Power Minimizing BBU-RRH Group Based Mapping in C-RAN with Constrained Devices

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Abstract—C-RAN presents an advanced mobile networking architecture that promises to tackle various challenging aspects of 5G such as increasing energy efficiency and providing high capacity. Indeed, C-RAN paves the way toward better energy efficiency by centralizing the baseband processing at cloud computing based servers (BBU pool). In this paper, we propose an RRH group based mapping (RGBM) that aims to minimize the power consumption at the BBU pool, while considering users’ QoS and BBU capacity constraints. To achieve this, the proposed scheme uses two key steps: i) the formation of RRH groups aimed at improving the QoS of weak users, ii) the formation of RRH cluster to be mapped for minimal number of BBUs requirement. The proposed scheme uses an efficient greedy heuristic to solve the optimization problem. The performance of the proposed approach was evaluated using simulations, which indicate a significant gain in terms of BBU minimization, power reduction and energy efficiency, while preserving QoS constraints, against well studied legacy solutions.

Index Terms—C-RAN, BBU minimization, QoS, Energy Efficiency, Clustering.

I. INTRODUCTION

Cloud-Radio Access Network (C-RAN) concept has been recognized as one of the promising technologies adopted by the fifth generations (5G) of mobile networks. In C-RAN architectures, the baseband resources, that used to be distributed in legacy RANs, are pooled at baseband processing units (BBUs) situated at a remote central office. A BBU pool serves a particular area with a number of radio remote heads (RRH) for centralized signal processing and management [1]. In comparison with distributed radio base station architecture, C-RAN has the potential of providing valuable benefits for mobile networks operators (MNOs) [2], [3]. Particularly, it promises an improved utilization efficiency of the infrastructure resources by capitalizing on traffic peak diversity. Energy efficiency can also be improved by assigning many RRHs to one BBU, so that the number of simultaneous active BBUs is reduced.

Despite these promising benefits, there are many challenges such as designing efficient RAN resource allocation schemes that can balance the trade-off between reducing costs while meeting the quality of service requirements of a specific service [4], [5]. Also, when it comes to re-designing of these schemes, hybrid nature of resources at the C-RAN (RRH radio element and computation BBUs) must be considered.

Several research efforts have been carried out to address the aforementioned challenges [6], [7], [8], [9]. In the previous works, particular focus has been given to the BBU minimization problem, when mapping baseband processing workload from RRHs, by setting dynamically an optimal number of a BBU to support the traffic load. Indeed, increasing the number of BBUs above the requirement hinders the energy efficiency and leads to unnecessary interference between BBU clusters. Whereas, allocating too few BBUs would lead to resource shortage and affects the users QoS. In most research works, this problem has been formulated as a bin packing minimization (BPM) and solved via heuristic [10], [11] or meta-heuristic [12] approaches. The majority of works solved the problem with legacy BPM which accounts only for the per BBU capacity as a constraint [8], [10], [11], [12]. Although such approaches proved to be efficient for minimizing the active number of BBUs, and power consumption, however, they do not consider the user QoS requirement. Recent research works undertook steps toward inclusion of QoS constraint by formulating the problem to modified BPM or through set partitioning problem (SPP). In research work [8], it was solved by a modified BPM after adding a constraint that implies mapping contiguous RRHs to the same BBU. Catering to QoS while minimizing the number of BBUs has also been considered in [9], which formulated the problem to a QoS aware SPP, while considering a BBU capacity that varies as a function of interference.
We propose an RRH groups based mapping (RGBM) approach that caters not only for interference level/ QoS requirement and the maximum available resources in the system but also for the improvement of QoS for weak users. The objectives of our RGBM approach are two fold: i) the improvement of throughput for users experiencing bad radio conditions while meeting a minimal required throughput for all users in the network, and ii) the minimization of number of BBUs units aiming to reduce power consumption and increase the spectral efficiency, while maintaining the minimal throughput required for users. Particularly, it applies to the case of constrained devices. To achieve this objective, the scheme relies on the formation of cooperative RRHs groups [15][16][17][18], where RRHs groups are first formed to bring throughput improvement for weak users [18]. Then, RRHs clustering formation is done with mapping consideration to decrease the number of BBUs units at the pool level without violating the minimum user QoS demands. 

The remaining paper is organized as follows: In Section II, we introduce the system model whereas in section III, we describe our RGBM approach. In section IV, we formulate the RGBM mapping problem. Section V provides the devised algorithm to solve the the RGBM. Performance evaluation of our proposal by simulations is discussed in section VI. Section VII concludes the paper.

II. SYSTEM MODEL

We consider a C-RAN system composed of a set of N distributed RRHs, \( R \) where, \( R = \{r_1, r_2, ..., r_N\} \), connected to a BBU pool through high performance links, for centralized baseband processing and resource block scheduling tasks. We also consider that RRHs grouping for the improvement of weak users forms the set of groups \( G = \{g_1, g_2, ..., g_b\} \). The set of formed cluster is denoted \( B = \{b_1, b_2, ..., b_n\} \). These clusters are mapped according to a one by one association relation to a set of baseband units at the pool level. Within one cluster, members are RRHs groups including singleton RRH groups. Given this relation, for all \( i \neq j; b_i \cap b_j = \phi \), and \( \bigcup_{r \in R} r = R \). The radio resource allocation and RRH-BBU mapping of our considered C-RAN model according to the following assumptions:

- RRHs are uniformly distributed over network with equal transmission power and bandwidth, while UEs are randomly distributed over RAN and their association to RRHs is based on the highest received power condition.
- Initially all RRHs start operating with a frequency reuse of 1. Then, the scheme relies on attributing the DAS behaviour to formed groups and then cluster formation.
- In more details, attempts for bandwidth sharing are first considered among small scale groups, which consist of cooperative RRHs following the RRH group formations steps, then for larger scale groups, which are composed of RRHs cluster (BBU units), during the clustering formation procedure. We also consider joint transmission co-

ordinated multi-point (JT-CoMP) and Transmission-Point Selection (TP-Selection), which are employed among a group of RRHs associated to a single BBU for serving weak and normal users, respectively.

- RRH group formation must result in improvement of radio conditions and throughput for weak users, while keeping an acceptable throughput for normal users. To measure the improvement of formed group’s throughput, we refer to two performance indicator denoted \( \kappa \) and \( \chi \). \( \kappa \) is a group performance indicator used to measure the efficiency of each group, where \( \kappa(g) \) is the increase in throughput of a group g. \( \chi \) is an individual performance indicator for all RRH part of groups, where \( \chi(r) \) denotes the increase of throughput resulting from the coalition for users associated to RRH r.

III. RRH GROUP BASED MAPPING

In this section, we describe the details of our proposed approach: RGBM. RGBM comprises two steps, which are described here.

A. Cooperative RRH group formation

The RRH selection phase starts by identifying all weak users. A weak user is a user that is experiencing a signal to interference and noise ration (SINR) below a fixed threshold \( T_{sinr} \). For every weak user \( u_a \) which is initially being associated to an RRH \( r_a \), a list of the most interfering neighboring RRHs will be considered first for the formation of an RRH group (coalition aiming to help this user), denoted as \( g_a \). The first most interfering neighboring will be considered as a candidate to form \( g_a \). If the RRH grouping conditions with respect to the minimal required throughput are not met for other users, the next most interfering RRH \( r_b \) is checked. If it meets the group formations conditions and order, the later will form a group for \( u_a \), \( g_a = \{r_a, r_b\} \).

In another case, if a weak user \( u_c \) finds its most interfering \( RRH_g \) already part of a group, and the condition for group formation is met, then, its associated \( RRH_g \) join the existing group \( g_a \). Hence, the group size increases with more member RRHs, \( g_a,c = \{r_a, r_b, r_c\} \) to help the two weak users.

The group formation condition ensures that the throughput of non-weak users does not drop below a threshold. Also the order of group formation stipulates that in the case where a given RRH \( r_k \) encounters two different possibilities for joining two different groups \( g_l \) and \( g_k \), and if \( \kappa(l) > \kappa(k) \), then \( g_l \) is privileged. On the other hand, individual network gains \( \chi(l) \) and \( \chi(k) \) are only examined if \( \kappa(l) = \kappa(k) \)

B. RRH cluster formation

By following previous steps, small cooperative RRH groups are formed, sharing the same bandwidth while bringing better radio resource conditions to weak users through coordinated multi-point (CoMP) and ensuring acceptable overall radio conditions for remaining users. The second step is the formation of clusters of RRHs groups to be associated according to the
one by one relation to BBU. This step aims to minimise the number of BBU, while preserving the gain in throughput obtained from the RRH group formation and meeting the minimal throughput requirement for all users present in the network. Indeed, it aims to extend the DAS behaviour by allowing larger groups (cluster of RRHs groups) association to a single BBU and share the whole bandwidth $B_b$ with no intra-cluster interference. However, inter-cluster interference is experienced by users associated to RRHs belonging to different clusters mapped to different BBUs.

IV. PROBLEM FORMULATION

The mathematical problem formulation of our RGBM is provided below.

A. Throughput

The throughput of all users must increase after group formation. Let $u_c$ be a weak user connected to $r$ then its SNIR on resource block $rb$ can be expressed as:

$$\Gamma_{r,b}^{rb} = \log_2\left(1 + \frac{P_t r c, e, h_{e,r,rb}}{\sum_{r' \in R, r' \neq r} P_t c, e, r', h_{e,r',rb} + N_0}\right)$$  

(1)

Here, $P_t r$ is the fixed transmission power of connected RRH $r$, $l_{e,r}$ is the path loss between user $u_e$ and RRH $r$ and $h_{e,r,rb}$ is the small-scale fading between RRH $r$ and user $u_e$. $N_0$ is a fixed noise power on the network. The first term on the denominator is the overall interference from every other neighbor neighborhood RRHs $r$. The throughput of user $u_e$ connected to RRH $r$ is:

$$Th_{e,r} = B_0 \log_2(1 + \Gamma_{e,r}^{rb})$$  

(2)

where, $B_0$ is the sub-channel bandwidth. The RRHs part of a group would use JT CoMP for simultaneous transfer of RBs to the connected weak user. The objective is to improve the weak users and overall network throughput with energy efficiency maximization by forming cooperatives groups among RRHs. The weak user $u_e$ would be associated to an RRH $r_e$ and it forms a group $g_e$ with set of neighboring RRHs, $r'$. Assuming that the different RRHs are synchronized, the improved SNIR of $u_e$ after group formation is [20]:

$$\Gamma_{n,g}^{rb} = \log_2\left(1 + \frac{\sum_{r \in g} P_t r c, e, j, h_{e,j,rb}}{\sum_{r' \in g', g' \neq g} P_t c, e, r, h_{e,r,rb} + N_0}\right)$$  

(3)

Here, the nominator represents the total power and gain of all members of a group $g$, while the first term of the denominator shows the total power and gain of every other interfering RRHs (singleton or group). Similarly, the throughput of weak user $u_e$ after group formation is:

$$Th_{n,g} = B_0 \log_2(1 + \Gamma_{n,g}^{rb})$$  

(4)

The SNIR and throughput of normal users part of a group $g$ are defined as:

$$\Gamma_{n,g}^{rb} = \log_2\left(1 + \frac{\sum_{r \in g} P_t r c, e, j, h_{e,j,rb}}{\sum_{r' \in g', g' \neq g} P_t c, e, r, h_{e,r,rb} + N_0}\right)$$

(5)

We assume that initially the bandwidth allocated to each RRH is $B_g$ and upon the group formation procedure, RRHs, which are part of the same group would share the same bandwidth $B_g$. We further consider that given $B_g$ there are a number $RB_g$ of available resource blocks per TTI assigned to all users within the same group, $U_g$. And, the cumulative throughput of a group $g$ is:

$$Th_{u_g} = \sum_{u_e \in U_g} \sum_{rb \in RB_g} Th_{n,g}^{rb}$$

(6)

where $Th_{u_g}^{rb}$ is:

$$Th_{u_g} = \begin{cases} Th_{e,g}^{rb}, & \text{The user is a weak user.} \\ Th_{n,g}^{rb}, & \text{otherwise.} \end{cases}$$

(7)

We refer to a binary variable $x_{b,g}$, which determines the association of a group to a BBU, expressed as:

$$x_{b,g} = \begin{cases} 1, & \text{if group } g \text{ is associated to BBU } b. \\ 0, & \text{otherwise.} \end{cases}$$

(8)

The throughput processed by a cluster $b$ is defined as:

$$Th_b = \sum_{g \in G} x_{b,g} Th_{u,g}$$

(9)

B. Power Calculation

We consider a power consumption at the BBUs that varies linearly as a function of the load processed in terms of offered throughput. The power consumed at one BBU $b$ is:

$$PC(b) = \tau + \mu Th(b)$$

(10)

Here, $\tau$ is the minimum power consumption by active BBU $b$ with no traffic, and $\mu$ is coefficient varying with $Th(b)$.

C. Utility Function

The optimization utility function for cluster formation targets the power consumption minimization at the BBU pool, while guaranteeing the minimum required throughput for all users. That said, our optimization problem is formulated as follows:

$$\text{Minimize}(UT) = \sum_{b \in B} PC(b)$$

(11)

where

$$y_b = \begin{cases} 1, & \text{if cluster } b \text{ is chosen.} \\ 0, & \text{otherwise.} \end{cases}$$

(12)

subject to:

$$\sum_{b \in B} y_b x_{b,g} = 1$$

(13)

$$\forall b, RB_g \geq \sum_{g \in b} y_b RB_g$$

(14)
C3: \[
Th(b)/N_b > Th_{min}
\] (15)

Here condition C1 reflects that a group g is mapped to only one cluster b. Condition C2 guarantees that the number of resource blocks available at a BBU b is higher or equal than the sum of required resource blocks of each group g mapped to BBU b. Condition C3 ensures that the number of users \(N_b\) processed by the same cluster b, must satisfy the minimum throughput threshold. \(G\) is set of group of RRHs = \(\{r_1,..r_m\},\{r_p,..r_q\}\) after following group formation conditions.

V. RGBM SOLUTION ALGORITHM

The problem formulated in the previous section belongs to the integer linear integer linear programming (ILP) class and is NP-Hard. To find a low complexity solution, we make use of an efficient greedy approach for our RRHs group based mapping. The proposed solution is given by Algorithm 1 where inputs are: the set of groups \(G\), the number of user at each group \(U_g\), the number of used resource blocks by each group and the number of resource blocks available at each cluster \(R_c\). At each iteration, an RRH group that minimizes the utility function \(UT\) is only added to currently filled cluster \(b\), if it meets C2 and C3 constraints.

**Algorithm 1:** RRHs groups-BBU Mapping

| Inputs: RRH groups |
|-------------------|
| \(G = \{g_1, g_2, \ldots, g_n\}\), \(U_g\), \(RB_g\), \(RB_c\) |
| Outputs: Set of optimal clusters \(B\) AND \(BBU_r\) |
| Initialization: \(G_{unmapped} = G\) and \(B = \emptyset\); |
| while \(G_{unmapped} \neq \emptyset\) do |
| Map first group \(g_1\), \((B \cup \{g_1\})\) AND set \(b = \{g_1\}\); |
| Update: \(Queue = G - g_1\) AND \(G_{unmapped} = g_1\); |
| while \(Queue \neq \emptyset\) do |
| Choose \(g_i\), such that \(UT(B \cup \{g_i\})\) is minimal; |
| if \(C2\) and \(C3\) are satisfied then |
| \(b = b \cup g_i\), AND \(Queue = G - g_i\); |
| Update: \(Sum(RB_g)\) AND \(Sum(U_g)\); |
| else |
| \(Queue = G - g_i\); |
| end |
| end |

VI. SIMULATION AND PERFORMANCE EVALUATION

A. Simulation Setup

In this section, we evaluate the performance of our proposed RRH grouping based Mapping solution by comparing it to the state-of the art bin packing minimization (BPM) based mapping and to the conventional One-To-One (OTO) mapping. Simulations are conducted on MATLAB, considering a C-RAN comprising 19 RRHs, each one at the center of a hexagonal cell. We also considered that users have uniform distribution and accounted for different users densities.

In order to provide a clear view on the performance of our proposed solution, we consider different performance metrics for comparison: number of required BBUs, total power consumption, average users’ throughput and energy efficiency. Also, we consider the same number of RBs per BBU, for the two capacity aware RRH-BBU Mapping. Table 1 summarizes the parameters used in the simulations.

| Description                                      | Value          |
|--------------------------------------------------|----------------|
| Frequency                                        | 2.14 GHz       |
| No. of RRHs                                      | 19             |
| No. of users per RRHs                            | Different densities [2-18] |
| Transmission power                               | 20 Watt        |
| Receiver height                                  | 1.5 meters     |
| Transmitter height                               | 32 meters      |
| Maximum antenna gain (Tx)                       | 17 dBi         |
| No. of Tx antennas                               | 2              |
| No. of Rx antennas                               | 2              |
| LTE mode of transmission                         | CLSM           |
| Propagation Channel model                        | Typical Urban (TU) |
| Scheduling Scheme                               | Fair Resource Sharing |
| Shadow fading                                    | Claussen       |
| Bandwidth                                        | 20 MHz         |
| Receiver noise figure                            | 9 dB           |
| Thermal noise density                            | -174 dBm/Hz    |
| Throughput Threshold \((Th_{min})\)              | 2 Mbps         |
| \(\tau\)                                        | 50 W           |
| \(\mu\)                                         | 0.6            |

B. Simulation Results and Discussion

Figure 1 compares the number of required BBUs for the average number of UEs per RRH. As shown in the figure, the one by one mapping exhibits highest number of BBUs, which is directly linked with total number of RRHs in the network. Our RGBM solution exhibits the lowest number of BBUs required for all user densities, followed by the BPM based Mapping. This behaviour is considerably accentuated as the number of average UEs per cell increases. Interestingly, for high user densities > 14 UEs/cell the BPM reaches its gain limit by activating all BBUs same as the OTO. On the other hand, the proposed scheme succeeds to maintain a considerably lower number of BBUs. The better performance comes from the fact that the proposed scheme combines two essential features impacting directly the optimization of number of active BBUs. The first is its interference aware nature that tends to maximize the number of RRHs groups belonging to a same BBU (DAS), to cancel their potentially mutual interference outside a DAS. The second is the capacity aware optimization, which is similar to the bin packing minimization nature (in the sense that it considers the maximum capacity imposed by the system bandwidth on each BBU). The RRH based grouping established prior to the clustering/Mapping fosters drastically
the capability of the two features to minimise the number of BBUs. In fact, in our proposal, RRH groups are a set of highly interfering nodes which trivially consolidates the interference aware behaviour, leading to fewer BBUs with the aim of achieving no intra-cluster interference between these nodes. It also uses the optimality of the bin packing minimization-like behaviour due to the creation of larger inputs granularity [21].

Figure 2 shows the induced BBU pool power consumption for each of the mapping schemes. We recall that in our adopted BBU pool power consumption model, the power consumed by each BBU depends linearly on the aggregated throughput processed by given BBU and the total power consumption increases with the increase in number of BBUs. Simulation results displayed in this figure are aligned with this model. Indeed, for the BPM as well as for our RGBM, as the number of UE increases, the total power consumption increases. This is due to the activation of more BBUs for both schemes, where RGBM activating comparatively less BBUs and consuming less power. Analyzing results from Figure 1 and Figure 2, we can deduce that at low user densities, where only a few number of BBU are active, the lowest power consumption achieved by our scheme compared to the BPM is mainly impacted by the higher processed throughput by each of these active BBUs. This directly emanates from the interference aware behaviour of the proposed scheme, that tends to maximize the number of RRHs within each BBU. As the number of users increases, the significant difference in terms of used BBUs prevails. It is noted that for the OTO mapping, which is a non adaptive approach, each RRH is assigned to a BBU operating with the maximal power, that justifies the fixed power consumption.

Figure 3 depicts the average throughput per user as a function of the number of UEs per cell. As shown in the figure, OTO, where no optimization is applied to minimize the number of BBU, this metric decreases as the number of UEs per cells decrease. On the other hand, for the two BBUs minimization based mapping schemes, the metric experience
some fluctuation as both schemes tend to minimize the number of active BBUs required to map a given radio load. They increase the BBU spectral reuse by allowing more users to share the bandwidth which comes at the cost of a decrease in their average throughput. Nevertheless, both schemes succeed to maintain an average throughput equal or higher than the required minimal throughput. The higher average throughput obtained with BPM is justified by the activation of a higher number of BBUs to support the same load conditions.

Figure 4 shows evaluation of the mapping schemes capability to ensure trade-off between acceptable throughput and power consumption. Results with respect to the energy efficiency metric shows, OTO is least energy efficient due to its extreme power consumption. As for optimized mapping schemes, they show competitive results for low user density. The energy efficiency gain of the proposed scheme is maintained for scenario of medium and high user density. The proposed scheme achieves a distinctive trade-off between ensuring low power consumption and acceptable throughput for medium users densities as well.

It is worth noting that the minimization of the number of required BBUs does not only impact the overall power consumption and the overall energy efficiency on the C-RAN but also creates less overhead in the front-haul of the network, since groups are formed in a distributed way and the information required for cluster formation would only be sent per group instead of per RRH.

VII. CONCLUSION

C-RAN has helped in realization of next generation communication evolution and it will remain one of the important pillars for 5G and beyond. However, C-RAN architecture has its inherent challenges and energy efficient use of BBUs is one of the key issue of C-RAN. In our solution, the use of BBUs is optimized by forming clusters after choosing optimal groups of RRHs, based on QoS requirements of weak users. Also BBU capacity and energy constraints are considered which provides us better clusters that are then linked to BBUs. Our solution performs better when compared with other approaches in terms of the overall energy efficiency of the network, which is clear from presented results as well. The presented work provides a foundation which can be enhanced into more complex environment in future for more elaborate scenarios and performance analysis.

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REFERENCES

[1] J. Wu, Z. Zhang, Y. Hong and Y. Wen, “Cloud radio access network (C-RAN): a primer,” in IEEE Network, vol. 29, no. 1, pp. 35-41, Jan.-Feb. 2015.
[2] A. W. Dawson, M. K. Marina and F. J. Garcia, “On the Benefits of RAN Virtualisation in C-RAN Based Mobile Networks,” 2014 Third European Workshop on Software Defined Networks, London, 2014, pp. 103-108.
[3] F. Marzouk, R. Alhejro, J. Rodriguez, and A. Radwan, “Perspectives for 5G Network Sharing for Mobile Small Cells,” Broadband Communications, Networks, and Systems, Faro Portugal, 2018, Pages 377-386
[4] R. Wang, H. Xu and X. Yang, “Potentials and Challenges of C-RAN Supporting Multi-RANs Toward 5G Mobile Networks,” in IEEE Access, vol. 2, pp. 1187-1195, 2014.
[5] H. Dahrouj, A. Douik, O. Dhifallah, T. Y. Al-Naffouri and M. Alouini, “Resource allocation in heterogeneous cloud radio access networks: advances and challenges,” in IEEE Wireless Communications, vol. 22, no. 3, pp. 66-73, June 2015.
[6] M. Y. Yazidi, L. Giapponi, J. Manguex-Baflaylu, N. Aitsaadi and R. Langar, “ A Novel Optimization Framework for C-RAN BBU Selection Based on Resiliency and Price,” 2017 IEEE 86th Vehicular Technology Conference (VTC-Fall), Toronto, ON, 2017, pp. 1-6.
[7] M. Y. Yazidi, N. Aitsaadi and R. Langar, “Dynamic resource allocation for Cloud-RAN in LTE with real-time BBU/RRH assignment,” 2016 IEEE International Conference on Communications (ICC), Kuala Lumpur, 2016, pp. 1-6.
[8] K. Boulos, M. El Helou and S. Lahoud, “RRH clustering in cloud radio access networks,” 2015 International Conference on Applied Research in Computer Science and Engineering (ICAR), Beirut, 2015, pp. 1-6.
[9] K. Boulos, M. E. Helou, M. Ibrahim, K. Khawam, H. Sawaya and S. Martin, “Interference-aware clustering in cloud radio access networks,” 2017 IEEE 6th International Conference on Cloud Networking (CloudNet), Prague, 2017, pp. 1-6.
[10] T. Sigwele, A. S. Alam, P. Pillai, and Y. F. Hu, “Evaluating Energy-Efficient Cloud Radio Access Networks for 5G,” in 2015 IEEE International Conference on Data Science and Data Intensive Systems, 2015, pp. 362–367.
[11] H. Guo, K. Wang, H. Ji, and V. C. M. Leung, “Energy saving in C-RAN based on BBU switching scheme,” in 2016 IEEE International Conference on Network Infrastructure and Digital Content (IC-NIDC), 2016, pp. 44–49.
[12] M. Qian, W. Hardjawana, J. Shi, and B. Vucetic, “Baseband Processing Units Virtualization for Cloud Radio Access Networks,” IEEE Wirel. Commun. Lett., vol. 4, no. 2, pp. 189–192, Apr. 2015.
[13] H. Taleb, M. El Helou, K. Khawam, S. Lahoud and S. Martin, “Centralized and distributed RRH clustering in Cloud Radio Access Networks,” 2017 IEEE Symposium on Computers and Communications (ISCC), Heraklion, 2017, pp. 1091-1097.
[14] Akhtar T., Politis I., Kotsopoulos S. (2019) Wireless Channel Characterisation over Simulations for an Indoor Environment at 2.4 GHz. In: Susacas V., Mantas G., Althumait S. (eds) Broadband Communications, Networks, and Systems. BROADNETS 2018. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, vol 263. Springer, Cham.
[15] P. Georgakopoulos, T. Akhtar, I. Politis, C. Tsiloi, E. Markakis and S. Kotsopoulos, “Coordination Multipoint Enabled Small Cells for Coalition-Game-Based Radio Resource Management,” in IEEE Network, vol. 33, no. 4, pp. 63-69, July/August 2019.
[16] T. Akhtar, I. Politis, P. Georgakopoulos and S. Kotsopoulos, “Efficient Radio Resource Management Scheme in Cooperative Network using Coalition Game,” 2019 IEEE 24th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD), Limassol, Cyprus, 2019, pp. 1-6.
[17] P. Georgakopoulos, T. Akhtar and S. Kotsopoulos, “On Game Theory-Based Coordination Scheme for Multi Small Cells,” 2019 IEEE 24th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD), Limassol, Cyprus, 2019, pp. 1-5.
[18] P. Georgakopoulos, I. Politis and S. Kotsopoulos, “Considering CoMP for efficient cooperation among heterogeneous small cells in 5G networks,” 2018 IEEE 23rd International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD), Barcelona, 2018, pp. 1-6.
[19] J. Rodriguez, et al. “SECRET— Secure Network Coding for Reduced Energy next Generation Mobile Small Cells: A European Training Network in Wireless Communications and Networking for 5G.” In 2017 Internet Technologies and Applications (ITA), 329–333. IEEE, 2017.
[20] S. Zhan and D. Niyato, “A Coalition Formation Game for Remote Radio Head Cooperation in Cloud Radio Access Network,” in IEEE Transactions on Vehicular Technology, vol. 66, no. 2, pp. 1723-1738, Feb. 2017.
[21] W. Leinberger, G. Karypis and V. Kumar, “Multi-capacity bin packing algorithms with applications to job scheduling under multiple constraints,” Proceedings of the 1999 International Conference on Parallel Processing, Aizu-Wakamatsu City, Japan, 1999, pp. 404-412.