Balance of uplink and downlink energy consumption based on geometric weighting

Peng Xu1, 4, Yanfei Yang2, Xin Song3 and Guangli Liu2

1College of Electronic and Information Engineering Shenyang Aerospace University, Shenyang, China
2School of Computer Science and Engineering, Northeast University, China
3School of Computer and Communication Engineering, Northeast University at Qinhuangdao, Qinhuangdao, China
4Email: 1701908@stu.neu.edu.cn

Abstract. In this paper, we study a full-duplex MIMO single-cell system in which a full-duplex MIMO base station simultaneously exchanges information with multiple single-antenna users. Full-duplex introduces additional self-interference and multi-user interference compared to half-duplex, resulting in conflicting coupling between the uplink and downlink. Therefore, we use the geometric weighted multi-objective method to weigh the uplink and downlink transmit power minimization problem under the minimum rate constraint. By transforming the original non-convex problem into a convex problem, a new weight function is established by means of geometric weighting to balance energy consumption better between the uplink and downlink. Through numerical simulations, it shows that the proposed algorithm shows better energy saving gain than the original method.

1. Introduction

Compared to the traditional half-duplex mode, full-duplex wireless communication theoretically doubles the capacity of the system and is therefore considered one of the competitive solutions for wireless communication in the future [1]. Full-duplex systems can simultaneously exchange information at the same frequency, yet with additional self-interference and co-channel interference, which poses challenges for the implementation of full-duplex systems. On the other hand, with the development of self-interference technology, self-interference cancellation has been able to reduce self-interference to very low levels, such as analog cancellation [2] and digital cancellation [3]. The development of these technologies has made the implementation of full-duplex technology even closer. The project of local access to full-duplex radio has been funded by the EU’s Seventh Framework project [4]. Full-duplex technology is theoretically applicable to cellular base stations and mobile users, but small cells are considered to be very suitable for full-duplex technology due to low transmit power and mobility [5].

In the half-duplex communication system, the uplink and downlink are separated from each other, while in the full-duplex communication system, due to the existence of self-interference and co-channel interference, they are coupled and conflict between the uplink and downlink. In [6], the author introduces the idea of game theory to solve the conflict between the uplink and downlink in full duplex. The paper decouples the maximum rate problem by giving the known information of the uplink [7]. However, during energy consumption optimization, the transmission power of both uplink
and downlink is unknown, so it is impossible to decouple the energy consumption problem with given information.

The energy consumption of mobile base stations is much larger than that of mobile users, which leads to the large difference between the two target ranges [8], to relieve the problem induced by [8]. [3] proposes a multi-objective method based on Arithmetic weighting for energy optimization of full-duplex multi-user MIMO system uplink and downlink. However, according to [9-10], the weight change of arithmetic weighting may cause the change of target vector to be insignificant, so it is impossible to select better solution in Pareto solution set [9-10]. Therefore, a geometric weighted multi-objective algorithm is proposed in this paper to minimize the power consumption of the uplink and downlink under the constraints of the user's minimum rate and base station antenna transmit power.

2. System model
A single small cell scenario is considered as in Figure 1, where the full-duplex base station has $N$ full-duplex antennas, and the same frequency and $J$ uplink users and $K$ downlink users exchange information, and all users are equipped with a single half-duplex antenna. It is also assumed that the Global Channel State is known to facilitate efficient resource allocation. In this paper we use the symbols $D_k$ and $U_j$ to represent any of the downlink and uplink users.

First, the downlink channel model is given to represent the signal vector received by the user $k$, The formula is expressed as follows

$$y^{DL}_k = h_k^H x_k + \sum_{m\neq k}^K h_k^H x_m + \sum_{j=1}^J \sqrt{P_j} f_{j,k} d_{ul} + n^{dl}_k$$

(1)

Where $h_k \in C^{N \times 1}$ represents the complex channel from the base station to the downlink user $k$, and $f_{j,k}$ represents the co-channel interference from the user $j$ to the user $k$, and $n^{dl}_k \sim CN(0, \sigma^{dl}_k)$ is assumed to be additive white Gaussian noise (AWGN). In addition, $x_k = w_k s_k^{dl}$, $s_{k}^{dl} \in C^{N_T \times 1}$ is data information sent to the user by the downlink channel, which is normalized to $E(|s_k|^2) = 1$, and $w_k \in C^{N_T \times 1}$ is the corresponding beamforming vector, which is an optimized variable in this paper. The solution to the problem automatically allocates the optimal solution vector.

Then an uplink signal model is established, which indicates that the signal vector of all users is received at the base station

$$y^{ul} = \sum_{j=1}^J \sqrt{P_j} h_j x_j^{ul} + H_{st} \sum_{k=1}^K X_k + n_{ul}$$

(2)

Where $h_j \in C^{N_T \times 1}$ represents a complex channel vector from the base station to the uplink users, and the matrix $H_{st} \in C^{N_T \times N_T}$ is represented as a self-interference channel between the transmitting
antenna and the receiving antenna at the base station. \( P_j \) is the transmit power of the mobile user, and \( x_j^{ul} \) is the data signal transmitted by the uplink user. Finally, \( n_u \sim CN(0, \sigma_u^2) \) is also represented as additive white Gaussian noise at the uplink.

From Equations (1) and (2), we establish the ratio of the received signal to the various interferences (SINR) of the uplink and downlink users as follows

\[
\text{SINR}_k = \frac{|h_k^H w_k|^2}{\sum_{m=1}^{K} |h_k^H w_m|^2 + \sum_{j=1}^{J} p_j |f_{j,k}|^2 + \sigma_n^2}
\]

(3)

\[
\text{SINR}_j = \frac{|h_j^H v_j|^2}{\sum_{r=1}^{R} p_j |h_r^H v_j|^2 + \sum_{k=1}^{K} |v_j^H H_{Sti} w_k|^2 + \sigma_n^2}
\]

(4)

Equations (3) and (4) represent the signal to interference and noise ratio received by the downlink user and the uplink user. The information rate \( \log_2 (1 + \text{SINR}_k) \) indicates the information rate of the user, and \( v_j \in C^{N \times 1} \) indicates that the uplink user receives the beamforming vector transmitted by the base station, and this paper considers zero-forcing (ZF) for decoding.

Although great progress has been made in self-interference cancellation, the amount of self-interference cancellation is limited, and power constraints on the transmit antenna are necessary, which facilitates self-interference cancellation (SIC) at the base station [8]. The power constraint received by each base station is expressed as

\[
\sum_{k=1}^{K} w_k^H Q_{j,k} w_k \leq q_{j,L}, \quad L = N
\]

(5)

Where the parameters \( Q_{j,k} \) and \( q_{j,L} \) are fixed, representing the constraints of each antenna and array, and \( N \) is the number of antennas of the base station.

3. Problem formulation

3.1. Preliminaries

Our goal here is to minimize the transmission power of both the uplink and downlink. In order to ensure fairness, each user receives the same minimum rate constraints, and the antenna at the base station receives the maximum transmission power constraints for better self-interference cancellation.

\[
\text{minimize}_{w_k, p_j} \sum_{k=1}^{K} ||w_k||^2 + \sum_{j=1}^{J} p_j

\text{subject to: } \log_2 (1 + \text{SINR}_k) \geq \gamma_k, \quad \forall k

\log_2 (1 + \text{SINR}_j) \geq \gamma_j, \quad \forall j

\sum_{k=1}^{K} w_k^H Q_{j,k} w_k \leq q_{j,L}, \quad \forall L
\]

(6)

Due to the target problem (6), the minimum rate constraint formed by the beamforming vector makes the original objective function non-convex. In some beamforming design problems, the global optimal solution is generally solved, and the rank relaxation technique using the semi-determined relaxation (SDP) method is usually adopted to solve such problems [11].

In order to solve the target problem (6), we reconstruct the problem by using \( W_k = w_k w_k^H \), where \( W_k \geq 0 \) and rank\((W_k)\leq1 \). In addition, \( H_k = h_k h_k^H, \ G_k = h_j h_j^H \) and \( V_j = v_j v_j^H \) are set in advance, so the target problem of reconstruction is as follows

\[
\text{minimize}_{w_k, p_j} \sum_{k=1}^{K} Tr(W_k) + \sum_{j=1}^{J} p_j

\text{subject to: } \frac{Tr(H_k W_k)}{\gamma_k} \geq \sum_{m=1}^{K} Tr(H_k W_m) + \sum_{j=1}^{J} p_j |f_{j,k}|^2 + \sigma_n^2, \quad \forall k

\frac{Tr(V_j G_k)}{\gamma_j} \geq \sum_{r=1}^{R} p_j Tr(V_j G_r) + \sum_{k=1}^{K} Tr(W_k H_{Sti} V_j H_{Sti}) + \sigma_n^2, \quad \forall j

\sum_{k=1}^{K} Tr(Q_{j,k} W_k) \leq q_{j,L}, \quad \forall L

\text{rank}(W_k) \leq 1, \forall k
\]

(7)
In Equation (7) we convert the rate constraint to the target constraint of SINR, where $\gamma^*_k = 2^{r_k} - 1$ and $\gamma^*_j = 2^{r_j} - 1$ represent the value of SINR. Reconstructed formula (7) apart from the rank constraint, the solution problem is convex, and the problem can be solved by relaxing the rank constraint to transform the problem into a convex semi-definite optimization problem [1]. At the same time, we notice that the uplink and downlink powers cannot be minimized because of the SINR constraint with the self-interference and co-channel interference. In the next section, an improved weighted multi-objective method is proposed to balance the uplink and downlink transmission power in this paper.

3.2. Weighted multi-objective algorithm
Since we pay attention to the minimization of uplink and downlink transmission power in full-duplex systems, and the inherent coupling and conflicts of full-duplex uplink and downlink, the minimization of one goal will lead to the deterioration of the other. The paper uses weighted Tchebycheff method to solve conflict problems [3]. The mathematical formula is as follows.

$$\text{max}_{x \in S_{opt}} (\lambda \cdot (f(x) - z))$$ (8)

Equation (8) is an arithmetic-weighted arithmetic mean. In the problem of dealing with different target scales, geometric weighting is better than arithmetic-weighted display [3] because the arithmetic-weighted relative scaling has no effect. In a full-duplex system, the transmit power of the base station is much larger than the transmit power of the user. The range is huge. There is no limitation in using simple arithmetic weighting, and the uplink and downlink transmit power cannot be better balanced. So we use a geometric weighting algorithm

$$f_{\text{product}}(\cdot) = \prod_{m=1}^{M} (g_m(x))^w$$ (9)

Next, we apply formula (9) to our problem. We establish a new effect function to represent the optimal transmission power of the system. The formula is as follows

$$f_{\text{power}}(P_{ul}, P_{dl}) = \lambda^{w} - \lambda^{1-w}$$ (10)

In order to better reflect the balance between the uplink and downlink transmission power, we will normalize the uplink and downlink transmission power. In formula $w \in (0,1)$ represents the preference factor, while $w \to 0$ indicates that the optimization goal pays more attention to energy saving of Uplink users and vice versa. Parameters $\lambda_{ul} = P_{ul}^{min}/P_{dl}$ and $\lambda_{dl} = P_{dl}^{min}/P_{dl}$ denote constant parameters after normalization of transmission power for both uplink and downlink.

$$\text{minimize } f_{\text{power}}(P_{ul}, P_{dl})$$

subject to

$$\sum_{k} \text{Tr}(H_k W_k) \geq \sum_{m,k} \text{Tr}(H_k W_m) + \sum_{j=1}^{J} \sum_{k} p_j |f_{j,k}|^2 + \sigma^{2}_{dl}, \forall k$$

$$\sum_{j} \text{Tr}(V_j G_k) \geq \sum_{j} \text{Tr}(V_j G_k) \geq \sum_{k=1}^{K} \text{Tr}(W_k H_{jk}^H V_j H_{sk}) + \sigma^{2}_{ul}, \forall j$$

$$\sum_{k=1}^{K} \text{Tr}(Q_{j,k} W_k) \leq q_{j,k}, \forall L$$ (11)

Finally, we use the standard convex optimization solver to simulate and verify it.

4. Simulation results
In this section, we verify the proposed energy optimization algorithm through simulation. We consider a full-duplex cellular network system with a radius of 200 meters, in which full-duplex base stations are located in the center of the system, and users are uniformly distributed in the cell, and there are 5 uplink users and downlink users in the cell. The user communicates with the base station at the same time. Simulation parameters are given in Table 1.

Full-duplex communications introduce additional interference, but the capacity of full-duplex systems doubles that of half-duplex systems. Therefore, in order to make a comparison between full-duplex and half-duplex energy consumption, $\log_2 (1 + SINR_{dl,ul}) = \frac{1}{2} \log_2 (1 + SINR_{dl,ul}^{HD})$ is usually set. From Figure 2, we can see that full-duplex system achieves higher energy-saving gain than half-duplex system under the minimum rate constraint, but the energy-saving gain of full-duplex uplink
decreases gradually at higher rate. It is that the increase of transmission power of the uplink leads to more serious co-channel interference.

Table 1. Channel Parameters in the numerical evaluation.

| System parameter          | Value                          |
|---------------------------|--------------------------------|
| System bandwidth          | 200 kHz                        |
| Noise variance $\sigma^2$ | -127 dB                        |
| Path fading parameters $L_{10}(d)$ | $148+37log_{10}(d)$ dB         |
| Path fading between users | $127+30log_{10}(d)$ dB         |
| Self-interference cancellation | -80 dB                       |

In order to compare the two weighting algorithms, the same weighting factor $w=0.7$ is chosen to show more attention to the energy saving of the uplink. From Figure 3, we can see that the geometric weighting algorithm shows better energy-saving effect. Because the total energy consumption of downlink is much larger than that of uplink, the weight change of arithmetic weighting algorithm may cause the change of target vector to be insignificant. As a result, it is impossible to select better targets in Pareto solution set.

Figure 2. Full-duplex and half-duplex energy consumption under minimum rate constraints.

Figure 3. Contrast energy consumption.

Figure 4 shows the trend of normalized uplink transmission power $p_u$ and downlink transmission power $p_d$ with the preference weighting factor. When the weighting factor $w \rightarrow 0$ Express that we are concerned about Downlink transmission power, whereas we are more concerned about Uplink users' transmission. Normalized effect function reflects the trade-off between different differences, which provides a reference for designers to balance the energy consumption of conflicts. Figure 5 shows that increasing the number of antennas in the system reduces the total energy consumption of the full duplex system. More antennas reduce the downlink transmission power, while the downlink transmission power reduces the transmission power of the uplink users through self-interference, thus reducing the overall power consumption of the system. However, as the number of antennas increases, the energy-saving effect decreases gradually.
5. Conclusions

In this paper, the transmission power minimization of the uplink and downlink in a full duplex MIMO cell is studied. Due to the coupling conflict between the uplink and downlink, it is impossible to minimize simultaneously, and the multi-objective programming problem often fails to obtain the global optimal solution. However, the proposed geometrically weighted multi-objective algorithm perfectly conquers the trouble and balances better the conflict between the Uplink and downlink.

Acknowledgments

This work was supported by the National Nature Science Foundation of China (No. 61473066 and No. 61601109), the Fundamental Research Funds for the Central Universities (No. N152305001), and the Natural Science Foundation of Hebei Provinces of China (Grant F2017501039).

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