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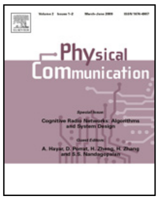

Full length article

Model and comparative analysis of reduced-complexity receiver designs for the LTE-advanced SC-FDMA uplink☆,☆☆

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ABSTRACT

Due to its favorable peak-to-average power ratio (PAPR), a single-carrier frequency-division multiple access (SC-FDMA) scheme has been chosen for the 3GPP Long Term Evolution Advanced (LTE-A) uplink, as opposed to the orthogonal frequency-division multiple access (OFDMA) scheme used in the downlink. SC-FDMA, however, is prone to suffer from the effects of inter-symbol interference. When combined with multiple-input multiple-output (MIMO) transmission, the complexity of optimal detection for SC-FDMA grows exponentially with the product of the number of transmitting antennas and the channel length. A means to reduce the complexity is to equalize the channel in the frequency domain first, similar to OFDMA, followed by detection in the time domain, using well-developed standard receivers for flat fading MIMO channels. Apparently, these reduced-complexity two-stage receivers suffer from a rate loss as a consequence of their simplifying design assumptions. In this paper, we provide an extensive model of SC-FDMA transmission with frequency domain equalization (FDE). Based on this model, we derive the achievable rates of four reduced-complexity two-stage receivers within the mismatched receiver framework in terms of generalized mutual information (GMI). The rate expressions allow us to assess the rate loss as compared to the optimal receiver for varying channel parameters such as channel length and spatial correlation. It is shown, for instance, that a distributed subcarrier mapping which is beneficial from a frequency diversity point of view substantially deteriorates the achievable rates. It is also explained how this loss can be compensated for by combining time-domain detection with frequency-domain interference cancelation.

1. Introduction

For its uplink scenario, the LTE-A standard [1,2] makes use of a SC-FDMA transmission scheme. The reasoning behind choosing this particular scheme is twofold. First, SC-FDMA possesses the same flexibility as compared to OFDMA, present in the downlink scenario, regarding dynamically allocating the available spectrum among multiple users. Second, it results in a much lower PAPR [3]. Having a low PAPR is crucial, since the uplink transmitter typically is a battery-powered device.

Despite the benefits in terms of PAPR, SC-FDMA, as opposed to OFDMA, is prone to suffer from the effects of inter-symbol interference (ISI). Hence, SC-FDMA receivers turn out to be significantly more complex than OFDMA receivers, which may use single-tap equalization in the frequency domain [4, Chapter 12.4]. In fact, the complexity of the optimal receiver, implemented in terms of the Viterbi algorithm, grows exponentially in the number of channel taps [5].

For MIMO transmission, which is a key part of the LTE-A standard, the receiver becomes even more complex, as it needs to take into account both ISI and multi-antenna interference (MAI), posing a challenge to the task of

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☆ This paper has been presented in part in [13,14].

☆☆ Invited paper.

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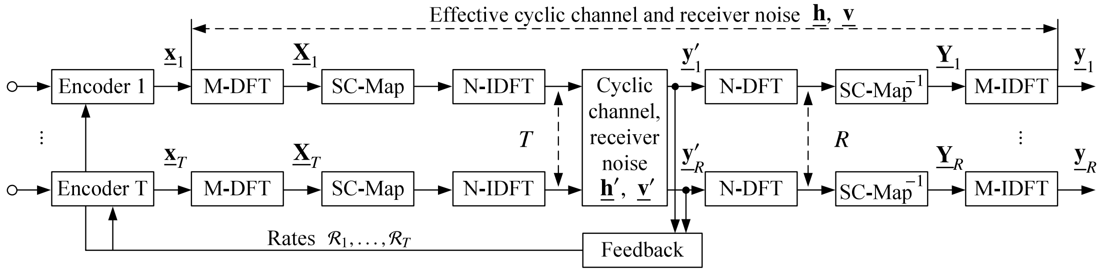

Fig. 1. SC-FMDA transmission model. The SC-FDMA symbol index j is not shown.

designing high-performance yet computationally feasible receivers.

A number of reduced-complexity receiver designs have been devised recently. Among them are trellis-based approaches, which process the original trellis but keep the number of surviving paths small using the M-algorithm [6] or which reduce the number of trellis states by channel shortening [7,8] before processing the reduced trellis. On the other hand, for short channels which are dominated by a single tap, ISI may even be accounted for as Gaussian noise [9].

Another attempt is to mitigate ISI and MAI using two-stage receivers. In these schemes, the first stage corresponds to per-subcarrier frequency domain equalization (FDE), while the second stage applies standard MIMO detection techniques for flat fading MIMO channels in the time domain, similar to OFDMA. Examples comprise the linear receiver [10] or sphere search-based receivers [11,12].

In particular, the latter two-stage receivers are attractive from an implementation point of view since their complexity is independent of the channel length. This benefit, however, comes at the cost of a performance degradation, depending on the specific time-domain receiver design and channel parameters such as length and spatial correlation. For the system designer, it is essential to know about the performance degradation which has to be accepted under a certain parameter set.

In this paper we will tackle this problem from an information-theoretic perspective based on our previous work [13,14] by deriving achievable rates, coupled to different reduced-complexity receiver designs. Each receiver design is represented by a detection metric, which differs from the detection metric of the optimal maximum likelihood receiver. For these mismatched receivers, we exploit the concept of generalized mutual information (GMI) [15] to explicitly relate detection metrics to achievable rates. The results are valid, regardless of the choice of input alphabet, and they enable an achievable rate comparison, e.g., for using M-QAM modulated signals, but also for Gaussian input signals. Note that information rates of a transmission over MIMO ISI channels have been analyzed in the literature (e.g., [16]), however, without connection to reduced-complexity receivers.

The remainder of this paper is structured as follows. A detailed mathematical SC-FDMA model is derived in Section 2. The optimal receiver is discussed in Section 3, followed by a model and an analysis of FDE and respective reduced-complexity receivers. In Section 4, achievable rates are derived in terms of GMI. Numerical examples are discussed in Section 5. The paper is concluded in Section 6. The equivalence of block-based time-domain equalization and per subcarrier frequency-domain equalization as well as the rate loss of a parallel receiver are derived in the Appendices A and B, respectively.

Notation. Normal (a) and boldface ($\mathbf{a}$) letters denote scalars and vectors/matrices, respectively. The notation $\underline{\mathbf{a}}$ and $\underline{\underline{\mathbf{a}}}$ characterizes signals which correspond to a complete SC-FDMA symbol or to a block of J SC-FDMA symbols, respectively. $\Pr(\cdot)$, $p(\cdot)$, $\mathbb{E}_{\mathbf{a}}[\cdot]$, and $I(\cdot;\cdot)$ denote a probability, a probability density function (pdf), the expectation with regard to random vector $\mathbf{a}$, and the mutual information. $\mathbf{I}_T$, $(\cdot)^T$, $(\cdot)^H$, and $\otimes$ denote the identity matrix of size $T \times T$, the matrix transpose operator, the Hermitian operator, and the Kronecker product, respectively. The operation $\mathbf{A} = \mathrm{diag}(\mathbf{a})$ creates a diagonal matrix $\mathbf{A}$ from the vector $\mathbf{a}$. $\mathbf{F}_M \in \mathbb{C}^{M\times M}$ denotes a Fourier matrix with elements $[\mathbf{F}_M]_{m1,m2} = 1/\sqrt{M}\,\exp(-j2\pi m_1 m_2/M)$. $\boldsymbol{\Phi}_{\mathbf{ab}}$ denotes the covariance matrix between vectors $\mathbf{a}$ and $\mathbf{b}$. $\mathcal{N}_{\mathbb{C}}(\boldsymbol{\mu}, \boldsymbol{\Phi})$ denotes the complex normal distribution (mean $\boldsymbol{\mu}$, covariance matrix $\boldsymbol{\Phi}$).

2. Single-carrier FDMA transmission

Fig. 1 illustrates the basic SC-FDMA transmission block diagram. Payload data is encoded in time domain, independently at each of the T transmit antennas, followed by a conversion to frequency domain. The payload data may originate from different users (multi-user MIMO) or from a single user (single-user MIMO). The data in the frequency domain is mapped to different subcarriers of an OFDMA symbol, offering flexibility to employ, for example, subcarriers with a high channel gain. The subcarrier mapping is identical for all transmit antennas. The mapped frequency-domain data is converted back to the time domain for transmission over the wireless channel. Upon receiving data at R antennas, the base station receiver implements the same processing steps in reverse order, as shown in Fig. 1. In addition, the receiver computes the achievable data rate $\mathcal{R}_t$ per channel input, and sends it back to the transmitter. The transmitter uses this information to adapt its coding rate in order to ensure error-free transmission.

In the following, we present a rigorous mathematical signal and channel model.