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Coalition Games for Performance Evaluation in 5G and Beyond Networks: A Survey

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ABSTRACT The 5G network is an emerging field of the research community. 5G is a multi-disciplinary network that aims to support a wide range of services. 5G network has an objective to support a massive number of connected devices. Game theory has an extensive role in wireless network management. Game theory is an approach to analyzing and modeling the system where multiple actors have a role in decision-making with independent objectives and actions. The game theory is an exciting methodology to control the strategic behavior of players and generate an efficient outcome. Coalition game theory can play a crucial role in ensuring cooperation among a massive number of devices. This article provides insight into the current research trends in 5G using coalition games. The work presented in the survey is divided into three categories, namely resource management, interference management, and miscellaneous. This article also provides the foundation about 5G and coalition games highlight the scope of future research.

INDEX TERMS Game theory, 5G NR, coalition games, interference management, resource management.

I. INTRODUCTION

We have been witnessing immense growth in the amount of mobile data and the number of connected devices. As per the Cisco Annual Internet Report (2018–2023), the number of connected mobile devices will be three times more than the world population by 2023. Half of the connected devices will be of Machine Type Communication (MTC). Connected home appliances will have the highest share, and connected cars will get rapid growth. The total number of internet users globally will grow to 5.3 billion in 2023, which was 3.9 billion in 2018. That is 66% of the world population. Ericsson predicted that the average global mobile data grows up to 164 EB per month by 2025, which was 33 EB per month by 2019. Recently, unprecedented growth in connected devices and a high volume of mobile data traffic drive toward a demand for communication technology that can fulfill the communication's future requirement. Fig. 1 shows the evolution of the generation of wireless communication.

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The Fifth-Generation New Radio (5G NR) can meet the demand for high-speed data transfer, massive connectivity, and very low latency. A new generation of cellular communication technology developed in approximately ten years. The 5G NR is expected to be deployed by 2022. 5G NR is being standardized to aim for a Fiber-Like mobile broadband experience with more than 1 Gbps of data transfer speed and >300 KMph of mobility [1], [2].

5G NR is not a specific radio access technology (RAT). It collects different RATs with improvements in existing ones with novel advancement in design to address 1000x connectivity and data transfer speed and ultra-reliable low latency communication (uRLLC) [3]. 5G NR enables to support of flexible RAT sharing among different service providers. 5G enables several new application domains like augmented reality / virtual reality (AR / VR), Internet-of-Things (IoT), Internet-of-Vehicles (IoV) [4], Device-to-Device (D2D) communication [5], and machine type communication (MTC). These new application domains are leading to a rapid increase in data rate and massive device connectivity. Application domains like autonomous vehicles, AR / VR, and drone communication requires ultra-reliable-low -latency that is less than 1 ms [6], [7].

5G NR aims to support a multidisciplinary communication system with an order of magnitude enhancement in bandwidths (mmWave, 6∼300 GHz), connectivity (∼ 1M devices per square kilometer), and coverage (99.999%). 5G NR also aspires to a massive reduction in round-trip delay (<1 ms) and energy consumption per bit (up to 10 years of battery life for MTCD) [1], [8], [9]. The 5G NR aims to operate on high frequency up to 300 GHz, as shown in fig. 2. A higher frequency increases the possibility of getting the larger bandwidth at a reduced cost; it implies reduction in per bit transmission cost. As the frequency of the carrier wave increases, it significantly decreases the probability of deep fade using the antenna arrays due to reduced antenna length and distance between two antennas. The antenna arrays increase spatial diversity and allow beam-centric transmission. The ultra-lean design of the 5G NR aims to minimize the transmission of reference signals to reduce interference to other devices and energy consumption. Reduction in interference increases the data transmission rate. Moreover, the 5G NR design is forward compatible to allows significant future evolution [6], [10], [11].

A. NEED FOR COALITION GAMES IN 5G

Game theory has proven to be an effective tool in dealing with many complex problems in various fields. Game theory accurately models many issues in 5G and usually provides solutions to the underlying problems. A variety of entities in a system can find themselves to be the interacting players in these games. Coalitional games provide a unique insight into various aspects of the technologies that build up 5G. Coalitional games help to model many of the problems of 5G. Ideas in game theory ranging from coalition formation games to axiomatic bargaining find within themselves parallels within 5G. Section V elaborates the work done by the research community in 5G using coalition game theory.

B. CHALLENGES IN APPLICATION OF COALITION GAMES

There are many challenges faced in the application of the coalitional game-theoretic models. The first, of course, is finding the appropriate model. Coalitional game theory provides many models, such as transferable and non-transferable utility games, interval games, matching games, and bargaining games. Finding an appropriate model is itself a difficult task [7], [12]. Another issue is optimality, an underlying issue that besieges most problems where game theory is applicable. An optimal solution to such problems is usually too inefficient to implement. A coalitional game-theoretic approach usually provides an efficient solution, but not perhaps to most optimal solutions. Of course, there are cases where optimality is guaranteed to some degree. However, stability, which is present in most coalitional models, rarely translates into optimality. Coalitional games provide potent tools for 5G problems, but they must always be dealt with as a means to an end, never pursued as an end in themselves [6], [13].

TABLE 1. Table of abbreviations.

Abbreviation	Expanded
UDMN	Ultra Dense Millimetre-wave Networks
UE	User Equipment
D2D	Device To Device
BS	Base Station
SBS	Small Base Station
MCA	Multi-flow Carrier Aggregation
MD	Mobile Device
RAN	Radio Access Network
C-RAN	Cloud Radio Access Network
F-RAN	Fog Radio Access Network
AP	Access Point
FAP	Fog Access Point
NOMA	Non-Orthogonal Multiple Access
MIMO-NOMA	Multiple Input Multiple Output NOMA
MU	Mobile User
D2MD	Device To Device Multicast communication
MNO	Mobile Network Operator
VCFG	Virtual Coalition Formation Game
MOS	Mean Opinion Score
RRH	Radio Resource Head
MINLP	Mixed Integer Linear Programming
DAA	Deferred Acceptance Algorithm
P2P	Peer To Peer
STP	Successful Transmission Probability
CSI	Channel State Information
RB	Resource Block
RRM	Radio Resource Management
TDD	Time Division Duplex
WR	Wireless Router
NLIP	Non-Linear Integer Programming
MUI	Multi User Interference
RSI	Residual Self Interference
IA	Interference Alignment
TO	Traffic Offloading
IASL	Interference Alignment with Spectrum Leasing
TOSL	Traffic Offloading with Spectrum Leasing
SAP	Small cell Access Points
CU	Cellular User
ZF	Zero Forcing
OFDMA	Orthogonal Frequency Division Multiple Access
TDMA	Time Division Multiple Access
SCMA	Sparse Code Multiple Access
NFV	Network Function Virtualization
VNF	Virtual Network Function
VM	Virtual Machine
CN	Cloud Network
TA	Tracking Area
LAA	License Assisted Access
MEC	Multi-access Edge Computing
LA	Learning Automata

C. MOTIVATION

5G is a multi-disciplinary network to support today's communication requirements. 5G is expected to be revolutionary. The higher data rates and reduced latency, among others, are expected to open up a whole world of opportunities with the IoT. There is a massive number of connected devices of different types. Cooperation among the devices may play a significant role in accommodating ultra-dense connectivity. Cooperation among devices required a transparent and socially efficient regulation to make cooperation

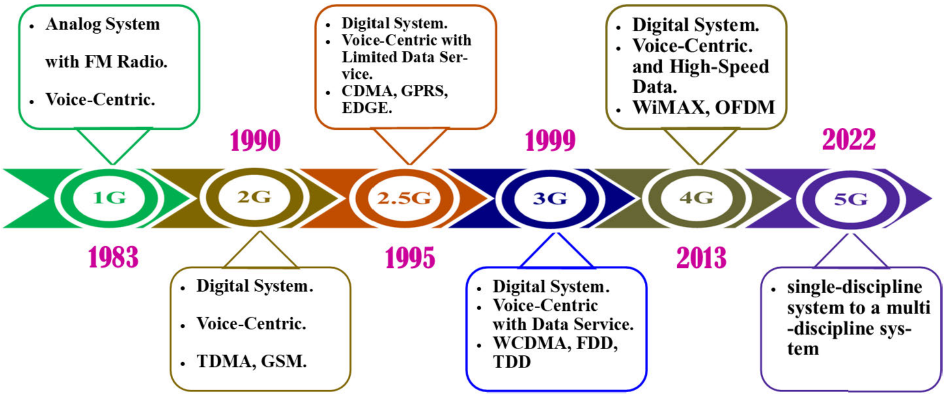

FIGURE 1. An illustration of the evolution of telecom technologies.

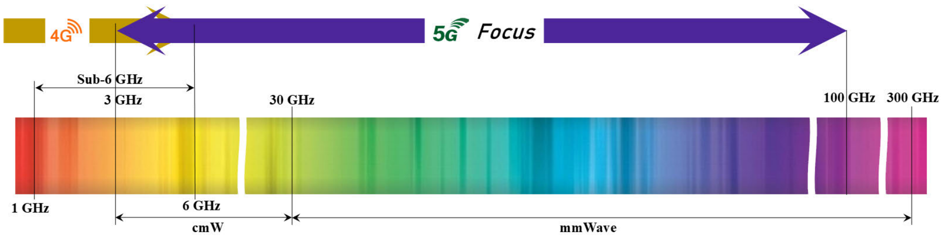

FIGURE 2. Spectrum used in various 5G technologies.

stable. The game theory can control strategic conspiracy by the players. Game theory is rapidly becoming more and more popular in 5G as a potential source of solutions. Coalitional game theory is rapidly growing, with new models created regularly and existing models finding more creative applications in various fields. It helps that the inherent selfishness of game theory, which passes on to some extent to coalitional game theory, is very easily found in many potential applications. There is, in our opinion, enough innovative work in this field to warrant such a survey.

D. CONTRIBUTION

This article provide insight to current research trends in applications of game theory in 5G through the classification and analysis. Article also provides the foundation to 5G and coalition game theory platforms. The rest of the paper is organized as follows.

- Section II provides statistics to highlight the contribution given by the research community in 5G network management using coalition game theory.
- Section III provides a foundation to 5G network architecture and basic concepts. This section highlights resource management and interference management issues, which contribute most to the surveyed literature.
- Section IV provides an introduction to coalitional game theory, including the concepts of the core, partition function form games and the recursive core, the Shapley and Banzhaf values, Bayesian coalitional games, interval games, matching games, and bargaining games.
- Section V describe the applications of game theory in 5G, divided into subsections of resource allocation, interference management, and other uses. Each subsection also has a comparison of the approaches.
- Section VI presents the learning's from study and possible future research directions in this field.
- Section VII presents the conclusions of this work.

II. RESEARCH METHODOLOGY

This section provides statistical information about the scholarly work carried out by the research community using coalition games to improve the 5G system. The survey methodology propelled from Casino *et al.* [14] and Briner *et al.* [15] to provide a clean and transparent literature survey on the application of coalition games in 5G network management.

A. LOCATING STUDIES

To address our primary objective a systematic search is carried out in scientific literature databases including IEEE and Science Direct without a time constraint in December 2020. A subsequent search is carried out in April 2021. Through the literature search we have found total of 147 article corresponding to coalition game theory and 5G. Fig. 5 shows the year wise classification of retrieved articles. The retrieved articles classified in three groups journal, conference, and

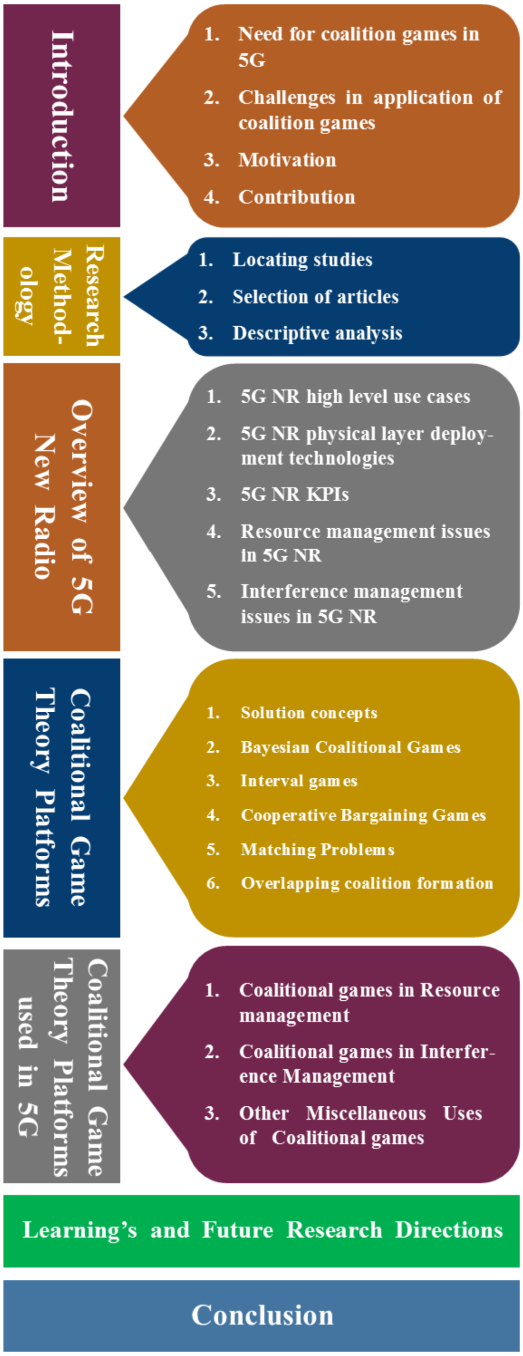

FIGURE 3. Organisational scheme of this paper.

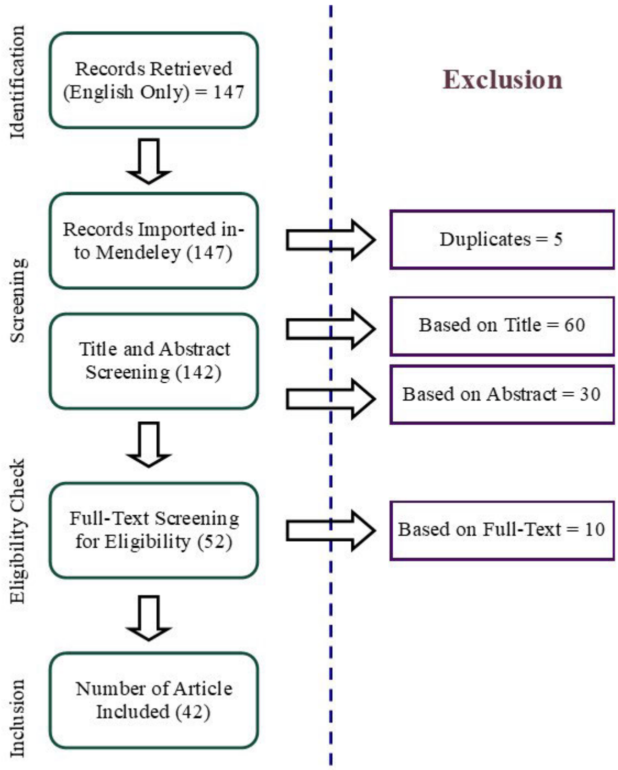

FIGURE 4. Flowchart of inclusion and exclusion of articles.

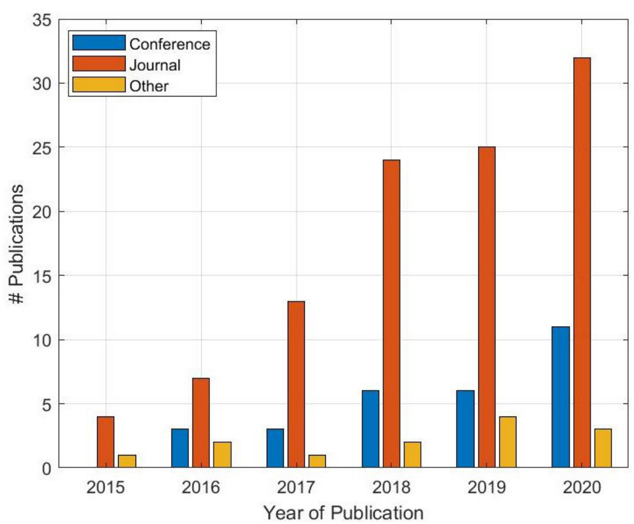

FIGURE 5. Year wise classification of retrieved articles.

other including book chapters, magazines. Application of coalitional games in 5G get a boost in year 2018. Journal publications hold the majority share in type of publications.

B. SELECTION OF ARTICLES

All the retrieved articles ware gone through a screening process. The steps followed in screening are as follows.

- Total of 147 articles is checked for duplicates using a reference manager (Mendeley). There were five duplicates removed.
- After removing duplicate articles, further screening is carried out based on the article title and abstract. We have removed a total of 90 articles in this phase.
- For the articles retrieved from phase 2, a full-text screening is performed to final select the articles.
- Total of 42 articles included for the analysis which meet the objective of this study. Fig. 4 shows the flowchart of inclusion and exclusion of articles.

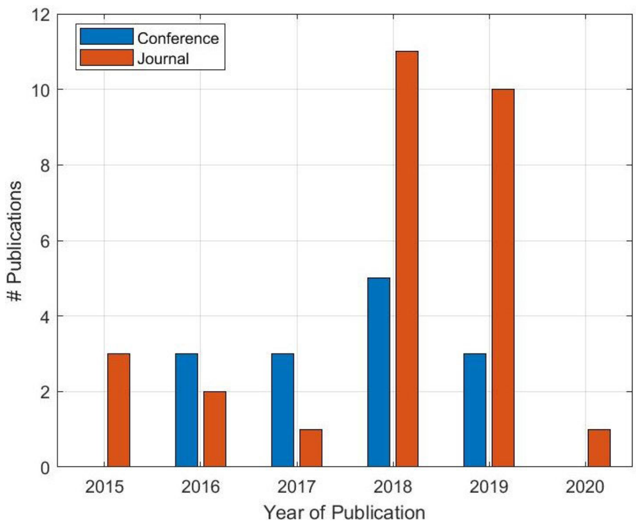

FIGURE 6. Year wise classification of included articles.

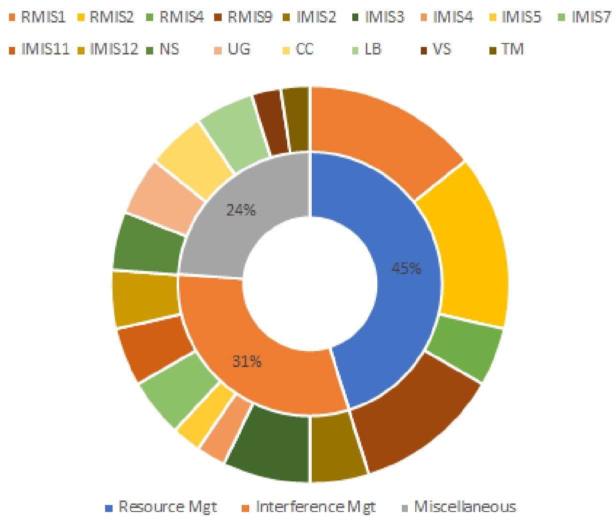

FIGURE 7. Classification of the articles with respect to table 2, 3, 5, 6, and 7.

C. DESCRIPTIVE ANALYSIS

This study analyzed 42 conference and journal articles published between the year 2015 to 2020. Fig. 6 shows the yearly counts for included journal and conference articles. We did not find any relevant articles through the second iteration of the literature search in April 2021. The study intended to provide insight on the subfields of 5G in which coalition games are applied and which type of issues are solved [16]. This study relates the coalition game platforms with the particular 5G issue. The study's objective is to provide a clear view of current research trends in the identified area. The analysis found that 45% of articles focus on resource management, 31% focus on interference management, and the remaining 24% solved various issues. 72% articles use Bayesian coalition games, 14% articles use overlapping coalition game, 10% articles use matching game, and each interval

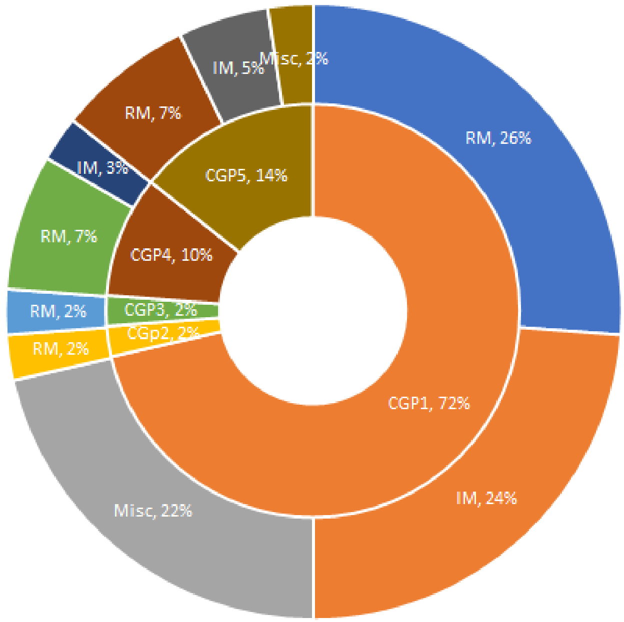

FIGURE 8. Classification of the articles with respect to table 4, 4, 6, and 7.

game and cooperative game contribute to 2% in 5G network management issues. Fig. 7 and 8 show the classification of articles to highlight the current research trends.

III. OVERVIEW OF 5G NEW RADIO

This section provides a comprehensive foundation about 5G NR network architecture, high-level use cases, and physical layer deployment methodologies with key performance indicators (KPIs). Majority of work found in literature using coalition games in 5G focus on resource management and interference management. Subsections III-D and III-E briefs the related issues. Today's high data rate and energy efficiency requirement influence 5G network architecture to increase node density through small cell deployment. 5G includes macro cell, picocell, and femtocell deployment layouts to increase node density. 5G supports massive MIMO to increase spatial diversity, reducing the probability of deep fade and increasing the network's availability and reliability. The high-frequency use is aimed to improve the overall system throughput and reduced transmission cost. Through higher frequency operations, a larger bandwidth can be provided, which significantly improves the system capacity. High frequency enables the wireless backhaul (mmWave Back-haul) implementation. The small cell deployment, beamforming, antenna arrays, limited reference signals, larger bandwidth, and advanced sleep mode at gNB are implemented to improve the energy efficiency in the 5G system. Nevertheless, 5G supports device-to-device (D2D) communication and cognitive radio communication through spectrum sharing. The Fig. 9 shows the 5G radio access network architecture. Next subsections III-A and III-B briefs 5G high level use cases and physical layer technologies.

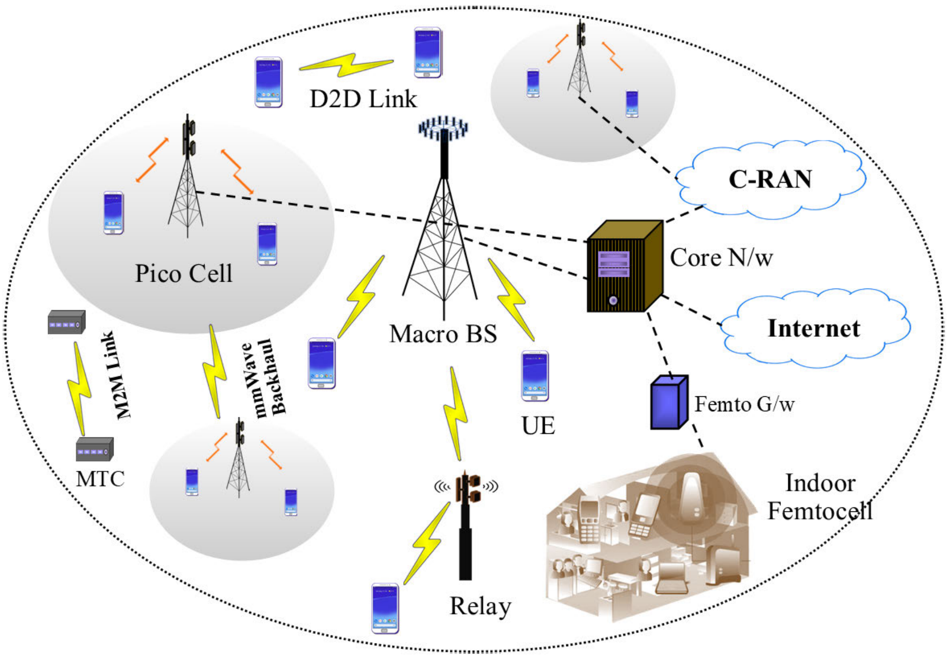

FIGURE 9. 5G radio access network architecture.

A. 5G NR HIGH LEVEL USE CASES

The key features of 5G NR enables diverse application areas. 5G NR radio interface is a multi-disciplinary design. The relationship between the high level use cases and the KPIs with requirement level is shown in fig. 10. The some of high level use cases are as follows [2], [7], [17].

1) eMBB: enhanced Mobile BroadBand (eMBB) can serve the huge number of connected devices. The typical uses of eMBB are applications like VoIP, video streaming, interactive games etc.
2) massive MTC: 5G NR design aims to support massive number of machine type communication devices (MTCDs) such as sensors, meters, and actuators. The design of 5G features the requirements of machine type communication (MTC) such as variable packet size, ultra dense connectivity, energy efficiency, and etc.
3) uRLLC: Ultra reliable and low latency communication (uRLLC) provides support to mission critical applications. Small cell deployment and NOMA through grant free access significantly reduce the end-to-end and user plane latency.

B. 5G NR PHYSICAL LAYER DEPLOYMENT TECHNOLOGIES

5G NR incorporates many physical layer technologies with existing RAN to support the aims specified. The relationship between the physical layer deployment technologies and the KPIs with requirement level is shown in fig. 11. Some of the physical layer technologies used by 5G NR are as follows [2], [7], [9], [18].

1) mmWave MIMO: Only a limited number of frequency-bands are available in the currently used sub 6 GHz spectrum. It is not sufficient to support the increased demand for data-rate and connectivity—the mmWave exploits the high-frequency band from 6 to 300 GHz.
2) Massive MIMO: Massive MIMO provides ease of signal processing and huge spatial multiplexing gain using a large number of antennas (antenna arrays). Massive MIMO offers better energy efficiency by reducing radiated power.
3) Non-orthogonal multiple access (NOMA): In NOMA, more than one user can be allocated to a single time-frequency resource to increase the spectral efficiency and massive connectivity. NOMA also offers low latency through grant-free access.
4) Cooperative communication: Cooperative communication (CC) reduced the outage probability and offered a high diversity gain by employing more relays between the user equipments (UE) and gNB. Relays enhance the quality of received signals.
5) Cognitive Radio: Cognitive radio (CR) enables the opportunistic use of the spectrum by secondary users, which is allocated to primary users. It offers better spectrum utilization.
6) Small Cell: The small cell deployment enhance the coverage for deeper areas, reduces network latency, support massive connectivity, and reduce energy consumption.
7) Beam-forming: Generally, energy of radio waves spreads in spherical direction. The beam-forming is way of transmitting the radio signals in only the direction of the receiver, which significantly decreases the energy consumption.
8) Reduced reference signals: Unlike LTE, there is numerous always on signals which increase energy consumption and interference between devices. 5G NR

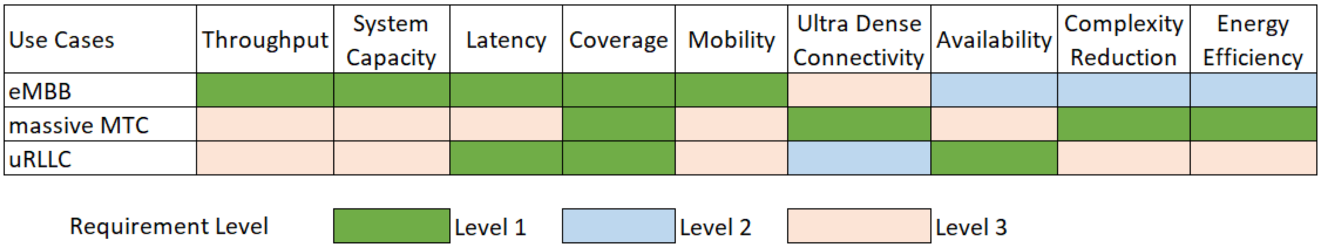

FIGURE 10. Relationship between the high level use cases and the KPIs with requirement level.

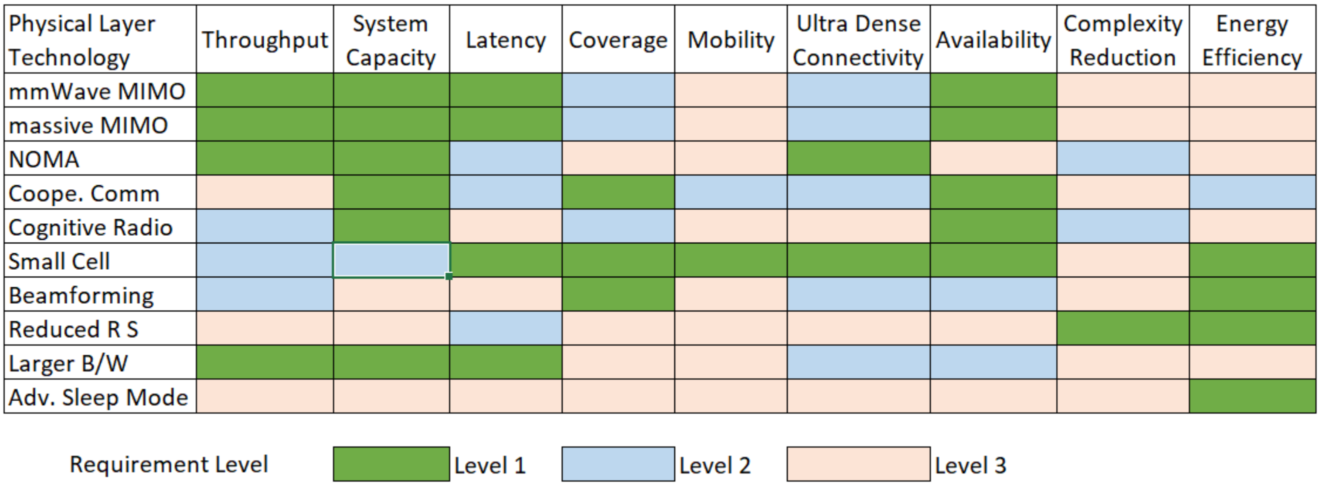

FIGURE 11. Relationship between the physical layer deployment technologies and the KPIs with requirement level.

uses very less number of reference signals to improve energy efficiency and device throughput.

9) Larger bandwidth: The lower radio frequencies are occupied by different services, so it is difficult to get larger bandwidth. 5G NR aims to operate on larger frequencies to get a larger bandwidth on reduced price. This reduce the cost of data transmission per bit.
10) Advance sleep mode: 5G NR implements advance sleep modes at gNB to improve energy efficiency.

Key performance indicators (KPIs) are used to evaluate the performance of deployed physical layer technologies and fulfillment of the objective of the use case.

C. 5G NR PERFORMANCE MEASUREMENT

The key performance indicators demonstrate that how effectively and efficiently a system can work. The KPIs for 5G NR are defined as follows [10], [18], [19].

1) Throughput: The data transfer rate experienced by the end-user is closely related to the bandwidth allotted and the spectral efficiency. There is a trade-off between KPIs like system capacity, mobility, and dense connectivity.
2) System capacity: System capacity is defined as the amount of traffic supported by the system.
3) Latency: The latency is defined in two ways. One is end-to-end latency in data transfer from the source application layer to the destination application layer, and another is user plane latency in data transfer from the MAC layer to the physical layer.
4) Coverage: Coverage is defined as the availability of the radio signals with a minimum required strength for a certain distance and at inaccessible locations.
5) Mobility: The user equipment (UE) may have low to high mobility. The network should support the mobility efficiently.
6) Ultra dense connectivity: It is the measurement of how many user can be serviced simultaneously.
7) Availability: The availability can be seen as how much the probability of deep fade can minimize.
8) Complexity reduction: This is defined as how efficiently, with minimum resources, the radio signals can be processed.
9) Energy efficiency: Energy efficiency can be defined as the power consumption per bit data transfer.

D. RESOURCE MANAGEMENT ISSUES IN 5G NR

Managing access to shared resources for a large number of entities is commonly known as the resource management problem. The solution to this problem should address the

TABLE 2. Common resource management issues in 5G NR.

Issue No.	Issue	Objective	Metric	Remark
RMIS_1	B/w Allocation	Spectrum Efficiency	GBR, Delay	As per the B/w requirements of UE or groups of UE's
RMIS_2	Spectrum Sharing	Spectrum Efficiency	Type of UE/Services	Licensed / unlicensed spectrum sharing.
RMIS_3	Power Allocation	Energy Efficiency	CQI	Optimal power allocation.
RMIS_4	Beamforming / Antenna Selection	Energy Efficiency	Directivity gains	Directiona data transfer.
RMIS_5	User Groupping	Massive Connectivity	Trrafic Patterns, QoS	Traffic aggrigation to reduce number of packets.
RMIS_6	Frame Aggregation	Throughput	Buffer, Delay	Havey uplink / downlink transmission.
RMIS_7	Relay Selection	Coverage	CQI	Extend signal coverage.
RMIS_8	E2E QoS	QoS Satisfication	QoS of UEs	Like priority, delay, GBR etc.

TABLE 3. Common interference management issues in 5G NR.

Issue No.	Issue	Scenario	Metric	Remark
IMIS_1	Adjacent channel interference	Single Cell	Filtering of a receiver	Channel leaks its energy and signal added to the frequency adjacent to that band.
IMIS_2	Inter-cell interference	Multi cell	Frequency reuse	Due to proximity cell edge users
IMIS_3	Intra-cell interference	Single Cell	Frequency reuse	Proximity of same cell users
IMIS_4	Intra-channel interference	Multi cell/Femto	Filtering and Sampling factor	Observed in multi-low power cells within a macro cell mobile network
IMIS_5	Inter-channel interference	Single Cell	Guard Band	Two different but partially overlapping channels
IMIS_6	Inter-symbol interferenc	Single Cell	Cyclic prefix	Caused by the phase as well as amplitude dispersion in the channel
IMIS_7	Inter-carrier interference	Single Cell	Subcarrier spacing	Due to the frequency offsets, the signal lost the orthogonality among the subcarriers
IMIS_8	Inter-numerology interference	Single Cell	Coding Scheme	Due to non-orthogonality between the multiplexed signals/subcarriers
IMIS_9	Cross-link interference	Multi cell	Time Frequency Separation	Neighboring cells transmit signals in different directions simultaneously on the same or partially overlapping time-frequency
IMIS_10	Inter-beam interference	Single Cell	Sidelobe level	The space division of multiple beams introduces inter-beam interference
IMIS_11	Co-tier interference	Single Cell	Frequency reuse	Observed when both users reside in the same network tier
IMIS_12	Cross-tier interference	Multi cell HetNet	Frequency reuse	Interference is received when macro BS at a distant location to the macro user but close to the femto access point

individual access requirements of the entities trying to gain access to the network. This is a key part of resource management in 5G and is an assignment problem, where radio resources need to be allocated to competing entities. The objectives of this assignment problem are to allow the maximum number of simultaneous connections, consume the least amount of energy, and ensure that quality of service (QoS) requirements of communicating devices [20]. IoT or M2M systems have a massive number of devices, and the data traffic pattern is heterogeneous; for example, most of the M2M devices need to send small data, MTDCs may require to send data frequently or periodically, maybe delay bound or delay-tolerant. Clustering of machines for better spatial reuse has been considered as one key technology for supporting machine- to-machine (M2M) communications with a large number of communicating devices. The benefits of clustering include not only the possibility of using smaller transmission powers for improving spatial reuse, but also the possibility of performing data aggregation and data compression at the cluster head for reducing the required aggregate data rate [21]–[23].

Device's applications are versatile and have different QoS requirements associated with them based on the context in which they are being used, and these requirements need to be satisfied once they are granted access to the network. Access and scheduling of devices to the shared network resources needs to be managed efficiently, and a satisfactory service level has to be maintained. The following metrics are identified as the most essential ones when managing accesses and scheduling of a massive number of devices [24].

- ***Access delay:*** The adopted access management strategy should take the access delay requirements into account while granting or rejecting access to the network.
- ***Success rate:*** The success rate of access attempts should be high under heavy load.
- ***Energy efficiency:*** The energy consumed by the access management strategy should be reasonable.
- ***Quality-of-Service (QoS):*** QoS guarantee includes some service requirements that need to be met. One major requirement is the delay requirement.

Several authors addressed the different types of interference in the 5G network and proposed solutions. In this study, we analyze the work done by the authors towards resource management and the proposed solution based on the coalitional game theory.

E. INTERFERENCE MANAGEMENT ISSUES IN 5G NR

Interference is the distortion in the transmitted signal due to other signals transmitted by nearby devices. The standard types of interference in the cellular network are self-interference due to shared transmitter, multiple-access interference due to multiple radios using the same frequency, co-channel interference due to full frequency reuse, and adjacent channel interference caused by sending multiple links in the same direction [25], [26]. Generally, interference is caused by the frequency offset due to oscillator mismatch, Doppler effect, and fast fading due to the motion of transceivers. The different types of interference issues in 5G are listed in table 3. To accommodate the densely deployed large number of different type of devices, 5G use multiple technologies to meet the expectations as shown in Fig. 9. 5G NR supports heterogeneous network architecture by incorporating different types of physical layer technologies. Concurrent operation of multiple small cells and uses of multiple communication technologies in a limited area increase co-tire and cross-tire interference [27]. A multi-cell with full frequency reuse scenario causes inter-cell interference, especially to the devices at the cell boundary. 5G supports direct device-to-device (D2D) communication in a shared spectrum model. D2D communication is not scheduled by eNB. Therefore D2D communication may cause interference to other nearby devices [28], [29]. Interference caused in any manner affects the overall network performance. Thus, interference is crucial to work a cellular network efficiently. It is desirable to provide required services efficiently to all users include cell edge users. Interference degrades system utilization and increases energy consumption [30], [31]. Several authors addressed the different types of interference in the 5G network. In this study, we analyze the work done by the authors towards interference, and the proposed solution based on the coalitional game theory.

IV. COALITIONAL GAME THEORY PLATFORMS

Among the many classifications of games in game theory, one of the perhaps more important is that based on binding agreements. This is essentially a classification between games where players can choose to work together and those where every player competes with every other player [32]. These two classifications are the same because only the presence of a binding agreement, abstract as the concept may be, can prevent a player from making a choice that would benefit him more than the current choice. The first type of game is called a co-operative game or a coalitional game, and the second is called a non-cooperative game. In both games, the main focus of players is self-interest, but for a player himself in non-co-operative games and form a coalition in a co-operative game.

Solution concepts in coalitional games are pretty different from those in non-cooperative games. Firstly it is assumed in coalitional games that the coalition of all players forms, called the grand coalition. Thus a significant part of coalitional game theory, which is the focus of most solution concepts, is trying to distribute the payoff gained by the grand coalition amongst all it's players.

Coalitional game theory is a sub-field of game theory dealing with groups of players [33]. In a most basic form, it deals with possible groups of people and the payoffs these groups get [13]. A coalitional approach tries to answer the following two questions:

1) Which coalition will form out of all possible coalitions?
2) How will the total payoff be divided amongst all coalitions?

Note that the internal mechanisms and functioning of any coalition will be ignored in a coalitional game-theoretic perspective. It is also not concerned with how any coalition will form, in the sense that it does not bother with which events lead to the formation of a coalition [13], [34].

A coalitional game is formally defined as an ordered pair (N,v) where N is the set of all players (or actors) and $v : 2^N \rightarrow \mathbb{R}$ is a payoff function (also called a characteristic function) assigning to each possible coalition return a real number as a payoff. Denote the set of all games with the player set N as $\mathcal{G}^N$ (precisely the set of all games with player set N with transferable utility, which will be elaborated upon later). This set can be considered to be just the set of all possible payoff functions. It is evident that g a coalition, in this case, is modeled by any subset of N.

Under this framework, there are two common solution concepts used. The first concept is the core, which is modeled around ensuring that the coalition formed is stable and does not collapse. The second is modeled around ensuring fair distribution of payoff amongst all coalition members and is known as the Shapley value. It is important to note that the two concepts, by definition, seem to deal with two independent aspects of games and do not seem to be mutually exclusive ideas. It is indeed true that in an extensive class of crucial games, the payoff profile constituted of the Shapley values falls within the core [35], [36].

One almost axiomatic assumption is taken when dealing with coalitional games, which is known as the transferable utility assumption. This assumption states that the payoffs for any two players are comparable. This assumption allows for statements of the form ''Outcome X is better for player A than for player B'' in slightly more colloquial terms. This assumption is almost inherent in coalitional games since the payoff for a group must eventually be divided amongst its members. However, there are coalitional games where it does not hold [37].

There is a large class of games called cohesive games. A cohesive game is one where a coalition has a payoff greater than or equal to the sum of the payoffs of any set of complete disjoint sub-coalitions and defined as follows.

$$v(S) \geq \sum_{i=1}^{k} v(S_i) \quad \textit{for any partition } (S_1, S_2 \ldots, S_k) \textit{ of } S \quad (1)$$

A. THE CORE

How would any coalition formed be stable? It would disintegrate if any of its players would benefit by forming or joining other coalitions [38], [39]. Assume that the game being considered is cohesive. In this case, leaving the question of the division of payoff still open makes sense for only the grand coalition to form. Call any sequence of N real numbers $(x_1, x_2 \ldots, x_N)$ a feasible payoff profile, if

$$\sum_{i=1}^{N} x_i = v(N) \tag{2}$$

Define, for any coalition S and a given payoff profile $(x_1, x_2 \ldots, x_N)$, $x(S)$ as follows.

$$x(S) = \sum_{i \in S} x_i \tag{3}$$

Define as an imputation any payoff profile which is both feasible and satisfies

$$x_i \geq v(\{i\}) \tag{4}$$

The core is the set of all imputations x such that there is no sub-coalition S with $x(S) < v(S)$. There is a natural question regarding the emptiness or non-emptiness of the core. Specifically under which conditions the core will or may be empty. This question turns out to have an answer, fortunately. For a coalition, S, let $\mathbb{R}^S$ denote the $|S|$-dimensional Euclidean space with coordinates indexed by the players i in S. Also represented by 1_S the characteristic vector of the coalition S; the N-dimensional vector with the i^{th} coordinate being 1 if $i \in S$, and 0 otherwise. Assign a non-negative weight to each coalition S λ_S such that for each player,

$$\sum_{S \ni i} \lambda_S = 1 \tag{5}$$

Such a collection of weights is called a balanced collection of weights. Evidently for each λ_S, $0 \leq \lambda_S \leq 1$. Finally, call a game balanced if for every balanced collection of weights (λ_S),

$$\sum_{S \in 2^N} \lambda_S v(S) \leq v(N) \tag{6}$$

The following result, called the Bondareva-Shapley theorem relates the ideas of a balanced game and the core when the transferable utility assumption holds [40], [41].

B. THE RECURSIVE CORE

The recursive core is defined to deal with externalities in a coalitional game. This concept is defined through Partition Function Form games. Partition Function form games generalize Transferable Utility games by using a partition function, defined as $V : \Pi \rightarrow (2^N \rightarrow \mathbb{R})$, which assigns to each *partition* of players a different characteristic function [42], [43]. In such a game, the payoff of a coalition can itself vary between the different partitions it is in. A Partition Function form game is now defined as a pair (N, V).

What is an outcome of such a game? Now, an outcome must involve more than just a coalition, and it must incorporate an entire partition. In this case, an outcome consists of both a payoff division and a partition. Specifically, an outcome is a pair $(x, \mathcal{P})$ satisfying $x_i \geq 0$ and $x(S) = V(S); \forall S \in \mathcal{P}$. The first condition is a much weaker generalization of the notion of an imputation, which cannot be well defined anymore. Denote as the set of all outcomes for (N, V) $\Omega(N, V)$.

This definition of a Partition Function form game cannot generalize the notion of the core very quickly. The dependence of the payoff of one coalition on the entire partition implies that the deviation of some sub-coalition can change the payoff of distinct coalitions. The deviators themselves can have different payoffs in different partitions [44]. A new solution concept over such a game is defined based on the concept of a Residual game. Consider some subset of players $R \subset N$. Assume that the players $N - R$ have formed a partition of coalitions $\mathcal{P}_{N-R}$. Define a function $V_{P_{N-R}}$ as $V_{P_{N-R}}(P_R)(S) = V(P_{N-R} \cup P_R)(S)$ for each coalition $S \subseteq R$. Then the residual game is defined as $(R, V_{P_{N-R}})$. Note that $V_{P_{N-R}}$, though defined using $N - R$, is in itself a function over the partitions of R. Thus the residual game is by itself a full Partition Function form game over R. Specifically note that any solution for N must also solve R.

The recursive core is defined in many steps. The recursive core of the game $(1, V)$ is the only outcome of that game. The recursive core of a general game (N, V) is the set of all undominated outcomes. An undominated outcome here refers to an outcome that is not dominated by any coalition. The notion of an assumption about a game is used to define dominance via coalitions. The assumption about (R, V), $A(R, V)$ is its recursive core if that is nonempty and is the set of all outcomes of that game otherwise. Optimistic and pessimistic cores are defined, for each of which the definition of dominance is slightly different [42], [43]. For the optimistic core, the outcome $(x, \mathcal{P})$ is dominated via the coalition S forming partition $\mathcal{P}_S$ if $\exists (y_{N-S}, P_{N-S}) \in A(N - S, V_{P_{N-S}})$ such that $((y_S, y_{N-S}), P_S \cup P_{N-S})$ is an outcome of (N, V) and $y_S > x_S$. For the pessimistic core, the outcome $(x, \mathcal{P})$ is dominated via the coalition S forming partition $\mathcal{P}_S$ if $\forall (y_{N-S}, P_{N-S}) \in A(N - S, V_{P_{N-S}})$ such that $((y_S, y_{N-S}), P_S \cup P_{N-S})$ is an outcome of (N, V) and $y_S > x_S$.

C. THE SHAPLEY AND BANZHAF VALUES

The next solution concept, called the Shapley value, is modeled around a fair division of the total payoff given to the coalition. The Shapley value, as the name implies, is a value. The term "value" here has a different meaning, however. A value is defined as a map ψ, where $\psi : \mathcal{G}^N - > \mathbb{R}^N$ [45]. Assume again that the games being discussed are cohesive. Fairness in the context of the Shapley value is modeled by marginal contribution; each member of the coalition deserves a payoff proportional to how much he/she adds to the coalition [39].

There are many approaches to the definition of the Shapley value. For a Transferable Utility coalitional game (N, v), let

$\sigma : N \rightarrow N$ denote any permutation of the player set. Note that this permutation can also be construed to represent some order in which the grand coalition is formed. In this sense, $\sigma(i)$ represents the i^{th} player to join the coalition [46], [47]. In this case, let $P_\sigma(i)$ denote the coalition of all players before i in the permutation σ. It can be formally be defined as follows.

$$P_\sigma(i) = \left\{ j \in N | \sigma^{-1}(j) < \sigma^{-1}(i) \right\} \tag{7}$$

For this permutation, it is now possible to measure the marginal contribution for each player. The vector of marginal contributions, denoted by m^σ, can be defined as follows.

$$m_i^\sigma(v) = v(P_\sigma(i) \cup \{i\}) - v(P_\sigma(i)) \tag{8}$$

The Shapley value is a vector. It is denoted by $\varphi(N, v)$ and is quite simply the component-wise average of the marginal vectors over all possible permutations. It is defined as follows.

$$\varphi(N, v) = \frac{1}{|N|!} \sum_{\sigma \in \Pi(N)} m^\sigma \tag{9}$$

where $\Pi(N)$ is the set of all permutations of the set N. The Shapley value of a player i has another form. It is clear that overall permutations, the set of all values of $P_\sigma(i)$ is exactly the set of all coalitions that do not contain i. Furthermore, $P_\sigma(i)$ appears as S exactly $|S|!$ time. Thus each component of the Shapley value takes an alternate form [44].

$$\varphi_i(N, v) = \frac{1}{|N|!} \sum_{S \subseteq N - \{i\}} |S|!(|N| - |S| - 1)! * (v(S \cup \{i\}) - v(S)) \tag{10}$$

A second interpretation of the Shapley value is the axiomatic interpretation. The Shapley value is the only value that satisfies the properties of additivity, efficiency, symmetry, and null players simultaneously.

1) EFFICIENCY

The Shapley value can be used to construct a fair payoff profile $(x_1, x_2 \ldots, x_N)$ as follows and easy to prove.

$$x_i = \varphi_i(N, v) \tag{11}$$

and

$$\sum_{i \in N} \varphi_i(N, v) = v(N) \tag{12}$$

2) SYMMETRY

Two players could be considered equivalent when discussing coalitions if they contribute precisely to every coalition for which they are not a part [43]. Two players i and j interchangeable for a game (N, v) if

$$v(S \cup \{i\}) = v(S \cup \{j\}); \quad \forall S \in 2^{N-\{i,j\}} \tag{13}$$

The Symmetry property states that the payoff allotted to any two interchangeable players should be equal. Mathematically, given that the payoff profile $(x_1, x_2 \ldots, x_N)$ is fair, it must satisfy the following.

$$(v(S \cup \{i\}) = v(S \cup \{j\})) \longrightarrow x_i = x_j) \quad \forall i,\ \forall j,\ \forall S \in 2^{N-\{i,j\}} \tag{14}$$

3) NULL PLAYERS

A player is a null player if he contributes nothing to any coalition he is a part of [43]. Mathematically i is a null player if

$$v(S) = v(S \cup \{i\}); \ \forall S \subseteq N - \{i\} \tag{15}$$

The Null Player property states that no payoff should be allotted to any null player. Mathematically, given that the payoff profile $(x_1, x_2 \ldots, x_N)$ is fair, it must satisfy

$$(v(S) = v(S \cup \{i\})) \longrightarrow x_i = 0); \quad \forall i\ \forall S \subseteq N - \{i\} \tag{16}$$

4) ADDITIVITY

Given that the payoff function v can be additively decomposed into two payoff functions v_1 and v_2, the Additivity property states that the payoff for any individual player must also decompose to the two functions [43]. Mathematically,

$$\varphi_i(N, v_1 + v_2) = \varphi_i(N, v_1) + \varphi_i(N, v_2); \quad \forall i \in N \tag{17}$$

There is another property satisfied by the Shapley value called strong monotonicity. It is defined below.

5) STRONG MONOTONICITY

For two games v and w with the same player set N, if the player marginally contributes at least as much for every coalition in the game v as he/she does in the game w, this player should get at least as much payoff from the Shapley value for game v as he/she should for the game w [46]. This property, defined for any value ψ, is called strong monotonicity. Mathematically, for a value ψ,

$$\forall i \quad (\forall S \subseteq N - i \quad v(S \cup i) - v(S) \geq w(S \cup i) - w(S)) \rightarrow \psi_i(v) \geq \psi_i(w) \tag{18}$$

Strong monotonicity leads to yet another interpretation of the Shapley value. The Shapley value is the only value that satisfies the axioms of efficiency, symmetry, and strong monotonicity simultaneously. There is yet another important reason this value is beneficial. Define a convex game as a (N, v), which satisfies the following.

$$\forall S \subset N \quad \forall T \subset N\ (v(S \cup T) \geq v(S) + v(T) - v(S \cap T)) \tag{19}$$

It can be shown that for all Convex games, the core is not only non empty, but also contains the payoff profile constructed off the Shapley values. To wind up this discussion, there are many other solution concepts. One of them is called the Banzhaf value. This value, ψ is defined by

$$\psi_i(v) = \frac{1}{2^{|N|-1}} \sum_{S \subseteq N - \{i\}} v(S \cup \{i\}) - v(S) \tag{20}$$

The Banzhaf value, like the Shapley value, can be axiomatically characterized. This characterization requires another property, called 2-Efficiency, defined below.

6) 2-EFFICIENCY

This property deals with some sense with the process of combination of players. Specifically, amalgamate two players i and j in N to some other player p. This entails removing the two players and any coalitions they can be a part of from the game and introducing an "amalgamated" player p in their stead [46]. Mathematically, for the game (N,v), with $i, j \in N$, define $p = \{i, j\}$ and define the game $((N \cup \{p\}) - p, v_p)$ where

$$\forall S \subseteq N - p \quad v_p(S) = v(S) \tag{21}$$

and

$$\forall S \subseteq N - p \quad v_p(S \cup \{p\}) = v(S \cup p) \tag{22}$$

The value ψ satisfies 2-Efficiency if

$$\psi_i(v) + \psi_j(v) = \psi_p(v_p) \tag{23}$$

Having defined 2-Efficiency, it can be shown that the Banzhaf value is the only value that satisfies the 2-Efficiency, Symmetry, Strong monotonicity and Null Player properties simultaneously [40], [47].

D. BAYESIAN COALITIONAL GAMES

A Bayesian coalition game is a game where each player does not know everything about the game he/she is playing. It is implemented by modeling the information and beliefs that players have. The ideas are expounded below. Consider a set of events that may have occurred, S. Let this set have N elements, labeled $1..N$. A player need not know which event has occurred. However, he/she can partition the set of all events into *Information Sets*. The idea behind this *Information Partition* is that the player knows that it is one of the events in a given set that has occurred, but no event outside of the set has happened [48]–[50].

Further, the player does not know which event in a set has occurred. Some events in a set may be more likely than others, but none are specific. To some extent, each set represents some similarity between the events it contains. For a simple example, consider events described by two properties, A and B. A can take two values $A1$ and $A2$, and B can take three values $B1$, $B2$ and $B3$. Now let E be the set of five such possible events {E1 (described by values ($A1$,$B1$)), E2 (described by values ($A1$,$B2$)), E3 (described by values ($A1$,$B3$)), E4 (described by values ($A2$,$B1$)), E5 (described by values ($A2$,$B3$))}. Two players 1 and 2 know that some event has occurred, but they have incomplete information about the event itself. Player 1 knows the value of property A, while player 2 knows the value of property B. They, of course, know that the event that occurred was from set E. Now the information partition for player 1 is {{E1,E2,E3},{E4,E5}} while the information partition for player 2 is {{E1,E4},{E2},{E3,E5}}. Assume that event E1 occurred. Player 1 hence knows that the event had the value $A1$ for the property A. He thus knows that one of events E1, E2, and E3 has occurred or that the first information set contains the event that occurred. Player 2 knows that the value of B for the event that occurred is $B1$ and that thus the information set containing the correct event is {E1, E4}. Both these players also know that none of the events outside these information sets occurred [51], [52].

Consider the claim above that states that both players know that the event occurred in set E. It raises a natural question; what else is known to every player? Consider another set of two players, with six possible events {E1, E2, E3, E4, E5, E6}. Let their information partitions be {{E1},{E2, E3}, {E4}, {E5,E6}} and {{E1, E2}, {E3}, {E4, E5}, {E6}} respectively. In this case, there is more *Common Knowledge* between the players. More formally, there is another information partition that represents the knowledge common to every player. In this case, one such partition is {{E1, E2, E3}, {E4, E5, E6}}. Observe that if E1 has occurred, both players know that none of the events in {E4, E5, E6} has occurred. Observe that in this case, both players know that E3 has also not occurred. However, player 1 thinks that E2 is also a possibility, and in this case, he cannot be sure what player 2 knows. Thus, common knowledge represents information that every player has and the knowledge that any player knows every other player also to have. For this to happen, every player needs to know every player's information partition, and they need not know which specific information set of every player. Any such partition is called a *Common Knowledge Partition* [48], [49]..

In the context of the above example, consider that the event that occurred was E2. Players 1 and 2 now have different information sets. They need to take further action based on their information sets. Nevertheless, they need to know the likelihood of each possible event in their information set for this action. There can be many ways to model these *beliefs* the players have, but probability using Bayes' theorem provides a way for players to improve upon their beliefs iteratively. Using this rule implies that there should be a prior probability distribution over all the possible events that represent their likelihood. Bayesian belief updating using this distribution should make the beliefs of all players consistent, both with this distribution and with each other. Furthermore, this probability should be known to all the players. This distribution is called a *Common Prior* [51], [52].

In the case of Bayesian Coalitional Games, each player is assumed to have a *type*. This type completely characterizes the behavior of the player. Each player has some set of possible types, any of which they can be. Each player, of course, knows their type. The Cartesian Product of all the possible type sets is the set of *type profiles*. If T_i is the set of types for player i, and N is the set of possible players, then $\times_{i \in N} T_i$ is the set of all possible types profiles. Every player need not know the types of other players, but they do have *beliefs* about the types other players can have. They need to take action based on these beliefs. These beliefs are expressed through

Bayesian probability, hence the name of the game. There is also a *common prior* over all the possible type profiles. Players form their beliefs based on this common prior [48], [49].

Some more abstraction is required to resolve the uncertainty with regards to payoffs here. For every coalition C is defined a set of possible *coalitional actions* A_C. Each action is associated with an *outcome* or a *state*. The outcomes associated are not deterministic; the same coalitional action taken by a coalition, assuming that the players of that coalition have fixed types, can lead to various outcomes. For instance, any skilled workers have a chance, and no might how small that chance may be, to perform a shoddy job. Let the probability of the outcome s, for an action α performed by a coalition C with relevant components of type profile $\vec{t}$ being $\vec{t_C}$ be denoted by$Pr(s|\alpha, \vec{t_C})$. Under these circumstances, the uncertainty of types is modelled, and now a reward R(s), which is assumed to satisfy transferable utility, is assigned to each outcome s. It completes the definition of a Bayesian Coalitional Game [51], [52].

E. INTERVAL GAMES

A cooperative interval game is one defined by an ordered pair (N,w) [53] where N is the set of players and $w : 2^N \to I(\mathbb{R})$ is the characteristic function such that $w(\emptyset) = [0, 0]$. $I(\mathbb{R})$ is the set of all compact, non-empty intervals in $\mathbb{R}$. For each $S \subseteq N$, the worth set $w(S)$ of the coalition S is denoted by $[\underline{w}(S), \overline{w}(S)]$. It is evident that in this notation, $\underline{w}(S)$ is the minimal reward S could get and that $\overline{w}(S)$ is the maximum such reward [54]. Also define $|w(S)|$ as follows.

$$|w(S)| = \overline{w}(S) - \underline{w}(S) \tag{24}$$

Let the set of all possible interval games with the player set N be denoted by IG^N. The following operations are also defined over intervals I and J.

$$I + J = [\underline{I} + \underline{I}, \overline{I} + \overline{J}] \tag{25}$$
$$I - J = [\underline{I} - \underline{J}, \overline{I} - \overline{J}] \tag{26}$$
$$\alpha \in \mathbb{R}_+,\ \alpha I = [\alpha \underline{I}, \alpha \overline{I}] \tag{27}$$

The equation (26) is only applicable if $|I| \geq |J|$. Interval subtraction has also been defined differently in some texts as follows.

$$I - J = [\underline{I} - \overline{J}, \overline{I} - \underline{J}] \tag{28}$$

Also define a $\succeq$ operator as $I \succeq J$ if and only if $\underline{I} \geq \underline{J}$ and $\overline{I} \geq \overline{J}$. Similarly define a $\preceq$ operator. This use of notation with intervals will recur in this paper.

For a given N, IG^N has some desirable properties. Firstly, it is a partially ordered set concerning the order described above. Secondly, it forms a cone over the above-mentioned interval operations defined over w. These games are an extension to coalitional games with Transferable Utility. Interval solutions are built out of interval payoff vectors (vectors whose components are intervals). The set of all these vectors is $I(R)^N$ [55]. The interval imputation set $\mathcal{I}(w)$ is defined as follows.

$$\mathcal{I}(w) = \{(I_1, I_2, \ldots I_n) \in I(\mathbb{R})^n | \sum_{i=1}^{n} I_i = w(N) \wedge \forall i \in N, I_i \succeq w(i)\} \tag{29}$$

And define the interval core $\mathcal{C}(w)$ as follows.

$$\mathcal{C}(w) = \left\{(I_1, I_2, \ldots I_n) \in \mathcal{I}(w) | \forall S \subseteq N \sum_{i \in S} I_i \succeq w(S)\right\} \tag{30}$$

Note the parallels between interval games and non interval coalitional games. Call an interval game (N, w) size monotonic if

$$S \subset T \to |w|(S) \leq |w|(T) \tag{31}$$

Henceforth denote the set of all size monotonic games by $SMIG^N$. This definition is useful to define the parallel for marginal vectors, the marginal operator. This operator m^σ : $SMIG^N \to I(\mathbb{R})^N$ is defined by its components as follows [56], [57].

$$m_i^\sigma(w) = w(P_\sigma(i) \cup \{i\}) - w(P_\sigma(i)) \tag{32}$$

Specifically note that the above operation is defined over intervals only because of size monotonicity. Now again, the interval Shapley value is defined as the average of all marginal vectors. The Shapley value, defined for each game is a function as $\Phi : SMIG^N \to I(\mathbb{R})^N$, is again the average of marginal vectors an defined as follows.

$$\Phi(w) = \frac{1}{|N|!} \sum_{\sigma \in \Pi(|N|)} m^\sigma \tag{33}$$

This value again is the only value satisfying the four properties of efficiency, additivity, symmetry and null players. The interval Banzhaf value can also be defined. For any interval game w and any real number $\alpha \in [0, 1]$, define an associated TU coalitional game v(α) as follows [55], [57].

$$v(\alpha)(S) = (1 - \alpha)\underline{w}(S) + \alpha \overline{w}(S) \tag{34}$$

It can be shown that if w is size monotonic, then the Banzhaf value of v(α) is non-decreasing over α. Hence define the interval Banzhaf value for the size monotonic interval game w as follows.

$$\psi_i(w) = [\psi_i(v(0)), \psi_i(v(1))] \tag{35}$$

where $\psi(v(\alpha))$ is the Banzhaf value of the coalitional game $v(\alpha)$.

F. COOPERATIVE BARGAINING GAMES

A common thread in cooperative game-theoretic models is an abstraction of concrete strategies that players have at their disposal. Bargaining problems can and have been approached from both a cooperative and a non-cooperative point of view. There is a close relationship between both approaches [45]. The first definition needed is that of a two-person bargaining

TABLE 4. Coalition game theory platforms used in 5G NR.

Platform No.	Platform Name	Methodology	Advantage	Disadvantage
CGP_1	Bayesian Coalitional Games	Common knowledge partition	Player does not know everything about other players.	More abstraction is required to resolve the uncertainty with regards to payoffs.
CGP_2	Interval games	Defined by an ordered pair (N,w) for the set of N players.	Extension to coalitional games with Transferable Utility.	No probabilistic assumptions about the range of coalition values are known
CGP_3	Cooperative Bargaining Games	Focus on possible outcomes of bargaining rather than how the bargaining takes place.	Independence from irrelevant alternatives.	Weak pareto-optimality
CGP_4	Matching Problems	Elements of some set have to be coupled with elements of another set.	Agents need not have a preference over all elements	There should not be two people matched with some other members when they would both instead prefer to be matched with each other.
CGP_5	Overlapping coalition formation	Overlapping coalition allows a player to participate in more than one coalition simultaneously.	Through the overlapping coalition formation, players get flexibility in resource sharing.	An agent would not be able to participate in all possible coalitions due to lack of time, cash flow, or energy.

problem. In cooperative bargaining, how the bargaining takes place is not relevant. The possible outcomes of bargaining, however, are known. In a two-person bargaining problem, the outcomes are defined by the payoffs that these two people receive [58]. In particular, one specific outcome that occurs when the bargaining is unsuccessful is called the disagreement point and is also defined. Such a problem is defined as a pair (S, d) where

- $S \subseteq \mathbb{R}^2$ is convex, closed and bounded.
- $d = (d_1, d_2) \in S$ such that $\exists(x_1, x_2) \in S$ with $x_1 > d_1$ and $x_2 > d_2$

In this definition, S is called the feasible set, and d is the disagreement point. Denote the set of all possible two-person bargaining problems as $\mathcal{B}$. A two-person bargaining solution is defined as a function $F : \mathcal{B} \rightarrow \mathbb{R}^2$, which assigns to each bargaining problem a feasible point $F(S, d) = (F_1(S, d), F_2(S, d)) \in S$. Again, various solution concepts can also be axiomatically characterized [59]. What are possible axioms that should perhaps characterize a bargaining solution?

1) WEAK PARETO-OPTIMALITY

Both players in this game should perhaps not agree on any solution when there is some other solution that benefits them more. Specifically for any S, define the set P(S) as follows [60].

$$W(S) = \{x \in S | y \in S \wedge y_1 \geq x_1 \wedge y_2 \geq x_2 \rightarrow y = x\} \quad (36)$$

The axiom of weak pareto-optimality states that if F is an ideal solution, $F(S, d)$ should belong to the subset of *pareto-optimal* points $P(S)$ of that game for every game $(S, d) \in \mathcal{B}$.

2) SYMMETRICITY

A bargaining problem $(S, d) \in \mathcal{B}$ is symmetric if

$$S = \{(x_1, x_2) \in \mathbb{R}^2 | (x_2, x_1) \in S\} \quad (37)$$

By defining a symmetric problem, it is clear that there is no underlying difference between players. There shouldn't be any underlying difference in the rewards assigned to these players in any symmetric problem in an ideal solution. This is precisely the axiom of symmetry [61]. Mathematically, F is symmetric if

$$\forall(S, d) \in \mathcal{B} \quad (S, d) \textit{ is symmetric} \rightarrow F_1(S, d) = F_2(S, d) \quad (38)$$

3) SCALE COVARIANCE

Scale covariance tries to make the set of feasible points more abstract. It plays on the fact that utilities are useful only relative to each other [62]. In particular, neither a translation of axes of the system of points in S nor a positive scaling of said axes should change the correct solution, whatever it may be in the new axes, for any game. Mathematically, F is scaled covariant if

$$\begin{aligned} &\forall(S, d) \in \mathcal{B} \quad \forall a_1, a_2 \in \mathbb{R}^+ \forall b_1, b_2 \in \mathbb{R} \\ &\quad F(\{(a_1x_1 + b_1, a_2x_2 + b_2) \in \mathbb{R}^2 | (x_1, x_2) \in S\}, \\ &\quad (a_1d_1 + b_1, a_2d_2 + b_2)) \\ &\quad = (a_1F_1(S, d) + b_1, a_2F_2(S, d) + b_2) \end{aligned} \quad (39)$$

4) INDEPENDENCE FROM IRRELEVANT ALTERNATIVES

For any game (S, d), let $F(S, d)$ be some point z. Now let $T \subseteq S$ with $z \in T$ and $d \in T$. Of course, now any solution $F(T, d)$ belongs to S as well. Since the best solution in S was z, the best solution of T should also be z. A solution F is thus said to be irrelevant of independent alternatives if

$$\forall(S, d), (T, d) \in \mathcal{B} \quad T \subseteq S \wedge F(S, d) \in T \rightarrow F(T, d) = F(S, d) \quad (40)$$

A final note is that these axioms can help define a solution but not every possible solution need necessarily satisfies all of these axioms. For instance, in the case of independence from irrelevant alternatives, it is perfectly acceptable that in the subset T. Pareto-optimal solution may be more suitable for both players than the solution in the superset S is also present in T [58], [60]. The axioms defined above uniquely define a solution called the Nash bargaining solution where

$$F^{Nash}(S, d) = z \ \ where$$
$$(z_1 - d_1)(z_2 - d_2) \geq (x_1 - d_1)(x_2 - d_2)$$
$$\forall (x_1, x_2) \in S \ \ with \ \ x_1 \geq d_1 \wedge x_2 \geq d_2 \tag{41}$$

Firstly, a utopia point is defined as follows.

$$u(S, d) = (max\{x_1 | x \in S, x \geq d\}, max\{x_2 | x \in S, x \geq d\}) \tag{42}$$

5) INDIVIDUAL MONOTONICITY

Individual monotonicity is based on the utopia point. This axiom states that unlike independence from irrelevant alternatives, the best utility a player can reach depends on all alternatives present in S. If the utility attained by a player for each possible utility of the other player is weakly larger, then so should this player's utility be in the final agreement? Mathematically,

$$\forall (S, d), (T, e) \in \mathcal{B}$$
$$d = e \wedge S \subseteq T \wedge u_1(S, d) = u_1(T, e) \wedge u_2(S, d)$$
$$= u_2(T, e) \longrightarrow F_1(S, d) \leq F_1(T, e) \wedge F_2(S, d) \leq F_2(T, e) \tag{43}$$

Another solution used is the Kalai-Smorodinsky bargaining solution. Fig. 12 shows the feasible region in Kalai-Smorodinsky bargaining solution. This solution disagrees with the independence from irrelevant alternatives axiom [62]–[64]. The Kalai-Smorodinsky bargaining solution, denoted by $R : \mathcal{B} \rightarrow \mathbb{R}^2$ is axiomatically defined by the axioms of weak Pareto optimality, symmetry, scale covariance, and individual monotonicity. The following procedure also defines it.

1) Draw a straight line from d to u(S,d).
2) Obtain the intersection of W(S) and this line
3) The point obtained is the required solution.

G. MATCHING PROBLEMS

In a matching problem, elements of some set have to be coupled (or *matched*) with elements of another set. A one-one matching means each element of some set matches exactly one element of the other set. Specifically, there are two sets M and W of equal size, and each agent in some set has a preference over some elements of the other set [12], [45].

Agents need not have a preference over all elements; they are not a part of the set. Some agents may prefer to remain unmatched over being matched to some elements in the other set. It is precisely these elements that are not present in the preference relation of that player. These problems are also called marriage problems, with the two sets being men and women. For further discussion, the sets are labeled M and W, respectively [65].

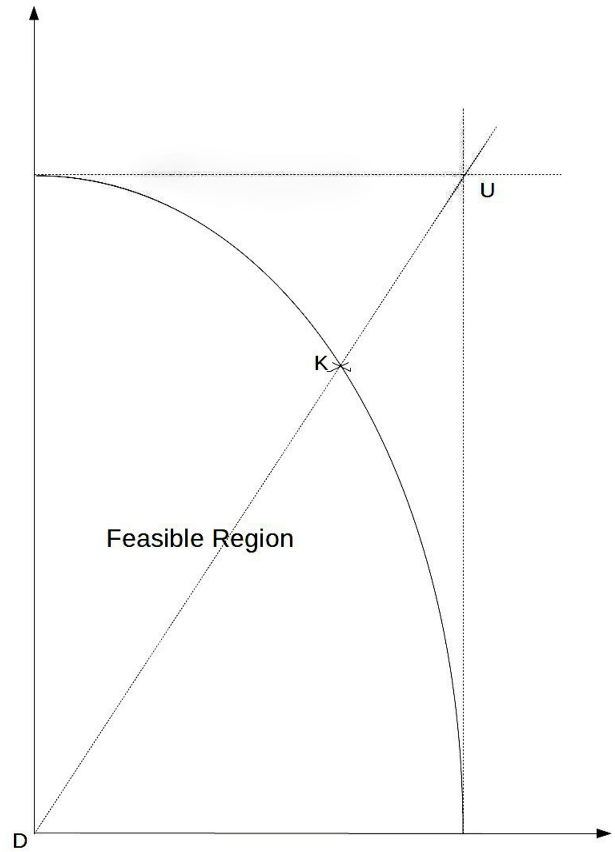

FIGURE 12. An illustration of the Kalai-Smorodinsky solution.

In this problem as well, stability is of importance. In particular, there should not be two people matched with some other members when they would both instead prefer to be matched with each other. Also, no one who would prefer being single over being matched with some member should match that member. All possible matchings that follow these conditions form the core in this case. Furthermore, matching problems have the very beneficial property that some elements in the core can be found algorithmically. The algorithm used here is called the Deferred Acceptance Algorithm. Fig. 13 shows an example of a stable matching. It proceeds as follows [66].

1) Have each unengaged man propose to the highest person on his preference list whom he has not proposed to yet.
2) Mark, each woman along with her highest preference from among all people who proposed during this round and the person she was engaged with possibly during some prior round, as engaged. If the woman was already engaged, her former suitor is now marked as unengaged.
3) The above two steps are repeated until every proposal is accepted.

It can be proved that this algorithm finds a matching in the core. It runs in $O(n^2)$ time [12].

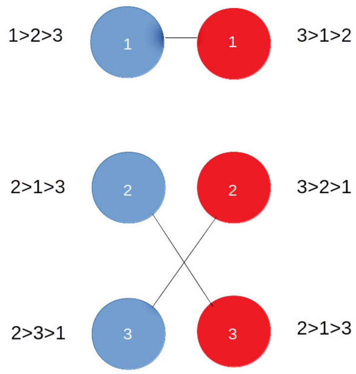

FIGURE 13. An example of a stable matching.

H. OVERLAPPING COALITION FORMATION

Overlapping coalition allows a player to participate in more than one coalition simultaneously. One of the major advantages of an overlapping coalition is to use the resources efficiently. The different coalitions can give different payoffs for sharing the resources [67], [68]. Let, $X = \{1, 2, \ldots, X_N\}$ is a set of N players and $\pi = \{1, 2, \ldots, \pi_M\}$ is a set of coalitions. A player participates in k number of coalitions, and the received $x_i(r)$ payoff from k^{th} coalition, and r is a subset of coalitions in which player i participate. Therefore, to maximize the individual payoff of player i is

$$P_i(\pi, x) = max \sum_{\pi \in r} x_i(r) \tag{44}$$

Through the overlapping coalition formation, players get flexibility in resource sharing. A player can optimize resource sharing and get a better payoff by participating in multiple coalitions.

V. COALITIONAL GAME THEORY PLATFORMS USED IN 5G

Coalitional games are applied in a plethora of sub-areas in 5G. They can be used for various types of 5G resource allocation, to minimize interference, or for scheduling. Fig 14 shows the classification of applications of coalition game-theory in 5G NR and Fig. 15 shows the contribution percentage of coalition games in different areas of 5G NR in surveyed literature.

A. COALITIONAL GAMES IN RESOURCE MANAGEMENT

The field of 5G in itself has multiple subfields where some form of resource allocation is of importance. Coalitional game theory lends itself very well in many of these areas. Fig. 17 shows the contribution percentage of coalition games in resource management in 5G NR. Fig. 16 shows the 5G network deployment types including heterogeneous networks and table 5 shows the comparison of various game theoretic approaches to resource management.

Liu et al. [69] has proposed a joint user association and bandwidth allocation algorithm for ultra dense millimetre-wave small cell networks (UDMN) based on maximizing network sum rate and accommodating downlink traffic of small cells (in the current cell association period) by their wireless back-haul. They have done this by intermediately framing the problem as a mixed integer non linear optimization problem, and then using coalitional games to solve this problem. In the game, the players (the user equipment) form coalitions to associate to small base stations (SBS), to satisfy the objectives.

Coalitional games have been used by authors Yuan et al. [70] to also model bandwidth sharing for 5G 3-layer HetNets. In this case, users can either be connected to the Femto Cell, Pico Cell, or the Macro Cell. Each cell should also divide resources amongst it's members. The authors have modelled this situation as a bandwidth sharing game which has as its players in three cells. The authors assume that bandwidth is transferable. In their simulations, the authors show that the surplus capacity increases with the number of users. When interference is accounted for, the author's simulations show a big gain over a random access algorithm. However, this paper does not consider the case with Coordinated Multi-Points.

Kim [75] has presented a spectrum allocation scheme for HetNets using multi-flow career aggregation (MCA). This approach is based on interval games, and utilizes the bankruptcy game. The classical bankruptcy game divides an estate E among players in the set N where player $i \in N$ claims estate c_i. The difficulty in division is constructed from the assumption that

$$\sum_{i \in N} c_i \geq E, \tag{45}$$

which means that every player cannot simply be given their entire claim, since the estate is large enough. The pair (E, c) defines a classical bankruptcy problem and a corresponding bankruptcy game is defined by the payoff function $v_{E,c}$ as

$$\forall S \subseteq N \quad v_{E,c}(S) = max(E - \sum_{i \in N-S} c_i, 0) \tag{46}$$

$v_{E,c}(S)$ represents the maximum payoff available to S if every player outside S received their entire claim.

In particular, a generalization of the classical bankruptcy claim is the interval bankruptcy game, where each player's claim d_i is represented by a lower and upper bound. In this case too, the estate is insufficient to satisfy the claims in full in any possible division; i.e.

$$\sum_{i \in N} \underline{d}_i \geq E \tag{47}$$

The associated interval game in this case is a little more involved. Firstly, for the interval bankruptcy problem, an associated classical problem is defined called the t-compromise problem. Here, the t-compromise claim is defined as

$$c_i^t = (1 - t_i)\underline{d}_i + t_i\overline{d_i} \tag{48}$$

given a vector $t \in [0, 1]^{|N|}$. As in 34, this function is also non-decreasing in t_i. Now, the associated classical division game

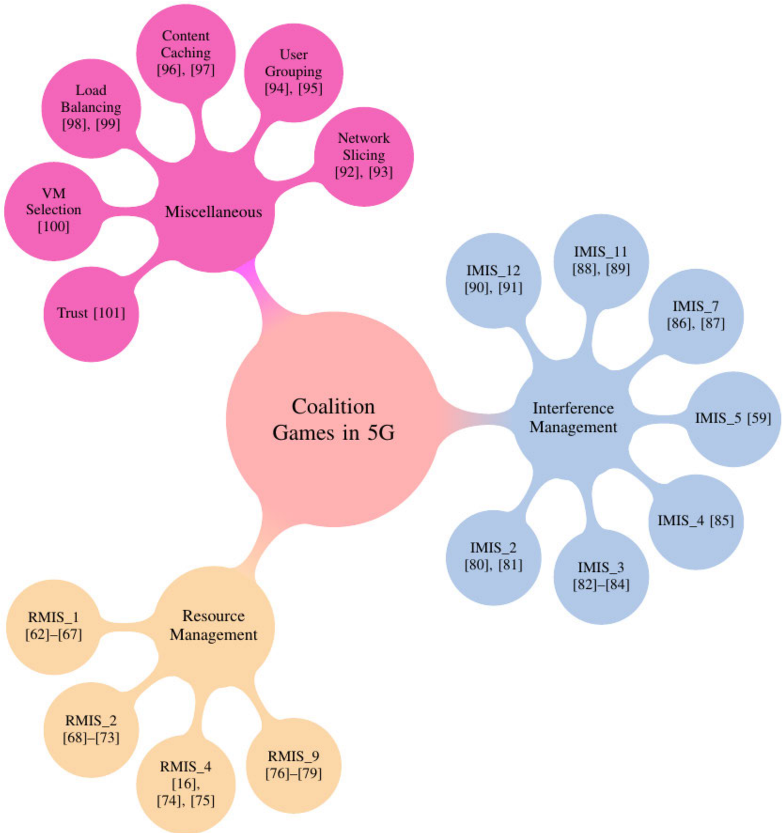

FIGURE 14. Classification of applications of coalition game-theory in 5G NR.

v_{E,c^t} is used to define the interval bankruptcy game $v_{E,d}$ as

$$v_{E,d}(S) = [max(E - \sum_{i \in N-S} \overline{d}_i, 0), max(E - \sum_{i \in N-S} \underline{d}_i, 0)] \quad (49)$$

which is the same as

$$v_{E,d}(S) = [v_{E,c^1}(S), v_{E,c^0}(S)] \quad (50)$$

This interval stands for the maximum amount a coalition can receive if all the players outside it receive their complete claims, against the maximum amount the coalition can receive is all the players outside it receive their minimum claims. Kim has modelled the interaction between each mobile device (MD) and its corresponding base stations (BS) in MCA, for each application, as an interval coalitional game. They have first defined an interval value that represents the service capacity for each BS for each application. This interval value takes into account the two factors spectrum availability and communication distance, that represent service capacity. Based on these values, the MD allocates spectrum from each base station for each application. All multimedia services are divided into two types, class I (which are highly delay sensitive) and class II (which are more delay tolerant). The payoff function is then defined based on the bankruptcy games, and the interval Shapley value and interval Banzhaf value are calculated. Based on the interval values calculated, resources are allocated according to the interval Shapley value for class I services and according to the interval Banzhaf value for class II services.

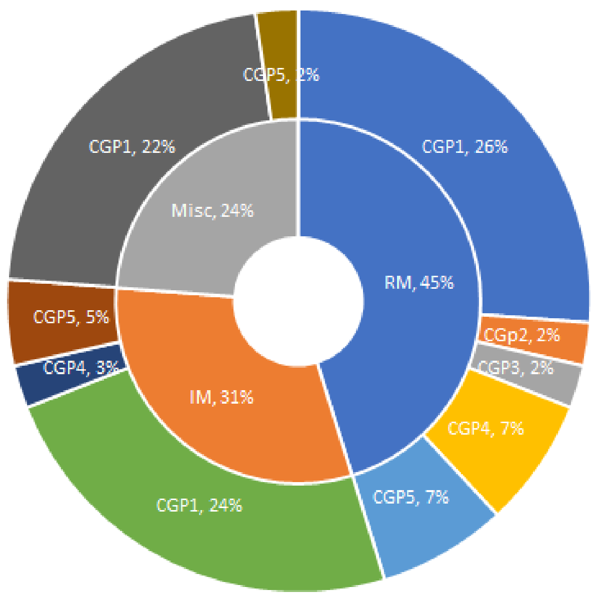

FIGURE 15. Contribution percentage of coalition games in different areas of 5G NR (RM- Resource Management, IM- Interference Management, Misc.- Miscellaneous.

Sun *et al.* [83] has applied coalitional games to Fog Radio Access Networks (F-RAN). Fog Access Points (FAPs), which have edge caching and local radio resource management capabilities, need to jointly optimize their cache and radio

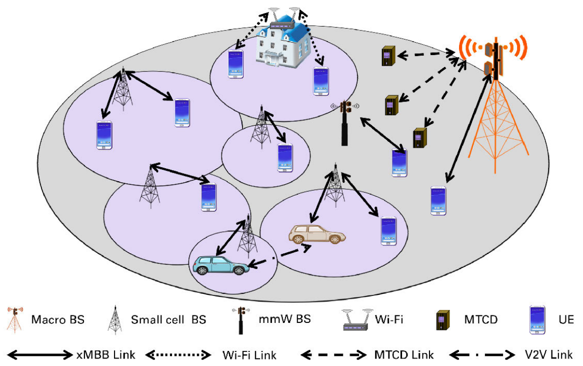

FIGURE 16. 5G network deployment types including heterogeneous networks.

resources. This optimization is done in a hierarchical architecture. In this architecture, the upper layer resource manager optimizes the cache (and subsequently maximizes a long term utility function), which is adaptive to the statistics of channel gains and user content requests. The lower layer FAPs then self organize into multiple clusters to mitigate inter-FAP interference in each transmission interval given user content requests, channel gains and cache configuration. This FAP cluster formation process in each transmission interval is then naturally modelled into a coalitional game. The final joint cache and radio resource management is modelled as a Stackelberg game with the leader being the upper level resource manager and the followers being the FAPs. This is done because the cluster formation strategies of the FAPs depends on the strategy of the resource manager.

In the field of multiple access schemes, Ding *et al.* [81] has proposed a multiple input multiple output non orthogonal multiple access (MIMO-NOMA) cluster beam forming design, based on which they have concluded that power reduction occurs due to mobile users (MU) clustering, and that for each cluster, the maximum power reduction is only due to MUs in the cluster. They have then modelled the subsequent MU clustering problem as a coalitional game. They have modelled the utility for each MU in a cluster based on the average cluster power reduction.

In the case of device to device multi-cast communication (D2MD), Hmila *et al.* [76] has proposed a joint resource and power allocation scheme formulated as a transferable overlapping coalition formation game. These coalitions have each D2MD device or cellular user as members. Coalitions are formed by merge and split rules. This game is not super-additive, so the grand coalition can never be formed.

Authors in Xiao *et al.* [77] have also used overlapping coalitional games, for sharing spectrum resources in licensed and unlicensed bands. Mobile Network Operators (MNO) are the players in this game, each of whose main objective is to slice the shared licensed spectrum and the access probability of unlicensed spectrum to support all types of service. The game is defined by the set of MNOs, the spectrum that can be accessed by MNOs in both bands,the set of service types for each MNO and the utilities obtained by each MNO. Authors in Srinivasan *et al.* [78] have also applied coalitional games

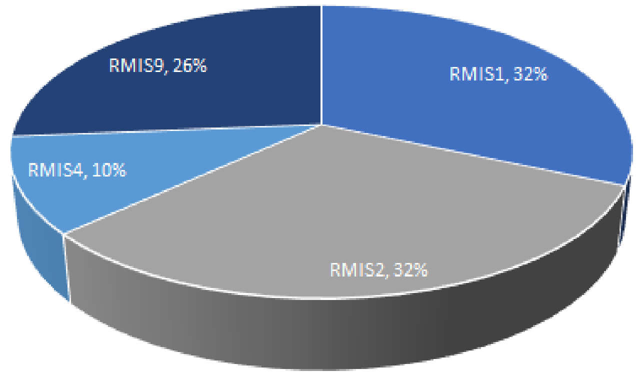

FIGURE 17. Contribution percentage of coalition games in resource management in 5G NR (RA- Resource Allocation, SA- Spectrum Sharing, PA- Power Allocation, BS- Beam Selection).

to spectrum slicing. Their approach also uses overlapping coalitional games. The players in this game are the base stations.

Bairagi *et al.* [84] addressed joint unlicensed band selection and resource allocation in 5G networks. A Virtual Coalitional Formation Game (VCFG) algorithm solves the band selection problem. An optimization problem is formulated within each coalition with the aim of maximizing the users' Mean Opinion Score (MOS). This optimization problem is decomposed into two sub-problems; time sharing between LTE-U and WiFi systems (in which the cooperative Kalai-Smorodinsky bargaining solution is used) and a resource allocation problem for LTE-U (solved using the Q-learning algorithm). The stability of the VCFG is proven in this paper.

As MNOs are incentivised to shift from regular Radio Access Networks (RAN) to Cloud Radio Access Networks (C-RAN), there is potential for application of coalition games in sharing of spectrum and network elements among MNOs. Authors in Vincenzi *et al.* [79] have exploited this potential and designed a scheme to evaluate how QoS and profits can be improved due to more efficient spectrum utilization caused by C-RAN sharing among coexisting MNOs. In their simulations, they observe that it is always better for MNOs to co-operate as opposed to acting alone.

The deferred acceptance algorithm is also used by authors in Zhang *et al.* [21]. They have formulated the joint problem of beam and power allocation onto the sub-carriers and presented beam-forming structure as a mixed integer non-linear programming problem. They then split the problem into the two sub-problems of beam selection and power allocation. They proposed a coalitional game based solution for beam selection and two algorithms for the power allocation problem, one of which is based on non-cooperative games. The beam selection algorithm is based on the deferred acceptance algorithm. The non-cooperative game algorithm for the power allocation problem is shown to be sub-optimal compared to the other algorithm proposed.

Wu *et al.* [82] observed that most channel allocation methods allocate only a single channel for each user and do not

TABLE 5. Comparison of various game theoretic approaches to resource management.

Reference	Issue No.*	Platform No.#	Metric	✓D2D Coexistence	✓Remark
[69] Liu *et al.*	RMIS_1	CGP_1	GBR, Delay	55	Ultra dense mmWave small cell network.
[70] Yuan *et al.*	RMIS_1	CGP_1	GBR, Delay	55	5G 3-layer HetNet.
[75] Kim *et al.*	RMIS_2	CGP_2	Type of UE/Services	55	HetNet using multi flow carrier aggregation.
[83] Sun *et al.*	RMIS_9	CGP_1	Channel gain	55	Fog Radio Access Network.
[81] Ding *et al.*	RMIS_4	CGP_1	Directivity gains	55	MIMO-NOMA access network.
[76] Himla *et al.*	RMIS_2	CGP_5	Type of UE/Services	51	D2D multicast communication.
[77] Xiao *et al.*	RMIS_2	CGP_5	Type of UE/Services	55	Specrtum sharing among mobile operators.
[78] Srinivasan *et al.*	RMIS_2	CGP_5	Type of UE/Services	55	Spectrum slicing among base stations.
[84] Bairagi *et al.*	RMIS_9	CGP_3	Mutiple	55	Joint band selection and resource allocation.
[79] Vincenzi *et al.*	RMIS_2	CGP_1	Type of UE/Services	55	QoS and profit miximization in C-RAN.
[21] Zhang *et al.*	RMIS_4	CGP_4	Directivity gains	55	joint beam selection and power allocation.
[71] Lin *et al.*	RMIS_9	CGP_1	Mutiple	51	Spectum and file sharing.
[72] Chen *et al.*	RMIS_1	CGP_1	CQI	51	Spectrul reuse.
[85] Ahmed *et al.*	RMIS_9	CGP_1	Mutiple	51	Physical layer security and resource allocation.
[80] Tseng *et al.*	RMIS_2	CGP_4	CQI	51	Two stage coalition formation.
[86] Sawyer *et al.*	RMIS_9	CGP_1	CQI	51	Adjusting tradeoff between channel rate and energy consumption.
[82] Wu *et al.*	RMIS_1	CGP_4	QoE	55	Inter-cell and Intra cell channel allocation.
[73] Yu *et al.*	RMIS_1	CGP_1	Delay	55	Delay aware resource allocation.
[74] Wang *et al.*	RMIS_1	CGP_1	Throughput	51	Sub-channel allocation in small cell mmWave network.

*From table 2; #From table 4

take quality-of-experience (QoE) of both macro cell users (caused by cross-tier interference) and small cell users into account, and then presented a scheme based on matching coalitional game for multi channel allocation that addressed these issues. This matching game is unique in that the preference order changes as the matching proceeds, and thus precludes the use of the deferred acceptance algorithm. The problem is divided into the two sub-problems of intra-cell allocation for small cell users (solved as a many to one selfish matching game) and inter-cell allocation for small cell base stations (solved separately as an altruistic overlapping coalitional game). The complete solution is built out of the two sub problems. Channel allocation based on this algorithm is then shown to be stable.

Lin *et al.* [71] suggested a peer to peer (P2P) resource sharing strategy, where both spectrum and common files required by many devices are shared, for distance constrained device to device (D2D) networks. This algorithm aims to maximize the sum download rate. The utility is expressed in terms of the successful transmission probability (STP) of each player. The subsequent utility maximization problem is then solved. The algorithm is shown to be Nash stable.

Chen *et al.* [72] proposed a resource allocation scheme for D2D pairs amongst both the mmWave and cellular band. They formulate this problem as a coalition game with C cellular users. In this case, each D2D pairs can choose to use either the resources of any of the C cellular users or the resources of the mmWave band. All the D2D pairs using the resources of some user or the mmWave band form a coalition. Thus there are $C + 1$ coalitions. In this way, a coalition formation game is proposed where statistical average system sum rate is maximized. The authors prove that their game converges to a Nash-stable equilibrium.

Ahmed *et al.* [85] addressed the issue of eavesdropping in D2D communications. A joint physical layer security and resource allocation problem is formulated. In their coalitional game, multiple D2D users can share one cellular user's spectral resources. This paper considered imperfect Channel State Information (CSI), inter and intra cell interference, and multiple eavesdroppers. The algorithm is proven to be stable and converge. It is shown to maximize the sum rate and the secrecy capacity.

In an attempt to improve the utilization of the cellular uplink spectrum, Tseng *et al.* [80] suggested a 2 stage coalition formation based resource allocation scheme for D2D communications in inband underlaid 5G networks. D2D pairs are organized into either stage 1 or stage 2 coalitions based on pairwise distances and number of requested Resource Blocks(RB). The Bron-Kerbosch algorithm is used for stage 1 coalitions, while pairs are organized into stage 2 coalitions based on the number of requested resource blocks. Resources are first allocated to stage 1 coalitions, and the Nash bargaining solution is used to further allocate RBs to D2D pairs instage 2 coalitions. Performance is compared against the greedy algorithm, and the proposed algorithm is shown to perform better in the authors' simulations.

Sawyer *et al.* [86] jointly optimized network layer mode selection, resource allocation from the cell and cellular users, to maximize the channel rate and minimize the transmit power for both cellular users and D2D pairs in a distributed wireless network with D2D communications. Their approach of using coalitional games stands out as it uses non-transferable utility. Their dynamic cross layer coalition formation games has as it's players the cellular and D2D users. The utility function is a trade off between maximizing channel rate and minimizing transmit power. A player leaves a coalition and joins another if the player prefers the new coalition to the old one and the total average utility generated by the current and newly preferred coalition must be unchanged or improved. The coalition partition is proven to converge to a Nash stable outcome.

Yu *et al.* [73] addressed collaborative resource sharing among proximal neighbours in smart systems to reduce delay. Their approach aimed to coordinate and align the goals of cellular users and IoT users using learning based and coalitional game based algorithms. The utility functions of these users are designed, and then coalitional games combined with the deep Q-learning framework to model and incentivize co-operation and competition. The algorithms are shown to converge to a Nash stable optimal or asymptotically optimal solution.

Wang *et al.* [74] addressed optimal sub-channel allocation in the small cells that underlie an mmWave network. They propose a cooperative sub-channel allocation algorithm whose utility is based on the system throughput. In this game, D2D links and access links are the players, and they form coalitions according to switch rules, where coalitions are formed in an attempt to increase utility. The convergence of the algorithm to Nash-stability is proven.

It is evident that the vast majority of resource management issues presented above are allocation problems. This is unsurprising, as coalitional games lend themselves well to resource allocation problems. This does not exclude the use of relatively rarer aspects of game theory like the deferred acceptance algorithm or the various solutions to Bargaining problems. The very presence of these approaches merits the exploration of applications of a variety of game theoretic models in 5G. It is also clear that there is a growing number of applications of game theory aimed at D2D communication. This is again to be expected, given the growing importance of D2D communication in 5G. Also to be noted is the breadth of areas in which coalition formation turns out to be applicable. Both non-overlapping and overlapping coalition formation games are used, with non-overlapping games being used much more frequently. There is great scope, as is evident above, for further application of overlapping games. Further more, many games presented above use non-transferable utility. This is perhaps because of the increased generality offered by these games. Last but not least, many games are designed with power management as a primary focus.

B. COALITIONAL GAMES IN INTERFERENCE MANAGEMENT

The future of 5G will largely revolve around densely deployed small-cell networks to boost bandwidth. Fig 18 shows the interference management in a 5G UDN dynamic deployment. Despite the advantages offered, this close deployment has the potential to cause greater interference in multiple parts of 5G. Thus, dealing with interference is a pressing issue, and coalitional games step up to the challenge.

The use of coalitional games to deal with interference is well established. Fig. 19 shows the contribution percentage of coalition games in Interference management in a 5G NR and table 6 shows the comparison of various game theoretic approaches to interference management. Nash axiomatic cooperative game theory, for instance, has been used in multiple different problems in signal processing and communications. However, there is much potential for application of the rarer studied parts of game theory. One example of these applications is that of the Nash bargaining solution and its extensions to the various trade-offs between efficiency and fairness by Yang *et al.* [89]. They model symmetric and asymmetric cooperative game theoretic frameworks formulated based on a β coefficient. They design a use case based on an α parameter and analyze the frameworks. They characterize the effects of the β coefficient on the efficiency and fairness and those of the α parameter on spectral efficiency and energy efficiency.

Akhtar *et al.* [87] has introduced cooperation amongst small cell RRHs to help weak users (users affected due to their location or interference) in the network. They have chosen the most interfering RRH for each user and tried to form a coalition with the user's RRH included. While doing so they try to increase the throughtput of weak users, while not decreasing the throughput of other normal users beyond a certain limit, or making the coalition too big. The algorithm proposed executes with $O(n^2)$ iterations in the worst case, and $O(n \log n)$ iterations in the average case.

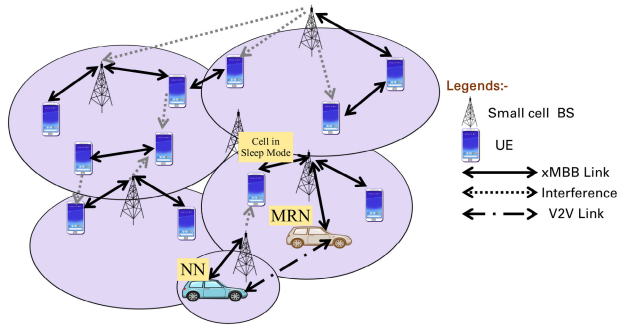

FIGURE 18. Interference in a 5G UDN dynamic deployment.

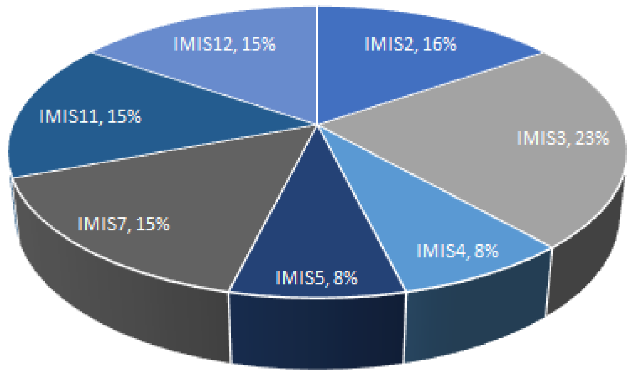

FIGURE 19. Contribution percentage of coalition games in interference management in a 5G NR.

TABLE 6. Comparison of various game theoretic approaches to interference management.

✓Reference	✓Issue No.*	✓Platform No.#	✓Objective	✓D2D Coexistence	✓Remark
[89] Yang *et al.*	IMIS_3	CGP_1	Trade-offs between efficiency and fairness.	55	Game theoretic frameworks formulated based on a β coefficient.
[87] Akhtar *et al.*	IMIS_2	CGP_1	Throughput	55	Coalition based on interference level.
[66] Zhang *et al.*	IMIS_5	CGP_4	QoS	51	Many-to-one matching sub-game with externality followed by a coalition sub-game.
[93] Georgakopoulos *et al.*	IMIS_7	CGP_1	Throughput	55	A split occurs only if the throughput of at least one edge UE increases.
[95] Akhtar *et al.*	IMIS_11	CGP_1	Throughput	55	Spilt until the total throughput cannot be increased any further.
[97] Zhang *et al.*	IMIS_12	CGP_1	Throughput	55	Allows a player to leave one coalition and join another or allows two coalitions to exchange players.
[94] Jiang *et al.*	IMIS_7	CGP_1	Throughput, QoS	55	Interference and scheduling in mmWave network.
[88] Yang *et al.*	IMIS_2	CGP_1	Interference Alignment and Traffic Offloading.	55	Spectrum leasing as an incentive mechanism in Interference Alignment (IA).
[96] Ahmed *et al.*	IMIS_11	CGP_1	Spectrum efficiency	55	Interference mitigation using a network-side self-organized approach.
[90] Cao *et al.*	IMIS_3	CGP_1	Throughput	55	Merge and split operations are performed when the aggregate throughput of the system is improved.
[92] Xiao *et al.*	IMIS_4	CGP_5	Power efficiency	55	Overlapping coalition formation games to represent the cooperation between small cells.
[98] Hu *et al.*	IMIS_12	CGP_5	Throughput	51	Joint interference management and resource allocation in D2D communications.
[91] Eliodorou *et al.*	IMIS_3	CGP_1	Throughput	55	User association in ultra dense networks.

*From table 3; #From table 4

Zhang *et al.* [66] addressed the interference between D2D users and existing users when D2D communication is incorporated into heterogeneous C-RANs. This is done by analyzing the assignment of sub-channels of different bandwidth to multiple D2D pairs and RRH users, while maintaining QoS of all users and maximizing system performance. This problem is formulated as a Mixed Integer Linear Programming (MINLP) problem and then reformulated into a many-to-one matching sub-game with externality followed by a coalition sub-game. These problems are solved with a constrained deferred acceptance algorithm (DAA) and a coalition formation algorithm. Both algorithms are shown to converge.

Georgakopoulos *et al.* [93] has applied similar coalitional game theory to coordinated multi point operations in spectrum and interference management. In this algorithm, each RRH is considered a singleton coalition initially. A matrix is then formed based off of career-to-interference ratio values. A coalition is then formed if the throughput of every edge UE does not decrease, if the throughput of any non edge UE does not fall below a certain level, and if the backhaul capacity constraint is satisfied. A coalition can also split, but a split occurs only if the throughput of at least one edge UE increases, while that of all other UEs does not decrease.

Akhtar *et al.* [95] addressed RRM and mitigate co-tier interference in a cooperative network. In this work, the various RRHs are the players in the game. The payoff of each coalition in this paper is calculated in terms of throughput of the coalition. In essence, coalitions are formed and spilt until the total throughput cannot be increased any further.

Zhang *et al.* [97] addressed the interference between WiFi and LTE-U caused by 5G. They first emulate this scenario and evaluate mutual interference. They then propose a model for the co-existence of LTE-U and WiFi. Finally, the throughput is maximised by a proposed access point selection algorithm. This co-operation is useful because user connecting to a SBS utilizes a time-slot thus preventing all other users from utilizing the same time slot (assuming time division duplex (TDD)), and a user connecting to a wireless router (WR) competes with all other users connected to that WR for that channel. Based on a utility function, their algorithm allows a player to leave one coalition and join another or allows two coalitions to exchange players. This algorithm has complexity $O(N^4)$.

Authors Jiang *et al.* [94] proposed a new method for full duplex concurrent scheduling in mmWave wireless backhaul networks. This method aims to maximize the number of flows that have their QoS requirements satisfied. They transform this problem into one of maximizing the sum rate of concurrently scheduled flows in time slots using non-linear integer programming(NLIP). They address two types of intereference, multi user interefer-ence (MUI) between two flows that don't share any common node (where the receiver of one flow is the transmitter of the other) and residual self intereference (RSI) after self interference cancellation. Their procedure first finds a greedy approximation of the maximum independent set, which is divided into two coalitions. A defined switch operation is then repeated until the maximum sum rate is attained.

Yang *et al.* [88] utilized spectrum leasing as an incentive mechanism in Interference Alignment (IA) and Traffic Offloading (TO) to create two new schemes, IA with spectrum leasing (IASL) and Traffic offloading with spectrum leasing (TOSL). IASL jointly focuses on resource management and IA to optimize the revenue of each small cell. Each small cell eNB (SeNB) calculates the cost of cooperation and the utility from cooperating with an interfering SeNB and cooperates if it is beneficial. In TOSL, coalition formation is done with respect to each channel. For each sub-channel, the macro cell eNB (MeNB) chooses to cooperate with SeNBs if a defined revenue increases.

There are many approaches to interference coordination using coalitional games. For instance, authors Ahmed *et al.* [96] addressed interference coordination heterogeneous small cell networks. They address intra-tier interference mitigation using a network-side self-organized approach. In this approach, the players are the small-cell access points (SAP) who mitigate interference within coalitions. Their algorithm uses merge and split rules but is different in that it offers partial reversibility. The stability of this algorithm is based on the notion of the recursive core.

Cao *et al.* [90] addressed the problem of interference management in ultra-dense networks. Their approach stands out in that it is user-centric as opposed to access point centric. The players are the users, and they attempt to join coalitions containing neighbouring users according to a defined highest potential interference. Merge and split operations are performed when the aggregate throughput of the system is improved. This algorithm is also based on the recursive core. The authors also propose a novel resource allocation algorithm based on graph theory.

Xiao *et al.* [92] jointly addressed interference mitigation. They approach the issue from multiple domains (including time, frequency, space and power). In their approach, the joint problem is first decomposed into the four sequentially solved sub-problems of OFDMA scheduling, IA, TDMA scheduling and power optimization [109]. The first problem of OFDMA scheduling is solved based on SINR. The second problem of IA is solved here using overlapping coalition formation games to represent the cooperation between small cells. Following this, TDMA reduces interference between overlapping coalitions that reuse the same sub-channel. The final sub-problem of transmission power optimization is solved using a water-filling algorithm.

Hu *et al.* [98] proposed a scheme for joint interference management and resource allocation in D2D communications. In their approach, each D2D chooses multiple best resource blocks to reuse based on cross-tier interference with cellular users (CUs). All the users (D2D and CU) using one RB form one overlapping coalition. Then, utility in terms of sum rates of throughput of D2D links is maximised. The algorithm is proven to always converge to a stable structure.

Eliodorou *et al.* [91] used cooperative game theory to deal with user association in ultra dense networks. The aim of their approach is to mitigate interference and maximize system sum rate. In this approach, the cooperation between SBSs is modelled. There are two proposed algorithms, one where Zero Forcing (ZF) or regularized ZF beamforming is considered, and another where ZF beamforming is considered jointly with NOMA.

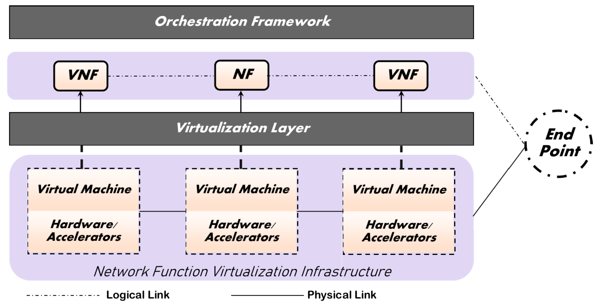

FIGURE 20. Architecture for network function virtualization.

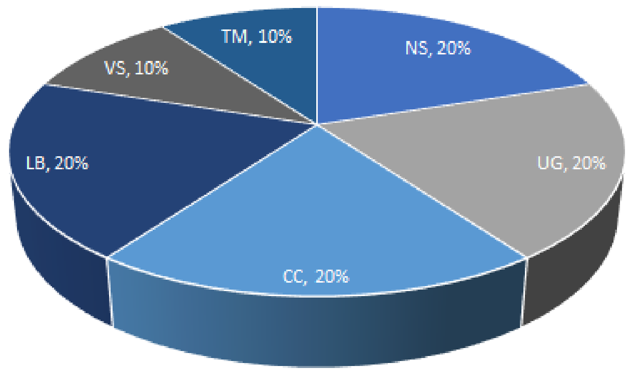

FIGURE 21. Contribution percentage of coalition games in other issues in a 5G NR.

It is evident that there are various different types of interference that coalitional games can deal with. However, the overwhelming majority of approaches do not venture beyond the realm of coalition formation in their approach to model cooperation. Of all the approaches presented here, only one is not based on a coalition formation game. That one approach utilizes Nash axiomatic bargaining. Furthermore, of those coalition formation games, only one approach here uses overlapping coalition formation. It is evident from the relationship between power management and interference that many interference management schemes have power management as a major concern; this is reflected here.

C. OTHER MISCELLANEOUS USES OF COALITIONAL GAMES

Consider, for instance, Virtual Network Function placement to form the 5G Core, using Network Function Virtualization (NFV) over a federated cloud. Authors Bagaa *et al.* [99] have tried to create efficient virtual core network slices using coalitional games. Fig. 20 shows the architecture for network function virtualization. They have done this in two steps. Firstly, they have decided how many Virtual Machine (VM) instances of each VNF are required, using Mixed Integer

TABLE 7. Comparison of various game theoretic approaches to miscellaneous sub-areas of 5G NR.

✓Reference	✓Issue	✓Platform No.#	✓Objective	✓D2D Coexistence	✓Remark
[99] Bagaa *et al.*	Network Slicing	CGP_1	Required VMs	55	Create efficient virtual core network slices using coalitional games.
[100] Li *et al.*	Network Slicing	CGP_1	Cost of VM	55	Cost efficient virtual core network slicing.
[101] Wang *et al.*	User Grouping	CGP_1		55	Two approaches using Preference Relation and Sequence Game.
[102] Liu *et al.*	User Grouping	CGP_1	Sum rate	51	D2D and cellular user mapping.
[103] Abouaomar *et al.*	Content Caching	CGP_1	Latency	55	Associate fogs to users based on a correlation between the already cached results in the fog and the tasks required by the user.
[105]Li *et al.*	Load Balancing	CGP_1	Throughput Opt.	55	Optimization of the throughput of Licence Assisted Access (LAA) and WiFi systems.
[106] Pham *et al.*	Load Balancing	CGP_1	Coalition size Vs Interference	55	The grand coalition is unappealing due to more UEs in coalition, the greater the interference.
[104] Zhou *et al.*	Content Caching	CGP_1	Cooprative content caching	55	Coalitions are formed based on merge and split rules.
[107] Kumar *et al.*	VM Selection	CGP_1	Energy efficeincy	55	The hypervisor that coordinates VM-Migration acts based of conditional probabil- ity and payoff.
[108] Militano *et al.*	Trust	CGP_5	Content uploading	51	Trust based coalition formation game to enhance content uploading services in D2D com- munications.

#From table 4

Linear Programming. Then they formulate the subsequent VNF placement problem into various Cloud Networks (CN) in a federated cloud as a coalitional game. In this game, the various CNs are the players, seeking to maximize their profits. In their model, each VNF would have various CNs form a coalition so as to host all necessary instances of that VNF. They assume that each CN handles some subset of all Tracking Areas (TA). These coalitions are formed to ensure that each TA is associated with at least one instance of every necessary VNF, while maximizing the profits of the coalition members. This approach however assumes that the cost of creating an instance of each VNF (which varies from player to player) for each player is common knowledge to all players. Li *et al.* [100] addressed this drawback in their algorithm NM-FN, using a Bayesian Coalition formation game.

Another application is user grouping. Consider for instance NOMA systems. The users in such a system are cooperative and communicate in the same time slot. Wang *et al.* [101] proposed a scheme for user grouping in these systems. In their scheme, users are divided into different coalitions, which are then allocated time slots. They propose two algorithms for this purpose, Preference Relation and Sequence Game. Both algorithms are shown to converge to Nash stability.

Sparse code multiple access (SCMA), a non-orthogonal multiple access scheme offers an opportunity to improve spectral efficiency in 5G, and D2D lines up to be one of its main users. This opportunity requires an efficient mapping scheme of SCMA layers to cellular users and D2D pairs, and one possibility is presented by Liu *et al.* [102]. The intention of this scheme is to maximize the system sum rate. In their scheme, first cellular users are mapped to one of those SCMA layers in which there are no cellular users. Then D2D users are partitioned into coalitions, one for each SCMA layer. Players leave and join coalitions based on their payoff, which in this case is the average data rate in the coalition.

Abouaomar *et al.* [103] explored edge computing and caching in fog computing networks. In their model, users request computation from fogs and fogs cache results of computation. They try to associate fogs to users based on a correlation between the already cached results in the fog and the tasks required by the user. Each coalition in their game consists of at least one user and at most one fog. The user tries to minimize the latency and the fog tries to take on as many tasks as possible that are already cached.

Li *et al.* [105] approached optimization of the throughput of Licence Assisted Access (LAA) and WiFi systems. In this game, a coalition amongst access points (AP) is first built to maximize the WiFi throughput. The motivation behind this coalition formation is that data of heavy-loaded APs can be transferred to the light-loaded APs. This step is executed periodically by the centralized controller. In the second step, an auction game is performed where the LAA BS is the auctioneer and the AP coalitions are bidders. A second price sealed-bid auction is applied.

Pham *et al.* [106] addressed computation offloading in multi-carrier NOMA enabled MEC systems. In their model, UEs are considered to be players and and sub-carriers are the coalitions that can be used for offloading. Each UE can either perform the computation locally or migrate it through some sub-carrier. In this game, the more UEs in some coalition, the greater the interference. Thus, the grand coalition is unappealing. The utility of each coalition is measured by the total computation gain of all members of the coalition.

Zhou *et al.* [104] proposed a new model for cooperation in content caching. They propose games assuming both the presence and absence of transferable utility. Their game with transferable utility is proven to be a convex game. This game thus has a non empty core. However, the grand coalition may not be stable if utility is not transferable. Coalitions are then formed based on merge and split rules.

Kumar *et al.* [107] applied coalitional games to intelligently utilize VMs in vehicular mobile cloud computing. They aim to minimize energy consumption by optimizing the context switching of VMs. The players in this game are learning automata (LA), which execute learning algorithms based on feedback from the environment. The hypervisor that coordinates VM-Migration acts based of conditional probability and payoff. Initially players perform random actions but they learn and make adaptive decisions. Then players form coalitions and elect leaders based on which player has the highest utility.

Militano *et al.* [108] proposed a trust based coalition formation game to enhance content uploading services in D2D communications. UEs are sources of data to be uploaded. They cooperate to opportunistically implement proximity based data exchanges. However, there is always a threat of malicious nodes to successful cooperation. Notions of reliability, reputation and social awareness of devices are used to model trust among players, to deal with this issue. All of this comes together in a coalition formation game with non transferable utility where certain constraints must be enforced. This game is again implemented using merge and split rules. Table 7 shows the Comparison of various game theoretic approaches to miscellaneous sub-areas of 5G NR.

VI. LEARNING's FROM STUDY AND FUTURE RESEARCH DIRECTIONS

The study provides a foundation about the 5G NR and its key performance indicators for 5G, high-level use cases, and physical layer technologies. This paper illustrates the performance evaluation of the 5G network through KPIs. Primarily, the work presented in the literature is focused on interference and resource management. This article provides an introduction to primary resource and interference management issues in the 5G network. This paper provides insight into the coalition games and their application in 5G NR.

Although, coalition games are not a new area of research. There is a colossal effort given by different researchers in the field of coalition games. Researchers utilize game-theoretic models in 5G network management. However, there are many issues identified in section III that are unaddressed. Coalition games can be used to address these issues. Moreover, there is a possibility for future research other than the mentioned fields in the context of 5G. Through the study, we found out some key areas where coalition games can be applied.

1) *Small cell deployment:* Small cell deployment is used to increase energy efficiency and dense connectivity. Coalition games can be used to form the coalition based on the QoS class identifiers (QCI), distance from gNB, and traffic loads of devices to improve QoS support, energy efficiency, and device throughput, respectively.
2) *NOMA power allocation:* In 5G, NOMA supports resource sharing in the power domain. A coalition among devices can be formed based on the device's power limitations to support optimal power allocation.
3) *Frame aggregation:* 5G provides variable frame structure to support the varying size of the data packets. Through frame aggregation, heavy UL and DL transmission can be achieved. A coalition among devices can be formed based on the traffic pattern, i.e., delay budget of the device, throughput required for GBR type.
4) *Data aggregation at gateway node:* Data aggregation at gateway nodes can improve the support dense-connectivity. A coalition can be formed based on the packet size to support the varying size of the packet.

VII. CONCLUSION

This paper presents a literature survey on the application of coalition games in the 5G cellular network and provides background details about 5G technology and coalition games. In the literature, most of the work focused on resource management and interference management. There is little work focused on other aspects like VM management and user grouping. We divide all the into three categories as 1) resource management, 2) interference management, and 3) Miscellaneous. Generally, in the resource management category, work focused on the spectrum and resource sharing, optimal power allocation, beam-forming, and energy efficiency to improve throughput. In the interference management category, the researcher focus on the interference between the small cells, channels, and nearby users to improve system capacity. This paper provides some future research directions where coalition games can be applied to improve the efficiency of the 5G network.

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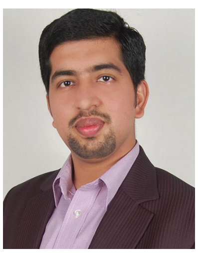

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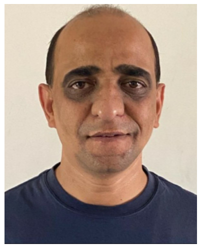

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