Coordination Multipoint Enabled Small Cells for Coalition-Game-Based Radio Resource Management

Panagiotis Georgakopoulos, Tafseer Akhtar, Ilias Politis, Christos Tselios, Evangelos Markakis, and Stavros Kotsopoulos

Abstract

Fifth-generation networks are becoming a reality, and radio access network architectures are being redefined and rebuilt to accommodate the emerging specifications and demands. The future radio access networks need to incorporate in their architectural design smooth reconfigurability and high flexibility without compromising the throughput and the perceived quality of the new services and traffic types that future networks introduce. Such densely distributed access networks suffer the effect of inter-cell interference. Robust and intelligent coordination of multiple access networks is required in order to minimize the effect of interference and maximize users' gains. Coordinated multipoint operation is already considered as a promising technique for satisfying the challenges of the spectrum and interference management, especially for users at the edge of the cell coverage area. To increase the benefits of coordination multipoint technology in optimizing service quality in dense small cell networks, this study proposes the adaptation of game theory, which will optimize the formation of cooperated base station clusters. The system-level simulations performed indicate that there is a significant increase in the throughput of users located at the edge of cells, without compromising the quality of service experienced by the rest of the users, thus rendering it a suitable candidate for the emerging next-generation networks.

Introduction

It is evident nowadays that the evolution of networking architectures and communication paradigms is being driven by the ever-expanding needs of mobile users for high-quality rich media, and the ubiquity and optimum exploitation of their devices' capabilities. Toward this end, fifth generation (5G) networks and services are forming the platform for cultivating and growing the demanding requirements for high levels of user experience by adopting redesigned network access architectures that incorporate and realize the principles of high network availability, efficient and low energy wireless connectivity, and high data rates independent of the networking context (i.e., urban or rural, indoors or outdoors, environmental conditions, type of device, access technology, etc.). With the launching of the new pilots and prototypes of 5G architectures currently underway, it is noted that the use case deploying highly dense heterogeneous small cells in order to optimize the access network capacity and radio resource allocation to large numbers of mobile users is the focal point of most studies [1-3]. Moreover, these future wireless prototype architectures are characterized by heterogeneous access technologies (i.e., 3G, 4G, 5G, etc.) and hybrid wireless cell types (i.e., macro, pico, and small cells).

The cloud is already anticipated to be the cornerstone of 5G deployments, and as such, the cloud radio access network (C-RAN) [4] is considered as a key enabler for efficient baseband processing over the cloud. Nowadays, the radio industry approach is to centralize the baseband units into baseband clusters, namely C-RAN, but it can only be applied to a limited, local geographical area. While C-RAN can provide benefits of centralization without the need for a total rebuild of the transport network, there are still unresolved issues such as coordination among different network elements. In this respect, Ericsson has proposed the use of elastic RAN [5]. Elastic RAN is envisaged to enable the coordination of all the baseband units across the entire network. Unlike traditional C-RAN deployments, where all basebands must be centrally located, elastic RAN supports tight coordination between adjacent sites connected by fiber with distances typically found in dense urban deployments. Since each site coordinates with all its neighbors in a fully peer-to-peer relationship, the area that can ultimately be coordinated is limited only by the area that the operator needs to support by implementing elastic RAN. Within the European research space, the H2020 5G Public Private Partnership (5G PPP) project SESAME [6] is aiming to extend the network functions virtualization (NFV) approach toward the placement of network intelligence and applications in the network edge through NFV proposing the cloud-enabled small cell (CESC) concept, which integrates a virtualized execution platform for deploying virtualized network functions (VNFs). At the same time, the H2020 5G PPP project SUPERFLUIDITY [7] is developing a decomposition of network components and services into elementary and reusable primitives for the virtualization of radio and network processing tasks permitting reuse of network functions across

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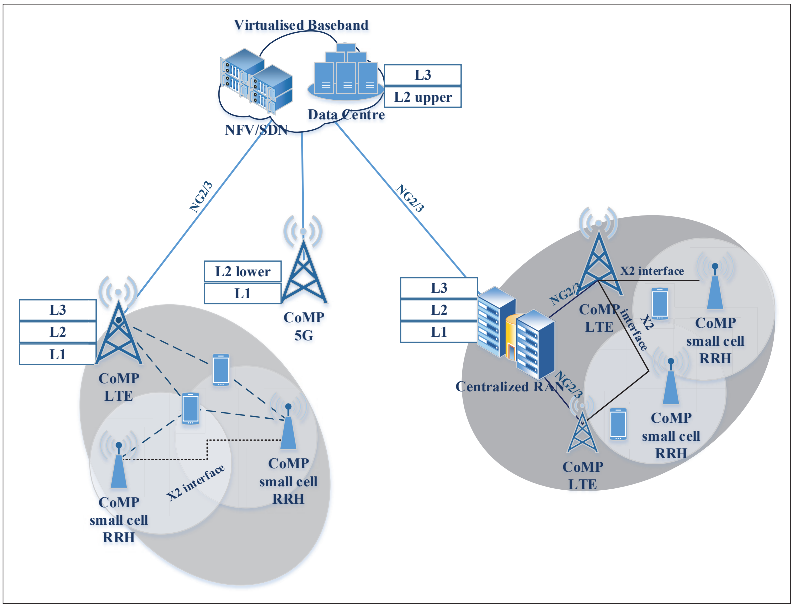

FIGURE 1. SONNET architectural vision for self-organized CoMP small cells.

heterogeneous hardware platforms and high-performance software optimizations along with leveraging of hardware accelerators.

Future heterogeneous wireless networks are required to combine low-power small cells (i.e., relay nodes, picocell, femtocell, and remote radio head, RRH) in the coverage area of a microcell. Although such an architecture can increase the overall throughput, it also enlarges the inter-cell interference zone due to differences in the transmission power. The Third Generation Partnership Project (3GPP) has proposed LTE-Advanced along with coordinated multipoint (CoMP) to mitigate the problem [8]. CoMP-based transmission and reception are considered as a tool to improve coverage, increase the throughput of cell edge users, and, as a result, the overall system efficiency. There are different modes of operation of CoMP, ranging from interference avoidance mode (coordinated beamforming and scheduling) to the more complex diversity gain mode, where the same data is transmitted from multiple cell sites. At the core of its operation, a CoMP enabled network allows geographically separated base stations (BSs) to cooperate in serving users. Specifically, mobile devices at the cell edge are in principle able to receive signals from multiple neighboring cell sites, while their transmitting signals can equally be received at multiple cell sites. Evidently, coordination among the different cell sites would benefit both the mobile device at the cell edge by allowing it to be served by different transmission points at the same time and the access network by avoiding cell edge users overloading already congested neighboring cell sites. Additionally, CoMP provides the means to mitigate the problem of inter-cell interference by coordinating the BSs to schedule and transmit data, at the cost of increased complexity and signaling overhead.

In the 5G era, C-RAN and CoMP should be considered as enablers for heterogeneous small cell networks to increase the coverage of cellular networks and improve their capacity by efficiently coordinating all the transmitting nodes. The future wireless access network, however, needs to be more complex and elaborative in order to satisfy the emerging service requirements. The array of enabling technologies will have to expand, involving among others, virtualization, new frequency bands, and improved context awareness. The aim of this article is to address the 5G inherent challenge of ensuring a high level of user perceived quality of service (in terms of user signal-to-interference-plus-noise ratio, SINR, and throughput) by minimizing the interference of neighboring small cells. This is achieved by investigating a game theoretic CoMP enabled small cell environment, with the focus on solutions like cooperative game techniques [9] that would impose self-organization attributes to the BSs' coordination, and improve energy efficiency and perceived user quality.

The rest of the article is organized as follows. The following section briefly introduces the main objectives of 5G heterogeneous small cell cooperation based on CoMP. We then describe the coalition game algorithm and the system-level simulation specifications. Following that, we dis cuss the obtained results and finally conclude the article.

5G Heterogeneous Small Cells

Heterogeneous small cells are a principle enabler for 5G deployment in dense mobile environments. In such environments, where resources are scarce and efficient communications depend on a multitude of different parameters, CoMP communication is expected to bring visible gains in terms of energy savings, as well as capacity and coverage improvements. Toward this end, a hybrid mode of self-organized heterogeneous networks (HetNets) that exploits the benefits of both the centralized and distributed interference management approaches is proposed (Fig 1). Specifically, in a centralized architecture all management and control algorithms and functions are located at a central controller, namely an operation and management unit. Centralization of the management operations requires timely and periodic feedback from all small cells in the network. The execution of these algorithms requires feedback from all small cells of the network, hence creating unwanted signaling overhead and increased complexity. On the other hand, the distributed management of interference requires each small cell to be capable of performing the required optimization algorithms. In such cases, small cells exchange information with each other utilizing the X2 interfaces, while the exchanges between femto-BSs are completed with network listening. Nevertheless, the distributed optimization suffers from a lower performance rate due to the lack of global network optimality. Game-theory-based cooperation between small cell sites is proposed to improve end-user experience for user devices served by coordinated BSs using joint processing.

Brief Overview of CoMP

CoMP enables inter-cell interference to be utilized as a useful signal; hence, users at the cell edge receive higher throughput and increased overall network performance gain. This can be achieved by employing efficient coordination between multiple transmission points (i.e., antennas, sectors), which form a CoMP area. A key element for the coordination in the CoMP area as well as the basis for transmission decisions and adaptations is the channel state information (CSI), reported by user equipment (UE). Each report transmitted by a user forms the basis for different transmission decisions of the cooperating BSs in the CoMP area. Such reports include a variety of measurements (i.e., channel quality indicator, CQI; rank indicator, RI; precoder matrix indicator, PMI), which are utilized by the cooperating network elements. According to 3GPP [10] CoMP can be classified as inter-site CoMP and intra-site CoMP, as illustrated in Fig. 2. In the former, the coordination is performed between BSs located at separate geographical areas, whereas intra-site CoMP allows the coordination between sectors of the same BS using multiple antenna units. There are three different scenarios where CoMP can be applied.

Homogeneous Network with Intra-Site CoMP: In this scenario, the coordination area is restricted to the sectors (cells) of a single site controlled by an eNB. This scenario has the benefit that there is no need for external connections between different sites and no need for fiber backhaul connection.

Homogeneous Network with Inter-Site CoMP: Compared to the first scenario, the coordination area is expanded to include the cells of different sites. This scenario may be realized by having a single eNB coordinate with multiple high-transmission-power RRHs at different cells or multiple eNBs at different sites coordinate with each other. The level of performance in this scenario is dependent on the number of cells involved and the latency of the site connections.

HetNets with Low-Power Picocells within the Macrocell Coverage Area: In this scenario, coordination occurs between a macrocell and multiple low-transmission-power RHHs. The transmission/reception points created by the RHHs have different cell IDs from the macrocell ID.

Although CoMP is applied in both uplink and downlink communication paths of mobile networks, the focus of this study is primarily on the downlink case, and particularly in the joint transmission (JT) scenario. JT-CoMP is an advanced scenario of CoMP implementation according to which each UE active in the CoMP area is capable of receiving the same data from multiple transmission points by using the same radio resources (i.e., time, frequency) in order to coherently or non-coherently improve the received signal quality and throughput. The data requested by the user are simultaneously available at all transmission points in the CoMP set, and each transmission point transmits the same resource block, thus improving the reception quality of the user. The article studies coherent JT CoMP, which assumes precoders able to exploit the phase and amplitude correlations between channels of different transmission points. In coherent JT CoMP, the transmission signal from multiple TPs is jointly precoded to achieve coherent combining in the wireless channel.

Coalition-Game-Based CoMP

The emergence of 5G as the new networking paradigm allowed the concept of cooperation among networks and networking elements to re-emerge as a potential solution to optimize the spectral efficiency in a highly dense wireless network environment [11]. Toward this end, game theory and coalition forming games provide a platform for solving complex wireless network cooperation scenarios by forming coalitions between transmitting nodes that cooperate to maximize the total payoff for the players [12]. Significant research has been conducted over the last few years on how such game theoretic approaches can be combined with C-RAN. A cooperative interference management problem is addressed in [13], where RRHs form coalitions to maximize the users' throughput. Additionally, in ad hoc networks or device-to-device (D2D) communications, coalition-based games are being utilized to form frameworks for solving packet forwarding problems between nodes and increase the overall performance gain of the system.

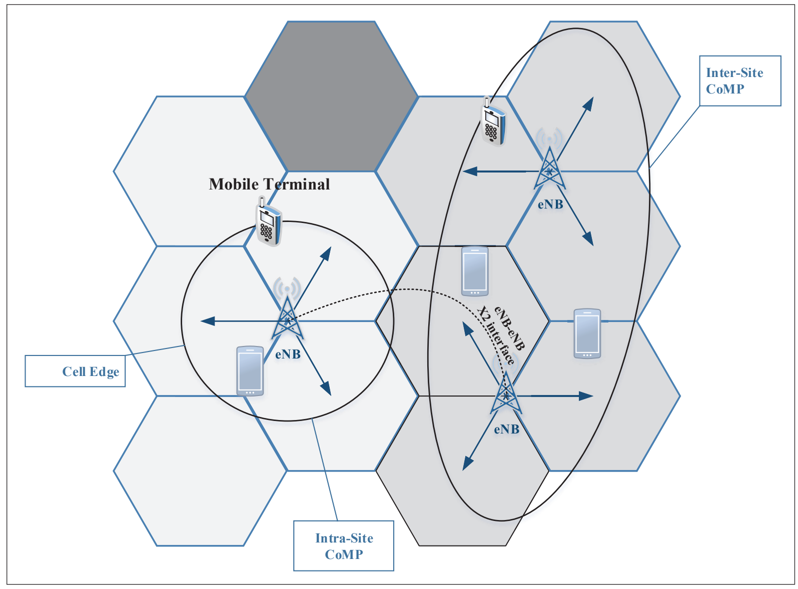

FIGURE 2. Visualization of CoMP intra-site and inter-site CoMP.

Forming the Coalitions

The proposed coalition-game-based JT CoMP involves three main stages: the formation of the list of interfering RRHs, the formation of coalitions of interfering RRHs, and the coalition game. Specifically:

•Initially, the small cell network includes all non-cooperative RRHs (K), which are referred to as singleton coalitions.

•A search of potential coalition patterns among RRHs begins as soon as all users (U) are scheduled and receive interference from the neighboring singleton RRHs. Each UE at the edge of every RRH's cell (edge UE) calculates a matrix of carrier-to-interference ratio values between the serving and interfering RRHs. The interfering RRHs are assigned a unique ID by each user, and this ID is forwarded to the C-RAN. If an RRH is serving multiple edge UEs, the proposed functionality at the C-RAN averages their values, resulting in (K) total interference matrices, which are then sorted in ascending order based on the carrier-to-interference values. The corresponding priority list consisting of the IDs of the interfering RRHs is formed, based on the entries in the top row of the matrices. This priority list indicates the order

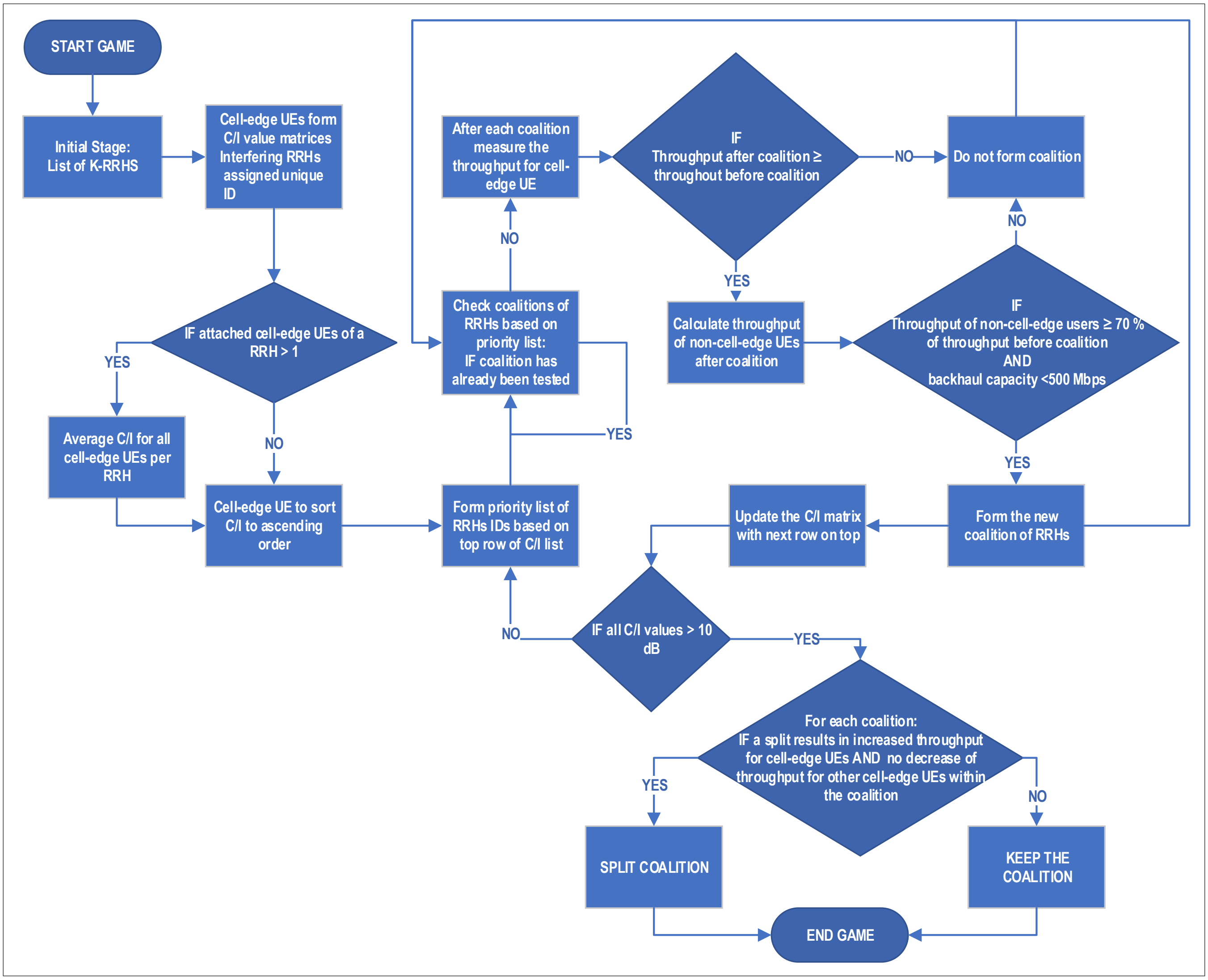

FIGURE 3. Proposed coalition formation algorithm flow chart.

in which each coalition between the most interfering RRHs will be tested.

•In the third stage, all possible coalitions are tested for a duration of 10 transmission time intervals (TTIs), and their members are coordinated based on the JT CoMP technique. A coalition among two or more interfering RRHs is formed if a set of constraints is satisfied. First, the tested coalition increases (or at least does not decrease) the throughput of every edge UE (i.e., the game's payoff). Second, the throughput of the non-edge UEs is not decreased below a certain threshold value set beforehand. Third, the backhaul capacity constraint, which is explained in the following section, is satisfied. The coalition that is formed remains unaltered until the completion of the game. If a coalition has already been tested, the next one (based on the priority list) is examined. Also, if an RRH is already a member of a coalition and its turn, based on the priority list, comes, the total coalition between the new candidate and all the existing members of the coalition is tested. A formed coalition will split only when this split results in the increase of the throughput of at least one edge UE of a member RRH, while the throughput of the other members' edge UEs do not decrease. Following this process, the next rows of the interference matrices are considered, and a new priority list is made. This stage will be repeated until all the considered values of the interference matrices exceed the pre-defined threshold (i.e., 10 dB in this case), in which case the game ends.

Figure 3 depicts the algorithm of the described coalition formation game that enhances the JT-CoMP functionality by providing self-organization attributes to the participant RRHs.

System-Level Simulation

The simulation architecture consists of a C-RAN-based small cell network where the core network communicates with the baseband unit (BBU) pools via the S1 interface. The BBUs inside the BBU pool and the different BBU pools can communicate with each other via the X2 interface to exchange data and signaling. This feature is an enabler for CoMP that relies on very fast communication between BBUs by increasing the uplink and downlink bit rates. The RRHs receive the baseband signals from the BBU pool through the fronthaul links, convert them, and transmit the corresponding RF signal to their attached UEs using a suitably designed precoding vector. The

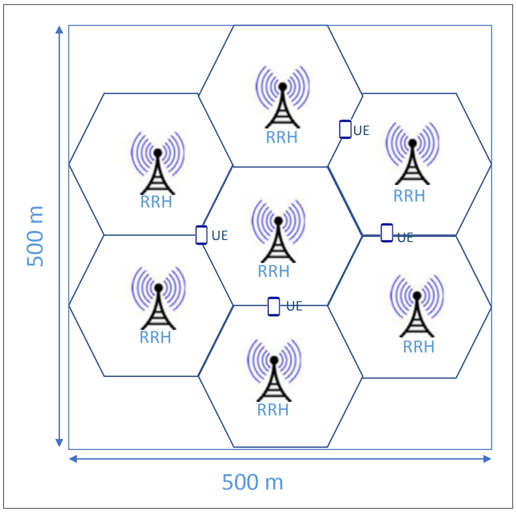

FIGURE 4. Simulation topology.

transmission links between the BBU pools and the RRHs use the common public radio interface (CPRI) fronthaul over dedicated fiber or microwave links. This CPRI fronthaul has tight latency and large bandwidth requirements.

In order to produce comparable results, the system-level simulation was based on the Vienna System Level Simulator [14]. Several modifications were required in order to facilitate the coalition-game-based CoMP in the C-RAN. Seven RRHs are assumed to form an equal number of small cells serving four stationary UEs each. Eleven of these 28 UEs were randomly placed at the edge of the corresponding cells. The RRHs were placed in a topology of a 500 m x 500 m area as in Fig. 4. The data blocks for every UE in the network were transferred from the BBU cloud to the corresponding RRHs via fronthaul links. The transmission power of all RRHs was set to 20 W, and their coverage was omnidirectional. It was assumed that each RRH and UE is equipped with two antennas each. For the simulation setup, the typical urban (TU) channel model was selected with carrier frequency of 2.14 GHz and 20 MHz bandwidth available to every RRH. These system-level simulation parameters are summarized in Table 1. The outcome of each phase of the proposed coalition game (i.e., the effect of a new coalition on the user's throughput etc.) was calculated over a duration of 10 TTIs, where every TTI has the duration of an LTE subframe.

In order to implement JT CoMP, a new scheduler was required. When JT CoMP is not activated, each small cell head (in this case RRH) allocates orthogonal resource blocks (RBs) to its attached UEs based on a round-robin scheduler. Once the clustering is completed and JT CoMP activated, all users at the edge of the cells (i.e., UEs with SINR less than 4 dB) can be served from all the RRHs of the cluster. Hence, according to the proposed scheduler, as soon as a UE at the edge is scheduled, all the members of the corresponding cluster assign an RB to this UE. The assignment of the same RB to the same user from multiple RRHs results in improved SINR for the specific user, since no interference is caused from the RRHs in the cluster. Moreover, the user's throughput is increased as the same data are received from

Parameter description	Value
Carrier frequency	2.14 GHz
Number of eNodeBs	7
Number of UEs per eNodeB	4
Transmit power	20 W
Transmitter height	32 m
Receiver height	1.5 m
Antenna gain pattern	Omnidirectional
Max Tx antenna gain	17 dBi
Number of Tx antennas	2
Number of Rx antennas	2
LTE transmission mode	CLSM
Channel model	Typical urban
Shadow fading type	Claussen
Receiver type	Zero-forcing
Feedback delay	1 TTI
Bandwidth	20 MHz
Receiver noise figure	9 dB
Thermal noise density	−174 dBm/Hz

TABLE 1. Simulation parameters.

multiple sources and the channel quality indicator (CQI) improves. As an effect, a higher modulation coding scheme will be selected, and the transport block size will be increased. UEs with SINR larger than or equal to 4 dB are considered non-edge users (or normal users). When a non-edge user is scheduled, all the other RRHs in the corresponding cluster schedule are also attached to normal users. If an RRH does not have any attached normal users to serve, it does not transmit at this RB, and hence is not interfering with the other scheduled UEs. As a result, less interference and better performance can be achieved for the normal users as well. Assuming that the percentage of users located at the edge of the cells is moderate, the number of RBs provided by the proposed scheduler for the non-edge users is sufficient.

JT CoMP stresses the backhaul network since it requires the transmission points to transmit the same data to multiple receivers. Moreover, the proposed game theoretic scheme utilizes the backhaul even further since a serving cell receives not only its local data but also additional data that belong to all the other cells in the small cell cluster. In order to model the backhaul traffic, the formula from [15] is used, which describes such traffic as a function of the bandwidth, the downlink spectral efficiency of the serving cell, the sum of the spectral efficiency values from the other transmission points of the cluster, and the intersite ratio. In the described coalition game scheme, this traffic represents the cost function.

Results and Analysis

The system-level simulation results indicate that the proposed coalition-based game CoMP succeeds in forming cooperating small cell coalitions

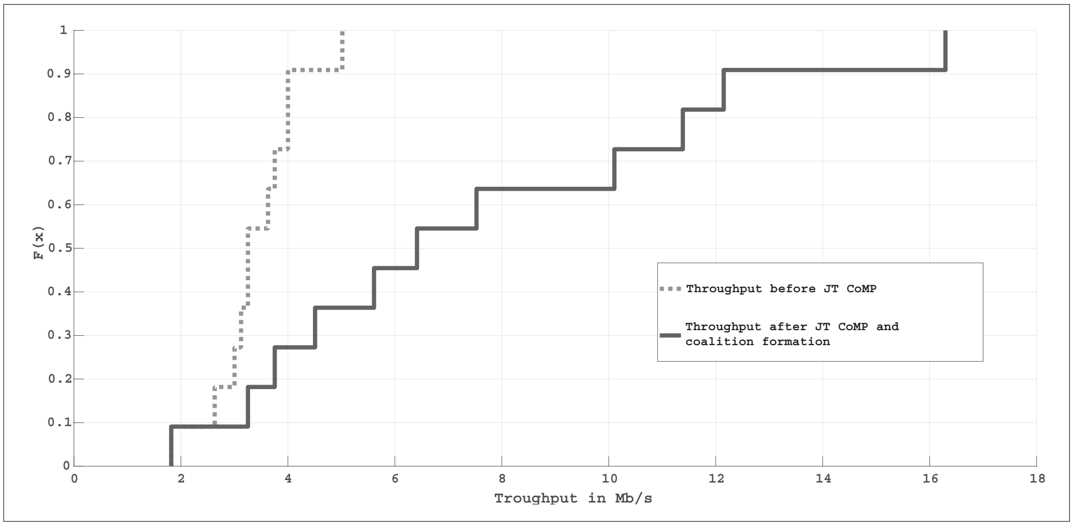

FIGURE 5. CDF of throughput achieved for users at the cell edge with and without the coalition game-based CoMP.

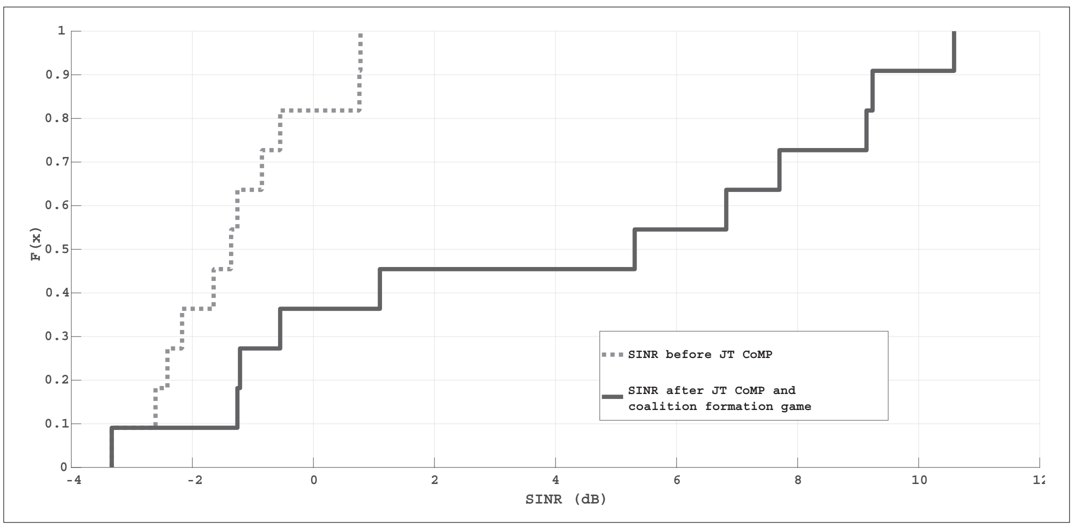

FIGURE 6. CDF of SINR achieved for users at the cell edge with and without the proposed coalition-game-based CoMP.

that significantly improve the quality of service of the UE at the edges of the cells in terms of SINR and throughput. In order to study the effect of the game-theoretic-based JT CoMP on a user's throughput, a baseline scenario is used for comparison, in which there is no CoMP support (i.e., a singleton coalition is formed). The cumulative distribution function (CDF) of the resulting throughput of the users at the cell's edge before and after the coalition is showcased in Fig. 5. Evidently, the mean throughput of the users at the edge of cells is more than twice that of the no-CoMP case due to multiple RRHs serving the users at the edge of the cells. Furthermore, the CDF of SINR of the users at the edge of cells is illustrated in Fig. 6. The mean SINR of the UEs at the edge of the cells is significantly higher than when no-CoMP is in place. The forming of coalitions between the small cell headers minimizes the number of interfering RRHs per UE at the cell's edge, thus increasing the perceived SINR.

The proposed coalition game emphasizes the self-organization aspect of CoMP. The proposed scheme identifies the users at the edge of the cells as the triggering criteria for initiating the game, which eventually optimizes the network coordination to satisfy the requirements (SINR and throughput in this case) of these users. The proposed scheme is triggered as soon as new UEs enter the network, or existing users move toward the edge of their corresponding cells.

Conclusions

The 5G era imposes a set of strict requirements for achieving ultra-low latency, high reliability, and high throughput across wireless mobile devices. Such requirements are more difficult to achieve in densely connected networks. Several technology enablers such as CoMP and C-RAN are being considered as candidates for ensuring the migration from the legacy networks to the future wireless radio access architectures. In this study, the benefits of JT CoMP in increasing spectrum efficiency and interference management are enhanced with the adaptation of a coalition formation game among interfering RRHs. A system-level simulation was performed that indicates an obvious advantage of the proposed game-theory-based CoMP in terms of throughput and SINR achieved for users located at the cell edge.

This is ongoing research, and there are still open challenges that need to be addressed. The system-level simulations need to scale up and display the efficiency of the enhanced CoMP over large numbers of small cells and users, while also considering indoor environments. Moreover, the cell edge user criteria for running the algorithm may change to satisfy the need of some users for bandwidth hungry services (e.g., 4K video streaming, augmented/virtual reality) without compromising the throughput thresholds of other types of users.

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