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Game theoretical method for sum-rate maximization in full-duplex Massive MIMO Heterogeneous Networks

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In this paper, we consider Massive MIMO in two-layer Heterogeneous Networks. The system has a large self-interference and co-channel interference due to operation in full-duplex mode. By using Game Theory, an optimized sum-rate is achieved. We investigate the potential sum-rate before and after the optimization under the power constraints. It is shown that the game theoretical method performed a very good access scheduling. Compared to non-optimized model, game theoretical method can achieve higher sum-rate.

1. Introduction

4G LTE standard has been released several years ago, however, high speed data demand is still increasing. Although 4G network is not yet universal on a global scale, engineers start studying 5G technologies. 5G does not have a unique definition yet [1,2]. Generally, 5G network is considered working in high frequency band from 20 GHz to even 50 GHz [3], and it has a higher spectrum efficiency and also higher power efficiency [4]. Pekka Pirinen summarized recent years' research on 5G and suggested a possible technical requirements over currently existing technologies (4G) [5]:

- 1000 times higher mobile data volume per area,
- 10–100 times higher typical user data rate,
- 10–100 times higher number of connected devices,
- 10 times longer battery life for low power devices,
- 5 times reduced end-to-end latency.

However people proposed many techniques to achieve these requirements, i.e. Full-Duplex Radios for Local Access [6] and Massive MIMO technology [7–9]. The half-duplex wireless communication system, usually are called FDD and TDD in 4G standard, use two different channels for uplink and downlink. Full-duplex wireless communication, compared to half-duplex, allows devices to transmit and receive data simultaneously [10,11]. It has been considered as a promising technique to next generation wireless communication systems because it is possible to double the capacity theoretically [12–15]. However, the full-duplex wireless system has an interference problem which cannot be ignored. Refs. [16–18] proposed some approach to solve interference problem. Ref. [19] presented an interference alignment method for K-user interference channel and [20] discussed the feasibility of this method over measured MIMO-OFDM channels.

Heterogeneous Networks (HetNets) were proposed several years ago and became a part of 4G-LTE standard.

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Although it is not been widely deployed, some wireless operators have deployed it in the market. It is foreseeable that the HetNets will become a more popular technique in next generation wireless communication system. If all base stations (BS) are equipped with large number of transmission and reception antennas, the technical realization and even the system modeling will be very complicated. HetNets modeling and potential gains with Massive MIMO were analyzed in [21]. Ref. [22] studied a density HetNets over a Massive MIMO channel.

In a cellular HetNets, if a user locates in a small cell, then it has more than one access strategies. Assumed that inside the macro-cell, there are multiple pico-cells in this area. The user can either connect to macro-cell BS or communicate with pico-cell BS. It is really hard to find a universal strategy in this situation, because it depends on the number users in this small cell and also the system has to know all users' QoS. Moreover, for each user, the interference from other users and other cells should be taken into account. Game Theory is a good choice for this kind of problem. The Nash Equilibrium, as the optimized solution of a non-cooperative game, indicates that for any user, it cannot get more utility by changing its strategy. Past research on HetNet using Game Theory covered many aspects. Ref. [23] analyzed cooperation and competition games in MIMO HetNets. Ref. [24] studied the information rate for a MIMO system using Game Theory. However, very few papers focus on Massive MIMO in HetNets.

In this section, we consider a scenario that one macro-cell and several small cells deploy in HetNets, and Massive MIMO are equipped on all BSs and users. Each link between BS antennas and user antennas working in full-duplex mode allows nodes to exchange information simultaneously. Due to the full-duplex, each pair of nodes suffered from self-interference, and the inter-user interference is considered in our model. The game theoretical approach is applied in this problem to find an optimal access strategy. For each user device and all BS, power constraint is considered and the system total power consumption is limited.

The rest of this section is organized as follows. Section 2.2 introduces the system scenarios and a system model is built. In Section 2.3, a cooperative game is introduced to achieve the maximum sum-rate with an optimal user access strategy. Some numerical results as well as essential analysis are provided in Section 2.4. Finally, conclusions on this research are made in the last section of this section.

2. System model

In this section, a HetNet with Massive MIMO will be modeled (as shown in Fig. 1). It is a cellular system in which both macro-cell and small cells communicate with users in full-duplex mode. Thus BS can transmit (receive) data to (from) multiple users simultaneously. It is assumed that users are communicating with BS in half-duplex mode. In this area as shown in Fig. 1, there are two types of users. Some users have to connect to macro-cell as they are not covered by pico-cell signals. Another situation is that users have to connect to macro-cell because the small cell has too many users to serve and it reaches the capacity limit defined by the system. The other type of users is to connect to small cells.

Assume there are K uplink (UL) users and J downlink (DL) users in this area and they will be served by macro- and pico-cells. There are M_0 transmission and N_0 receiving antennas equipped by macro-cell BS. And for each small cell BS, it has M_s antennas for DL transmission and N_s antennas for receiving data from its subscribers. M_k denotes k-th UL user's antenna number and N_j is the j-th DL user's antenna number respectively $k=1,\ldots,K$ and $j=1,..., J$. And d_k^{UL} represents the number of data steams transmitted from k-th UL user. Similarly, d_j^{DL} is the number of data steams transmitted to j-th DL user.

For the UL channel, if the user communicates with p-th small cell BS, we have $H_{k,SC_p}^{UL} \in C^{N_s * M_k}$ to represent the k-th UL user's channel. And if k-th user transmits data to mBS, then the channel is $H_{k,mBS}^{UL} \in C^{N_0 * M_k}$.

For the DL channel, if the user communicates with p-th small cell BS, we have $H_{j,SC_p}^{DL} \in C^{N_j * M_s}$ to represent the j-th DL user's channel. And if j-th user receives data from mBS, then the channel is $H_{j,mBS}^{DL} \in C^{N_j * M_0}$.

Several types of interference are considered in this model. $H_p^{mS} \in C^{N_s * M_0}$ denotes the CCI channel from DL of mBS to reception antenna of p-th small cell BS. $H_p^{Sm} \in C^{N_0 * M_s}$ is the CCI channel from DL of small cell BS to reception antenna of mBS. And $H_{jk}^{DU} \in C^{N_j * M_k}$ represents CCI channel from k-th UL user to j-th DL user. $H_{mBS} \in C^{N_0 * M_0}$ denotes the self-interference channel from transmission antennas to reception antennas of mBS. Respectively, $H_{SC_p} \in C^{N_s * M_s}$ denotes the self-interference channel from transmission antennas to reception antennas of p-th small cell BSs. Note that there is no interference from DL users to UL users since all users are working in the half-duplex mode.

Fig. 2 illustrates all channels considered in this model. User's device is working in half-duplex mode. So when it is transmitting data, it cannot receive at the same time. So it does not have the self-interference.

The original symbols need precoding process before transmitting. For the UL process, $V_k^{UL,mBS} = [V_{k,1}^{UL,mBS}, \ldots, V_{k,d_k^{UL}}^{UL,mBS}] \in C^{M_k * d_k^{UL}}$ denotes the precoders for transmission data stream from k-th UL user if the user connects to mBS. And if the user is a p-th small cell's subscriber, the precoders of data stream should be $V_k^{UL,SC_p} = [V_{k,1}^{UL,SC_p}, \ldots, V_{k,d_k^{UL}}^{UL,SC_p}] \in C^{M_k * d_k^{UL}}$. Respectively, for the DL process, $V_j^{DL,mBS} = [V_{j,1}^{DL,mBS}, \ldots, V_{j,d_j^{DL}}^{DL,mBS}] \in C^{M_0 * d_j^{DL}}$ denotes the precoders for j-th user's DL data stream if user connects to mBS. Similarly, $V_j^{DL,SC_p} = [V_{j,1}^{DL,SC_p}, \ldots, V_{j,d_j^{DL}}^{DL,SC_p}] \in C^{M_k * d_j^{DL}}$ represents the precoders for j-th user's DL data stream if the user receives signals from p-th small cell BS.

The k-th UL user's transmission source symbols is represented as $S_k^{UL} = [S_{k,1}^{UL}, \ldots, S_{k,d_k^{UL}}]^T$. Similarly, $S_j^{DL} = [S_{j,1}^{DL}, \ldots, S_{j,d_j^{DL}}]^T$ denotes the transmitted source symbols to j-th DL user. As in [25], we assumed that the symbols are i.i.d. with unit power $(E[S_k^{UL}(S_k^{UL}H)] = I_{d_k^{UL}}, E[S_j^{DL}(S_j^{DL}H)] = I_{d_j^{DL}})$. Then we can define the