Abstract

The recent significant progress in realizing full-duplex (FD) systems has opened up a promising avenue for increasing the capacity of future wireless networks. In addition to hardware design and signal processing techniques, radio resource management is essential in the design and implementation of practical FD communication networks. FD communications introduce additional dimensions of network resources requiring the development of new resource allocation algorithms. In this article, we concentrate on distributed radio resource allocation, and show how the game-theoretic models can be used to effectively solve the optimization problems in FD communication systems. Finally, we outline several key open research directions in this emerging area.

I. INTRODUCTION

A full-duplex (FD) system, in which a node can send and receive the signals at the same time and frequency resource, can potentially double spectral efficiency. However, for many years it has been considered impractical in implementation as the signal leakage from the transmission unit to the local receiving unit may overwhelm the receiver, thus making it impossible to recover the desired signal. Recently, there are significant progresses in hardware design and signal processing techniques, which can reduce the self-loop interference comparable to the noise level. This has offered a great potential for realizing the FD radios [1] in physical layer, which also makes the investigation of higher layer issues necessary for the next generation wireless networks.
Since the FD technology enables to explore another dimension of the network resources to increase the network capacity, it requires the new design of resource allocation algorithms by taking the residual self-interference (RSI) into account. This promising opportunity has recently inspired the rapid research development [2], [3] in this area. So far, most existing work in FD wireless networks mainly focuses on centralized resource allocation [3]–[5]. However, the centralized allocation dramatically increases the computational complexity, especially for large-scale networks in the near future [6]. In this regard, there is a significant need for distributed resource allocation solutions to address the various challenges in the theory, design, and development of FD communication networks.

In this article, we discuss the latest development and novel distributed resource allocation algorithms for FD communication systems to optimize their network performances. The distributed algorithms do not require any central infrastructure for coordinating the common channel access procedure. For example, in contention based wireless access networks, each FD user needs to compete with other users for the channel access, which causes serious collisions when there are multiple users. Therefore, how to tackle the radio resource allocation in a distributed manner without the centralized control while achieving a satisfactory performance in the network level presents a great challenge.

In literature, there are following major application scenarios:

- **Centralized Full-duplex Communication Networks**: in wireless networks, FD access points (APs) or base stations (BSs) establish the connection with the mobile users, which are served in the coverage area of the APs and BSs. In this scheme, resource management as well as the transmissions can be coordinated under the condition imposed by the APs and BSs [3], [7];

- **Distributed Full-duplex Communication Networks**: this type of scheme does not have any central infrastructure for coordinating the common channel access procedure. Hence, each FD user that is going to transmit has to take the contention procedures and resolve possible collisions. The complicated part of the distributed resource management is to achieve a satisfactory performance in the network level due to the lack of any centralized coordination [8], [9].

Obviously, in different FD application scenarios, corresponding network resources need to be optimized by exploring different resource allocation algorithms. In many scenarios, FD users may be selfish and rational and they would like maximize their own benefits through cooperation and/or competition; while on the other side, the APs that own radio resources would like to maximize their own benefits to optimize
the network-level resources instead of the individual one [10]. This requires the solutions by considering both factors in the design and optimization in the following aspects:

- **Theoretical Foundation:** a theoretical basis or framework needs to be established to analyze the behavior of interacting entities (wireless FD Users or Devices) in the FD communication networks.
- **Distributed Operation:** FD users or devices should be able to make their decisions independently based on local information with a small amount of signaling overhead for interaction with other users/devices.
- **Mechanism Design:** The parameters of independent and self-interested FD users/APs need to be designed and optimized towards a system-wide desirable outcome.

It is well recognized that game theory provides powerful mathematical tools enabling the study of complex interactions among interdependent rational players and predict their choices of strategies [10], [11]. And game-theoretic models have been widely used for channel assignment, power control, random access, and cooperation enforcement in wireless networks [10]. Therefore, game theory should also offer suitable tools to model and investigate the resource allocation problem for communication networks by using FD radios. In this article, we demonstrate how game theory can be applied to study the resource allocation problems for FD communication systems. In addition to reviewing the existing approaches, we also highlight some potential research directions towards using game theory to address other open problems in FD communication networks.

The rest of article is organized as follows: Section II reviews the basics of FD communications. In Section III, we present main application schemes. The key game-theoretic models and solutions in these applications are discussed in Section VI. In Section V we elaborate one example for user pairing and subcarrier assignment in FD cellular networks by using matching theory. In Section VI, we draw the main conclusions and present some open problems.

**II. Basics of Full-Duplex Communication**

Fig. 1 shows a two-node FD communication system with a transmit and a receive antenna at each node, where node $i$ transmits to the other node, with a transmit power $P_s$. Each node is equipped with a FD radio, which can concurrently transmit and receive the signals at the same frequency and time leading to severe self interference caused by the signal leakage from the transmit RF unit to receive RF
unit. The self interference may overwhelm the analog-digital conversion (ADC)/digital-analog conversion process due to its limited dynamic range. Therefore, the self interference needs to be mitigated before the ADC in analog circuit. However, due to the practical constraint, the interference cannot be completely suppressed, resulting in the residual self-interference (RSI) [1], [2].

As a result, the signals received at each node is a combination of the signal transmitted by the other source, the RSI, and the noise

$$y_i = \sqrt{p_s}h_{ji}x_j + \sqrt{p_s}\tilde{h}_{ii}x_i + n_i, i, j = 1, 2 \text{ and } i \neq j,$$

where $h_{ji}$ denotes the channel from node $j$ to node $i$, $\tilde{h}_{ii}$ is the RSI channel from the transmit to the receive antenna of the $i$th node, and $n_i$ represents the additive white Gaussian noise (AWGN) noise. The RSI depends largely on the transmit power, and also varies due to the practical constraint such as the amplifier’s dynamic range. Furthermore, the values of $|h_{ji}|^2$, $|\tilde{h}_{ii}|^2$, and $P_s$ have a strong impact on signal to interference noise ratio (SINR), and in turn will affect the system performance significantly. Therefore, the effective resource allocation that can further reduce the effects of RSI is crucial for FD communication networks.

III. KEY FULL-DUPLEX COMMUNICATION NETWORKS

In this section, we present some commonly considered FD wireless systems and their system models.
A. Centralized Full-Duplex Communication Networks

1) Full-Duplex OFDMA Cellular Networks: Orthogonal frequency division multiple access (OFDMA) has been widely applied in many wireless and cellular communication systems such as WiMax and LTE which greatly increases the network capacity [6]. As shown in Fig. 2, in FD-OFDMA cellular networks, the BS operates in the FD mode, and all the mobiles use half duplex (HD) transmission. The uplink (transmit) and downlink (receive) users need to be properly paired into separate transceiver pairs, and each pair of the uplink and downlink users simultaneously communicate with the FD BS over the same subset of subcarriers [7].

Within each pair, the transmission of uplink user will cause the co-channel interference to the downlink user, and this interference varies largely with the mutual distance between the uplink and downlink user of each pair. Hence, users pairing, subcarrier and power allocation among different user pairs need to be jointly optimized to achieve the optimal sum rate performance in the network. Due to the combinatorial nature of pairing multiple uplink/downlink users and subcarriers, and because of the complexity of optimal power allocation to each subcarrier-transceiver pair, distributed resource allocation in such a FD OFDMA network can be very challenging.

2) Full-Duplex Cooperative Relay Networks: Relaying technology has been widely used in many wireless communications systems. Traditional relay systems, where a source node communicates with a destination node with the help of one or multiple relays, operates in the HD mode. This leads to the loss
of spectral efficiency because the relay node needs to receive and retransmit the signals in the orthogonal frequency or time resources. By equipping the relay nodes with FD radios, the relay can receive and forward signals simultaneously, and thus improve spectral efficiency [3].

Fig. 3 illustrates a simple FD relay network consisting of multiple HD source and destination pairs, and one FD OFDM relay node. Both the source and relay nodes use the same time-frequency resource and the relay nodes work in the FD mode with two antennas (one for transmission and one for reception). The communication process can be briefly described below:

- The source transmits signals to both FD relay and destination at a given subcarrier.
- At the same time, the FD relay forwards the signals received in the previous time slots to the destination with a proper transmit power.

Hence, the resource allocation problems lie in the joint source-and-destination nodes, subcarrier and power allocation, by taking into account the RSI at the relay nodes.
B. Distributed Full-Duplex Communication Networks

In traditional random access scheme, it typically adopts CSMA/CA principle by listen-before-talk protocol, which divides the total transmission time into sensing and transmission slots [6], and thus reduces the spectrum efficiency [9], [13]. FD techniques allows transmission and reception at the same time, and thus, provide the possibility of a new design of decentralized random access networks. Specifically, it enables each user to sense the spectrum and determine whether other users are occupying it and at the same time transmit its own data. This results in a new MAC protocol design in which users are aware of the channel utilization situation when transmitting [9].

As shown in Fig. 4, it shows a distributed FD communication network, which consists of a number FD contention user pairs working in an ad hoc way without any central controller. The communication process can be briefly described below:

- **Sensing and Transmitting**: All users keep sensing the channels continuously to determine whether other users are present. Once a user senses that channel is idle, it checks its own backoff timer for transmission.
- **Contention Window**: if the spectrum is sensed idle, the user does not access to the spectrum and
transmits immediately. Instead, it randomly chooses one time slot from the set of contention free periods, and waits till the selected time slot for transmission.

- **RSI Effect**: one key issue of using FD techniques is the impact of RSI, which also happens in the new distributed FD scheme. When a user is transmitting, the sensing signal will be interfered by its own transmission, and thus make sensing results imperfect.

The resource allocation problems in this scheme involve power control, contention window length selection, and random channel access, etc.

### IV. Game Theory-Based Resource Allocation for FD Networks

In this section, we develop several main game-theoretic models for resource allocation problems in FD communication systems. Some key resource allocation problems and corresponding game modes for FD communication networks are summarized below [8].

#### A. Game-theoretic Models for Centralized Full-Duplex Communication Networks

- **Evolutionary Game for Adaptive Mode Switching**: FD radio allows a node to send and receive signals at the same time in the same frequency band as shown in Fig. 1. However, it is practically impossible to have perfect self interference cancelation, and thus the amount of RSI greatly affects the performance of the FD system. As a result, in some scenarios, the HD mode may outperform the FD mode for certain RSI values. On the other hand, due the limited size of transmitters and receivers, many wireless communication systems suffer from the spatial correlation which degrades the performance gain of the HD mode. Taking into account the practical RSI and spatial correlation, either FD or HD might be optimal. To this end, it is essential to understand the performance of these two transmission modes in order to identify the conditions for which FD or HD performs best. This motivates the adaptive mode switching between the FD and HD modes based on the RSI and channel conditions to maximize the ergodic capacity [12]. This process can be well modeled by evolutionary games [10]: the each FD node is the player, and the strategies associated with each player in a population is the algorithm which decides the proper operation modes the node should select. A player tends to switch to the strategy that provides a higher payoff. The change of strategy by a FD node according to the channel conditions can be considered as the evolution process. The
solution of the game is the evolutionary equilibrium, which has the property that at the equilibrium, there is no change of choosing the different strategies.

- **Auction-based Model for Power Allocation:** Auction theory is one branch of game theory which has been widely used in trading if the price of a commodity and service is undetermined. There are many possible designs (or sets of rules) for an auction. The typical issues in the auction include the efficiency of a given auction design, optimal and equilibrium bidding strategies, and revenue comparison. Some typical auctions include the Vickrey-Clarke-Groves auction, share auction, double auction, and combinatorial auction. In many FD applications, the resource allocation problems can also be modeled and solved by using the efficient auction games. For example, under the total power constraint of a centralized system, the BS in Fig 2 and the relay in Fig 3 can be auctioneer which provides power resources, and the mobile users can be considered as the bidders that have communication demand. The problem of power allocation for the BS/relays to serve the mobile users can be formulated as an auction game and solved by using auction theory. Since the transmitted signals are corrupted by the RSI, increasing the transmit power will increase the power of desired signal at the destination, but on the other side it will increase the RSI in the destination received signal.

- **Matching Theory for Subcarrier Allocation:** In an OFDMA system as shown in Fig 2 and Fig 3, at each time slot, disjoint sets of subcarriers can be assigned to different users based on some target objectives. The users then in turn transmit data by spreading the information across the assigned subcarriers. For example, in a FD-OFDMA network consisting of one FD BS and multiple uplink/downlink users in Fig 2, a fundamental challenge arisen in such a system is how to pair uplink/downlink users to form multiple FD links with the BS, and allocate subcarrier across these user pairs, in order to optimize the network performance. The subcarrier allocation involves allocating the different subsets of subcarriers to different users by taking into account the RSI and the co-channel interference within each user pair. This is significantly different from the traditional subcarrier allocation problem and present further research challenges in resource allocation. Similarly, in FD-Relay networks, consisting of multiple source and destination nodes, and FD relay nodes using OFDM transmission, the corresponding subcarriers should be properly allocated at the relay for different source-destination pairs [7].
Table II summarizes the game theoretic approaches used for radio resource allocation of centralized FD communication networks.

<table>
<thead>
<tr>
<th>Application</th>
<th>Game model</th>
<th>Solution</th>
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<tbody>
<tr>
<td>Mode Switching [12]</td>
<td>Evolutionary game: mobile users as players</td>
<td>Mode switching for mobile users by evolutionary algorithm [10]</td>
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### B. Game Models for Distributed Full-Duplex Communication Networks

In a distributed network, users compete to access the medium channel without any specific pre-assignment of the channel. For example, random access protocols can be improved by FD-MAC protocol. The associated resource allocation games are given below:

- **Non-Cooperative Game for Power Control**: Power control has been a commonly used approach in multi-user communication systems to optimize system performances such as link data rate, network capacity and coverage. Unlike traditional wireless networks, FD communication suffers from the RSI, and thus, increasing transmit power can improve the signal strength in the receiver side. However, on the other side, it increases the RSI at its own receiver. Therefore, due to the existence of RSI, the corresponding power control algorithm needs to be properly redesigned in order to maximize system performances of all users by using non-cooperative game, which optimizes individual utility in a distributed fashion. The different power constraints, e.g. individual transmit power, will lead to different designs and final solutions.

- **Non-Cooperative Contention Control Game**: Contention based MAC protocol is a distributed approach which shares the wireless channel among competitive nodes. Since the spectrum is shared among multiple nodes, the collision will occur when two or more nodes try to access the spectrum at the same time. To alleviate the network congestion, reduce the collision and improve the performance
of system and fairness in sharing the resources, an efficient distributed medium access protocol is essential. Game theory can be used to design the distributed protocols in wireless networks. The contention based MAC can be formulated by a random access games, where multiple nodes share a common channel and want to maximize their utilities independently. A selfish node may choose to wait for a smaller backoff interval to increase its chance of accessing the medium, and hence reducing the channel access chance of well behaved nodes. Thus, the non-cooperative game with pricing can be used to adapt the contention window to maximize the system throughput by introducing cooperation among users. The difference with traditional carrier sense multiple access protocol is to consider the RSI effect on the utility calculation.

- **Matching Game for Opportunistic Channel Assignment**: In a FD distributed multiple access system, where the FD users can sense all the channels while transmitting over a chosen channel. To achieve the stable spectral allocations among the multiple access users, the robust matching theory can be used by formulating the allocation of frequency channels to the multiple FD users as a distributed matching problem. According to the Gale-Shapley Stable Marriage theorem [11], whenever there exist two sets of men and women, where every man and woman has his or her own preference regarding the opposite sex players, there exists a stable matching. Specifically, this theorem is general, can be realized in a distributed way and proves to stable. The theorem also applies to the proposed matching between the FD users and channels, and thus, the stable spectral allocation can be achieved by using the proposed matching algorithm. As RSI varies under different channel conditions, the design of the distributed matching algorithms needs to take into account the RSI.

- **Coalition Game for Collaborative Spectrum Sensing**: In FD MAC, each user can sense the spectrum and determine whether other users are occupying it while transmitting its own data. In order to combat the hidden terminal or deep fading, collaboration among users can improve the sensing performance by providing additional spatial diversity [14]. However, the existence of RSI greatly affects the collaborative sensing process and leads to deterioration in the sensing performance. This can be solved by the coalition formation game [10], where a set of players (i.e., users) intend to form cooperative groups (i.e., coalitions). A coalition represents an agreement among the players to act as a single entity formed by players to gain a higher payoff (i.e., better sensing performance), and the worth of this coalition is called a coalitional value. A typical algorithm is the merge-and-split
algorithm involving the following two operations:

- **Merge**: Coalitions merge to a single coalition whenever mutual benefits exist.
- **Split**: A coalition splits whenever this splitting can provide better payoffs.

Table II summarizes the game theoretic approaches used for radio resource allocation of distributed FD communication networks.

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<tr>
<td>Power Control [3], [8]</td>
<td>Non-cooperative game: FD users as players, and pricing can be used to introduce cooperation</td>
<td>Power level adjustment for FD users by iterative update algorithm</td>
</tr>
<tr>
<td>Contention Control [8]</td>
<td>Non-cooperative game: FD users as players, and pricing can be used to introduce cooperation</td>
<td>Contention window length adjustment for FD users by iterative update algorithm</td>
</tr>
<tr>
<td>Collaborative Spectrum Sensing [14]</td>
<td>Coalition game: players are FD users, and coalition value is the transmission rate</td>
<td>User selection by merge-and-split algorithm [10]</td>
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### V. Matching Theory for Resource Allocation in Full-Duplex OFDMA Networks

This section briefly introduce matching theory, and then as an illustrative example, we apply this theory to resolve the subcarrier assignment problems in FD-OFDMA cellular networks.

#### A. Matching Theory Basics

In economics, matching theory is a mathematical framework attempting to describe the formation of mutually beneficial relationships over time. It has been especially influential in labor economics, where it has been used to describe the formation of new jobs, as well as to describe other human relationships like marriage. It recently has been widely used in wireless communications. Matching theory is one general and practical tool for analyzing wireless markets that studies the interaction of competitive agents in a network.

The matching problems can be classified as follows:
1) Bipartite matching problems with two-sided preferences: Here the participating agents can be partitioned into two disjoint sets, and each member of one set ranks a subset of the members of the other set in order of preference. Example applications include: assigning junior doctors to hospitals, pupils to schools and school leavers to universities.

2) Bipartite matching problems with one-sided preferences: Here the agents are partitioned into two disjoint sets, but only one set of the agents have preference over the other set. Example applications are like: campus housing allocation, DVD rental markets and assigning papers to reviewers.

3) Non-bipartite matching problems with preferences: Here all agent form one single homogeneous set, and each agent ranks a subset of the others in order of preferences. Example applications include: forming pairs of agents for chess tournament, finding kidney exchanges involving incompatible patent-donor pairs and creating partnerships in P2P networks.

Besides the above way of classification, we can also classify matchings by the number of agents in each side, i.e., one-to-one matching, many-to-one matching and many-to-many matching. We present below an example to show how matching problems with two-sided preferences can be applied to solve resource allocation problems in FD communications.


As shown in Fig. 2, in a FD-OFDMA cellular network consisting of one FD BS and multiple HD uplink/downlink users, uplink/downlinks users are paired and the BS assigns a subset of subcarriers to each pair of uplink/downlink users. Specifically, each pair of users and the BS form a FD transceiver unit, in which one user acts as a transmitter (TX) and the other acts as a receiver (RX), and each subcarrier (SC) is assigned to a user pair only. Thus, this user pairing and subcarrier assignment can be formulated by a matching problem with two-side preferences. The objective is to maximize the sum-rate of the system by jointly optimizing the pairing variables $TX - RX - SC$.

Define a subcarrier-RX (SR) unit that consists of one subcarrier and one RX. Since there exist $K$ SCs and $M$ RXs, there are $MK$ different SR units. Thus, we have a matching with $M$ TXs on one side and $MK$ SR units on the other side. The matching algorithm can be briefly described as follows:

1) First, define a price for each SR unit and set the price to zero. These prices are fictitious money without any physical meanings that are considered as the matching cost for each TX.
2) Then in each step, any TX that is still not matched proposes to its most preferred SR unit according to the achieved sum-rate and the corresponding cost.

3) If one SR unit receives offers from more than two TXs, they increase their prices with a price step number until only one offer is received.

4) When one SR unit receives only one offer, which comes from the same TX, they will be matched together.

5) The matching algorithm is iterative and ends if all the TXs are matched and no new offer is being made. This point is called the *equilibrium point* of the matching, which also indicates that the convergence has been achieved.

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**Fig. 5.** Sum rate performance in terms of transmitted power of each user.

To evaluate the performance, the proposed distributed matching algorithm is compared with the centralized solution. Fig. 5 illustrates the total sum-rate vs. transmitted power of each user. It shows that the proposed matching algorithm provides a total sum-rate of the network quite close to the centralized
algorithm. Besides, the complexity of the proposed algorithm is much lower than that of the centralized algorithm such that when $M = 5$, and $K = 7$, the number of iterations in the centralized algorithm is 7200, which is 928.57\% higher than that in the proposed algorithm which is no more than 700.

VI. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

In this tutorial, game theory has been introduced to model and analyze the noncooperative and cooperative behaviors of FD communication networks. The game theoretic models are useful for designing distributed radio resource allocation algorithms to achieve stable and efficient solutions by applying FD radios for future wireless networks. We have discussed different game models developed for allocating radio resources for centralized and distributed scenarios. These models have been categorized based on the types of games. The associated resource allocation problems in these systems are discussed, including mode switch, power allocation, contention control and subcarrier assignment. We have presented a matching game model in detail, and also outlined potential research directions on developing game theoretic models to solve several important radio resource management problems for FD communication networks.

Besides, there are still many potential future research directions in various wireless FD applications, for example,

- **FD Heterogeneous Networks (HetNet):** In such a network, the macro base stations (MBSs) and femtocell access points (FAPs) are equipped with FD radios. Thus, each user can select to communicate with either MBSs and FAPs to reduce the self-interference and the inter-cell interference. In contrast to the traditional HetNet systems where FAPs in the adjacent cells typically do not interfere much with each other, in FD-HetNet the simultaneous uplink and downlink communications between the users and MBSs/FAPs can lead strong interference among the FAPs. In this scheme, the game models can be still applied to cope with the power control, subcarrier allocation, and user pairing problems.

- **FD Cognitive Radio Networks:** In traditional cognitive radio networks, secondary users (SUs) first sense the spectrum holes before transmit. With a FD radio, it allows SUs to simultaneously sense and access the vacant spectrum [13]. As a result, research topics such as spectrum sensing algorithms [14], dynamic spectrum access, etc., need to be redeveloped. Thus, the game-theoretic approaches such as contract game, evolutionary game, etc., can be applied to solve the dynamic spectrum access
problems, and coalition and overlapping coalition games are suitable for collaborative spectrum sensing problems [10], [15].

REFERENCES

[8] L. Song, R. Wichman, Y. Li, and Z. Han, “Full-Duplex Communications and Networks,” in contract with Cambridge University Press, UK.