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Promoting fractional frequency reuse performance for combating pilot contamination in massive multiple input multiple output

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ABSTRACT

Massive multiple-input multiple-output (MIMO) improves spectrum efficiency by increasing the capacity of the wireless structure. Therefore, massive MIMO is promising for fifth generation (5G) wireless communications. In massive MIMO, channel estimation is a crucial part that should achieve reliable performance. Pilots are sent from the end-users to be used for estimating the channel. However, the problem of interference in pilot contamination affects the performance for cell-edge users. Specifically, pilot contamination appears when the same pilot sequence is utilized at the same time by more than one terminal. This lead to an inaccurate estimation of the channel. Consequently, the decoded data will not be reliable. For mitigating these pilot contamination effects, an enhanced fractional frequency reuse (eFFR) scheme is proposed that uses an algorithm in the allocation of pilot sequences to end users' devices based on the locations of the users from the target base station (BS). The simulation results exhibit that the proposed scenario outweighs the traditional FFR within both signal to interference, and noise ratio (SINR), and capacity. Consequently, the suggested scenario enhances the performance of more than 80% of the cell terminals and the other 20% of the terminals have a slightly lower performance compared to the FFR.

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1. INTRODUCTION

The fifth-generation (5G) of mobile communication is the latest type of wireless cellular network which allows a larger data rate and high capacity in comparison with the former generations along with the appearance of novel technologies and the acquirement of the latest cellular structures [1]–[7]. As the number of mobile subscribers grows and the volume of multimedia content such as photos, videos, and audio recordings increase continuously, we are constantly in need of higher capacity by using the systems of wireless communication systems that can support high data rates. In addition, there is a global trend called green communications to eliminate pollution in the environment by reducing the amount of electricity used in communication systems. The current technologies of the fourth-generation (4G) system do not enable it to meet future requirements for several reasons such as the spectrum allocated for wireless cellular communications is very busy, and the 4G system is supported and not designed to save energy. These limitations have prompted researchers and experts to think beyond 4G or in other words, plan for a 5G system.

Massive multiple-input multiple-output (MIMO), cognitive radio (CR), and multiple spatial data are promising technologies for use in 5G [1]–[3]. MIMO technology operates with multiple antennas in the receiver and the transmitter. This effect resulted in the use of time-frequency on multiple communication channels as it is done by means of the channel's spread factor, to determine each communication channel with the other communication channels, MIMO technology significantly improves spectrum capabilities with better and large capabilities, with a limited number of antennas at the main base station (BS) with the mobile terminal for appropriate terminal size. To maximize the benefits of MIMO, as well as increasing system capacity and maintaining a small size of the mobile terminal, massive MIMO technology was proposed [8]–[13].

In massive MIMO, the BS has too many antennas to handle many terminals on similar time-frequency slots [14], [15]. It should be noted that there are a lot of problems and difficulties that must overcome the experimental deployment of massive MIMO such as pilot contamination, frequency division duplex (FDD) operation, accurate deployment model, and end users' devices limitations [15].

The MIMO technology is empowered to develop broadband networks (fixed and mobile) in the future, which will be energy-efficient, safe, powerful, and will allow for effective use of the spectrum [14], [15]. Based on [16], the MIMO transmission design can achieve doubling capacity in SNR and 1.5 additional b/s/Hz capacitance at 5 dB signal to noise ratio (SNR) for a four-input two-output system over independent Rayleigh channels with the symmetric flat fade distribution. The contribution of this work is to find an enhanced fractional frequency reuse (eFFR) scheme that uses an algorithm in the allocation of pilot sequences to end users' devices based on the locations of the users from the target BS that we want to enhance its performance.

In this work, an improved FFR scheme is suggested that takes the ability to get and track large-scale fading factors into account when assigning the pilot sequences to mobile terminals. The suggested scheme takes the advantages of both using FFR factor rather than reuse factor one and at the same time using an allocation algorithm according to the channel condition rather than random allocations. The suggested scheme reinforces the average achievable capacity of each terminal. The rest of the paper is arranged in the following way. In section 2, a survey about the intended problem and the researcher's efforts will be introduced while in section 3, we will explain in a simplified manner the troubleshooting of pilot contamination and the methodology followed in our proposal to mitigate it. In section 4, the optimized simulated results of the proposed scheme are displayed and discussed. In section 5, the conclusions of the proposed work are presented.

2. RELATED WORKS

The troubleshooting of pilot contamination [15]–[18] is a bottleneck in the performance of a massive MIMO system. This troubleshooting is produced during the channel estimation process when a similar pilot arrangement is used by several mobile terminals at the same moment. This problem leads to channel estimation errors, which affect the reliability of data decoding even if the BS is equipped with a huge number of antennas. Due to its importance, the problem of pilot contamination has been widely investigated in many research studies [19]–[25]. In [19]–[21], a time-shifting protocol was proposed. This protocol significantly mitigates the pilot contamination problem by dividing the structure into sets by employing various time protocols, so that each group transfers pilot sequences in non-overlapping times in regard to the other groups, which means that when a single group sends pilot sequences, the other groups send data, and it has been proved in these papers that the interference between data and pilot vanishes by using an infinite number of antennas. As a result of this proposal, the number of interfering cells will be reduced in order to equal the number of the system groups.

The precoding-based method has been suggested in [22] to alleviate the pilot contamination problem by collaboration among the BSs of the cellular system. In [23], FFR method was proposed for alleviating the pilot contamination problem by using different reuse factors. Reuse factor of 1 is used in the centers of the cells, and a reuse factor of 3 is used in the edges of the cells. However, all these papers [19]–[22] assign the pilot sequence available randomly to the terminals. It would be mentioned here that FFR of [23] is considered random, because after determining if the user is center or edge, the pilot sequences were taken randomly to center users and similarly to edge users. This is the weak point that we try to avoid in our proposal by assigning the pilot sequences using an algorithm. In [24], [25], pilot allocation codes are used to assign the pilot sequences. In [24], the users are sorted according to their channel quality in a certain cell, then the pilot sequences are assigned randomly in the other cells with a reuse factor of 1, and finally the pilot sequences are arranged n consonance with the level of interference. After that, the pilot sequences are assigned to the users of the target cell so that a user of low channel quality is given a pilot that is subjected to low interference.

In [25], the users are sorted according to their channel quality in a certain cell, then the users of all the additional cells are arranged in consonance with the level of interference they cause on the target cell, and finally, the pilot sequence is given to a user of low channel quality in the target cell which is given to the users of the additional cells that produces a small interference for a reuse factor of 1. In [24], [25], pilot allocation algorithms are already used, a regular reuse factor of 1 is also used. The simulation results of [23] show that the FFR is better than the reuse factor of 1. Thus, while [24], [25] tried to avoid the random allocation, they used a non-ideal reuse factor, which is the weak point that we try to avoid in our proposal.

3. MATERIAL AND METHODS

3.1. Modeling of the problem

We built our investigated models inspired by the models of [15]–[17] as shown in Figure 1. We considered that the suggested system consists of L cells, each cell has a BS located in its center and is equipped with M antennas. The BS of each cell serves K terminals each has a single antenna. These terminals are consistently spread in the cell zone, which is a hexagon of radius R.

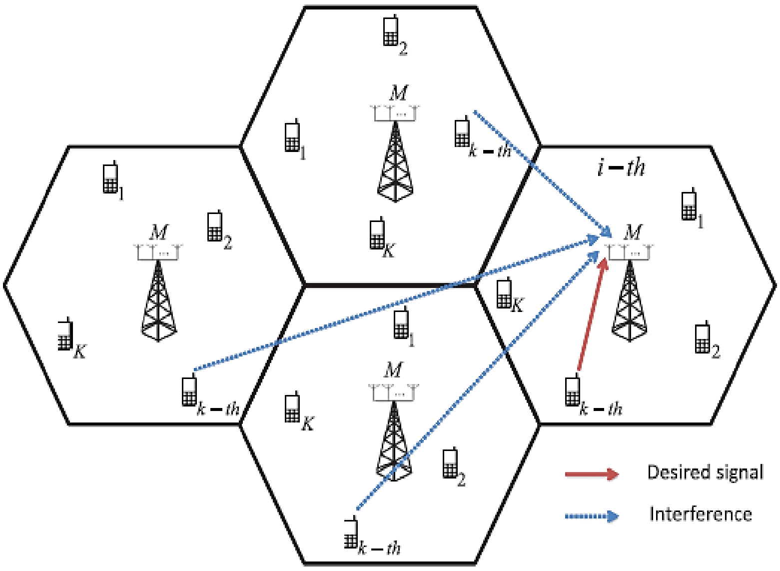

Figure 1. A model of the cellular system of L cells

Transmission channel between any terminal K situated in any cell l and m-th antenna of the i-th BS can be characterized as (1):

$$g_{mikL} = h_{mikL}\sqrt{\beta_{ikL}} \tag{1}$$

where g_{mikl} is a mixture of the small-scale fading coefficient characterized by h_{mikl} and the large-scale fading coefficient characterized by $\sqrt{\beta_{ikl}}$ which is the equivalent for all the M antennas at the i-th BS. β_{ikl} remains steady for several synchronous times and can be more easily acquired and tracked [21], [23], [24]. β_{ikl} accounts for the shadow fading (SF) and geometric attenuation and can be modeled as:

$$\beta_{ikL} = \frac{Z_{ikL}}{r_{ikL}^{\gamma}} \tag{2}$$

where Z_{ikL} is a log-normal random variable, which means that $(10\ log_{10}Z_{ikL})$ forms a Gaussian distribution of zero mean and σ_{SF} standard deviation, r_{ikl} is the distance from the k-th terminal of the l-th cell to the i-th BS and γ is the attenuation factor. Each BS must have the channel state information for all terminals served by it. For this purpose, each BS must execute a channel estimation process. In the suggested model, we followed the algorithm:

- The terminals of each cell send uplink orthogonal pilot sequences,
- The BS process the received pilot sequences to evaluate the propagation channels of its terminals,

- Assuming channel reciprocity, the estimated channel can be used for signal processing in both the uplink and the downlink.

Ideally, each terminal in the system must have an orthogonal unique pilot sequence for the proper channel estimation process. However, the number of orthogonal pilot sequences available at each coherence time is limited. For serving a lot of users, the same pilot sequences should be reused. In the suggested model, we assume that the same set of orthogonal pilot sequences $\Phi = \{\Psi_1, \Psi_2, \dots, \Psi_k\}$ is reused through all the system cells. Furthermore, we expect the worst-case scenario, where pilot transmissions from different terminals in different cells of the system can occur at the same time. Thus, each BS receives the pilots not only from terminals in the corresponding home cell but also from the terminals in the neighboring cells. This leads to what is known in the literature by pilot contamination. The equation (3) models the obtained pilot indication by the *i*-th BS after pilot sequences transmission:

$$Y_i = \sqrt{P_P}\sum_{l=1}^{L} G_{il}\Phi^T + W_i \tag{3}$$

where P_p is the power for single terminal in pilot transmission, $G_{il} \epsilon C^{M\times K}$ is the coefficients matrix between the *l*-th cell terminals and the *i*-th BS, the superscript T is matrix transpose, and W_i is the additive white noise.

After channel estimation process at the *i*-th BS, the estimated channel matrix is not the actual one, but it is a linear combination of all channel matrices as shown in (4):

$$\underline{G_{il}} = \frac{1}{\sqrt{P_P\tau}} Y_{il}\Phi^* = G_{ii} + \sum_{l\neq i}^{L} G_{il} + \frac{1}{\sqrt{P_P\tau}} W_i\Phi^* \tag{4}$$

where * is the matrix conjugate and τ is the dimension of pilot sequence and Y_{il} is the pilot indication from the *l*-th cell terminals by the *i*-th BS.

Using the estimated channel matrix for transferring and receiving data from and toward terminals results in inter-cell interference, because in this case the *i*-th BS will send/receive data symbols to/from all the cells not just its own cell. Considering the mathematical derivation used in [14], when the number of antennas at the BS tends to infinity, the estimated received data symbol by the *i*-th BS from its *k*-th terminal is given by (5).

$$\widehat{x_{k\iota}} = \sum_{l=1}^{L} \beta_{ikl}x_{kl} = \beta_{iki}x_{ki} + \sum_{l\neq i}^{L} \beta_{ikl}x_{kl} \tag{5}$$

This estimated symbol is not the actual one, but it is a combination of the direct signal characterized by the first term and inter-cell interference (the received information symbols from the *k*-th terminals of totally the extra neighboring cells that used the same pilot sequence in the stage of pilot transmission) characterized by the second term. The signal to interference ratio (*SIR)* of the *k*-th terminal of the *i*-th cell is calculated using [16], [26].

$$SINR_k = \frac{(\beta_{iki})^2}{\sum_{l\neq i}^{L}(\beta_{iki})^2} \tag{6}$$

This $SINR_k$ is converted to the capacity for each terminal using Shannon relation:

$$C_k = \left(\frac{B}{\alpha}\right)\left(\left(\frac{T-\tau-n}{T}\right)\left(\left(\frac{T_S-T_c}{T_c}\right)(1 + SINR_k\ )\right)\right) \tag{7}$$

where *B* is the system bandwidth in megahertz, α is the frequency reuse factor, *T* is the coherence time expressed in terms of the number of symbols, τ is the number of symbols used for pilot transmission, *n* is the number of symbols exhausted in signal processing, T_s is the symbol duration in seconds, and T_c is the periodic prefix in seconds.

3.2. Proposed enhanced FFR scheme

As discussed in the previous section, the troubleshooting of pilot contamination is harmful, because it results in inter-cell interference, which in turn limits the capacity per terminal that should be achieved because it gives a low SINR. In this part, we will show the proposed scheme for justifying the pilot contamination outcome and for obtaining higher capacity per terminal. The suggested structure combines the advantages of either the FFR scheme presented in [23] or the pilot allocation algorithm presented in [25]. In our scheme, all cells of the system are connected to a central processing unit (CPU) [27]. This CPU is responsible for assigning the pilot sequences to the end users' terminals in the network. A terminal per cell is classified either as a central station or an edge in relation to its distance from the BS cell. A pilot sequence set is divided into four subsets: Center, Edge1, Edge2, and Edge3 as displayed in Figure 2. The center is the subset used to assign pilot sequences to center terminals of all the cells with a reuse factor of 1 as shown in Figure 3. Edge1, Edge2, and Edge3 are the subsets used to assign pilot sequences to edge terminals of the cells with a reuse factor of 3 as shown in Figure 3.

Each BS estimates the large-scale fading features of all the system terminals and sends them to the CPU, which uses them as indicators for the propagation channels. Any β_{ikl}^2 is either called the channel gain for the k-th terminal, if i equals l or called the level of nosiness produced through the k-th terminal of the l-th cell on the k-th terminal of the i-th cell, if i not equals l. In the CPU, for a goal cell i, the terminals of the i-th cell are arranged consistent with channel gain and the terminals of any additional cell are arranged in consistent with their interference level on the i-th cell. The CPU assigns the pilot sequences, where the pilot sequence is given to a user of low channel gain terminal in the destination cell which is given to the other cells' terminals of low interference, respectively.

Figure 2. The division of pilot sequences

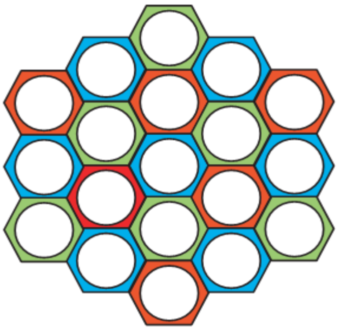

Figure 3. The division of individual cell toward center and edge parts

4. RESULTS AND DISCUSSION

In this section, we evaluate the performance of our proposed enhanced FFR scheme by using simulations. In our simulation, we assumed the area is divided into 37 cells and each cell is assumed to have a radius of 1600 m. The considered bandwidth is 20 MHz, attenuation factor of 3.8, and standard deviation of 8 dB. The coherence, number of symbols used for pilot transmission, and the number of symbols exhausted in signal processing are 7, 2, and 1 OFDM symbols, respectively. The symbol duration is 71.4 µs, and the periodic prefix is 4.76 µs. The simulation parameters used in our evaluations are summarized in Table 1.

4.1. Enhanced FFR

In place of the random pilot sequences assigned to the end users' terminals adopted in [23], our proposed scenario employs the pilot allocation algorithm presented in [25] that allocates pilot sequences for end users' terminals. We built a system model that executes our algorithm using MATLAB, and then we allocated the values given in Table 1 to our simulation parameters. To evaluate and test the performance of the proposed algorithm, we plotted Figure 4 to compare the performance of the proposed algorithm with that in [23] in terms of the signal to interference, and noise ratio (SINR).

Figure 4 compares the cumulative distribution function (CDF) of the SINR of our proposed scenario with that of the FFR in [23]. It is clear from Figure 4 that our proposed scenario improves the minimum achievable SINR and thus, it improves the minimum achievable capacity per terminal compared to the FFR of [23]. From Figure 4, we can note also that our proposed scenario enhances the performance of nearly 80 percent of the cell terminals and the other 20 percent of the terminals have slightly lower performance compared to the FFR of [23]. This interprets has been summarized in Table 2. The proposed results in Table 2 show that the suggested scenario enhances the average achievable capacity for each terminal compared to the FFR of [23].

Another comparison that reinforces the proposed scenario is presented in Figure 5, the figure displays the cumulative distribution function of the spectral efficiency for each terminal for both the FFR scheme of [23] and the proposed scenario. As we can see the suggested scenario improves the spectral efficiency. From Figure 5, it can be observed that the suggested scenario enhances the performance of more than 80 percent of the cell terminals and the other 20 percent of the terminals have a slightly lower performance compared to the FFR of [23].

Table 1. Simulation factors

Factor	Amount
R	1600 m
B	20 MHz
γ	3.8
σ_{SF}	8 dB
T	7 OFDM symbols
τ	2 OFDM symbols
n	1 OFDM symbols
T_s	71.4 µs
T_c	4.76 µs

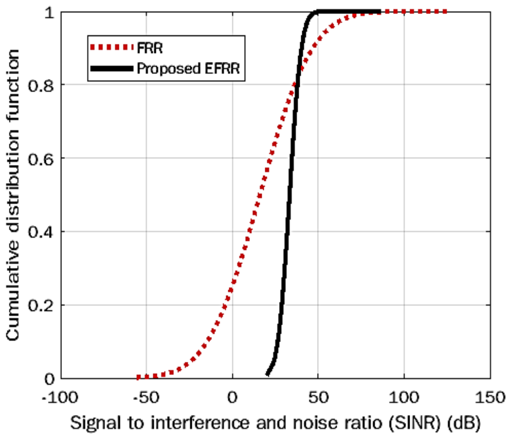

Figure 4. The cumulative distribution function of the SINR for each terminal for both the FFR scheme of [23] and our proposed scenario

Table 2. Comparison of the mean per terminal capacities of the FFR of [23] and our proposed scenario

Scenario	FRR	Proposed EFRR
Mean capacity per terminal (Mbps)	46	75

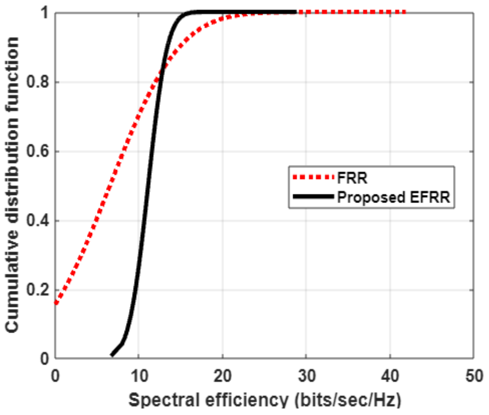

Figure 5. The cumulative distribution function of the spectral efficiency for each terminal for both the FFR scheme of [23] and our proposed scenario

5. CONCLUSION

The troubleshooting of pilot contamination is a major obstacle and a major demand that obstructs the distribution of the colossal MIMO in the 5G wireless communications schemes. Therefore, we have presented the proposed idea as a solution to mitigate the effects of this problem. The structure that we have suggested, combines the advantages of both the FFR scheme presented and the pilot allocation algorithm, so the algorithm reinforces the traditional FFR performance by allocating pilot sequences to terminals so that the low channel gain terminals in a particular cell do not interfere with the terminals of other cells that cause a high level of interference. Simulation results show that the proposed scheme could improve and enhance the minimum capacity achievable per terminal as well as the mean achievable capacity of served terminals. Also, the results have indicated that the proposed system outweighs other systems in SINR.

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