CU) and the Distributed Units (DUs). We integrate the WiFi access in the network as a DU component, controlled through the same CU as it happens for the cellular access case (see Figure 1). Based on the generic energy detection method and by minimal signaling between the involved entities, our framework is able to dynamically discover and avoid every possible source of interference at both WiFi DU and UE sides with minimum overhead. By utilizing commercial WiFi hardware and Software Defined Radio (SDR) components for the cellular network, and after extensive testbed experiments, we prove the system's throughput and spectrum efficiency gains.

III. Proposed Framework

In this section, we initially detail the network architecture, and subsequently provide information on how the wireless network is reconfigured in order to ensure the optimal spectrum allocation.

A. System Architecture

As we have mentioned, we employ a disaggregated Cloud-RAN architecture for cellular access, augmented with multiple

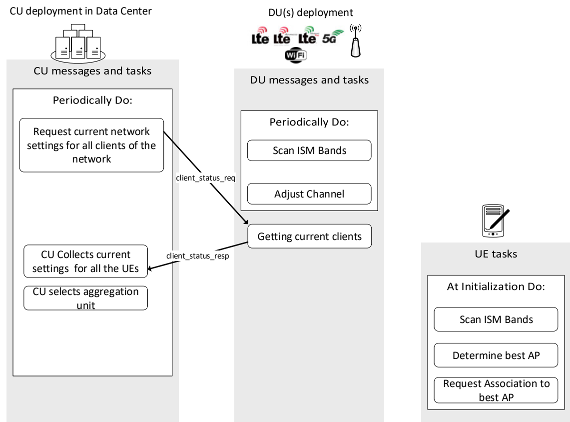


Fig. 2: Signaling and processes developed at each component for this work: DUs and UEs select their operating frequency based on their perception of the wireless conditions and the information is sent to the CU for selecting which WiFi DU will be aggregated with the LTE part for each specific UE.

non-3GPP cells. We target at optimizing the access at the non-3GPP technologies, assisted by the overall cell for the coordination and signalling exchange. According to the defined 5G NR specifications, the base station shall implement the Option 2 3GPP split, between the PDCP and RLC layers. This means that heterogeneous technologies can be integrated to the base station, as new DUs, supporting either cellular access (5G-NR or legacy LTE) or non-3GPP access (WiFi). Each CU may control multiple DUs, and select through which the traffic shall be transmitted for reaching the UE. This process can happen in a per packet basis. From the DU side, each DU can be controlled by only one CU.

In this context, in [3] we presented a prototype based on the OpenAirInterface (OAI) platform [16] which realizes this heterogeneous Cloud-RAN infrastructure. The solution introduces signaling between the PDCP and RLC layers of the cellular stack, and integrates the WiFi Access Point (AP) functionality to the base station level as a DU. In order to accomplish this, a thin software is used at the WiFi DU part in order to handle all the signaling and communication with the PDCP layer located at the DU. The software is aggregating DUs for providing access to a multi-homed UE through different wireless technologies concurrently for the Downlink channel (DL), taking place at the PDCP layer (CU side) and in a per packet and per UE basis.

In this work, we extend the introduced signaling between the CU and DU according to Figure 2. The DU parts of the network generate information about the clients that are associated with each DU, and send this information over the network at the CU side of the base station. Based on the information received from all the DUs, the CU concludes on which of the available WiFi DUs will be used as the aggregation unit for the cellular network and for each UE accordingly. Data is flowing over both DUs in order to reach the end user from multiple paths, ensuring that the optimal capacity of the network is ensured. In terms of spectrum management, we introduce a solution running independently at each DU of the network, ensuring that each one will use the spectrum that will provide the most efficient performance over the network. Similarly, the UEs do not use the standard approach of off-the-shelf devices considering the Received Signal Strength, but make their association decisions based on their perspective of the wireless channel. The result is to provide an optimally organized in spectrum DU-UE link, used for aggregating the traffic from the cellular network. More details on the organization of the participating DUs is presented in the subsections below.

B. DU's (WiFi) Channel (Re)configuration

Below, we describe how the DUs select their optimal operating spectrum, the model and the algorithmic implementation behind this work. In the proposed **Spectral Aware Channel Selection (SACS)** framework, each WiFi DU autonomously triggers a spectral awareness mechanism for extracting the optimal operating frequency ($targetF_c$). More specifically, the spectrum sense procedure is periodically enabled for all the available ISM channels (F_c) and thus we are able to discover and avoid interference sources in real time. It is also worth to be noted, that the aforementioned mechanism is implemented with using exclusively commercial WiFi adapters (Atheros) and on the top of TP-link routers. Based on our prior work in [13], we follow the scan and evaluation procedure in order to calculate the Duty Cycle (DC) for every channel within the ISM band.

The proposed framework serially scans all the available ISM channels by retrieving several Spectral Samples ($\mathcal{N}_\mathcal{S}$) at each of them. Thus, we are able to precisely evaluate and extract the conditions across the spectrum. We use $\mathcal{P}(\mathcal{S}, \mathcal{F}_c)$ to denote the power of each Spectral Sample $\mathcal{S}$ that has been collected on the central frequency $\mathcal{F}_c$. In this given $\mathcal{F}_c$ we calculate each spectral set's received power and if it is higher than a defined $\mathcal{P}_{TH}$, we consider this spectral set as "on". The $\mathcal{P}_{TH}$ parameter is following the IEEE 802.11n standards, matching the Clear Channel Assessment (CCA) parameter [17]. Finally, the Duty Cycle percentage in this specific $\mathcal{F}_c$ could be exported by applying Eq. (1).

$$\mathcal{DC}(\mathcal{F}_c) = \frac{1}{\mathcal{N}_\mathcal{S}} \sum_{\mathcal{S}=1}^{\mathcal{N}_\mathcal{S}} on(\mathcal{P}(\mathcal{S}, \mathcal{F}_c), \mathcal{P}_{TH}), \quad (1)$$

Eq. (1) is applied for all $\mathcal{F}_c$ scanned and therefore each WiFi DU is aware of its spectral environment.

In the context of this work we trigger the spectrum awareness mechanism every 5 seconds. It has been thoroughly illustrated in [13] and [18], that the spectrum sense procedure adds minimal overhead in the conventional operation of the WiFi adapter. Additionally, we similarly set the wireless adapter to obtain Spectral Samples of 20Mhz / 56 FFT bins. The aforementioned configurations can fluctuate from 20-80 MHz and 56-256 bins depending on the chipset type used.

Finally, after the completion of spectrum sense and DC extraction for all channels, the WiFi DU (re)configures its operating frequency in that with lowest DC detected. If a less utilized frequency other than the current is discovered, the the

DU carries seamlessly all the associated stations to it, by using the Channel Switch Announcement [19] (CSA) mechanism of IEEE 802.11. Algorithm 1 summarizes the sequence of all necessary operations conducted at DU's side.

Algorithm 1 WiFi DU Channel (Re)configuration

while TRUE **do**
  $senseSpectrum()$
  for each F_c in Channels scanned **do**
    $calculateDC(F_c)$
    if $DC(F_c) < DC(F_{c_{operating}})$ **then**
      $targetF_c = F_c$
    end if
  end for
  if $F_{c_{operating}} \neq targetF_c$ **then**
    $tuneAP(targetF_c)$
  end if
  $sleep = 5sec$
end while

C. UE's Spectral Aware DU Association

Apart from the continuous evaluation and channel reconfiguration applied in the WiFi DUs, we further adopt a spectral aware association approach at UE's side, in order to boost even more the system's performance. Unlike the association scheme proposed from the IEEE 802.11 standard, which considers only the received signal strength from the available APs, we follow the framework described in our previous work [13]. There, not only the RSSI but also the exact spectral conditions given at both DU and UE sides are involved in the association decision. Identically, the UE senses and evaluates the spectrum, exactly as described at Section III-B. Thereafter, by combining the DC values and each link's predicted MCS through RSSI indicators, we are able to precisely calculate and select the DU offering the highest performance (Mbps). For sake of the aforementioned calculations, we transfer the latest DC values captured from each DU to the UE, by using the 3GPP DUs of the system. Finally, we apply this association scheme for the UE only once and when she enters the network.

D. Coordination Signalling

In the sections above, we presented our architecture, and the respective algorithms taking place at each DU and UE respectively for determining the best operating channel. In this section, we present our approach in binding all the contributions together in a fully-fledged framework, able to control the flow of data to each UE from the CU side of the network. The differentiation for each UE resides at the PDCP layer of the network CU; the PDCP is used as the aggregation point for all the heterogeneous technologies supported in the base station cell. For the downlink operation, as data flows through the PDCP layer data plane packets (data exchanged between the UEs of the network), a 2-byte long PDCP header is added to the packet. At this point, the differentiation of UEs in the network is taking place through their Radio Network Temporary identifiers (RNTIs). Based on this information, and by assigning identifiers for each new incoming UE, we can select at the output of the PDCP layer to which DU the traffic shall be forwarded. This controller behaviour takes place per-packet and per-user basis, and is the enabler for differentiation between the access technologies used for each UE.

In such a distributed setup, where the UEs are not associated with all the available DUs but only with the one that they conclude will give them the optimal performance, the associations per each DU shall be communicated to the CU side of the network, and provided as argument to the technology selection controller. To this aim, we introduce new signalling between the DUs and the CU, as shown in Figure 2 that communicates this information. Periodically, at each non-3GPP WiFi DU of the network, we retrieve the associated clients through off-the-shelf tools (e.g. *hostapd_cli*) and parse this information. This is then encapsulated to an inform message, sent to the CU, which is informed for all the UE identifiers and associations per each DU. In this manner, the CU has a holistic view of the network status and DU associations, and can select the forwarding DU for each UE. As we use the non-3GPP DUs as our aggregation units, the traffic is split for each UE between the cellular and the non-3GPP DUs.

IV. Evaluation

In this section, extensive experiments were conducted in order to prove the proposed system's superiority. We evaluate the framework in the NITOS testbed [20], an open and remotely accessible infrastructure located in University of Thessaly, in Greece. NITOS is offering a wide selection of resources, spanning from commercial LTE to open source WiFi and several Software Defined Radio devices, used to configure our experimentation environment.

A. Experimental Setup

We deploy the disaggregated heterogeneous network setup as follows. One testbed node is used as our Core Network, where the measured traffic is injected, intended to the UE. One node equipped with a Software Defined Radio (SDR) is used as our 3GPP DU component. We use the LTE implementation of OpenAirInterface, with 10MHz channel bandwidth in the 2.6GHz FDD band, using SISO (one antenna). The same node is also hosting the CU implementation. One more node is used as the WiFi DU component, hosting the software for managing it through the CU side of the network, as shown in [3]. One node is playing the role of the UE, equipped with an LTE dongle (Huawei E3372) and a wireless card. The nodes of the disaggregated base station network are interconnected using 1Gbps Ethernet links. Finally, we employ 3 pairs of nodes in total, as our interference generators, set to operate in Channels 1, 6 and 11, creating traffic with different demands for resulting in three scenarios: 1) low, 2) medium and 3) high interference settings. The IEEE 802.11n configuration for these nodes is configured as 3x3 MIMO with 20MHz channel bandwidth. Intentionally, we set channels 1, 6 and 11 to be the operating channels for interfering APs 1, 2 and 3 accordingly, in order to cover the whole band with external

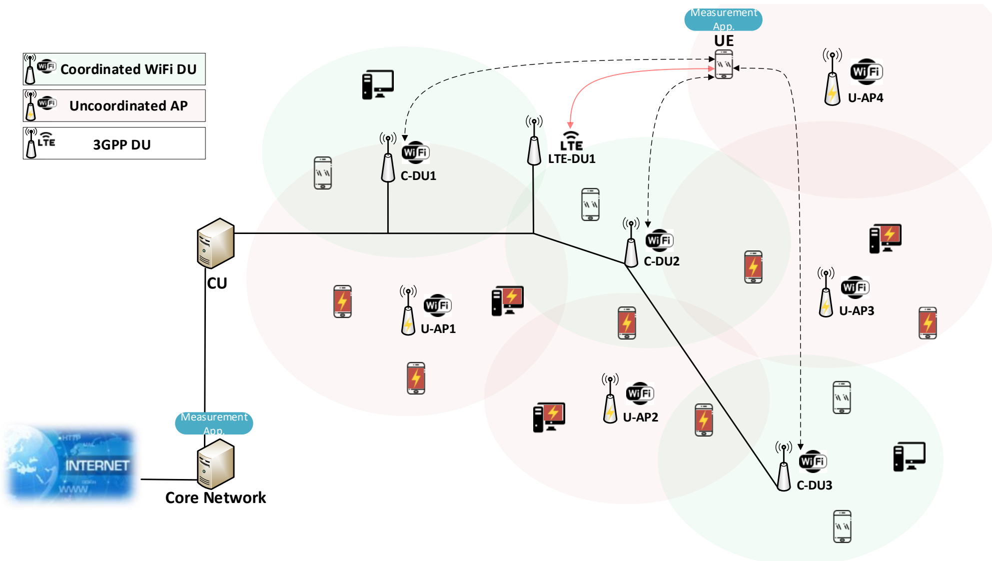


Fig. 3: Overview of the experimental architecture.

interference. Bearing in mind the uneven load distributions are given in typical WiFi networks, we randomly generate traffic demands for each uncoordinated AP during the experiment. More specifically, we randomly adjust the duration and the traffic demand individually for every stream generated. In such way, we maximize the presence of harmful uncoordinated interference in a limited spectrum portion like 2.4GHz ISM band. Table I shows the average amount of traffic for all interference scenarios that each of the uncoordinated pairs is trying to send over the network. The analytical overview of the examined architecture can also be found in Fig. 3.

TABLE I: Throughput Demands (Mbps) per each Uncoordinated AP (U-AP) / UE.

Scenario	**UE**	**U-AP1**	**U-AP2**	**U-AP3**
High Interference		263.0	261.2	295.6
Medium Interference	30	179.6	162.2	177.2
Low Interference		23.4	24.4	26.0

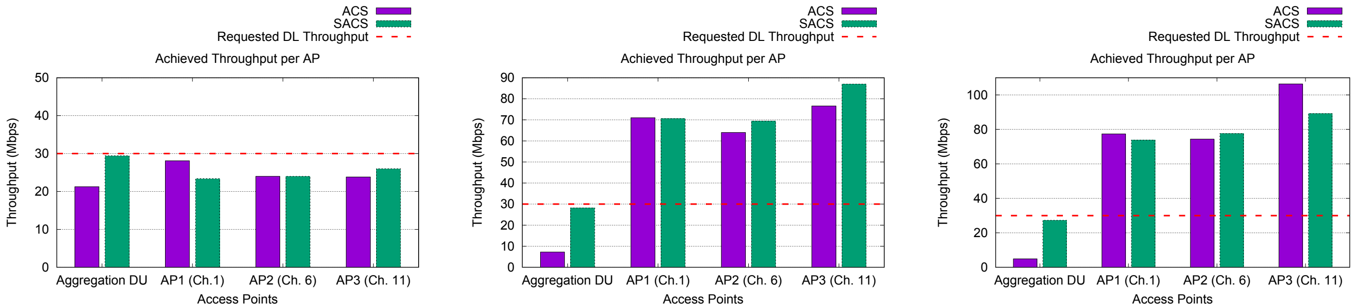
B. Evaluation

For the evaluation of the efficiency of our approach, we use different selection schemes for selecting the WiFi DU operating frequency. We measure the downlink (DL) channel operation by injecting UDP traffic at the Core Network side, splitting it over the LTE and WiFi DU and measuring the performance at the receiving multihomed UE. As we did not observe any fluctuations for the LTE link, we ommit plotting the traffic achieved over this network. However, as a reference, the achieved throughput is at 34.4Mbps.

We follow two approaches for selecting the wireless operating channel at the WiFi coordinated DUs (C-DUs). Initially, we employ Linux hostap's Automatic channel selection (ACS) tool [21]. At this case and during the AP's utilization procedure, the wireless adapter executes a survey based algorithm which reveals the less utilized frequency. This approach is based on the channel busy, active and tx times in order to export an interference factor for each frequency, and the channel which holds the lowest interference factor is selected as operating. Contrariwise, the proposed SACS framework is constantly aware of the channel conditions as it is periodically triggered every 5 seconds, as described earlier in this paper. Additionally, the generic energy detection applied, allows us to discover interference produced by both operating and nearby WiFi channels. Thus, SACS enables the awareness and avoidance of IEEE 802.11 and non interference for all frequencies and in real time.

Figure 4 depicts the results exported for ACS and SACS mechanisms averaged after 10 experiment runs of 100 seconds in the testbed. We plot the achieved throughput over the Aggregation DU (measured at the UE), and for each of the interfering APs. For the case of low external interference (Figure 4a), we see that the aggregation DU manages to get roughly 30% better throughput. This is due to the constant changes of the examined link with the CSA mechanism every 5 seconds. The interfering nodes seem to achieve the same performance for the case where we employ SACS on the aggregation DU, although one of the interfering APs seems to achieve less than with the off-the-shelf ACS tool. This is due to the choice of the ACS solution to select a channel from the ones that the interfering links work, in order to content for the medium access instead of selecting a channel where it would create and receive external interference. For the cases of medium (Figure 4b) and high interference (Figure 4c) the benefits of our solution are more evident; the throughput achieved through SACS is up to 5 times better, almost achieving the 30Mbps that we inject to the network.

As a conclusion, we note two severe drawbacks detected through our experiments for the off-the-shelf ACS tool. The less utilized channel is only adjusted once and during AP's initialization. This could be characterized as inconsistent with the rapidly fluctuating spectral conditions in today's dense networks, and hence degraded performance is expected at the interfering nodes as well. Furthermore, the channel busy time that is used as a metric to evaluate each channel exclusively



(a) Low Interference (b) Medium Interference (c) High Interference

Fig. 4: Experimental results for varying interference for the system under test.

takes into account the time in which the wireless adapter tries and fails to initiate a communication at this specific frequency. This entails the omission of possible interference caused by nearby overlapping WiFi channels, which is thoroughly considered in the proposed SACS framework.

V. Conclusions

In this work, we introduced a scheme for creating spectral awareness at non-3GPP DUs in a cloud-RAN infrastructure. Through dedicated signaling between the different participating units and the cloud located part of a base station, we are able to select the most efficient frequency within the operating band. Awareness is also enabled at the UE side of the network, which chooses to associate to the C-DU that is considered to be more efficient. By utilizing the WiFi Channel Switch Announcement mechanism, we are able to constantly switch the operating channel, along with the associated UEs. Our testbed experiments illustrate the benefits of our solution, as we are able to transfer up to 5 times more throughput over the network for the cases of heavy external interference. In the future we foresee extending this work towards allowing dynamic selection of the DU at the UE side. Moreover, through the application of convolutional neural networks, the framework can be expanded towards a self-learning network, that predicts the performance for different parts of the network.

VI. Acknowledgements

The research leading to these results has received funding by the European Horizon 2020 Programme for research, technological development and demonstration under Grant Agreement Number 857201 (H2020 5G-VICTORI).

References

[1] *"Cisco Visual Networking Index: Global Mobile Data Traffic Forecast, 2016-2021"*, goo.gl/AqHW8D, [Accessed: 06-Jun-2018].

[2] D. Lopez-Perez, I. Guvenc, G. de la Roche, M. Kountouris, T. Q. S. Quek, and J. Zhang, "Enhanced Intercell Interference coordination challenges in Heterogeneous Networks," *IEEE Wireless Communications*, vol. 18, no. 3, pp. 22–30, June 2011.

[3] N. Makris, C. Zarafetas, P. Basaras, T. Korakis, N. Nikaein, and L. Tassiulas, "Cloud-based Convergence of Heterogeneous RANs in 5G Disaggregated Architectures," in *2018 IEEE International Conference on Communications (ICC)*. IEEE, 2018, pp. 1–6.

[4] 3GPP, "3GPP TR 38.806 V15.0.0 (2017-12), 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study of separation of NR Control Plane (CP) and User Plane (UP) for split option 2; (Release 15)," 2017.

[5] ——, "3GPP TS 38.473 V15.1.1 (2018-04), 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NG-RAN; F1 application protocol (F1AP) (Release 15)," 2018.

[6] M. Agiwal, A. Roy, and N. Saxena, "Next Generation 5G Wireless Networks: A Comprehensive Survey," *IEEE Communications Surveys Tutorials*, vol. 18, no. 3, pp. 1617–1655, thirdquarter 2016.

[7] A. Gupta and R. K. Jha, "A Survey of 5G Network: Architecture and Emerging Technologies," *IEEE Access*, vol. 3, pp. 1206–1232, 2015.

[8] M. Kamel, W. Hamouda, and A. Youssef, "Ultra-Dense Networks: A Survey," *IEEE Communications Surveys Tutorials*, vol. 18, no. 4, pp. 2522–2545, Fourthquarter 2016.

[9] X. Ge, S. Tu, G. Mao, C. Wang, and T. Han, "5G Ultra-Dense Cellular Networks," *IEEE Wireless Communications*, vol. 23, no. 1, pp. 72–79, February 2016.

[10] H. Ramazanali, A. Mesodiakaki, A. Vinel, and C. Verikoukis, "Survey of user association in 5G HetNets," in *2016 8th IEEE Latin-American Conference on Communications (LATINCOM)*, Nov 2016, pp. 1–6.

[11] L. Wang, W. Chen, and J. Li, "Congestion aware dynamic user association in Heterogeneous cellular network: A stochastic decision approach," in *2014 IEEE International Conference on Communications (ICC)*, June 2014, pp. 2636–2640.

[12] M. H. Cheung, R. Southwell, and J. Huang, "Congestion-aware Network Selection and Data Offloading," in *2014 48th Annual Conference on Information Sciences and Systems (CISS)*, March 2014, pp. 1–6.

[13] K. Chounos, S. Keranidis, A. Apostolaras, and T. Korakis, "Fast Spectral Assessment for Handover Decisions in 5G Networks," in *2019 16th IEEE Annual Consumer Communications Networking Conference (CCNC)*, Jan 2019, pp. 1–6.

[14] N. Nikaein, R. Knopp, L. Gauthier, E. Schiller, T. Braun, D. Pichon, C. Bonnet, F. Kaltenberger, and D. Nussbaum, "Closer to Cloud-RAN: RAN as a Service," in *Proceedings of the 21st Annual International Conference on Mobile Computing and Networking*. ACM, 2015, pp. 193–195.

[15] 3GPP, "3GPP TS 36.360 V14.0.0 (2017-03), 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); LTE-WLAN Aggregation Adaptation Protocol (LWAAP) specification (Release 14)," 2017.

[16] N. Nikaein, M. K. Marina, S. Manickam, A. Dawson, R. Knopp, and C. Bonnet, "OpenAirInterface: A flexible platform for 5G research," *ACM SIGCOMM Computer Communication Review*, vol. 44, no. 5, pp. 33–38, 2014.

[17] IEEE, "Telecommunications and information exchange between systems Local and metropolitan area networks Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications Amendment 4: Enhancements for Very High Throughput for Operation in Bands below 6 GHz, IEEE Std 802.11ac - 2013," 2013.

[18] K. Chounos, S. Keranidis, T. Korakis, and L. Tassiulas, "Characterizing the Impact of Interference through Spectral Analysis on Commercial 802.11 devices," in *2017 IEEE International Conference on Communications (ICC)*, May 2017, pp. 1–6.

[19] *"Channel Switch Announcement (CSA)."*, bit.ly/2ISGiEn, [Accessed: 24-Apr-2019].

[20] *"NITOS testbed."*, goo.gl/VofsuT, [Accessed: 04-Apr-2019].

[21] *"ACS (Automatic Channel Selection)."*, bit.ly/2XDSwow, [Accessed: 24-Apr-2019].