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Joint user grouping and frequency allocation for multiuser SC-FDMA transmission☆

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ABSTRACT

This paper proposes strategies for user pairing and frequency allocation for a virtual multiple-input multiple-output (V-MIMO) single-carrier frequency-division multiple access (SC-FDMA) transmission over intersymbol interference (ISI) channels. N_{u} users, equipped with a single antenna each, compose one pair/group and transmit their data in the same frequency band to the base station (BS), equipped with multiple antennas. Multiuser equalization is applied at the BS. The pairs ($N_{\mathrm{u}} = 2$) are either transmitting in subsequent time slots in a time division multiple access (TDMA) scheme using all available bandwidth or in different frequency chunks in a frequency division multiple access (FDMA) scheme. A generalization for $N_{\mathrm{u}} > 2$ users, called user grouping, is given for the FDMA scheme. For the optimization of joint frequency allocation and pairing/grouping, a low complexity solution is proposed and evaluated by simulations for the uplink of Long Term Evolution (LTE). As optimization criteria, the capacity of the resulting V-MIMO channel and the bit error rate (BER) after equalization are evaluated, respectively. The simulation results show that the proposed algorithms yield significant gains compared to random user pairing and frequency allocation and that using BER as an optimization criterion yields a significantly better performance.

1. Introduction

Single-carrier frequency-division multiple access (SC-FDMA) transmission, also referred to as discrete Fourier transform (DFT) spread orthogonal frequency division multiple access (OFDMA), is employed in the uplink of the E-UTRA Long Term Evolution (LTE) mobile communications system [1]. The main advantage of SC-FDMA compared to OFDMA, which is used in the downlink of LTE, is its reduced peak-to-average power ratio (PAPR), which enables a low-complexity implementation of the mobile terminal. SC-FDMA is currently adopted in LTE usually along with only a single transmit antenna at each mobile station (MS).

In order to improve the spectral efficiency in the uplink, two or more users forming a pair/group can be assigned to the same frequency band and time slot. Using multiple receive antennas at the base station (BS), a virtual multiple-input multiple-output (V-MIMO) system arises, and a multiuser equalizer can separate the signals of all users within a pair/group, as long as the number of receive antennas N_{R} is greater than or equal to the number of (single-antenna) users per group denoted as N_{u}. For this, a low-complexity solution is minimum mean-squared error (MMSE) linear equalization (LE). Since the data streams of all users are independently encoded, an ordered successive interference cancellation (SIC) approach, employing decoded feedback, is another promising candidate for multiuser equalization.

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The BS allocates resources to all users within a cell and therefore decides which frequency band is assigned to a specific user so that N_u users share the same frequency resource at the same time. The allocation of users should be done in such a way that they cause minimal disruption to each other. In this paper we propose two algorithms that optimize the grouping of the users. The first algorithm allocates all users to pairs, where the pairs transmit on subsequent subframes using all available frequency resources. The second algorithm allocates different frequency chunks to groups and all groups transmit during the same subframe using different resource blocks (RBs). In general, all resource allocation schemes need to consider fairness issues, which typically enforces a trade-off between network optimality and user optimality. In this paper, the proposed resource allocation schemes guarantee a certain fairness by assigning all users the same number of SC-FDMA RBs. All users apply the same modulation and coding scheme and equal transmit power. It is assumed that they transmit over frequency-selective fading channels and slow fading has been compensated by perfect power control. For the time domain pair allocation scheme the channels are fixed for the duration of $K = N_{user}/N_u$ LTE subframes, whereas for the frequency domain group allocation scheme they are fixed for one LTE subframe. N_{user} is the total number of users considered for user grouping and N_u is the number of users per group, respectively. User grouping and time/frequency allocation is done according to the current channel snapshots of all N_{user} users. In the uplink of LTE the spectrum is allocated in multiples of resource blocks, where one resource block comprises 12 consecutive subcarriers [1]. Each group is assigned the same number of RBs.

Most previous work on user pairing in the uplink considers only flat fading channels [2–9] and the problem of joint user pairing and frequency allocation for frequency-selective fading is not considered in most cases. An exception are [10,11], where user pairing and frequency allocation are considered for frequency-selective channels. However, the problem of efficiently solving the frequency allocation problem without resorting to an extremely complex full search has not been addressed in [10] for combined user pairing and frequency allocation. User grouping is mentioned in [11], but similar to [10], only a full search for finding the optimum solution is considered. In [12], a greedy heuristic algorithm is proposed for reduced complexity joint user pairing ($N_u = 2$, no user grouping) and frequency allocation. However, this algorithm and all other mentioned algorithms are limited to a linear MMSE equalizer at the BS. The specific frequency allocation requirement, that only successive RBs can be allocated in the localized mode of SC-FDMA, is taken into account in [12], as well as in this paper. A direct comparison of our numerical results with that of the algorithms from [12] is not possible because in [12] the number of assigned RBs can be different for each user, whereas in our system model the same number of RBs is assigned to each user.

The main contributions of this paper are as follows:

- Different pairing criteria for a transmission system including channel coding, modulation, a frequency-selective fading channel, and equalization at the receiver side are compared.
- User pairing for time domain as well as frequency domain multiplexing is investigated.
- Joint user pairing and frequency domain multiplexing of the users is generalized to user grouping ($N_u > 2$), where user pairing is a special case with two users in a group ($N_u = 2$).
- A suboptimal algorithm, based on efficient mathematical optimization tools, is proposed in order to find a close-to-optimum solution with a significantly reduced complexity compared to a full search for user pairing as well as user grouping.
- We show that the capacity of the resulting V-MIMO channels, as it is considered by the majority of the papers in this field, is not always the most adequate criterion for user pairing. The bit error rate (BER) after decoding is shown to be a superior criterion in case of a transmission including channel coding.

This paper is organized as follows. In Section 2, the system model for a multiuser SC-FDMA transmission over a (virtual) frequency-selective MIMO channel is established. MMSE linear equalization in frequency domain and SIC equalization in time domain for a multiuser SC-FDMA transmission are revisited in Section 3. The adopted criteria for user pairing, based on the capacity of the resulting V-MIMO channels and on the BER after equalization, respectively, are introduced in Section 4. For multiplexing in time domain a low complexity optimum solution for user pairing, based on the Hungarian algorithm (HA) [13–15], is given in Section 5. User grouping algorithms for frequency allocation are presented in Section 6. Here, a low complexity strategy for multiplexing in frequency domain that also takes advantage of the HA in order to perform an assignment of user groups to RBs efficiently and employs the Binary Switching Algorithm (BSA) [16] for exchanging the users between groups in a suitable way is given. Sections 7 and 8 provide numerical results and conclusions, respectively.

Notation: $\mathcal{E}\{\cdot\}$, $(\cdot)^{\mathrm{T}}$ and $(\cdot)^{\mathrm{H}}$ stand for expectation, transposition and Hermitian transposition, respectively. $\mathrm{ld}(x)$ is used for the base 2 logarithm of x. Bold lower case letters and bold upper case letters refer to column vectors and matrices, respectively. Frequency domain vectors are an exception, for which bold upper case letters are also used. $\mathbf{0}_{K\times L}$ and $\mathbf{I}_X$ denote the all-zero matrix of size $K \times L$ and the $X \times X$ identity matrix, respectively; $\mathbf{1}_X$ is an $X \times X$ all-ones matrix. $[\mathbf{A}]_{m,n}$ stands for the element in the mth row and nth column of matrix $\mathbf{A}$. $\mathrm{bdiag}_{K\times L}\{\mathbf{X}_1, \mathbf{X}_2, \dots, \mathbf{X}_n\}$ denotes a $K \times L$ block diagonal matrix with blocks $\mathbf{X}_1, \mathbf{X}_2, \dots, \mathbf{X}_n$ on the main diagonal, and $\mathrm{circshift}\{\mathbf{A}, [q, r]\}$ stands for the cyclic shift of matrix $\mathbf{A}$ by q rows and r columns. $\mathbf{\Phi}_{vv}$ and $\boldsymbol{\varphi}_{\mathbf{a}b}$ are the autocorrelation matrix of vector $\mathbf{v}$ and the cross-correlation vector of vector $\mathbf{a}$ and scalar b, respectively.

2. System model

We examine a transmission with SC-FDMA modulation over a frequency-selective fading channel. The transmitter of the ith user and receiver structure at the BS in discrete-time equivalent complex baseband representation are