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Energy Efficiency in Mobility Management for 5G Heterogeneous Cloud Radio Access Network

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ABSTRACT: Thefifthgeneration(5G)cellularinfrastructureisenvisagedasadenseandheterogeneousdeploymentofsmallcells overlappingwithexistingmacrocellsintheRadioAccess Network(RAN).Densificationandheterogeneity,however, posenewchallengessuchasdealingwithinterference,accommodatingmassivesignalingtraffic,andmanaging increasedenergyconsumption.HeterogeneousCloudRadioAccessNetworks(H-CRAN)emergesasacandidate architecture for a sustainable deployment of 5G. In addition, the application of SDN concepts to wireless environmentsmotivatedrecentresearchintheso-calledSoftware-DefinedWirelessNetworking(SDWN).Inthis article,wediscusshowSDWNcansupportthedevelopmentofaflexible,programmable,andsustainable infrastructurefor5G.Wealsopresentacasestudybasedon SDWNtoperformfrequencyassignment,interference, andhandovercontrolinanH-CRANenvironment.Resultsallowtheestablishmentofatradeoffbetweenwireless communicationcapacitygainsandsignalingoverheadaddedbytheemploymentofSDWNconceptstoH-CRAN.

Keywords: Software-defined networking, Heterogeneous cloud-radio access network, Fifth generation

I. INTRODUCTION

Datatrafficincellularnetworkshasincreasedsignificantly over the past few years. Arguably, the current architectureofcellularnetworks,largelybasedonthedeploymentofmacrocells,willnotbeabletoaccommodatetheevergrowingtrafficandthenumberofconnecteddevices[1].Tocopewithsuchincreaseintrafficandnumberofcon- nections, industry, and academia have been designing and gradually deploying the fifth generation (5G) cellu- lar infrastructure. This infrastructure envisages denser andheterogeneousdeploymentsintheRadioAccessNet-work(RAN)throughamassivenumberofsmallcells(e.g., femtocells and picocells) to cover specific geographical areas,overlappingwithexistingmacrocells.We start discussing 5G and revisiting the original con- cepts of SDN to then discuss to what extent they can or cannot fulfill the needs of H-CRAN. Moreover, we indicate the design decisions that need to be made on the path towards the transition to a full SDWN-enabled cellular network and discuss how SDWN can be accom- modated in the context of H-CRAN. Afterward, we present our prototype followed by a case study based on SDWN to control frequency assignment, interference detection, and handover execution in H-CRAN. Finally, we finish this article presenting our final remarks and futurework.Thehighden-sityof5GRANincreasesdramaticallyitscost,turningit unsustainable for operators to cope with itsdeploymentconsideringcurrentbusinessmodels.Thisscenariomoti-vatedtheintroductionofanewcandidatearchitecturefor 5G,calledHeterogeneousCloudRadioAccessNetworks (H-CRAN) [2].With H-CRAN, traditional radio equip- ment of macro and smallcells can be gradually replaced bylessexpensiveRemoteRadioHead(RRH)thatoffloads wirelesssignalworkloadoveropticallinkstobeprocessed in centralized cloud data-centers, known as Base-Band Unit(BBU)pool.H-CRANpresentsbenefitssuchasopti- mized energy consumption and simplified coordination, synchronization, and signal precoding[3].

The evolution towards H-CRAN also poses new chal- lenges such as dealing with high intercell interference, accommodating massive signaling traffic, and meeting critical latency constraints in long-distance signal trans- mission and processing [4]. Recently, Software-Defined Networking (SDN) started being considered as a

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feasi-ble paradigm to tackle important issues of the deploy- ment and management of cellular networks [5]. Although originally conceived for wired networks, SDN intro- ducesadvantages(e.g.,networkprogrammabilityan dflex- ible operation, configuration, and can benefit H-CRANs as well. For example, concepts of SDN can be employed to enhance mobility man- agement, deal with inter-tier interference, and enable network- wideconfigurationthroughtechnologyagnostic abstractions[7].

Some of the enabling H-CRAN technologies present conceptual similarities with SDN, such as separation of forwarding and control planes, i.e., RRH and BBU, and the presence of logically centralized control elements e.g., Mobility Management Entity (MME). However, the effec- tive deployment of a wireless-focused implementation of SDN such as Software-Defined Wireless Networking (SDWN) in H-CRAN environments must still overcomea series of challenges, e.g., defining the responsibilities of programmable controllers and dealing with poten-tial additional control signaling overhead. As opposed to wired networks, RANs require handling a multitude of wired and wireless functions, e.g., fronhaul flow control, frequency assignment, handover, and interference mitiga- tion. High-level decisions related to these functions must be made by SDWN controllers, while their implementa- tion in lower levels is performed through the appropri-ate programming abstractions. Nevertheless, the adequate programming abstractions to handle wireless resources are still missing and are not as consolidated as current solution for wired environments, such as the established OpenFlow protocol. Therefore, a design of SDWN for H-CRAN to control wireless functions using proper pro- gramming abstractions without overloading the network with signaling messages is a matter ofinvestigation.

In this article, we discuss how SDWN can support the development of flexible, programmable, and sustainable H-CRAN infrastructures to help achieve the envisioned goal of the forthcoming next-generation cellular networks.

II. THEEVOLUTIONOF5GTOWARDS H-CRANANDSDWN

In this section, we describe our view of 5G, presenting H-CRAN as a candidate architecture for its future deploy- ments and challenges. Afterward, we show how SDWN can management [6])that handover execution in H-CRAN. Finally, we finish this article presenting our final remarks and futurework.Thehighden-sityof5GRANincreasesdramaticallyitscost,turn ingit unsustainable for operators to cope with its
be used to address some of thesechallenges.

1.1 5G–abriefoverview

Data traffic in mobile networks is increasing dramatically mainly because of the wide spread of smart devices as Users Equipment (UE) (e.g., tablets and smartphones), the popularization of streaming and real-time services (e.g., video and online games), as well as ubiquitous Internet access [1]. To cope with this increased traffic, 5G poses a target of 25 Gbps/km^2 area throughput [8], particularly considering densely populated urban areas. To achieve such an aggressive target, three main strategies are jointly exploited: (i) network densification, (ii) spectrum exten- sion, and (iii) spectrum efficiency. Network densification involves an increase in radio nodes per square kilometer ($\frac{node}{km^2}$) to enhance communication quality by shortening last mile links. Spectrum extension, in turn, enables a radio node to exploit more bandwidth to communicate ($\frac{Hz}{node}$), e.g., frequency aggregation in spectrum sharing. Finally, spectrum efficiency improves throughput in terms ofbitstransmittedpersecondforagivenbandwidth ($\frac{Gbps}{Hz}$),relying,forexample,inspectrumreuse,m assive Multiple-Input Multiple-Output (MIMO), and Coordi- nated Multipoint Transmission and Reception (CoMP). These three strategies combined can be represented as terms (Eq. 1) that need to be maximized to achieve the aimedaverageareathroughput(thr)of5G.InEq.1, den represents network density, extspectrum extension, and eff spectrumefficiency.

Thecontributionspresentedinthisarticleare:(i)the def-inition of the architecture and design decisions tocreatean SDWN-enabled H-CRAN, (ii) creation ofinterfaces toenableSDWNcontrollerstocontrolH-CRANwireless communications,and(iii)analyzingthetradeoffbetween capacity gains in the wireless communication and sig- naling message cost posed to H-CRAN when adopting SDWN.
We start discussing 5G and revisiting the original con- cepts of SDN to then discuss to what extent they can or cannot fulfill the needs of H-CRAN. Moreover, we indicate the design decisions that need to be made on the path towards the transition to a full SDWN-enabled cellular network and discuss how SDWN can be accom- modated in the context of H-CRAN. Afterward, we present our prototype followed by a case study based on SDWN to control frequency assignment, interference detection, and handover execution in H-CRAN. Finally, we finish this article presenting our final remarks and futurework.

The maximization of these strategies requires opera- tors to invest and expand their infrastructure. However, current cellular architecture has shown to be unsustain- able to cope with this maximization, which motivated theintroductionofH-CRAN[2].H-CRANinheritscon- cepts from both Heterogeneous Networks (HetNet) and CloudRadioAccessNetworks(C-RAN),suchasdepicted in Fig. 1. From HetNet, H-CRAN has in its architecture thepresenceofdifferentsortsofsmallcellsspreadalong a macrocell coverage area, promoting heterogeneity to improvespectrumefficiencyandnetworkcapacity.Pico-cellsandfemtocellsareexamplesofsmallcellscreatedby low power base stations such as Relay Nodes (RN) and AccessPoints(AP).C-RAN,inturn,reliesonconceptsof cloudcomputing,whereaBBUpoolcentralizesthework-loadofsignal,modulation,andprotocolstackprocessing of a set ofRRHs.

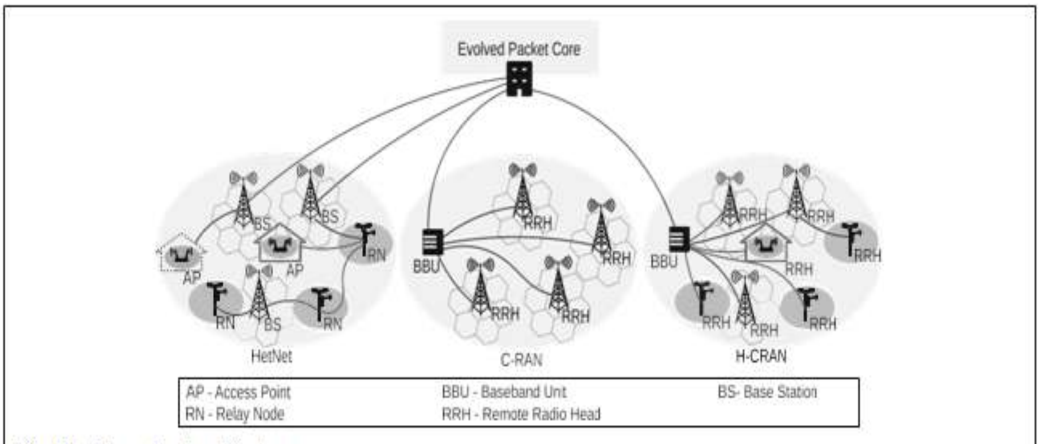

Fig. 1 Cellular network architectures

The C-RAN architecture reduces the cost and com-plexity of RRHs enabling cost-effective deployment of a massive number of cells. Finally, in H-CRAN, conceptsfrom both HetNet and C-RAN are combined to enable thedeployment of dense and heterogeneous networks, lever-aging cloud computing to centralize workload processing.Although H-CRAN brings several benefits, its employ-ment is not free from challenges. Interference and energyconsumption control, as well as creating a scalablebackhaul and complex radio resource orchestration mech-anisms are examples of challenges that need to be over-come in the realization of H-CRAN. Many of these challenges can be addressed in the control plane of cel- lular networks [7,9]. For example, to avoid the inter-ference generated by massive deployment of small cellsor to enable the allocation and orchestration of radioresources, an increasing number of signaling messagesmust be exchanged through the control plane [10]. How-ever, the current control plane of cellular networks neitheris designed to support this increased control traffic norprovides mechanisms to quickly accommodate new sig-naling messages [8]. We argue that the control plane ofcellular networks needs to be revisited to

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support the flex-ibility and programmability to overcome the aforemen-tioned challenges and also to meet the 5G area throughput
target in H-CRAN.

1.2 Relatedwork

Because of the evidenced benefits of SDN in wired networks, such as network programmability and flexi- ble operation, it is natural to consider this paradigmas a framework to deliver the same benefits to wire- less networks [5]. Before discussing the realization of SDN in the wireless world, we do a brief review on cur- rent SDN concepts. SDN is conceptually organized in fourplanes.(i)Applicationplane,(ii)Controlplane,(iii) Forwardingplane,and(iv)Managementplane[6]. Appli- cationssittingontheApplicationplanearedesignedand operated by service providers that serve their own sub- scribers. Applications eventually issue requests for net- workresources,whichareinterpretedandtranslatedinto fine-grain configurations by network controllers at the Control plane. Besides handling requests coming from services, controllers also react upon receiving events generated by devices from the Forwarding plane (e.g., to recover from failure or performance degradation). Finally,theManagementplanemanagesthecomponents of an SDN architecture (e.g., applications, controllers, and devices) by monitoring and tuning the health of the whole network across planes to meet high-levelpolicies andagreements.

SDN also assumes three main Application Program Interfaces (APIs): (i) Northbound API, (ii) Southbound API, and (iii) Management API. The Control plane pro- vides the Northbound API for service providers to create their network applications. Controllers,inturn,makeuseoftheSouthboundAPIto interactwithdevicesintheForwardingplane,i.e.,byissu- inglow-levelinstructionsandcollectinginformation.The ManagementAPIenablestheManagementplanetohan- dledevicesandservicesinallotherplanes,throughlegacy managementprotocols,suchasSNMP,ornewones,such as OF-Config[1].

Our vision of SDWN inherits many concepts from SDN as depicted in Fig. 2. The main additions we envision to the original SDN architecture are the new conceptual entities placed at the Forwarding plane (i.e., devices sup- porting wireless connectivity, such as BBUs/RRHs, relay nodes, and access points) and Control plane (i.e., spe- cific controllers for wireless functions, called SDWN con- trollers). Since wired SDN switches and other network boxes were required to comply with ONF'sspecifications

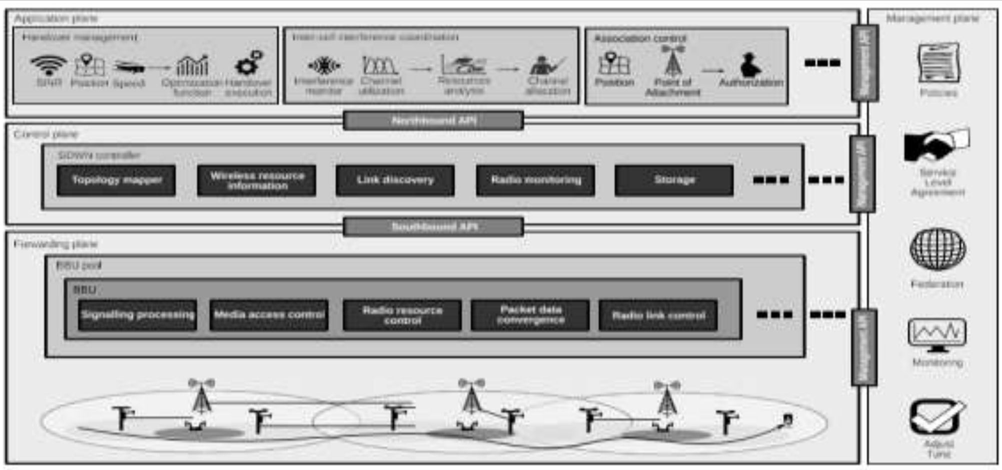

Fig. 2 SDWN conceptual blocks

of a Southbound API, we anticipate that the same will happen to SDWN devices. BBUs and eNBs, responsi- ble for processing all the wireless stack (e.g., signaling, media access control, radio resource allocation), must also be adapted to comply with a new Southbound API for SDWN. RANs require handling a multitude ofwire- lessfunctions,e.g.,frequencyassignment,handover,and interferencecontrol.High-leveldecisionsrelatedtothese functions must be made by application running on top ofSDWNcontrollers,whiletheimplementationof these decisionstolowerlevelsmustbeperformedthroughthe appropriateAPIcallsandprogrammingabstractions.For example,ahandoverfunctionrequiresanAPIdefinition to exchange messages containing relevant information, such as Signal-to-Interference-plus-Noise Ratio(SINR), PacketErrorRate(PER),andDestinationPoint-of-Access (DPoA)indicator,tobeproperlycoordinated.

A common strategy in current SDN setups is to place controllers at the core of the network, far from the edge where RANs are located. That is likely to lead to harmful delay of signaling traffic originating at the net- work edges. In addition, although SDN controllers are expected to handle ultra high speed data flows in wired networks [11], their placement at the network's core is unlikely to allow centralized SDN controllers to scale with the extra control traffic coming from RANs. As such, an important design consideration of distributed architecture of the RAN, regarding complex- ity and latency constraints [15]. In contrast, H-CRAN already envisions a topologically centralized architecture based on resource pools to perform signal processing of the distributed RAN. Therefore, SDWN can exploitthis concept to tackle complexity and latency constraintby using these pools and the existing optical backhaul [10]. In this case, SDWN controllers can take part as an enabling technology to perform centralized process- ing, becoming responsible for different wireless functions coordination [16,17].For example, SDWN controllers can be reprogrammed to analyze, allocate, and redis- tribute radio resources, in addition to controlling the handover, interference, energy, and radio resource shar- ing[18].Also,SDWNcontrollerscanserveasaframe

SDWN is that the SDWN controller needs to be positioned closer to the edge of the network. This entity adds scalabil-ity to the Control plane by directly handling wireless specific functions. Although the SDWN controller is a logically centralized entity, its implementation could be distributedacrosstheedgeof5Gnetworks,whichbrings aboutthediscussiononthedefinitionofhorizontal inter- controller APIs (e.g., Westbound and Eastbound) [12]. Therefore,SDWNcontrollerscanstillbedistributedand alsoperformcentralizedlogicalfunctions,suchas global topology mapping, neighbor wireless resource informa- tionretrieving,linkdiscovery,andradiomonitoring.Itis also worth mentioning that some of the current SDWN proposals are distributed and present hierarchical orga- nization of controllers that provides partial control cen- tralization[10,13]. Such distribution enable controllers to decrease management complexity keeping part of the centralization benefits [10]. There is also the possibility to pool resources, such as radio frequencies and pro- cessingpowerunderthecontrolofSDWNcontrollersin H-CRAN [9,14].

In cellular networks, centralized solutions turn feasible to achieve optimized objectives because of the availabil- ity of the overall state of the network [14]; however, theyareimpracticabletobeimplementedonthecurrent

work to design novel solutions, for example, based on artifi- cial intelligence to predict user handover mobility in a more harmonized manner, avoiding the need of special- ized protocols and network middle-boxes, such asIEEE 802.21andLTE'sMobilityManagementEntity(MME). Although, H-CRAN can benefit from SDWN to reach, for example, optimized solution for each different sup- portedwirelessfunction,thedefinitionofwhichwireless functions an SDWN controller must control and how, remainsundefined.

As in SDN, an SDWN controller can be tuned and reprogrammed by applications at the Application plane through the Northbound API. The main difference from a typical SDN setup is that SDWN allows applications to reconfigure wireless functions, such as handover, inter- cell interference, and association control. The

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Northbound API allows operators to dynamically redefine their entire RAN configuration, readjusting the modus operandi of SDWNcontrollers.

SDWN was already proposed to be used in H-CRAN and C-RAN. For instance, in [16], the authors proposedan SDWN controller able to cope with radio resource management at physical layer. Whereas, in [13], three transport models were proposed to measure the efficiency of employing SDWN concepts in a C-RAN optimizing its usage. The authors of[10], proposed a hierarchi- cal composition of controllers, responsible for different parts of the network, namely radio, optical, and BBU controller. Although SDWN enables endless possibili- ties, it is not a plug-and-play solution to all problems and despite the different architectures proposed, there is still the lack of a proper definition of what are the controller responsibilities to the realization of SDWN in H-CRAN. As a consequence, the Southbound API is weakly defined without proper specification and stan- dardization. In this sense, we take a step further by defin- ing the responsibilities that an SDWN controller must assume in H-CRAN and propose a new Southbound API definition.In the next section, we introduce the responsibilities thatanSDWNcontrollercanassumetocontrolwireless functions.

III.SDWN CONTROLLERRESPONSIBILITIES

The main benefit of using SDWN in H-CRAN is the cre- ation of a flexible programmability framework required to transform the current control plane into a more dynamic one that accommodates future wireless functions while still supporting current functions. SDWN controllers must assume responsibilities about these functions that nowa- days are enclosed in closed-source or technology specific solutions. We selected seven wireless functions to delve into details regarding the SDWN controller's responsibil- ities, such as presented in Table 1. Each row from this table presents: (i) a wireless function, (ii) responsibilities that shall be taken by SDWN controllers to cope with each function, and (iii) enabling technologies that can help con- trollers to fulfill their responsibility. A detailed discussion organized in subsectionsfollows.

1.3 Handovercontrol

ThehighdensityofH-CRANassociatedwithusermobil- ity may end up in throughput degradation issues dueto, for example, frequent UE handover and infrastruc- ture unbalancing. To avoid such degradation, different technologieswereproposedformobilitysupportandhan- dover control of UEs in current cellular networks, such asIETF's MobileInternetProtocolversion6(MIPv6)and IEEE's 802.21 standards, as well as the addition of the MobilityManagementEntity(MME)aparticular purpose elementin3GPP'LTEarchitecture.Toguaranteethecor- rectoperationof5G,H-CRANmustalsoprovidesupport to these technologies before implementing moresophis- ticatedmechanisms.Therefore,thesetechnologiescanbe combinedwithSDWNtodesignoptimalorsemi-optimal handovercontrolsolutions,whichcanleverageSDWN's centralizationofnetworkstatusasinput.Also,inaposte- riormoment,SDWNcontrollerscanserveasaframework todesignnovelhandoversolutions,forexample,basedon artificial intelligence to predict user mobility in a more harmonized manner, avoiding the need of specialized protocols,suchasIEEE802.21.Nevertheless,SDWNis limitedtothemobilitydetectionsystemofH-CRANcom- binedtotheRRHcapabilitiestolocateUEsandhastobe built with privacy mechanism to avoid user information leakage.

1.4 Interferencecontrol

As soon as macro and small cells start to intersectwith each other in H-CRAN, the improved data rate provided by these cell deployments degrades due tointra and inter-cell interference [15]. As a consequence, different technologies have been exploited toalleviate

Table 1 SDWN controller responsibilities

Wireless function	Controller responsibility	Technology
Handover control	• Mobilityaccounting • Mobilityprediction • Data floworchestration • Transparency	• IEEE802.21 • Mobile IPv6(MIPv6)
Interference control	• Intra-cell interferencecognition • Inter-cell interferencecognition • Interferenceavoidanceorchestration • Controlchannelpollution minimization	• EnhancedInter-CellInterferenceCoordination(eICIC) • Coordinated Multi-Point(CoMP) • AlmostBlankSubframe(ABS)
Radio resource allocation	• Calculateradioresourceallocation • UEsassociatedperRRHand BS	• eICIC • CoMP • Software-Defined Radio(SDR) • Cooperativeradioresourcecontrol • Cooperative self-organizednetworking
Sharing control	• Frequency bandsdivision • Accessgranting • Accounting • Policyassurance	• BidingandAuctionHouse • LicensedSharedAccess(LSA) • DynamicSpectrumAccess(DSA)
Network orchestration	• Data-flowmanagement • Data-flowredundancy • Cell associationcontrol • AdmissionControl	• ControlAndProvisioningofWireless AccessPoints(CAPWAP) • OpenFlow • LTE-Self OrganizedNetwork
Energy control	• Configuremaximumtransmissionpower • Switch On/Offdevices • Co-channelmaximumtransmissionpower	• Remoteenergycontrolmechanism • Wake upmechanism • TransmissionpowercontrolthroughSDR

interference at RANs, such as beamforming transmis- sions using multi-user MIMO antennas, Almost Blank Subframes (ABS), and Enhanced Inter-CellInterference coordination(eICIC)mechanism.Thesetechnologiescan havetheirperformanceimprovedbytheuseofcentralized solutions for inter/intra-cell interference coordination to reach near zero interference. As opposed to distributed solutions, largely based on local signal strength indica- tors, centralized interference coordination has thewhole networkstateandfrequencyallocation,facilitatinginter- ference management. In this sense, the processing cen- tralizationprovidedbyH-CRANcombinedtotheSDWN controllerenablesthecoordinationoftheinter/intra-cell interference,allowingoperatorstodesignalgorithmsfor interferencecoordinationthatbestfittheirnetworkneeds [15,16].SinceSDWNcontrollerscentralizeinterference coordination,parameters,suchasinterferenceatreceiver and frequency assigned for each cell, can be used as input for optimized interference avoidance inH-CRAN. Althoughtheinterferencecoordinationcanbeimproved, the number of signaling messages increases,

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radio cells need to support sensing mechanisms, and event-based systems (e.g., traps) are required to send messages in case of interference detection.

1.5 Radio resourceallocation

Channels, resource blocks, and spectrum are typical examples of radio resources that can be allocated infive domains,i.e.,time,frequency,space,power,andc oding. For instance, frequency might be dynamically assigned to each small and macro cell in H-CRAN to avoidinter- ference and improve spectrum efficiency by exploiting spectrum reuse [1]. Additionally, advanced radio virtu- alization techniques allow the allocation and sharing of radioresourcesamongmultiple(Virtual)mobilen etwork operators [19], the exploitation of dynamic access tech- niques[20],andevendifferentaccesstechniques,s uchas Machine-to-Machine (M2M) [21], to allocate resources in a cellular network. Technologies such as SDR pro- videtheprogrammabilityrequiredtoadapttheradi o

Wireless function	Resource
Radio resource allocation	• channel(*node*, *start_time*,*time_to_keep*,
	c_frequency, *c_bandwidth*,*radio_parameters*)
	• dmimo(*node*$_s$, *node*$_s$, *ue_id*,
	c_frequency, *c_bandwidth*,*c_rssi*)
Handover control	• handover(*ue*,*poa*,*dpoa*,*radio_parameters*)
	• handoff(*ue*, *poa*,*radio_parameters*)
Interference control	• rssi_event(*node*,*c_frequency*,
	c_bandwidth, *radio_parameters*)
	• interference_check(*node*,*c_frequency*,*c_bandwidth*)
Sharing con- trol	• dsa(*node_set*,*c_frequency*,
	c_bandwidth, *radio_parameters*)
	• lsa(*node_set*, *c_frequency*,
	c_bandwidth,*start_time*,*time_to_keep*)
Networking orchestration	• openflow(*)
	• connection(*ue*, *poa*,*radio_parameters*)
	• disconnection(*dpoa*)
Power control	• wakeup(*poa*)
	• standby(*poa*,*start_time*,*time_to_keep*)
	• maximum_power(*poa*, *power*,*radio_parameters*)

Table2 SDWNsouthboundinterface

Resource resource allocation in real time. This programmability alsoallowstheutilizationofadvancedCoMPande ICIC mechanisms to increase the spectral efficiency of radio communications.SDWNcanimprovesuchmech anisms by centralizing the knowledge of the wireless network exposing the programmability of networking devices to high- levelapplications.However,themainconstraints of using*SDWNcontrollers*forradioresourceallocat ionare related to the increase of signaling

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messages, the inte- gration of low-level radio baseband processing with the conventional network protocol stack and hardware, and complexitytodesigncentralizedresourcealgorithmsthat react to the local and fast paced changes of wireless channel conditions[16].

3.4 Sharing control

High leasing prices and spectrum scarcity lead opera- torstoexploitspectrumsharingtoimprovetheirresource pool and budgeting [22].To take advantage of spec- trum sharing, different techniques can be used,e.g., Access (LSA) in combination with cognitive radio and auction systems. With SDWN, operators can controlthe access technique used to explore shared frequen- cies. In this sense, SDWN controllers become responsi- ble for providing information sharing among operators, enabling better control of shared frequencies, andassur- ing that operators' policies are correctly applied.Never- theless, depending on spectrum access technique taken, theSDWNcontrollerrolechanges.Forexample,inLSA theSDWNcontrollerbecomeslimitedtocoordinatespec- trum sharing only if a spectrum broker is present in the coordinatedarea.

3.5 Network orchestration

H-CRAN infrastructure includes many heterogeneous elements, such as BSs, BBUs, RRHs, and APs, operat- ing under a variety of protocols to forward data and to interact with one another. Achieving, for example, opti- mal traffic routing in this context is infeasible without some sort of lingua franca among technologies. SDWN canimprovethisscenariowithnetworkorchestration,by centralizinginformationfromdifferentsourcesandcom- municatingwithelementsofinterestalloverthenetwork. While requiring trap systems for event detection and possibly increasing signaling traffic, SDWN controllers become a bridge for integrating well-known protocols, such as OpenFlow and CAPWAP, to coordinate other elements (including other SDN Controllers) performing cross technologyoperations.

• maximum_power(poa, power,radio_parameters)

3.6 Energy control

Energyconsumptioninacellularnetworkcanbedivided into two perspectives from (i) operators and (ii) UEs. In the former, operators are concerned with infrastructure equipmentenergyconsumption,forexample,RRHsand BBUs. In the latter, UEs must preserve their energy to maximizebatterylifebyminimizingtransmission power and retransmissions. There is a tradeoff between both perspectives, where infrastructure equipment consumes more energy to reduce UEs consumptions [23]. SDWN can be used to turn the energy control programmable. SDWN controllers must control the energy tradeoff by configuring the maximum allowed co-channel interfer- ence and transmission power, allowing operators to bal- ancethetradeoffastheyseefit.Also,theSDWNcontroller shall be able to switch off/on wireless equipment that is notinuse,forexample,anRRHwithoutUEsinitsvicinity. Thussavingenergy,butincreasingnodeunavailabilityin caseacelliserroneouslyturnedoffwhileinuse.Accessto suchacommandmustbeprotectedagainstunauthorized use.

It is important to notice that the aforementioned wire- less functions are not novel by themselves. In fact,therearepurposespecificcontrollersalreadyinplaceforsome of them, e.g., the MME controls intra-LTE handover events. However, these controllers were not designed for dynamic reprogramming, hindering the deployment of network applications and the fast evolution of cel- lular networks. Moreover, SDWN can be used in H- CRAN to achieve outstanding benefits, which include optimal interference avoidance and frequency assign- ment, as well as improved energy control and spectrum sharing.AlthoughSDWNenablesendlesspossibilities,it is not a plug-and-play solution to all problems. To bet- terunderstandthepotentialofusingSDWNinH-CRAN, inthenextsection,wedescribeourprototypeandacase study to quantify some of the benefits of SDWN when radioresourceallocationandhandovercontrolfunctions are coordinated by SDWN controllers in an H-CRAN scenario.

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IV. PROTOTYPEANDINTERFACEDEFINITION

We developed an SDWN prototype, where a controller exchangemessageswithH-CRANnetworkednodes,e.g., BBUs, and eNBs. First, we determine the southbound interface required to implement our proposed SDWN controller based on RESTful concepts. Afterward, we describe our SDWNprototype.

1.6 SDWN controllerinterfaces

For each wireless function, our southbound interface sum- marizedinTable2presentsasetofRESTfulresources that can be changed according to the methods: Create, Read, Update, and Delete (CRUD) [24]. These resources were designed to enable control and forwarding plane entities tointeract.

To perform radio resourceallocation, the south- bound resource channel can be instantiated by a con- troller using the create method determining which PoA(node) of a BBU will receive a determined frequency (c_frequency) with a certain bandwidth (c_bandwidht). Also, the resource can start to be used for a certain period (start_time) and send a notification to check whether the current configuration is still valid after a certain period (time_to_keep). The same resource can be used to get the current status of the channel in use of a node, receiving a list of radio parameters (radio_parameters), e.g., average RSSI and the number of UE currently connected con- suming the channel. Other methods, such as update and delete, can be used to change the current configuration or destroy it. Considering the same logic, we detail each of the other resources,briefly.

The dmimoresource can be used to enable, check, change, or stop the execution of MIMO between RRHs (node$_a$andnode$_b$).Toperformhandovercontrol,thehan- dover resource can be used to start, get status, changeorstopaUE(ue)migrationfromanorigin(poa)to adestination PoA (dpoa) considering different radio param- eters (radio_parameters). Whereas, the handoff resource cannot be instantiated by the controller directly, but can be used by a BBU or eNB to notify the controller about a UE (ue) departure from one of its RRHs (poa) containing radio parameters (radio_parameters) whennecessary.

The rssi_event, in turn, is a resource instantiated by BBUs and eNBs to inform that an RRH (node) is fac- ing bad channel (c_frequencyand c_bandwidth) qual- ity (radio_parameters) that must be investigated. The interference_checkresource enables BBUs and eNBs to request the SDWN controller to check whether there are other RRHs from different RANs using the same chan- nel frequencies (c_frequencyand c_bandwidth). To per- form sharing control, the dsaand lsaresources can be used to determine the current frequency sharing regime in use, in this case, Dynamic Spectrum Access (DSA) or Licensed Shared Spectrum Access (LSA), respectively. In both cases, a set of RRHs (node_set) must be deter- mined considering different inputs, i.e., frequencies in use (c_frequencyand c_bandwidth), radio parameters (radio_parameters), start period (start_time) and time to request update(time_to_keep).

Further network control can be accomplished by the usageofOpenFlowinterfaces(openflow(∗))toperform data flow management and control. Whereas, the asso- ciation and disconnection control of UEs can be per- formed through the use of connection and disconnec- tionresources, using messages containing e.g., the UE id ueand radio parameters, such as PER and RSSI. Finally, power control can be performed by the usage oftheresources:wakeup,standby,andmaximum_powerresources. In the first, wakeup enables to activate or deactivate an RRH. In the second, standby put the RRHs in standby mode, i.e., the RRH is on but do not perform transmissions or receptions. In the third, the maximum_powerenablestocontrolthemaximumtrans- mission power of an RRH. Considering the proposed interface,wedevelopedourSDWNprototype.

1.7 SDWNprototype

Our SDWN prototype was developed to operate on top of H-CRAN scenarios. Our scenario consists of an H- CRAN with low, medium and high density of UEs ([100, 500, 1000] UEs/Km^2 respectively). Each UE density is combined with a scarce, medium or dense number of RRHs([5,15,30]RRHs/Km^2,respectively).Thisresultsin nine different scenarios, varying from low-density-UEs- high-low-RRHs to high-density-UEs-high-density-RRHs [3]. Each of the nine scenarios was simulated in a custom- made simulation tool designed specifically for H-CRAN scenarios that have its source code

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publishedinGitHub[2].
We modeled the communication between UEs and RRHsthroughfreespacepathloss,withathermalnoise of −90 dBm, Orthogonal Frequency-Division Multiple Access (OFDMA), and modulation code scheme basedon ([25], Annex A). RRHs were configured with a maxi- mum transmission power of 23 dBm, the antenna gain of 0 dBi, and connected to the closest BBU pool. The energy being consumed by the RRH varies according to its oper- ation mode, 4.3 W when idle (sleeping) and 6.8 W when active [26]. A macrocell is placed in the center of the grid and configured with maximum transmission power of 46 dBm and antenna gain of 0 dBi. UEs move along the grid according to a random waypoint mobility model with a pause interval of 10s and with a speed ranging from 1 to 40 m/s [27]. Each UE is modeled with a Constant Bitrate (CBR) traffic demand of 5 Mbps. Thus, the total traf- ficdemandincreaseswiththenumberofUEsasfollows:
0.5Gbps/km^{2}for100UEs,2.5Gbps/km^{2}for500UEs,and

Gbps/km^2 for 1000UEs.

In each scenario, we deployed an SDWN controller responsible for managing radio resource allocation andthe operation mode of all RRHs. The SDWN controller receives control messages from the wireless substrate, similar to OpenFlow[3] messages in wired networks and also considering the RESTful interface proposed. As a proof-of-concept, we initially considered only five types of messages regarding different resources: (i) connection (connection create), (ii) disconnection (disconnection cre- ate),(iii)connection+BBUchange(handoverCRUD), (iv) bandwidth (BW) update (channel update), and (v) RRHstatus(channelread).InFig.3,weexemplifythe con- nectionmessage, which accommodates meaningful infor- mation for handover execution, such as SINR, PER, and DPoA. This information is received and used to popu- late the Handover and Channel tables within the SDWN controller.

Theconnectionanddisconnectionmessagesarereceived by the SDWN controller when a UE performs a han- dover, e.g., disconnects from one RRH and connects to another one. The connection + BBU change is a message sent when a UE connects to an RRH managed by a differ- entBBU, e.g., handover from RRH 3 to RRH 4 in Fig. 1. This message is similar to connection, but with additional informationabouttheRRHinwhichtheUEisconnecting. The BW update is sent when the RRH requires addi- tional radio resources. Finally, the RRH status is a power control message exchanged between BBU and SDWN controller, which can change the RRH operation mode to idle (standby) or active. This set of messages can be gen- erated in the following cases: (i) when a UE connects to anRRH,(ii)whenauserdisconnectsfromanRRH,or (iii) when the UE mobility turns the current modulation and coding scheme utilized by the RRH inappropriate, e.g., when the user moves far away from the connected RRH, and (iv) when a UE connects or disconnects from an RRH.

Algorithm 1 Bandwidth update, channel distribution, and powercontrolapplications

Ensure: RRH_u istheRRHthataUEuiscurrentlycon- nected
Ensure: UEL_r is the list of UEs connected to RRH r
Ensure: INT_r is the list of RRHs interfering with RRHr
1: **procedure** RECEIVEDBWUPDATEMESSAGE(RRHr)
2: trigger PowerControl(RRHr)
3: reqBW←Sum(BWrequiredbyUEsinUEL_r)
4: Configure RRH r channel to satisfy reqBW5: trigger ChannelDistributionUpdate(RRH r) 6: **endprocedure**
7: **procedure** CHANNELDISTRIBUTIONUPDATE(RRH r)
8: Estimate the channel with less SINR for RRH r 9: Configure RRH r to use channel with best SINR 10: **if** RRH r channel changed**then**
11: **for all** RRH iin INT_r**do**

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12: triggerChannelDistributionUpdate(i)
13: **endfor**
14: **endif**
15: **end procedure**
16: **procedure** POWERCONTROL(RRH r)
17: EstimatethesetofUEsinterestedinmigratetor
18: **for all** UE u in UEs**do**
19: **if** sizeof (UEL_r) smaller than sizeof(UEL_{RRH_u})
and RRH_u is unable to sustain u **then**
20: UE u has access granted to RRHr
21: **else**
22: UEuhastheaccessdeniedtoRRHr
23: **endif**
24: **endfor**
25: **endprocedure**

We designed an application in the SDWN controller that (i) reconfigures the channel bandwidth to fit best the UE demands according to the LTE configurations, i.e., [1.4, 3, 4, 5, 10, 15, 20] MHz, (ii) reduce the overall inter- ference by assigning the channel with the lowest SINR, i.e.,thechannelleastusedintheRRHneighborhood,and (iii) switch the operation mode of RRHs based basedon thenumberofUE'sintheRRHvicinity,i.e.,idleifnoUE's areintheRRHvicinityandactiveotherwise.Algorithm1 presents a pseudo code that contains the main opera- tions performed by the application. The power control andchannelbandwidthreconfigurationareexecutedonly whentheSDWNcontrollerreceivestheBWupdatemes- sage (line 1). As the first step, the power controlroutine istriggered(line2).Inthisroutine,theSDWNcontroller estimatesthepotentialsetofUEstomigratetoanRRHr duetotheirpositioning(line17).Afterward,theapplica- tiondeterminesifanRRHbeinganalyzed(r)willaccept

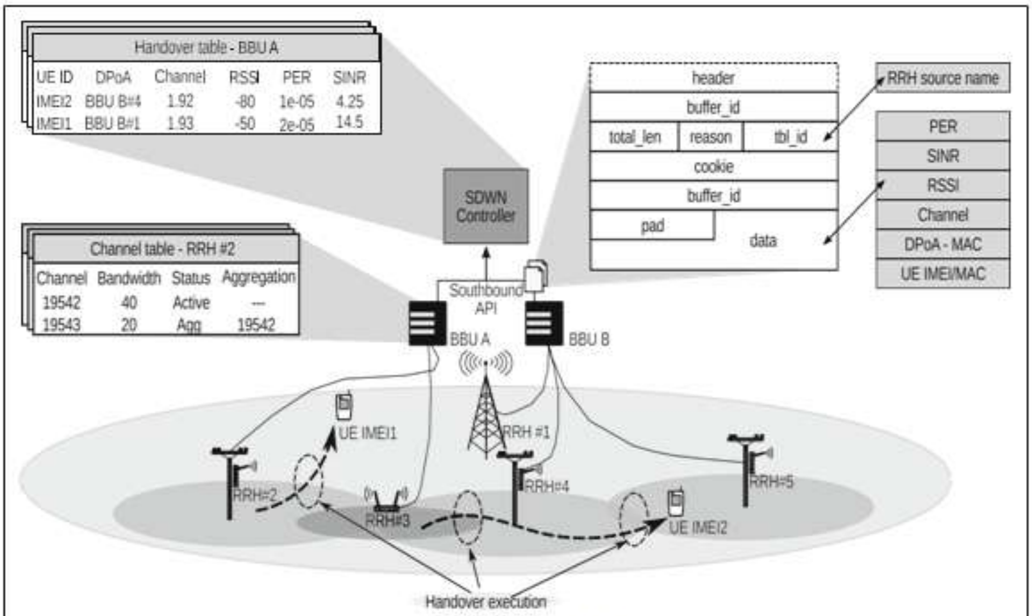

Fig. 3 H-CRAN with SDWN deployment

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a UE that is migrating from other RRH (RRH_u) determin- ing: (a) if r's current number of UEs connected is larger than the population of connected UEs from RRH_u; and (b) if RRH_u is saturated or cannot afford the capacity required by the UE (line 19). Otherwise, the RRH rejects the UE access (line 22). This way RRHs are used until achieving saturation before activating a new RRH.

Further, the application estimates the necessary channel bandwidth considering the UEs modulation and coding scheme, SINR, and PER for each connected UE (line 2). Afterward, the RRH is configured with the channel band- width that satisfies all UEs and that corresponds to a valid LTE configuration (line 3) and updates the channel distri- bution (line 4). Starting the update, the SDWN controller estimates the channel with best SINR (line 7) and assigns it to RRH (line 8). Because changing the channel of one RRH modifies the interference conditions of all adjacent antennas, the ChannelDistributionUpdateis performed per RRH (lines 10 − 12). Moreover, as clusters of small cells will hardly interfere with each other due to the small coverage area of RRHs, it is not likely that the ChannelD- istributionUpdatewill be executed for all RRHs in the H-CRAN.

As a baseline, we used a traditional network planning scheme based on 4G networks to organize H-CRAN, in whichRRHsreceivethechannelwiththebestSIN Rand with a fixed bandwidth during the network bootstrap. Finally, we measured the overall throughput andenergyconsumption enhancement as well as the control cost imposedbySDWNinH-CRANagainstthenon-SDWN baseline.

Inthenextsection,wepresentacasestudytoquantify someofthebenefitsofSDWNwhenradioresource con- trol, interference avoidance, and handover control func- tionsarecoordinatedbySDWNcontrollersinanH-CRAN scenario.

V. SDWNPROOFOFCONCEPT

WedemonstratetheuseofSDWNforfuture5Gdeploy- mentsinacasestudybasedontheH-CRANarchitecture, suchasdepictedinFig.3.Inthiscasestudy,weshow the SDWNgainsintermsofoverallthroughput,interference, and energy consumption in comparison to a H-CRAN without SDWN using 4G frequency planning, as well as the overhead added by control messages used by the SDWNcontroller.

5.1 ThroughputandenergybenefitsofSDWNinH-CRAN

We show the benefits of SDWN comparing the overall throughput achieved by all UEs with the traditional H- CRAN network, which uses a fixed channel bandwidth. Moreover, we compared the SDWN power control gains withabaselinewhereRRHsarealwaysactive.

Figure 4 shows the average throughput of UEs for each ofthenineevaluatedscenarios.Inallscenarios,employing SDWNtomonitorUEshandoverandperformfrequency

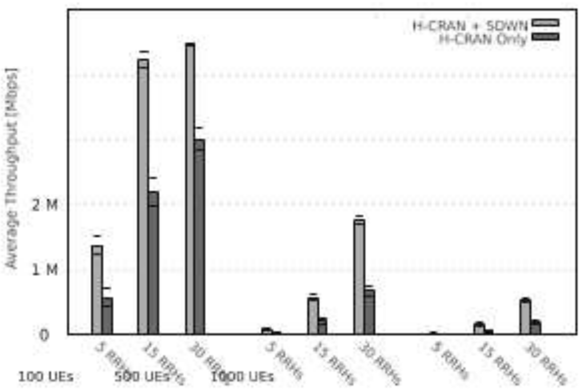

Fig.4 Averagethroughputexperiencedbymobilesubscribers

assignmentincreasedtheaveragethroughputbyapprox- imately 40% when compared with the 3G/4G baseline. This gain occurs because SDWN reduces the inter-tier interferencebymanagingthechanneldistribution during runtime, which in turn increases the average SINR and enablesbettermodulationandcodingschemes.However, forafixednumberofRRHs,increasingthenumber ofUEs decreases the average throughput. This occurs because the limited available radio resources are divided among a larger number of UEs. For the same reason, the aver- age throughput increases with the number of RRHs,i.e., theaveragenumberofUEsconnectedtoanRRHislower, facilitatingthereuseofradioresources.

To better understand the benefits of the channel band- width and distribution application, we show the percent- age of UEs transmission as a function of the number of RRHs interfering with their communication in Fig. 5b. Approximately 70% of the transmissions were performed without interference with the H-CRAN standard channeldistribution algorithm, whereas with the use of SDWN this number goes up to roughly 96%.

The power control application achieved energy gains maintaining RRHs in idle as long as others are not satu- rated, as can be seen in Fig. 6. For scenarios with small densities,suchas100UEs/km^2,thisapplicationachieved 20% of energy reduction for high number of RRHs, a sig- nificant mark for large networks. Whereas, for scenarios with high densities, such as 1000 UEs/km^2, the SDWN gains decrease achieving 6% at best for 30 RRHs. It is important to notice the tradeoff between increasing the number of RRHs and the energy gains achieved. In this case, the results in this work can serve as guidelines for operators to identify which is the best number of RRHs to be deployed in an H-CRAN comparing energy gains and the total capacity achieved.

5.2 ControlmessagecostofSDWNinH-CRAN

The main drawback of employing an SDWN Controller is the additional overhead incurred by controlmessages. Figure 7 shows the number of control messages of each type for all evaluated scenarios. As expected,increasing thenumberofUEsorRRHsleadstoadirectincrease in thenumberofcontrolmessagesexchanged.InthecaseofRRHs,thisincreaseoccursbecauseUEshavemorehandoveropportunities.Wealsohighlightthatthetotalnumberofcontrolmessagesexchangedperoperationdepends only on the number of UEs and RRH and not on exter- nalmobilityfactors,suchasthespeedinwhichthe UEis movingoritsdistancetotheRRH.

Figure 8a shows the average frequency of each message type for all scenarios without significant loss of gener- ality. Connection related operations, i.e., connection and disconnection,accountfor86%ofallmessagesexchanged. The higher number of connections messages, as com- paredtodisconnection,isduetousersattemptingto

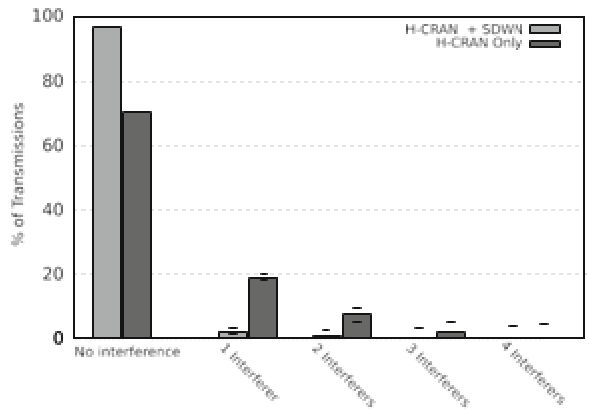

Fig.5Percentageofcommunicationsperformedrelativetothe number ofinterferers

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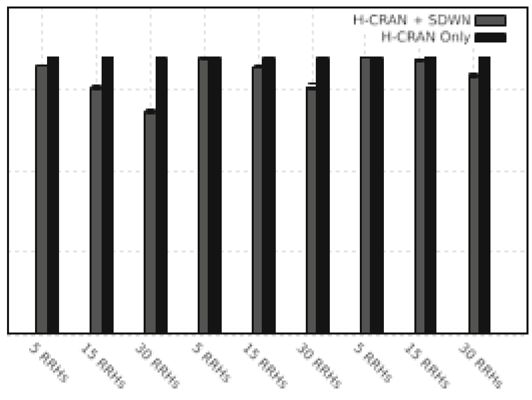

Fig. 6 Average energy consumption per RRH

1 M

0

100 UEs

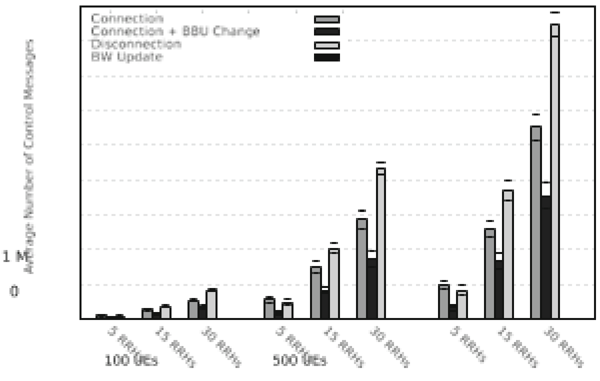

Fig. 7 Total of control messages in each scenario

migratebetweenRRHsandhavingtheirhandover denied by the power control application. Moreover, the num- ber of BBU change, BW updates, and RRH status (i.e., Enter normal mode and Enter idle mode) is below 13%. This result indicates that the channel bandwidth distri- butionandpowercontroloperationsarerarelyexecuted, althoughtheseoperationssignificantlyincreasetheover- all UEthroughput.

Figure 8b shows the traffic overhead of each message type considering its size and frequency. We defined the average packet size for each control message following the summation of their content with the OpenFlowstan- dard headers needed by each control action, resulting in: 512 bytes for connection, 288 bytes for disconnection,800 bytes for connection + BBU change, 384 bytes for BW update,288bytesforEnternormalmodeand274bytes

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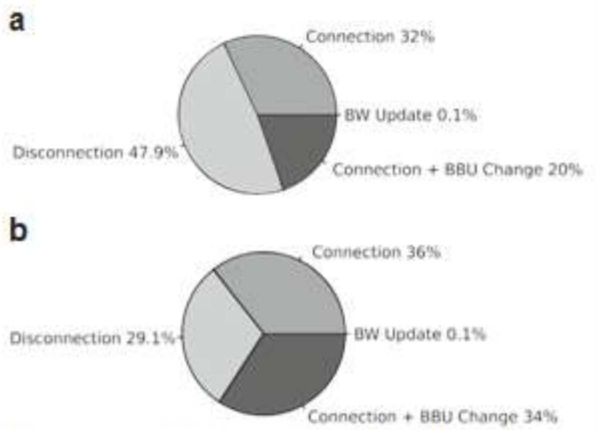

Fig. 8 SDWN control messages frequency and bandwidth consumption. aAveragefrequencyofeachcontrolmessagetypein allscenarios.bBandwidthconsumptionconsideringthemessage sizeandtheaveragefrequencyof(a)

forEnteridlemode.Resultsshowthattheconnection mes- sage is responsible for 65% of the traffic overhead. The connection + BBU change message represents 6% of the overhead, although it accounts for only 3% of the mes- sages exchanged. Moreover, the BW update summed to the RRH status message accounts for less than 10% of the trafficoverhead.ThelowoverheadofBWupdateand RRH status, allied with its low frequency, reinforces the advan- tages of moving suchamechanism toacentralizedSDWN controller. It is worth highlighting that the average control overhead represents less than 3% of the overall network traffic, i.e., UE and controltraffic.

1000 UEs

VI. CONCLUSION

In this article, we proposed applying the concepts of SDWN to support the development of flexible, pro- grammable, and sustainable H-CRAN infrastructures to achieve the area throughput target for the forthcoming nextgenerationcellularnetworks.Moreover,weobserved the design decisions that need to be made on the path towards a full SDWN-enabled cellular network and dis- cussedhowSDWNcanbeemployedinconjunctionwith H-CRAN. We also conducted a case study forH-CRAN whereanSDWNcontrollerhandlesfrequencyassignment andchanneldistributionofRRHsbasedonthehandover performed byUEs.

Our results show mainly an increase in the overall throughput of 40% and decrease of energyconsumption between 6% and 20% when SDWN is comparedagainst traditional 3G/4G network planning. Also, we analyzed the overhead posed by SDWN in terms of control traf- fic considering the number of UEs and RRH, which in theworstcaseevaluatedwas7%ofthetotaldatatraffic. TheoverheadtoemploySDWNinH-CRANseemsrea- sonable,consideringthebenefitsthatcanbeachievedas demonstrated in our casestudy.

As future work, we will deploy an SDWN case study over the FUTEBOL testbed[4] to study its effect in real deployments. Also, we intend to extend the SDWN con- troller to a case study involving spectrum sharing for two operators to prove its usability in such context and the potential of using three or more wireless functions at once.

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