A Game Theoretic Approach for Efficient Resource Allocation in 5G Networks

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Abstract—**Heterogeneous Networks (HetNets) have been lauded as a key technology for 5G communications, enabling fast growth in mobile traffic. HetNets may also expand the network's capacity and serve more users. However, interference between small cells and macro-cells makes Quality of Service (QoS) more difficult to achieve, and thus novel protocols, new technologies, and future trends should also be included in order to provide efficiency in Resource Allocation (RA). Game Theory (GT) concepts have been widely used in a variety of engineering design challenges in which one component's activity affects and perhaps conflicts with the actions of other components. As a result, game formulations are utilized, and the idea of equilibrium is applied to find a stable solution for the participants. In this paper, we compare two algorithms used for RA, the first being a classical RA algorithm and the second being a game theoretic one. The game implemented is called "Tragedy of the Commons", and is applied in a non-cooperative network.**

Keywords— 5G, Game Theory, Tragedy of the Commons, Resource Allocation, Networks

I. INTRODUCTION

The design and needs for Fifth Generation (5G) mobile communication necessitate a significant shift in current communication as stated in [1]. Massive amounts of data traffic, huge data rates, and extremely low latency are just a few of the essential needs of 5G. To meet these expectations, numerous new approaches and advances in current techniques are required.

Heterogeneous networks (HetNets) are expected to play a key role in the 5G dense and diverse networks by deploying different kinds of cells in order to improve the Quality of Service (QoS) of the network. For example, macro cells are used to improve coverage while pico and microcells are utilized in dense areas to improve the capacity. The installation of these cells plays a very important role and offers flexibility depending on the type of cell and the area of the placement. User association becomes difficult with the advent of diverse cell sizes and significant spectrum reuse, as it affects both user and network performance [2].

As stated prior, the cells can be of many sorts, and the cell selection choice can be either centrally coordinated (i.e., by the network) or dispersed (i.e., by each User Equipment (UE) deciding on each serving base station on its own). Because the distribution of transmitters and receivers (Base Stations (BSs) and users) is random and dense in a hyper dense network, interference and spectrum usage are two important challenges. Also, co-tier interference caused by neighboring interfering base stations is highly prevalent, and QoS degrades as a result.

Game Theory (GT) is a discipline aimed at simulating scenarios in which decision-makers must take specified actions with mutual or competing outcomes [3]. It focuses on decision-making in situations where each player's choice might affect the outcome of other participants. In such situations, the actions of other players are analyzed, and the best decision is made. The term "game" in GT refers to an abstract mathematical model of a multi-agent decision-making situation, with the goal of including just those characteristics of the domain that are relevant to the decisions that participants must make. In a game-theoretic environment, GT proposes a number of solution ideas that are often meant to articulate some notion of rational choice as presented in [4].

This context has been reviewed by many researchers. To solve the Resource Allocation (RA) issue the authors in [5], created a static game-theoretic model with incomplete information in which BSs are portrayed as game participants. The transmission parameters pertinent to Device to Device (D2D) pairings and BSs are considered to be personal details of each participant, and the probability distribution of these parameters is taken to be known to the general public based on prior observations of these parameters. The results of the simulation show that under the incomplete information condition, each player's utility, sum rate, and sum rate gain are higher than they are under the complete information condition, suggesting that each player has an incentive or motivation to withhold information in order to increase its profit.

The authors of [6], take into account the uplink of a hybrid HetNet that combines femtocells with macrocells and develop a two-layer game-theoretic framework to maximize Energy Efficiency (EE). By choosing a frequency band from the sub-6 GHz and mmWave ranges, the outer layer enables each Femtocell Access Point (FAP) to maximize the data rate of the users. Pure strategy Nash Equilibrium (NE) can be used to find the answer to this non-cooperative game. By employing a dual decomposition strategy, the inner layer ensures the energy-efficient user association method subject to minimum rate and maximum transmission power limits. The suggested hybrid HetNet method, which utilizes the mmWave frequency spectrum, enhances the sum-rate and EE, according to simulation results.

This paper proposes a novel way to compare algorithms used for RA and their efficiency is calculated by comparing their Reference Signal Received Quality (RSRQ) values and their rewards. The game implemented is called "Tragedy of the Commons" and refers to a situation in which individuals with access to a shared resource (also called a common) act in their own interest and, in doing so, ultimately deplete the resource [7].

Although resource sharing, utilization, and over-congestion consist common phenomena in wireless network optimization problems, so far literature has considered spectrum, or network capacity as infinite or imperishable variables. On the contrary, in this paper, we consider the probability of failure (i.e., fragility) for resource management in wireless networks in cases of over-exploitation according to the concept of the "Tragedy of the Commons". The above breakthrough creates a totally different landscape on how end users define their behavior and actions, based on risk aversion perceptions and probability weighting. This consideration allows the study and evaluation of satisfaction and resource effective utilization under more realistic and personalized assumptions.

The rest of the paper is organized as follows. In Section II, we are presenting the defined system model. Moreover, in Section III, the proposed mechanism is analyzed in detail; while in Section IV the proposed mechanism is evaluated and compared with other mechanisms that also provide efficient RA. Finally, the conclusions and our future work are provided in Section V.

II. SYSTEM MODEL

In order to implement the Tragedy of the Commons game we must firstly create a 5G environment. Therefore, the creation of a simulation that mimics the way a 5G HetNet operates is considered a necessity. HetNets have been developed to improve network performance and connectivity by combining dense small open or closed access cells with high power macrocells. Through the use of enhanced network architectures and technologies (e.g., femtocells, picocells, multicarrier deployment and carrier aggregation, cell splitting or adaptive resource partitioning, etc.), significant progress has been made and capacity in licensed spectrum, the number of connected users have increased, and overall throughput has also improved.

The topology we will be using throughout this paper is the one following. It consists of 7 Macro cell BSs (MABSs), their margins marked with black and forming that way a hexagonal configuration. Each MaBS has two micro cells marked with red and three picocells marked with blue. The users get allocated per cell.

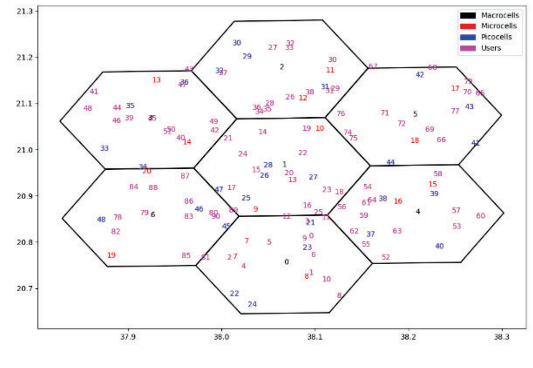

Figure 1 – Simulation Topology Scenario with 7 MaBSs, 14 MiBSs, 28 PiBSs and 120 Users.

Decisions about the connection are made throughout discrete time slots with a set duration. To assign each user to the best BS is the simulation's ultimate goal. We assume throughout the article that the same telecommunications provider deploys each cell in this simulation.

The said simulation will assign Resource Blocks (RBs) to stationary UE while taking into account path-loss and intracell interference. In this simulator, the UE has no idea what kind of BS it's connecting with. This indicates that the UE requests a bit rate from one (or more) BSs. The algorithm follows 5G restrictions and guidelines, as they are stated in [8] and it is the following:

1. The receiving power of each visible BS for each UE is calculated.
2. The BS with the most power is selected, based on the measured receiving power.
3. The UE sends a connection request by declaring the necessary bitrate.
4. The BS distributes the requested resources and notifies the UE about the bitrate that is allocated to them.

Each visible BS's receiving power (i.e., the RSRP) must be measured by the UE. The BS allocates resources for the UE's request based on the Signal to Noise Ratio (SNR) and notifies the UE with the true bitrate derived from the alleged total resources. By implementing the above algorithm, we are able to calculate the RBs that each UE requests. In the said simulation Reference Signal Received Power (RSRP) is computed. RSRP represents the transmission power and is calculated as follows:

$$RSRP_{i,j} = P_j + G_j - L_j - L_{i,j} \tag{1}$$

where P_j denotes the antenna power of the BS, G_j is the antenna gain of BS, L_j is the power supply losses of BS and $L_{(i,j)}$ is the path loss between $UE_i \epsilon I$ and $BS_j \epsilon J$. Furthermore, P_j is defined as follows:

$$P_j = \frac{1000BS_{power}}{\frac{BS_{prb}}{10\times 2^{\mu}}\cdot BS_{subcarriers}} \tag*{□2□}$$

For a 5G BS, the Physical Resource Block (PRB), BS_{PRB} represents the whole amount of the minimum distribution unit. Each PRB is made up of 12 frequency subcarriers with a bandwidth of 215kHz and a period of $2^{-\mu}$ ms, where $\mu = 1, 2, 3, 4$ is the numerical parameter defined by the 5G standards. The total bandwidth available and its numerology (μ), as described by the 5G NR standards [9], determine the number of PRBs available in the $BS_j \epsilon J$.

The path loss $L_{(i,j)}$ is calculated in our simulator using the COST-HATA model [10], which is a statistical model that considers a variety of characteristics such as building density (rural, suburban, urban), carrier frequency used for communications, and UE and BS heights. It is calculated as follows:

$$\begin{aligned} L_{i,j} = 46.3 + 33.9\log_{10} f - 13.82\log_{10} h_b - \\ a(h_r, f) + (44.9 - 6.55\log_{10} h_b)\log_{10} d \\ + C_m \end{aligned} \tag{3}$$

where f is the carrier frequency, h_b is the height of each BS, d is the distance between the BS and the UE, while UE's altitude from the ground is h$_r$. The COST HATA model's antenna height adjustment factor for mobile stations in urban areas is denoted as a(h$_r$, f) and depending on whether the situation is urban or rural situations, such as the one we're simulating, it is calculated as such:

$$a(h_r, f) = (1.1 \log_{10} f - 0.7)h_r - (1.56 \log_{10} f - 0.8) \qquad (4)$$

Lastly, the C_m is considered as a constant offset, and is defined as follows, with the case for suburban areas in mind:

$$C_m = \begin{cases} 0 \; dB \; for \; suburban \; areas \\ 3 \; dB \; for \; metropolitan \; areas \end{cases} \qquad (5)$$

Furthermore, we calculated Interference and thermal noise that can significantly degrade the QoS. SINR is also computed and offers insight on the signal's intensity in comparison to undesirable interference and noise.

After a UE requests a connection, the BS calculates the Signal-to-Interference-plus-Noise-Ratio (SINR) to estimate the maximum bitrate that each PRB can provide. This value can be used to determine the maximum number of PRBs that can be assigned to a UE.

$$SINR = \frac{RSRP_{i,j}}{I+N} \qquad (6)$$

where $RSRP_{i,j}$ stands for the strength of the incoming signal, N is the noise factor that can either be random or constant and I calculates the interference that other signals might create.

III.PROPOSED MECHANISM DESCRIPTION

Having implemented the above classic RA algorithm, we need to also formulate the game theoretic one. The Tragedy of the Commons is a situation in which individual users with open access to a resource act autonomously in their own self-interest, causing resource depletion against the common good of all users. Although open-access resource systems may collapse due to abuse, there have been and continue to be many examples of members of a society with regulated access to a common resource cooperating to exploit those resources wisely without collapsing, or even producing "perfect order" also known as NE [11]. That being said, a player can obtain the desired outcome by sticking to their initial strategy, according to the GT decision-making theorem is known as the NE. Each player's approach in the NE is the best one given what the other players have decided.

Let's suppose that the maximum resources that an antenna can offer is equal to 100. As stated earlier, if the resources are depleted, then no player can use them as the interference increases drastically. The reward u$_i$ for a player z$_i$ is calculated as follows:

$$u_i(z_i) = \begin{cases} 0, \; if \; \sum_{j=1}^{n} x_j > 100 \\ x_i(100 - \sum_{j=1}^{n} x_j, \; otherwise \end{cases} \qquad (7)$$

If the players request more than 100 RBs, their reward drops to 0, meaning they cannot use the resources needed. The allocated resource are RBs, being the smallest unit of resources assigned to a user. Each game has a utility table that notes the rewards of players when choosing an action. For the game we are describing we formulated a custom utility table, and that is the following:

Strategies	S1	S2
S2	1, 1	1, 2
G2	2, 1	0, 0

Table 1 – Utility Table

where S1 and G1 are the two strategies formulated for Player 1 and S2 and G2 the two strategies of Player 2. Depending on the strategy they choose, the players get the reward that is stated in the corresponding cell.

Each player can either be Greedy or he can be a Saint. In our case, the players are actually a group of players requesting resources from the network's BSs. The strategies determine the resources that each player needs and add up to a total sum of resources the group requires. By implementing these two strategies we aim to model interactions that logical players would have. The Greedy player is selfish and does not care about the possible depletion of the source and thus he requests more resources than needed. The Saint player however calls for only the necessary resources. While being part of the group, the players maintain their individual strategies.

That being said each decision has a risk. The optimal solution is the one that manages to mitigate said risk while maintaining or even increasing QoS. The state where players pick strategies from which unilateral departures do not pay, they reach a NE (also known as an "equilibrium point"). This is because in applications of GT to different disciplines, the basic solution concept—that is, behavior prediction—remains the same. As calculated using the above utility table the game has two NE and these are the states (S1, G2) and (S2, G1). Also, the game modulated is a mixed strategy meaning that the group decides according to a probability distribution over a set of possible actions rather than making a single, fixed decision.

Thus, the implemented mechanism organizes the players into two groups. The number of players is not necessarily the same in each group. Players randomly choose their strategy, either choosing between the Saint or the Greedy one, that does not change when assigned to a group. If the group's requested RBs do not exceed the selected threshold, they get assigned to a BS that can meet their needs.

If the sum of the requested resources does not exceed 350, the group connects to the corresponding BS. Also, if a group exceeds the set number, their reward becomes zero. The utility table indicates the group's rewards and how resources are to be split in case they both play the game. For example, if G1 and G2 can both play the game and choose simultaneously the Saint strategy, the network's resources are equally split between them. If G1 plays as a Greedy player, the G1 group gets the 2/3 of the resources and the group G2 get the remaining 1/3.

IV. PERFORMANCE EVALUATION

Before presenting the simulation results, we will lay out some of the simulated system's parameters. An example simulation scenario based on the developed simulator is summarized in the following table. The simulator's capacity to distribute users across three different cell sizes — Macro, Micro, and Pico — while also maximizing DL UE and requiring less power transmission — will be put to the test. Additionally, the system keeps track of all PRBs to ensure that the user's desired service may be effectively given.

Parameters	Values		
	Macro	Micro	Pico
Carrier Frequency (MHz)	2100	2400	2600
Bandwidth (MHz)	5	5	5
Maximum DL Power (W)	1	0.25	0.1
Maximum BS Power (W)	20	2	1
Antenna Gain (dB)	16	5	5
Path Loss (dB)	3	2	2
UE Antenna Gain (dB)	0	0	0

Table 2 - Simulation Parameters

An example simulation scenario based on the simulator is summarized in Table 2. The objective is to evaluate the algorithm's capacity to associate and distribute users among three different radio access technologies (Macro, Micro, and Pico), while enhancing UE downlink (DL) data throughput and lowering BS power transmission in a single environment. Finally, QoS is defined, network bitrate overall, and network EE as KPIs.

The MiBSs, PiBSs, and users are distributed evenly inside the radius of the MaBSs, which has a hexagonal grid arrangement and a cell radius of 200 meters. All of the signals that are being transferred from the BSs to the UE also have noise added to them, with a normal distribution.

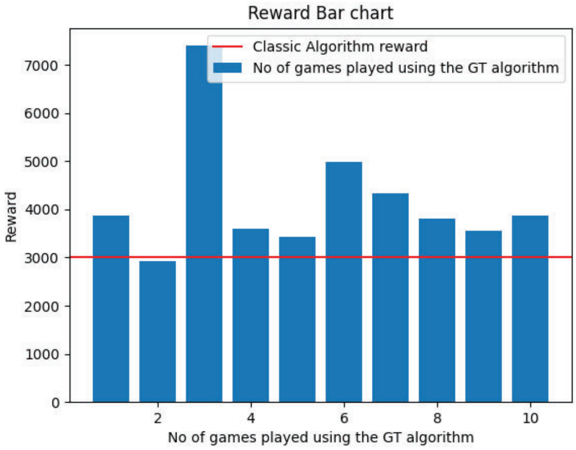

Figure 2 - Comparison between the rewards of two algorithms.

Figure 2 graphs the reward of the two algorithms and that way provides a comparison between them. The horizontal red line graphs the reward from the classical RA algorithm implemented in the simulation. The blue bars graph the reward that the GT algorithm provides in a scenario where 10 games are played consecutively.

The GT algorithm outperforms the classical one. Due to the algorithm implemented, in the case where players request more than the maximum amount of PRBs they do not get connected and their reward becomes zero. The GT reward of may vary depending on whether both groups play the game, meaning that they therefore request less PRBs than the upper limit. As stated in the previous section players maintain their strategy and become part of a group that can request a specific number of PRBs.

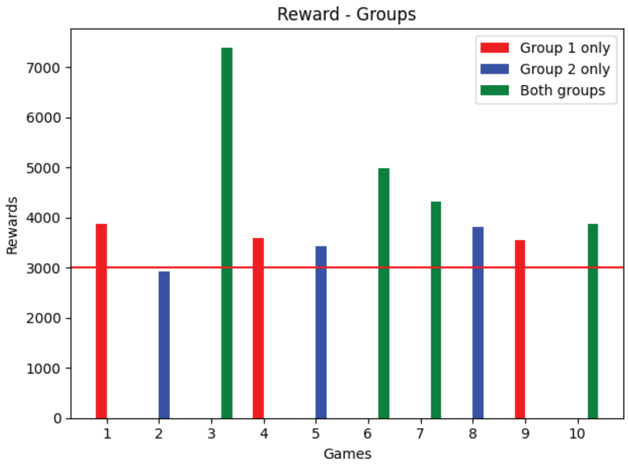

Figure 3 – Correlation between the number of groups playing and their cumulative reward.

Figure 3 indicates the correlation between the number of groups playing and the reward gains achieved. The total reward for each game using the GT algorithm is graphed using a bar chart. If both teams are playing, the reward is marked with green. Else if only one of the two teams plays the game, the reward is either marked with red or blue. The red horizontal line, similarly to Figure 2, graphs the gain of the classical algorithm. In the specific example, the classic RA algorithm outperforms the proposed GT once, in the case where only Group 2 plays the game. That happens because Group 1 requests more PRBs than the ones that can be allocated in the game. Therefore, as the algorithm implemented states, they are not eligible to connect to a BS.

Although the classic RA algorithm reward in game 2 is greater than the one from the GT algorithm, the proposed algorithm performs better in most cases as graphed in both Figures 2 and 3. It is evident from Figure 3 that in the games where both teams request fewer PRBs than the upper limit, the cumulative reward is higher when compared to the games where one or neither team plays. In the case where no team plays, the reward is zero since the players didn't take into account the risk and depleted the resource by requesting more resources than necessary. As a result, they don't connect to a BS and their corresponding QoS is zero.

Through the distribution of PRBs allocated to each user, we not only create a GT algorithm providing optimal allocation but also achieve EE. That is because a network's total energy consumption is closely related to the number of PRBs transmitted. The proposed GT algorithm allows players to request the necessary for them PRBs depending on their strategy.

Figure 4 displays the total power consumption of the two algorithms. The GT algorithm requires less power consumption when compared to the classic one. The power consumption is computed as the sum of energy each type of cell requires to serve all the users and is a function of the number of PRBs allocated.

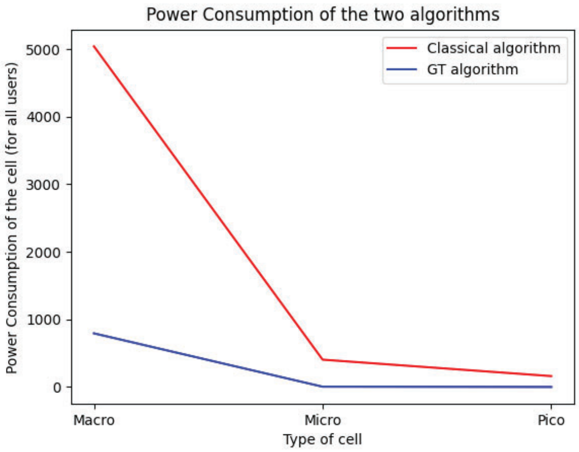

Figure 4 – Total Power Consumption measured in kW

We determine how much power each BS requires to transmit a single PRB and multiply that amount by the number of PRBs that a specific BS allots to users to determine how much power each BS uses. The energy usage is kept lower than with a traditional algorithm since the GT algorithm ensures that the number of PRBs is neither greater nor smaller than what each user needs.

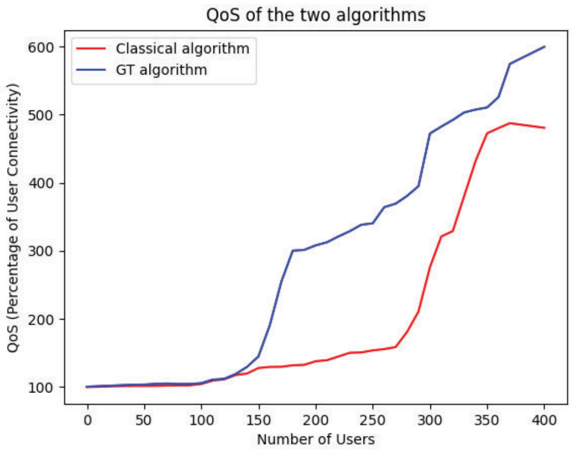

Figure 5 - Comparison of the QoS of the two algorithms

Furthermore, in the above Figure, the comparison of the QoS of the two algorithms is presented. It can be depicted from the graph that the QoS of the proposed mechanism outperforms the one of the classic RA algorithm. Thus, the proposed algorithm can employ techniques or technologies that operate on a network to manage traffic and guarantee the functioning of crucial applications with constrained network capacity. It is also important to note that while users increase, the QoS of the proposed scheme also tends to increase, as opposed to the one of the classic algorithm that tends to decrease.

Lastly, we will provide a comparison of the network KPIs that provide a general overview of the network's functionality. The overall power consumption, as also graphed in Figure 4, has decreased in the GT algorithm compared to the classic one. The corresponding value for the latter is 5050 kW, while for the former it is only 797 kW, marking a significant decrease.

Moreover, the network's bitrate is also calculated. In computing and telecommunications, bitrate refers to the number of bits transmitted or processed per unit of time, and its unit is bits/sec. Bitrate and QoS are closely related, so, understandably, the proposed algorithm has better bitrate in comparison to the classic RA algorithm. More specifically, the GT algorithm's bitrate is 182 bits/sec, while the classic RA algorithm has a bitrate of 167 bits/sec.

V. CONCLUSIONS

The fundamental requirements for 5G include enormous data traffic and data rates along with extremely low latency. Numerous innovative new strategies and advancements in existing procedures are needed to live up to these expectations. The integration of GT to enhance the already existing RA schemes is a promising new idea that will revolutionize the already existing algorithms. In this paper, we proposed a novel GT algorithm that manages to optimize RA and provides better EE through the better allocation of PRBs. Along with the algorithm, a simulation tool was created that mimics the functionality of a 5G HetNet. The findings presented provide enough justification as to why the proposed algorithms outperform the classic RA one.

VI. FUTURE WORK

A suggestion for possible future work would be one where intelligent user/agent are able to estimate risk and collaborate toward sharing finite resources in an efficient and socially equitable manner, mitigating wasteful resource over-consumption, and managing spectrum fragility. Thus, when using spectrum, users do not act as blind value maximizers, but instead adopt a risk seeking or adverse behavior.

VII. ACKNOWLEDMENTS

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