MEAN FIELD GAME-THEORETIC FRAMEWORK FOR INTERFERENCE AND ENERGY-AWARE CONTROL IN 5G ULTRA-DENSE NETWORKS

Chungang Yang, Jiandong Li, Min Sheng, Alagan Anpalagan, and Jia Xiao

ABSTRACT

Ultra-dense small cells with D2D communications can provide rich multimedia services for billions of smart terminals. Game theory helps to characterize rational behaviors, model strategic interactions, and design distributed algorithms. However, conventional games have been facing great challenges, for example, the number of the nodes is huge, thus leading to the well known curse of dimensionality. 5G ultra-dense networks call for an advanced game-theoretic framework, which should make it easy to analyze and facilitate distributed control policy, even when coupled with huge and complex interference state dynamics. In this article, we briefly survey the latest applications of advanced games. Following that, we summarize the most important features of 5G game-theoretic design. Then, we introduce the mean field game with its basics and survey the related applications. The mean field game can well satisfy the interference and energy-aware featured game requirements. Finally, we present an application of the mean field game in D2D communications with interference and remaining energy dynamics. We also look into the future research directions of mean field games in other 5G ultra-dense networking paradigms.

INTRODUCTION

Fifth generation (5G) mobile communication networks will face challenges of network capacity crunch, energy starvation, and cost expenditure surge. It mainly results from the proliferation of mobile Internet and Internet of Things, coupled with rich multimedia service requirements on billions of smart terminals. For instance, promising machine-to-machine (M2M) and device-to-device (D2D) communications call for higher capacity and diverse performance requirements, which challenges current network architectures and resource management technology [1–7].

Recent 5G activities from academia, industry, and standardization bodies summarize the following three dimensions to boost network capacity: advanced physical layer techniques, licensed or unlicensed spectrum expansion technology, and ultra-dense node densification. In this article, we take network densification as the most important feature and dimension to improve network capacity and save energy, thus the 5G spectrum and energy efficiency. On one hand, node densification possesses a large number of potential capacity gain, and on the other, flexible deployment of small cell nodes are suited for typical traffic distribution of current applications, e.g., office, outdoor music hall, and shopping mall. Thus, 5G ultra-dense networks should be well studied and standardized accordingly. In this article, we refer to the ultra-dense small cells with D2D communication networks as 5G ultra-dense networks, although there exist ultra-dense WiFi networks.

In the 5G era, the number of nodes and devices is huge, thus leading to the computational intractability of conventional games. This is mainly determined by the specific player's strategy in response to all the other players' strategies. Huge signaling overhead is involved, and extensive information with space-time dynamics exist when the number of players is huge. On the other hand, the optimal policy should be made over a period of time according to the space-time dynamics of context in 5G ultra-dense networks. That is why we introduce the advanced mean field game (MFG). In the MFG framework, the concept of mean field can characterize the space-time dynamics of context, e.g., two-dimensional interference and energy states, which helps the generic player make optimal decision only responding to the mean field, instead of the strategies of all the other players. It is a big difference from all conventional games, e.g., Nash non-cooperative games or evolutionary games. Therefore, MFG-based decision making is distributed with less signaling overhead [8–13]. The merits of MFG are obvious, in particular when the number of players is huge, since the mean field value of space-time dynamics of context approaches the real value with an increasing number of players.

It is known that the MFG is a well known approach; however, most of the MFG applications are in the automatic control fields. Certainly, several MFG-based formulations have been studied in the wireless communications field, which are summarized in this article [9–14]. However, there lacks a basic introduction, and most literature is based on the one-dimensional linear-quadratic MFG. In this article, we introduce the basics of MFG and its applications, and in particular, we concentrate on the interference and energy-aware control method. We summarize the contributions as follows.

•In this article, we see node densification with complex state dynamics and distributed self-orga-

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nizing control as the most important features of 5G communication scenarios, e.g., interference and energy-aware distributed control in ultra-dense networks. Therefore, we first summarize the typical technical problems in this article.

•From a game-theoretic perspective, we survey the latest advanced games to facilitate the design of distributed control methods, where we discuss the challenges of conventional games, in particular, from the interference and energy-aware distributed control perspective. The listed technical challenges of conventional games make us turn to the MFG in ultra-dense networks.

•Although MFG has found extensive research in automatic control, and some applications in cognitive radio networks, energy efficient networks, and the recent applications to ultra-dense small cells, the current MFG applications in wireless communications are one-dimensional linear-quadratic MFG. We first introduce the MFG to provide the background knowledge for wireless engineers, and then we study two-dimensional interference and energy states-aware linear-quadratic MFG application in ultra-dense networks.

•Simulation results verify the improved energy-efficiency performance, coupled with interference dynamics. Some interesting conclusions are finally summarized. We further look to future research directions. Basically, we think that the MFG will find wider applications in ultra-dense networks, and more types of MFG will also be implemented for various kinds of novel problems.

The remainder of this article is organized as follows. In the following section, we summarize typical technical challenges. Then, we summarize the features of 5G game-theoretic design. Next we introduce the mean field game with basics and survey the related applications. After that we present an application of the mean field game in D2D communications with interference and remaining energy dynamics. Then we look into the future research directions. Finally we conclude this article.

5G ULTRA-DENSE NETWORKS AND TYPICAL TECHNICAL CHALLENGES

Ultra-dense deployment of small cells and D2D links underlying macrocells form 5G heterogeneous ultra-dense networks [1–7]. It is one of the important ways to provide better coverage and reduce network congestion in a cost-effective way. We summarize the featured characteristics, concepts, and advantages and disadvantages of 5G ultra-dense networks.

First, ultra-dense small cells underlying macrocells is one powerful way to meet the 1000x capacity challenge in 2020 [1, 3, 5]. Small cells reuse macrocells' licensed spectrum. They use downlink powers and antenna gains to meet diverse traffic, thus leading to different coverage and application scenarios. For instance, various femtocells are located in the office or at home. Meanwhile, the formed ultra-dense small cell networks have other promising features, e.g., cloud-based centralized management and maintenance architecture [3], and autonomous environmental cognition-based distributed control [5]. The authors in [5] investigated self-organizing optimization for cognitive small cells, where cognitive small cells can sense the environment, learn from historical information, make intelligent decisions, and adjust their operational parameters. Meanwhile, these small cells may be implemented on unlicensed spectrum, e.g., WiFi spectra, which provide flexibility of traffic offload between heavily-loaded macrocells and lightly-loaded WiFi in specific application scenarios [4].

Second, D2D communications allows mobile devices to communicate by direct peer-to-peer transmission [6, 7], and it can improve energy and spectrum efficiency. These beneficial opportunities are achieved by device proximity and frequency reuse. Both D2D direct and multi-hop D2D networks are discussed from the game-theoretic perspective in [6], where D2D direct means one-hop D2D pair direct communication, while multi-hop D2D networks refer to the network-controlled smart devices that can realize cluster-based communication in an ad hoc manner.

However, these benefits also present technical challenges. Among various technical challenges, we concentrate on two of the most critical.

Interference Mitigation with Ultra-Dense Development: Both intra-tier and inter-tier interference degrade performance, which results by full frequency reuse among different nodes. Interference characteristics and distribution are complicated in ultra-dense networks. However, interference perception is important for optimal control of resources. The authors in [1] noted that the choice of a proper interference management technique calls for the exact interference distribution. To reduce information exchange, a dominant interferer should be found, where dominant interference ratio was defined as the ratio between the dominant interferer and the rest of the perceived interference.

Traffic Offloading with Various Promising Diversities: In most cases, macrocells are heavily loaded and some specific spectrum is over-crowded. Although heterogeneous small cells underlay macrocells, sometimes they cannot well fulfill their potential due to stronger downlink power and more antenna gains of the macrocells, in addition to the complex interference scenarios. Thus, heterogeneous ultra-dense networks can offload traffic, optimize coverage, and boost capacity of 5G cellular networks via cell range expansion and small cell traffic offloading. Moreover, small cells are envisioned to be cognitive and multimode, e.g., capable of transmitting simultaneously on both licensed and unlicensed bands [4], helping to release crowded spectrum. In addition, the integration of WiFi with cellular radio access technologies can efficiently cope with peak wireless data traffic and heterogeneous quality of service (QoS) requirements.

These challenges will be more severe in ultra-dense networks with a large population of nodes, and high-dimensional optimization variables and parameters. This calls for large-scale convex optimization methods to deal with design problems with discrete and continuous variables. The authors in [3] also designed stochastic beamforming with uncertainty of channel state information. However, with a huge number of small cells, centralized interference management encounters heavy signaling overhead, scalability, and flexibility, coupled with random deployments and lim-

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The dense and random deployment of cognitive small cells brings about some new challenges in terms of scalability and adaptation. Furthermore, the uncertain, dynamic, and incomplete information constraints also impose some new challenges in terms of convergence and robustness

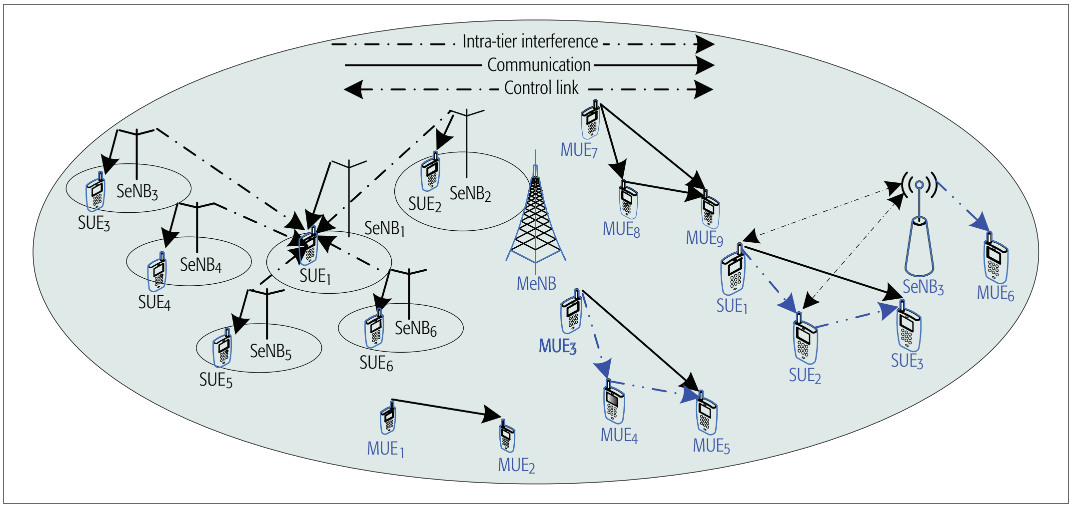

FIGURE 1. 5G ultra-dense communication networks with ultra-dense small cells with device-to-device (D2D) communications as an example.

ited backhauling capacity. Therefore, distributed interference management should be studied with self-organizing characteristics, and that is why game theory has found extensive applications recently [5–7].

Latest Application of Advanced Games and Motivation of Our Work

In this section, we first provide a brief survey of conventional game theory for small cells and D2D networks. This helps summarize the most important features of games in the 5G mobile era.

A Brief Survey of Several of the Most Recent Applications

Games provide a variety of mathematical tools to effectively model and analyze the individual or group behaviors of D2D users [6], where various games were surveyed for the applications to either one-hop transmission or multi-hop cluster based transmission. The authors in [7] presented a new spectrum sharing mode scheme for D2D communications by allowing two or more D2D links to share their spectrum. A Bayesian non-transferable utility overlapping coalition formation game was formulated in [7]. Game models can provide distributed solutions to the resource allocation problems for D2D communication. Specifically, the dense and random deployment of cognitive small cells brings about new challenges in terms of scalability and adaptation. Furthermore, the uncertain, dynamic, and incomplete information constraints also impose some new challenges in terms of convergence and robustness [5].

Most of the surveyed games in D2D networks [6] and cognitive small cell networks [5] are with the spectrum efficiency related utility functions. In practice, spectrum, energy, and cost efficiency should be jointly considered in 5G ultra-dense green and cost-effective networks. Energy efficiency is a critical performance requirement for green communications, especially when small cells are densely deployed to enhance the quality of the users' experience [14]. A novel bargaining cooperative game framework was formulated to improve energy efficiency in a dense small cell network [14]. In particular, a new adjustable utility function was employed in the cooperative framework to jointly address both spectral efficiency and energy efficiency issues.

Motivation of Our Work

We note that different kinds of game theory have found applications in ultra-dense small cells, D2D communications, and WiFi networks. They can be the strategic game (e.g., triple components including player, action, and utility) and some recent advanced games, e.g., Bayesian game including state and information in addition to player, action, and utility. Game structures can be with complete or incomplete information, and rational players cooperatively or non-cooperatively maximize the utility.

In Fig. 2, in 5G ultra-dense networks, the number of the players, for example, the nodes, is huge. In the traditional game theory, when the number of players exceeds the order of tens, the curse of dimensionality appears, and analysis and tracking of games become tedious, and the equilibrium computation becomes infeasible. Following that, this leads to scalability problems in the ultra-dense deployment. That is why strategy design should be with self-organizing and autonomous properties. Moreover, various preferences of different players in 5G games should be considered from the operators' to the subscribers' perspective. In the most recent 5G vision activities, in addition to spectrum efficiency, we know that the game design should well consider energy efficiency in a cost effective way. On the other hand, state dynamics and uncertainty of environmental information are important. Therefore, we summarize the technical challenges of game design in 5G ultra-dense networks as follows.

Coupled Systems: Due to a lack of spectrum resources, both small cells and D2D links reuse the licensed spectrum, thus inter-tier and intra-tier interference exist. Therefore, two systems are coupled by the interference. Always, two coupling systems interact with each other, which challenges the coexistence design for each system. The vector of actions chosen by one system at a given time may determine not only its own payoff, but also the evolution of the system state.

Computational Intractability: With a huge number of players, games with huge state and action lead to the curse of dimensionality. Hence the analysis and the tracking of the game become tedious, and the equilibrium computation becomes infeasible.

Information and Robustness: Information is important to optimal control decision-making and robustness. In practice, 5G systems are dynamic space-time systems. Therefore, research should be concerned with dynamics and uncertainty, analyzing with statistical approximation, designing a distributed self-organizing scheme. In addition, a frequent vast amount of information exchange results in a low convergence rate. Thus to reduce the requirement of information and release backhauling overhead, we should design the self-organizing and distributed control policy with less information overhead.

Both centralized optimization [3] and game theory [5] have been widely used to model, analyze, and design algorithms of interference management and traffic offloading. Optimization theory provides optimal solutions; however, it requires global network information and centralized control, thus yielding significant signaling overhead and computation complexity. To overcome the limitations of optimization, game theory has received wider attention. It can characterize rational behavior, analyze the dynamic equilibrium, and design distributed control algorithms. Interference management and traffic offloading always involve different players. Different players have various actions of parameters to adjust, and different preference and performance metrics always exist. For instance, traffic-aware offloading should be designed with heterogeneous throughput, taking into consideration delay tolerance and latency [4].

Although game theory has found extensive applications, conventional games have faced great challenges. The number of the nodes, for example, access points and small cell base stations, is huge, thus leading to the well known curse of dimensionality. Hence, it is a big challenge to analyze games because this involves dynamics, complexity, interaction, and signaling overhead among different rational players. Therefore, 5G ultra-dense networks call for a novel advanced game-theoretic framework, which should be easy to analyze and facilitate distributed control policy, even when coupled with state dynamics. Recently, several novel applications of games have been proposed. With ultra-dense deployment of nodes and the listed challenges, it is hard to analyze the game due to the involved dynamics, complexity, interaction, and signaling overhead. Therefore, researchers call for a novel mean field game-theoretic framework for 5G ultra-dense networks.

BASICS OF MEAN FIELD GAMES AND THEIR APPLICATIONS

We introduce the mean field game with its basics and the current applications. Mean field games characterize behaviors of multiple agents, and optimize players' strategy in space and time with dynamics.

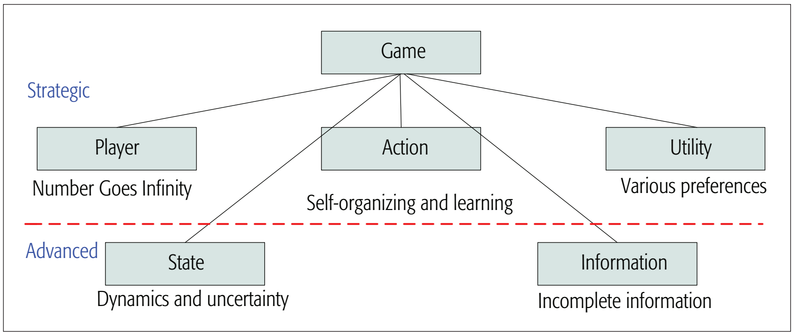

FIGURE 2. Advanced game theory for 5G ultra-dense networks with novel interference and energy-aware requirements.

CHARACTERISTICS OF AN MFG PROBLEM

Mean field games have found applications in different fields to formulate rational and interactive problems with the characteristics of:

1. Rationality of the players, which is generally applied in any type of game to ensure that the players can take logical decisions.
2. Existence of a continuum of the players, and it is generally applied to ensure that players can take logical decisions.
3. Inter-changeability of the states among the players, and each player is infinitesimal. Consequently, the contribution of each player on the mean field game is infinitesimally small.
4. Interaction of the players with the mean field. Each player selects its action according to its own interest state, and the state of the infinite mass of other players who simultaneously select theirs in the same way. In analyzing the game and finding the equilibrium, studying one typical player is sufficient.

MEAN FIELD

For a mean field game, the typical concept is the mean field, which is the statistical density distribution of the state dynamics of mass players. Without loss of generality, a mean field game always has a linear cost function and a Brownian stochastic linear dynamics function. Here, we should first introduce the mean field concept. In fact, mean field is a familiar concept in physics and economics, and it describes the mass behaviors of many particles. Mean field is a middle term relating the investigated generic player with other players. In fact, the generic player does not care about interactive impacts from others but the mass behavior.

Mathematically, let $s_i(t)$ be the state space of a generic player i at time t, which can be single-dimensional or multi-dimensional. For instance, both the perceived interference and the remaining energy should be investigated when designing an optimal power control policy for a generic D2D link. We define the mean field $m(t, s)$ as

$$m(t,s) = \lim_{n \to \infty} \frac{1}{N} \sum_{i=1}^{N} 1_{\{s_i(t)=s\}},$$

where $\mathbb{1}$ denotes an indicator function that returns 1 if the given condition is true and 0 otherwise. At a given time instance, the mean field is the probability distribution of the states over the set of players.

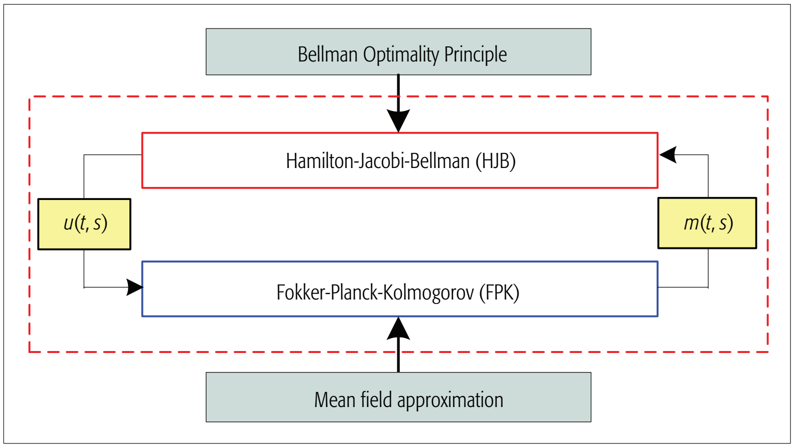

FIGURE 3. Basics of mean field games.

BASICS OF MEAN FIELD GAMES

Mean field games are expressed as a coupled system of two equations of Hamilton-Jacobi-Bellman (HJB) and Fokker-Planck-Kolmogorov (FPK), as shown in Fig. 3. An FPK type equation is evolving forward in time that governs the evolution of the density function of the agents. An HJB type equation is evolving backward in time that governs the computation of the optimal path for each agent.

Let $c(t, x, p)$ be the instantaneous cost function of the generic player at time t using policy p in state x. The objective is to design policy p to minimize the cost function over a period of $[0, T]$. Therefore, it can be summarized as an optimal control problem with state dynamics into consideration. According to Bellman's optimality principle, an optimal control policy should have the property that whatever the initial state or initial decision is, the remaining decisions must form an optimal policy with regard to the states resulting from the first decision. This value function should satisfy a partial differential equation that is a HJB equation. The solution of the HJB equation is the value function, which gives the minimum cost for a given dynamic system with an associated cost function.

The value function and the mean field interact with each other as shown in Fig. 3, where the value function is the solution of the HJB equation, while the mean field value is the solution of the FPK equation. Both the FPK equation and the HJB equation are partial differential functions, which can be derived by the standardized method [8]. In summary, the classical notion of solution in the mean field game is given by a pair of maps (u, m), where $u = u(t, x)$ is the value function of a typical small player while $m = m(t, x)$ denotes the density at time t and at position x of the population. The value function u satisfies an HJB, in which m enters as a parameter and describes the influence of the population on the cost of each agent, while the density m evolves in time according to the FPK equation in which u enters as a drift. More precisely, the pair (u, m) is a solution of the mean field game system. The HJB equation governs the computation of the optimal path of control of the player, while the FPK equation governs the evolution of the mean field function of players. Here, the HJB and FPK equations are termed as the backward and forward functions, respectively. The combination of both forward propagation and backward propagation in time creates some unusual phenomena in the time variable that is not seen in more conventional games. Backward means that the final value function is known, then we determine what is the value at time $[0, T]$ with control vector of $u(t)$. Therefore, the HJB equation is always solved backward in time, starting from $t = T$, and ending at $t = 0$. When solved over the whole of the state space, the HJB equation is necessary and a sufficient condition for an optimum. The FPK equation evolves forward with time. The interactive evolution finally leads to the mean field equilibrium.

APPLICATIONS OF MEAN FIELD GAMES

After we introduce the basics of MFG, here we summarize the MFG applications with new observations of typical contributions and insights.

Hyper-Dense Heterogeneous Networks: The inter-cell interference management was formulated as two coupled problems in [8], where the mean field theory was exploited to help decouple a complex large-scale optimization problem into a family of localized optimization problems. Thus, each small cell base station can implement its policy by using only its local information and some macroscopic information. The use of the mean field game approach for the interference problem in hyper-dense HetNets has not been considered previously. The authors in [8] analyzed the performance of two different cost functions for the mean field game formulation. Both of these cost functions were designed using stochastic geometry analysis in such a way that the cost functions are valid for the mean field game setting. A finite difference algorithm was then developed based on the Lax-Friedrichs scheme and Lagrange relaxation to solve the corresponding mean field game [8].

Green Communications and Cognitive Radio Networks: The authors in [10] studied mean field models for cognitive radio networks under mobility and energy constraints. The users are energy limited and each secondary user decides their transmission power depending on the primary signal strength and its remaining battery state. The access probabilities of secondary users were computed using Ito's formula. It is proved that when the number of transmitters is high, the stochastic differential game converges to a mean field game, where the equilibrium is the solution of a system of two partial differential equations, where the power spent to transmit and the channel coefficients of these same transmitters evolve in a stochastic manner, while in the general case, the resulting partial differential equations are hard to solve.

Other Applications: The authors in [11] considered the last-level cache sharing problems in large-scale cloud networks, where they provided the closed-form expression of the optimal pricing that gives an efficient resource-sharing policy. Most published works concentrated on power control with linear remaining energy state into consideration [8–10]. There are other applications of mean field games with different state dynamics in practical communication scenarios [11, 12].

Interference and Energy-Aware Power Control in Ultra-Dense D2D Networks

We concentrate on two-dimensional interference and energy states-aware linear-quadratic mean field game applications in ultra-dense networks.

Network Scenarios and Typical Problems

Traditional D2D devices are powered by batteries; therefore, extending battery life and saving energy is important to improve users' experience. However, both the interference dynamics and remaining energy should be fully considered during the power control of the device. In this section, we study the interference and energy-aware power control for a generic device in ultra-dense D2D networks in the mean field game framework.

In D2D communications, with a huge number of players, each player optimizes power control policy to minimize cost function, taking into consideration two-dimensional interference dynamics and remaining energy states. Compared to the framework in [8], we jointly investigate the impacts of interference dynamics and remaining energy on the power control of a generic D2D player. We assume linear differential dynamics of both energy and interference. Then, we employ a finite difference method to directly solve the FPK equation, but indirectly we solve the HJB equation [8]. These finally constitute the final iterative interference and energy-aware power control policy.

The Proposed Algorithm

In detail, the proposed interference and energy-aware power control in ultra-dense D2D networks is as follows.

Initialization: Randomly initialize the transmission powers of D2D pairs and the related parameters of state dynamics, where we have two-dimensional states of energy and interference. Here, the energy state dynamic is a linear function of the power and the time interval, while the interference state dynamics can be approximated by the linear function of the power and interference channel gain's differential function.

Compute Mean Field: With pre-defined state thresholds, first compute the interference and energy state values, thus leading to the mean field mass behaviors. Here, we assume that the initialized mean field distribution is in the uniform distribution.

Update HJB and FPK Equations: We implement the finite difference method to update both the HJB and FPK equations, where we know the power control policy $p^{(t+1)} = \min_p f(u(t, m, p))$, and mean field updates according to $m^{(t+1)} = g(m, p, t)$. Here, f and g are the derived HJB and FPK equations.

Obtain Power Control Policy: With the above updating process, achieve the final power control at each time.

To solve the HJB and FPK equations, we use the finite difference method, where we should mention that the FPK equation can be solved directly, with the HJB equation indirectly due to the involved Hamiltonian.

Simulation Settings and Results

We provide simulation results, where we use the battery life as the performance metric. Meanwhile, we assume that ultra-dense D2D links are uniformly distributed with the average communication distance of d = 20m and d = 10m. Without loss of generality, we assume all devices have the same constant circuit power consumption. To capture the non-linear impact, we model the battery lifetime using Peukert's law, where the expected battery lifetime l is

$$l = \frac{Cv^{1.3}}{T(p+p_0)^{1.3}},$$

where C = 800 mAh is the battery capacity, p is the average transmit power of the generic player, p_0 = 2.5 W is the constant circuit power, the term T is the control period, and υ = 4 V is the operating voltage .

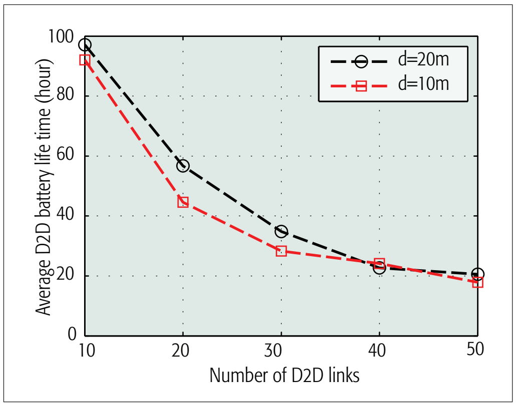

FIGURE 4. Average battery life with interference and energy dynamics-aware control.

Traditional D2D devices are powered by batteries; therefore, extending battery life and saving energy is important to improve users' experience. However, both the interference dynamics and remaining energy should be fully considered during the power control of the device.

We show the average lifetime of each device with respect to the increasing number of D2D links in Fig. 4, which is obtained by the proposed mean field game-based framework. We have the following conclusions. First, the average lifetime of each device decreases with the increasing number of D2D links, which is mainly due to the interference summation in the full frequency reuse case. Second, the average lifetime with far communication distance will be longer, which is interesting. Intuitively, the longer the communication distances, the shorter the battery lifetime is. The main reasons are summarized as follows:

•Signal to interference plus noise ratio (SINR) is defined as the ratio of the effectively received power and the interference power summation of all the interference sources plus noise power. Therefore, intuitively, higher transmit power or shorter distance means larger SINR. Thus, in the traditional manner, a longer distance means that signal strength received by the target user will be lower and SINR will be lower as well. Low SINR results in a higher number of errors that will trigger repeat transmissions and consume additional power.

•However, here the presented power control policy fully considers both the remaining energy and the perceived interference situations. Thus, a longer distance means less involved interference summation. With the number of D2D links increasing to more than 35, we can see that a similar battery lifetime is achieved for both cases, which is the result of the interference gap that has been fully filled. Therefore, it is safe to conclude that the presented mean field game-based framework can well implement the interference-aware

We are moving deeper into the networked society, and the connections that link things and people will become almost exclusively wireless. Massive connections and billions of devices form the densification, where the mean field game should find wider applications on modeling, analysis and design. There also exist typical features of promising problems in future networking scenarios in addition to the ultra-dense networks.

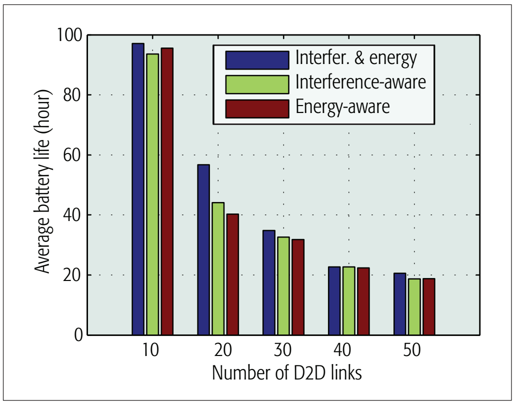

FIGURE 5. Improved performance compared to the interference or energy dynamics-aware control.

power control, and better react to the perceived interference summation.

The mean field game is a featured game in 5G ultra-dense networks due to the dynamic game model, the mean field computation, and the derived HJB and FPK. On one hand, mean field game-based decision making is an off-line optimal policy over a period of time according to the space-time dynamics of context in the 5G ultra-dense networks. Therefore, the policy is made fully considering the state evolution guided by the FPK equation, e.g., two-dimensional interference and energy states. Although we cannot find the comparing algorithms, we provide new simulation results of a single-dimensional mean field game scheme, e.g., we omit the effects of the remaining energy or the interference to reflect improved performance of the proposed two-dimensional scheme. We illustrate the improved performance of both interference and energy-aware control in Fig. 5. We can conclude that the proposed scheme can well save energy and extend battery life, compared to the interference or energy dynamics-aware control.

COMPUTATIONAL COMPLEXITY

In conventional games, each player $i \in N$ should collect all the other players' information $N - 1$ to make a decision in each time $t \in [0, T]$. In each time t, the proposed algorithm needs K iterations to converge. Therefore, the complexity of conventional game computation is $N \times (N - 1) \times K \times T$, and it is finally approximately given as $O(N^2)$ since $K \times T$ is always limited. However, for the mean field game, computational complexity is $O(N)$ since each specific player only needs to maintain and update one mean field value.

FUTURE RESEARCH ISSUES

We envision future research directions from different perspectives of novel mean field games and novel applications to various techniques in other promising ultra-dense networking paradigms.

MORE ADVANCED MFG WITH SPECIFIC CHARACTERISTICS

The mean field games we mentioned above are conventional, and these are other advanced mean field game models, which have been investigated recently. For the different network scenarios and featured problems, different mean field game models will find wider applications, including hierarchical mean field games and mean field games with dominators. In [10], different from other related works, the authors investigated a hierarchical mean field game for cognitive radio networks, where both the mobility and energy states were considered as the spatial-temporal dynamics. Essentially, the mean field game itself is developed with different types in [13], where the authors consider mean field games between a dominating player and a group of representative agents, each of which acts similarly and also interacts with each other through a mean field term being substantially influenced by the dominating player. This dominating player can influence both the mean field term and representative agents directly. Therefore, due to different downlink powers, the mean field game with an interference dominating player can be well used to formulate interference management between the macrocell and the ultra-dense small cells.

TECHNICAL PROBLEMS WITH NON-LINEAR STATE DYNAMICS

We are moving deeper into the networked society, and the connections that link things and people will become almost exclusively wireless. Massive connections and billions of devices form the densification, where the mean field game should find wider applications on modeling, analysis and design. There also exist typical features of promising problems in future networking scenarios in addition to the ultra-dense networks, e.g., the massive cloud and vehicle-to-vehicle networks. On the other hand, mean field games will also find applications to various techniques, e.g., scheduling in energy harvesting communication system, data centers, and pricing in smart grid systems. Meanwhile, massive data centers provide data services for cloud-assisted mobile ad-hoc networks in 5G [15], where the concentration should be on the physical state dynamics. Moreover, it is known that most state dynamics are non-linear in these listed promising technical challenges.

QUALITY OF EXPERIENCE (QOE)-AWARE MEAN FIELD GAME

By now, most utility functions defined in the mean field game are spectrum and energy efficiency-related. However, it is known that the performance metrics in the 5G era should be various, which should include the perceived delay, reliability, and cost, thus leading to the QoE. It is possible to investigate the personalized QoE when formulating the mean field game, which certainly leads to more complexity during the computation of the state mean field and the dynamics function. However, if all the players interact with each other through the context information instead of the direct utility functions, then a QoE-aware mean field game is available. In the mean field game, the context information can be formulated as the mean field, thus the critical part is to model, define, and compute the mean field.

CONCLUSION

In this article, we first summarized the typical interference and energy-aware control problems and technical challenges in fifth generation (5G) ultra-dense networks. Then, we briefly surveyed the latest applications of the advanced games. Following that, we summarized the most important features of 5G game-theoretic design. Then, we introduced the mean field game with basics and surveyed the related applications. Finally, we presented an application of a mean field game in D2D communications with interference and remaining energy dynamics. We also looked into the future research directions of mean field games in other 5G ultra-dense networking paradigms.

It is possible to investigate the personalized QoE when formulating the mean field game, which certainly leads to more complexity during the computation of the state mean field and the dynamics function. However, if all the players interact with each other through the context information instead of the direct utility functions, then a QoE-aware mean field game is available.

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