Interference Coordination in SDN-Based Heterogeneous Mobile Networks

Omer Narmanlioglu
P.I. Works,
Istanbul, Turkey, 34912
E-mail: omer.narmanlioglu@piworks.net

Engin Zeydan
Türk Telekom Labs,
Istanbul, Turkey, 34770
E-mail: engin.zeydan@turktelekom.com.tr

***Abstract*—Heterogeneous Networks (HetNets) adopted into Long Term Evolution Advanced networks, have become major candidate for next generation mobile networks. In HetNets, resource and interference management techniques become crucial to ensure high spectral as well as power efficiencies for Mobile Network Operators (MNOs) since they use frequency reuse of one and include cells that serve overlapping coverage regions. In this paper, we investigate a new architecture with emphasis on management applications of Heterogeneous Radio Access Networks (RANs) following Software-Defined Networking (SDN) paradigm. After giving brief explanations about advanced interference management techniques (i.e., enhanced inter-cell interference cancellation (eICIC) and Coordinated Multipoint (CoMP) transmission/reception) that are realized to top of the SDN/RAN controller, we present Monte-Carlo simulation results with the awareness of global view of the network infrastructure. Jain's fairness index and Shannon capacity are considered as key performance indicators. The simulation results indicate both fairness index and capacity value are improved with the use of eICIC technique and CoMP mechanism provides better service quality for cell-edge user equipments. SDN paradigm ensures realization of flexible architectures that can provide modular and pluggable platform for MNOs and we further provide joint evaluation of RAN controller's applications including radio resource management techniques.**

Keywords*—Software-Defined Networking, RAN Controller, Heterogeneous Networks, Interference Coordination.

I. INTRODUCTION

The number of mobile users and their strong demands for bandwidth hungry applications are increasing exponentially over the recent years. In order to meet these growing demands, Mobile Network Operators (MNOs) have been looking for innovative solutions that can increase their revenue and quality-of-experience (QoE) by providing better services to their subscribers [1]. Currently used cellular networks' requirements have been initiated by International Telecommunication Union (ITU) as International Mobile Telecommunications - Advanced (IMT-A) [2]. Long Term Evolution (LTE) Release 8 offering several significant improvements such as high data rate (up to 300 Mbps for downlink and 75 Mbps for uplink), low latency (less than 5 ms), all Internet Protocol (IP)-based flat network architecture etc. [3] has been provided by The 3rd Generation Partnership Project (3GPP). On the other hand, the provided network specifications have not been sufficient to meet the IMT-A requirements. In respect to this, Release 10 includes advanced technologies (i.e., enhanced multiple-input multiple-output (MIMO) transmission (up to eight antenna pairs) and carrier aggregation (CA)) in order to meet these requirements. However, since spectral efficiency of wireless link between users and base stations in cellular networks approaches the theoretical limits [4], increasing node deployment density has been the only possible solution to further improve the network performance [5] instead of changing radio link parameters.

Heterogeneous Networks (HetNets) including macrocells and smallcells such as picocell, femtocell, remote radio head (RRH) and relay node inserted into currently used network architecture in order to improve the system performance have been expected to play a crucial role in the next generation cellular networks. The basic idea of HetNets is to increase node deployment density via bringing the Base Stations (BSs) closer to user equipments (UEs), thereby, the signal quality can be improved. In addition to macrocells deployed for urban, suburban or rural area coverage, smallcells aim to enhance network throughput and provide better service quality to UEs that are far from macrocell evolved Node-Bs (eNodeBs). Deployment of smallcells that reuse the same Evolved Universal Terrestrial Radio Access (EUTRA) absolute radio-frequency channel numbers (EARFCNs) with the macrocells and setting frequency reuse to one among macrocells improve the system performance significantly. However, it causes inter-cell interference problems. Therefore, inter-cell coordination methods are needed to handle with these issues. Enhanced inter-cell interference cancellation (eICIC) methods have been proposed in Long Term Evolution Advanced (LTE-A) specifications in order to overcome these interference issues. eICIC is used especially to improve the system spectral efficiency by optimally orchestrating the activities of eNodeBs and leveraging techniques performing scheduling of users based on a time-slot basis. It basically compensates co-channel interference with the use of Almost-Blank Subframe (ABSF) in which macrocell eNodeBs almost mute their transmissions that lead the interference on UEs associated with the smallcell eNodeBs. In addition to this, Coordinated Multipoint (CoMP) transmission and reception mechanism improves the signal quality of cell-edge UEs via the coordination of two or more macrocell eNodeBs.

Both advanced interference management techniques should instantaneously adopt the parameters responding to time-varying nature of wireless channels and dynamically changing loads to achieve the maximum performance. However, currently used X2 interfaces among eNodeBs are not enough to respond the fast varying conditions as it selects the parameters under the consideration of average or slowly changing channel and load conditions. Moreover, those techniques run in distributed manner and eNodeBs can share relative information (e.g., interference from nearby cells) with neighbors as depending on X2 interface capabilities. Recently developed Software-Defined Networking (SDN) paradigm providing powerful and simple approaches to manage the complex networks, by creating programmable, dynamic and flexible architecture, abstraction from hardware and centralized controller structure can address those challenges.

SDN-based network architectures have been also investigated in the literature [6-12]. In [6], SDN architecture with four extensions to controller platforms, switches and base stations is proposed for cellular networks to simplify the design and management. SoftCell, supporting fine-grained policies for cellular core network, is proposed in [7] with the usage of packet classification on access switches that are next to the base stations and aggregation of traffic along multiple dimensions. In [8], SDN-based mobile network architecture increasing the operator innovation potential is presented and validated by testbed implementation. In [9], the authors point out application of SDN while minimizing the transport network load overhead against several parameters (i.e., delays, number and placement of data centers etc.) as the function placement problem and aim to model and provide a solution for LTE mobile core gateways. [10] examines several implementation scenarios of SDN in mobile cellular networks and SDN's contributions to inter-cell interference management, traffic control and network virtualization domains are explained. SoftRAN [11] abstracts all base stations in a local area as a virtual big base station that is managed by centralized controller to perform load balancing, radio resource management (RRM), handover etc. while considering global view of the network. In [12], the concept of eICIC is analyzed according to centralized and distributed RRM architectures and two different dynamic fast adaptation algorithms are proposed. By connecting macrocell eNodeBs and smallcell eNodeBs with high speed, low latency fronthaul connections, the platform for information exchange at high rate between nodes is satisfied. However, none of the approaches developed above investigate a flexible, modular and plug-and-play architecture exploiting the advantages of SDN-based model design with a centralized Radio Access Network (RAN) controller to manage eNodeB applications/functionalities of the heterogeneous cellular networks.

In this work, we propose a centralized RAN controller in HetNets in order to improve the system performance while coordinating all RAN processes such as RRM, eICIC, arrangement of ABSF, CoMP transmission and reception etc. With the introduction of a centralized RAN controller and related interfaces, all types of eNodeBs act as basic packet processing devices. They collect the information (channel quality indicators (CQIs), interference levels associated with other base stations etc.) from each UE and transfer to centralized controller. With the purpose of resource and interference managements, those information is updated and gathered by the central controller. Our main contributions are as follows we propose a centralized architecture with SDN based RAN controller for increasing spectral efficiency by using the recent advancements in the 3GPP RAN standards. After providing brief explanations about eNodeB functions that are running on the top of proposed SDN-based RAN controller, we provide evaluate both individual and joint performances of eICIC, CoMP and RRM techniques with the awareness of global view of the network infrastructure. We further discuss about the new requirements for obtaining maximum benefit from the proposed SDN-based architecture.

The rest of this paper is organized as follows. In Section II, we introduce our system model and architecture based on the proposed SDN-based RAN architecture. In Section III, we present sample RAN applications running at the top of SDN/RAN Controller and the performance evaluation of those applications is available in Section IV. Finally, we conclude the paper in Section V.

II. SYSTEM MODEL AND ARCHITECTURE

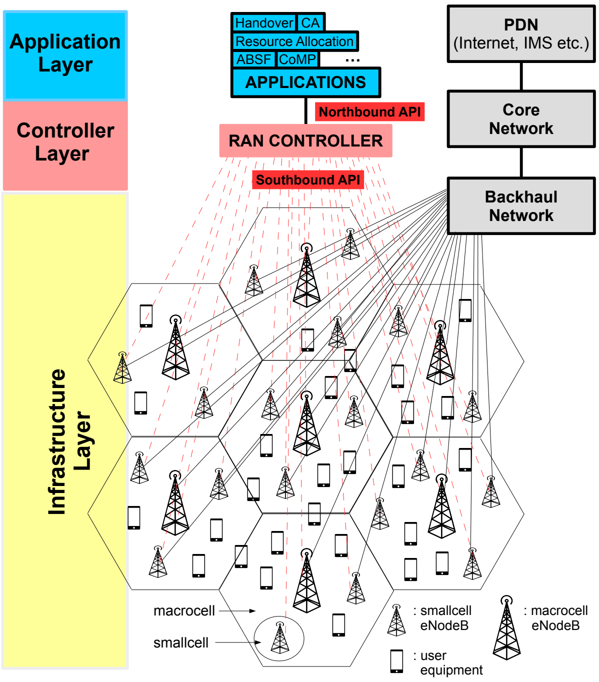


Fig. 1: Architecture of SDN-based RAN controller.

The overview of the proposed RAN optimized software-defined LTE-A architecture is shown in Fig. 1 which identifies the key architectural components as well as additional elements for SDN extension for mobile RAN design. This architecture contains three main levels: *application level* where applications such as CA, handover management, ABSF, CoMP and RRM are running, RAN manager/SDN *controller level* and *infrastructure layer* at the bottom of the stack. The elements in the *infrastructure layer* are connected to packet data network (PDN) services such as Internet, IP Multimedia Subsystem (IMS) via backhaul and core network of the MNO.

In *application layer*, applications such as ABSF and CoMP are running for functionalities such as controlling the service continuity of relevant mobile UEs at eNodeBs, increasing the relative rates and fair scheduling. All these applications are managed by RAN controller via Northbound Application Programming Interface (API).

Controller layer contains RAN controller which monitors and manages the RANs. It periodically collects data from RAN elements about the CQI, congestion, traffic, interference etc., at the time scales around milliseconds. The RAN controller handles the necessary coordination between multiple base stations for inter-cell interference cancellation (ICIC), CoMP transmission, joint RRM etc. as defined by the relevant 3GPP standards. This controller is able to communicate with those applications through northbound API to control the operation of the wireless interface. It will be able to perform different tasks related to RAN related enforcements based on the optimization problem that is managed by the MNO. Note that one RAN controller would serve several of eNodeBs (on the order of tens). For the management of applications running on top of RAN controller, resources of individual eNodeBs (and sometimes a group of eNodeBs) are allocated amongst UEs to maximize user throughput and quality-of-service (QoS) while minimizing interference of a flow to other flows nearby by the RAN Controller. For RAN resource monitoring, CQI from each active user is received by an eNodeB every transmission time interval (TTI) period. This feedback is then forwarded to the RAN Controller for further processing. RAN controller creates and dynamically utilizes the application elements in *application layer* by efficiently and fairly allocating resources according to the requirements MNO and QoS of each UEs. It also has the capability of establishing or modifying the usage of each access element in the *application layer* based on the demands of network.

In *infrastructure layer*, RAN controller controls the radio elements, the physical devices comprised of baseband processing and radio unit. RAN controller's main tasks include RRM, handover, interference management etc. and pushes relevant rule to eNodeBs using the southbound API. Such a layered architectural framework for *controller layer* can enable effective RRM and interference management as well as provide reliable QoS guarantees for the RAN part of a mobile cellular infrastructure provider.

There are several benefits of deploying this architecture compared to a distributed one where all the functionalities are deployed in each eNodeB. First of all, the centralized architecture can allow better optimization of network parameters as well as management of applications due to awareness of global view of the network infrastructure. Second, the processing power of eNodeBs are limited, hence a computation bottleneck can be created with the existence of each additional functionality into the access network element. Third, scaling issues can occur if the coordination between the eNodeBs need to performed in frequency time intervals. The main drawback of the proposed approach is the possibility of increase in signalling updates required for collecting the CQI values at each time for all participating users.

III. SAMPLE RAN APPLICATIONS OVER SDN/RAN CONTROLLER

In HetNets, RRM mechanisms have to avoid bandwidth segmentation among macrocells and smallcells as targeting to get the highest spectral efficiency. Because of this, frequency reuse has been set to one as in currently deployed cellular network architecture. However, this can introduce inter-cell interference issues. Under the consideration of that UEs are served by only one eNodeB, the process of associated eNodeB selection is based on the strongest downlink reference signal received power (RSRP). However, the large difference between the transmit power levels brings about load imbalance among macrocells and smallcells. LTE-A provides a solution to compensate the imbalance, adding a positive bias value called as range extension (RE) to low power nodes. Hence, more UEs are served by smallcell eNodeBs as depend on selected bias value. Cell range expansion (CRE) by a bias value is shown in Fig. 2.

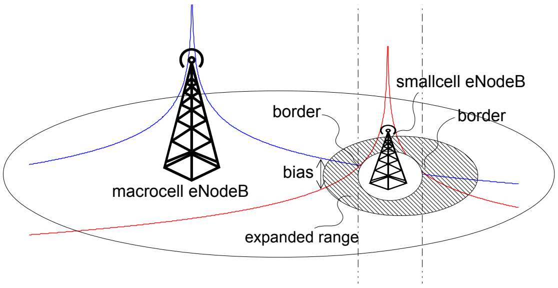


Fig. 2: CRE with bias value used in ABSF.

However, the bias value does not appear in signal transmissions hence, the UEs on the expanded cell range suffers from macrocell interference. In respect to this, a new standard approach, ABSF, has started to play a key role in the design of future networks. In the ABSF pattern concept, a bitmap is provided to every BS that indicates which TTIs must be blank per BS for no data transmissions. In summary, ABSF has mainly the following benefits: First, it allows co-existence of macro and smallcells in the same geographical area. Second, it increases the spectral efficiency of the network by managing the inter-cell interference amongst several macro-cells. ABSF is especially helpful for achieving an effective inter-cell interference mitigation when coping with the inter-cell interference coordination problem between macro and smallcell eNodeBs.

In each frame, RRM with the use of scheduling algorithms is one of the core components of medium access control (MAC) to optimize the system performance. In orthogonal frequency division multiple access (OFDMA), which is inserted into the physical layer of LTE-A for downlink direction, multiple access mechanism is based on sharing the resource blocks (RBs) among UEs. Each RB includes 12 subcarriers in which frequency spacing is 15 kHz. Under the consideration of that the length of cyclic prefix is equal to or longer than maximum delay spread of the channels, subcarriers do not effect each other and multiple access mechanism can be performed in both frequency and time without any interference. While allocating RBs to UEs, several scheduling algorithms (i.e., Proportional Fair (PF), Maximum Throughput (MT), Round Robin (RR)) can be considered and each one has different metric value and yields different performances with respect to considered key performance indicator (KPI). Therefore, Several RRM technique such as scheduler selection, parameter optimization etc. can be jointly performed under the consideration of the channel quality reports related to eNodeBs.

Another eICIC method that can be used for increased spectral efficiency as an application on top of RAN controller is CoMP. The basic concept of CoMP transmission is illustrated in Fig. 3. Cell-edge UEs suffer from the interferences created by the neighbor eNodeBs, thereby, the level of signal-to-interference-plus-noise ratio (SINR) decreases. It leads poor QoS and decrement on individual and overall data rates. In CoMP mechanism, the cell-edge UEs are served by two or more eNodeBs. The eNodeBs perform signal transmission and reception in a coordinated manner. Hence, the signal quality is improved. In summary, CoMP turns interference problem into beneficial signal for edge-cell users, while allowing cooperation with neighboring macrocell eNodeBs.

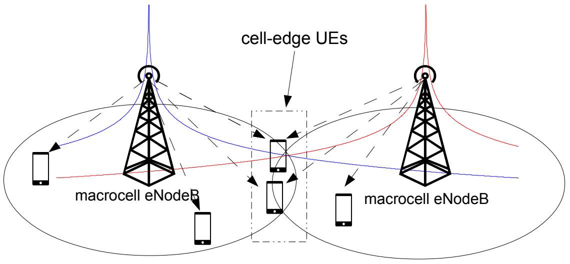


Fig. 3: CoMP transmission and reception mechanism.

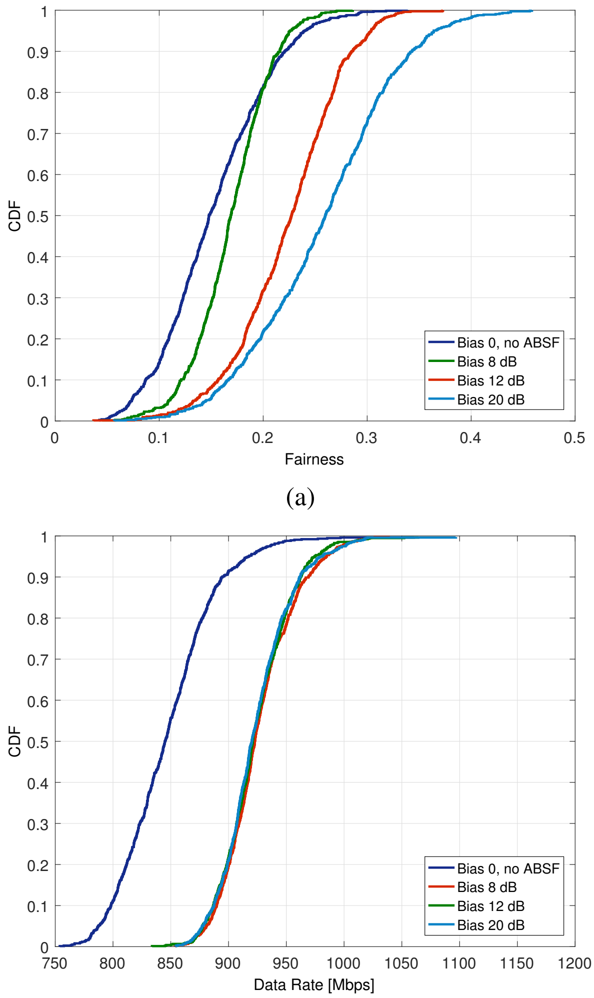
IV. PERFORMANCE EVOLUTION

In this section, we present the achievable data rate and fairness performances of the proposed centralized SDN-based RAN controller included cellular network topology for different RAN-optimized applications. The analyses are carried with respect to the different bias levels for smallcell range extension, ABSF to normal frames ratio, existence of CoMP mechanism and different scheduling algorithms. The simulation parameters defined in Table I where d denotes the distance between UE and eNodeB in km and it is assumed that perfect channel state informations (CSIs) are available at UE side and this information is perfectly transmitted to centralized RAN controller. The performance of ABSF mechanism is investigated in Fig. 2 with 500 UEs who are uniformly distributed under the consideration of one smallcell and one macrocell. On the other hand, we ignore smallcell eNodeB and consider the structures including two macrocell eNodeBs (see Fig. 3) with 250 UEs, while investigating the effect of CoMP mechanism. For calculating maximum achievable data rate and fairness of the different methods, we use Shannon's Capacity and Jain's fairness index.

TABLE I: Simulation parameters.

Macrocell eNodeB Power	46 dBm
Smallcell eNodeB Power	30 dBm
Noise Power Spectral Density	-179 dBm/Hz
Antenna Configuration	1x1
Terminal Speed	3 km/h
Carrier Frequency	2.0 GHz
The Number of RBs	100
Macrocell Path Loss Model	$128.1 + 37.6\log_{10} d$ [dB]
Smallcell Path Loss Model	$140.7 + 36.7\log_{10} d$ [dB]
The Number of Resolvable Path	7 (complex-Gaussian)
Shadowing (Macrocell)	Log-Normal (mean: 0, s.d.: 6 dB)
Shadowing (Smallcell)	Log-Normal (mean: 0, s.d.: 4 dB)

We first present the effect of different bias levels for smallcell range extension. While allocating RBs to UEs, PF scheduler is considered. In Figs. 4, the fairness and achievable data rate performances are presented with respect to different bias values for ABSF. Figures include the case without CRE and the cases with bias values of 8, 12 and 20 dB. During simulations, ABSF to normal frames ratio is set to $1:3$. As the bias value is increasing, more UEs are served by smallcell eNodeB since CRE becomes larger. These UEs are served without any interference from macrocell, fairness index is gradually improved as the bias level increases. When we turn to the data rate performance, significant improvement is achieved with the use of ABSF. However, changing the bias level does not lead to same improvement on data rate, since the signal power at UEs also exponentially decreases with distance.



(a)

(b)

Fig. 4: (a) Fairness and (b) data rate according to different bias values when ABSF to normal frames ratio is set to 1:3.

The effects of change in ABSF to normal frames ratio are shown in Figs. 5. The bias value is set to 6 dB in this case. The common trade-off between fairness and data rate terms exists in the comparison. Since ABSF does not include any interference from macrocell eNodeB, the signal qualities on expanded cell UEs are significantly improved. Therefore, when the ratio decreases, in other words, the number of ABSFs increases, the overall data rate is improved. However, imbalance on the number of UEs served in ABSF and the other UEs leads to lower fairness index as the frame ratio increases.

Jain's fairness index and Shannon capacity performances according to different ABSF ratio and selected bias value with the use of PF and MT schedulers are presented in Fig. 6. As the bias value is increasing, more UEs are served by smallcell eNodeB since CRE becomes larger. These UEs are served without any interference

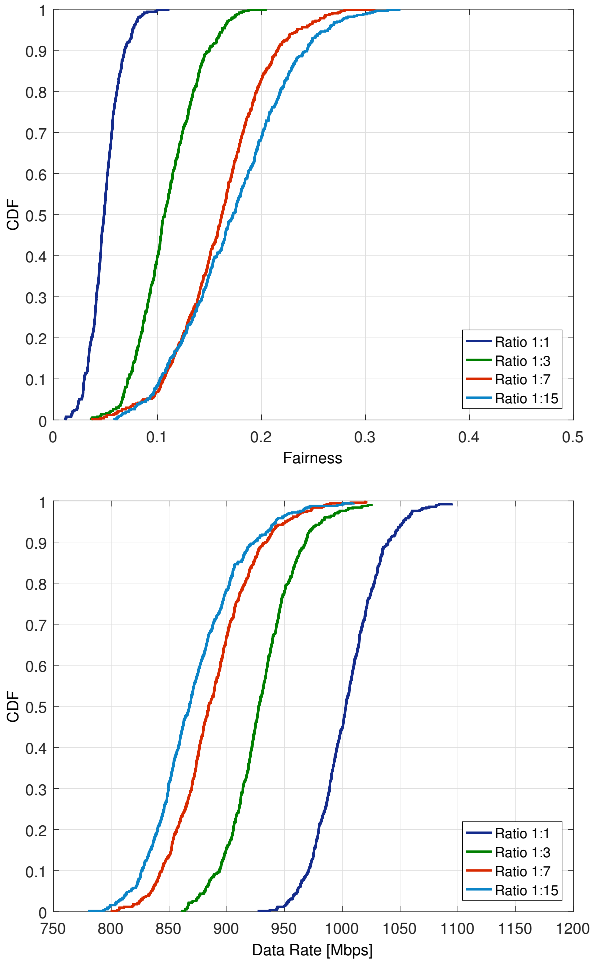
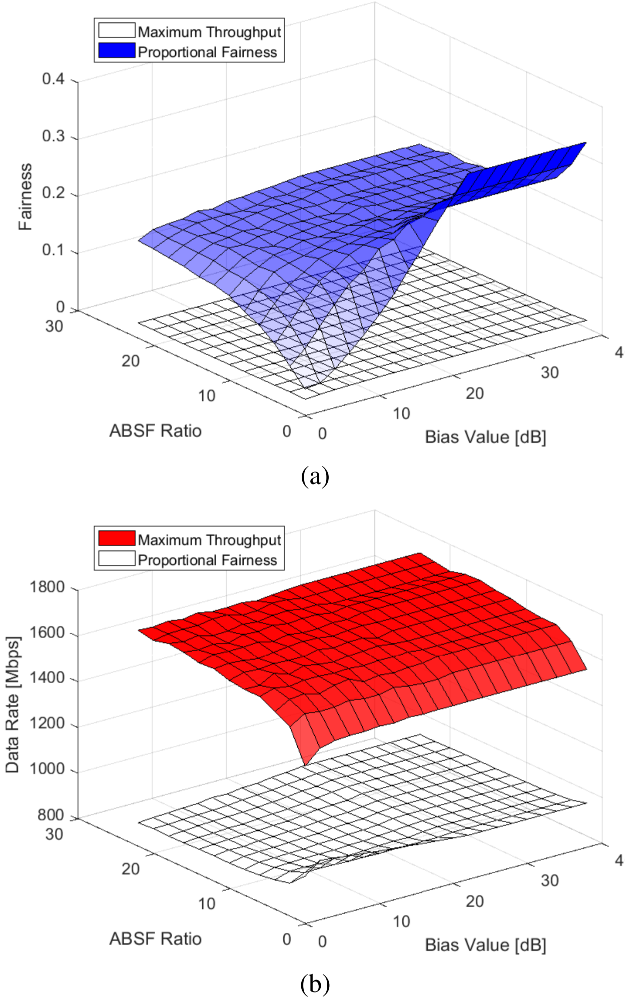


Fig. 5: Fairness and data rate according to different ABSF ratio for a bias value of 6 dB.



(a)

(b)

Fig. 6: (a) Fairness and (b) data rate performances according to ABSF ratio and bias value with the use of MT and PF.

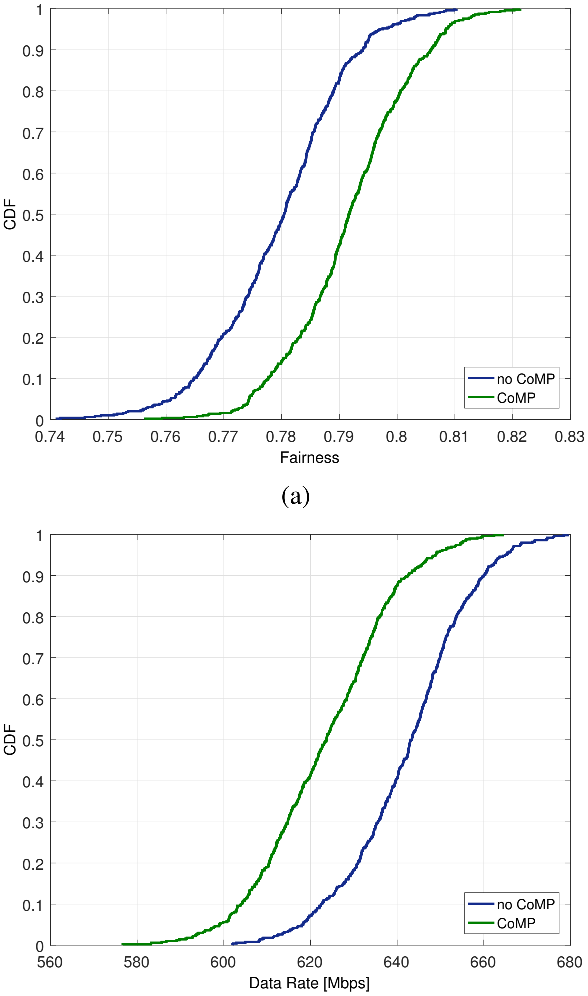
from macrocell, fairness index is gradually improved as the bias level increases for both scheduling algorithm. When PF scheduler is considered, as fairness index is gradually increasing, data rate reaches the optimum value with bias value of 4 dB and ABSF ratio of 2. However, after bias value exceeds 24 dB, changing the bias level does not lead to same improvement on data rate, since the signal power at UEs also exponentially decreases with distance. When we turn to performance of MT scheduler which aims to maximize system capacity via allocating more resources to UEs who have good channel quality, the bias value that saturates the performances is relatively less than PF scheduler's case. Additionally, since UEs who are closer to eNodeBs have more change to be allocated with resource, increasing ABSF ratio leads improvement on capacity value and decrement on fairness index.

The effect of CoMP mechanism is shown in Figs. 7. It can be seen that with the CoMP transmission and reception, the signal qualities of cell-edge UEs are improved, thereby, fairness index is increased. However, since more RBs are allocated to these UEs instead of UEs who have better channel quality, the total achievable data rate decreases.

The above results demonstrate that the designed algorithms of each RAN controller's application should work in cooperation with RAN controller and the southbound protocol of Fig. 1 for adjusting the RAN related parameters based on the desired optimal outcomes. Depending on the instruction sent by the application, RAN controller communicates with RAN equipments with special enabled functionalities using a new southbound protocol. For example, for ABSF, this southbound protocol needs to adjust bias and ABSF ratio values for maximum utility benefit depending on the selected metric (fairness, capacity, in our analysis). Moreover, this parameter readjustments over the southbound protocol also depend on the other applications such as selected scheduling algorithms performing resource allocation (e.g. PF or MT methods in our analysis). Therefore, devising a joint optimizing algorithms that can obtain appropriate RAN parameter settings for each multiple and correlated applications is utmost importance for obtaining maximum benefit in terms of network optimization and planning in RANs.

V. CONCLUSION

In this paper, a centralized RAN controller for heterogeneous cellular networks based on SDN paradigm is introduced and the architecture is modular and flexible to accommodate multiple RAN applications running on top RAN controllers. For an example use case, we have demonstrated the applicability of recent developments in



(a)

(b)

Fig. 7: The effect of CoMP mechanism on (a) fairness index and (b) data rate.

3GPP standards including eICIC and CoMP methods. Our simulation results demonstrate that the system data rate and fairness index are increased with the use of ABSF and the ratio of ABSF to normal frames has a trade-off between data rate and fairness terms under the consideration of different scheduling algorithms. We further provide a joint analyzes of them with different RRM techniques and we present the benefits of CoMP mechanism in terms of fairness index by serving cell-edge UEs.

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