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A novel distributed scheduling scheme for OFDMA uplink using channel information and probabilistic transmission

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ABSTRACT

Distributed uplink scheduling in OFDMA systems is considered. In the proposed model, mobile terminals have the responsibility of making their own transmission decisions. The proposed scheme is based on two dimensional reservation in time and frequency. Terminals use channel state information in order to favor transmissions over certain subchannels, and transmission is done in a probabilistic manner. The proposed approach provides more autonomy to mobile devices in making transmission decisions. Furthermore, it allows avoiding collisions during transmission since it leads to collision detection during the resource reservation phase. The proposed approach is compared to other random access methods and shown to be superior in terms of increasing sum-rate, reducing the number of users in outage, and reducing the collision probability in the reservation phase.

1. Introduction

In the era of broadband wireless access, users are expecting ubiquitous and seamless access to a variety of bandwidth demanding services. Mobile terminals (MTs) capable of supporting multiple standards are becoming more common in the market. Current research is not only ongoing on enhancing scheduling techniques within a given network, but also on optimizing the resource allocation in heterogenous networks. This involves selecting the best network to serve an MT, among several networks with completely different access technologies such as GSM/EDGE, UMTS/HSPA, WiMAX, and WLAN [1–3].

The benefits of distributed resource allocation are being widely investigated. Conversely to centralized resource allocation, mobile devices have more autonomy in making transmission decisions in distributed schemes. Distributed scheduling is usually studied in the context of ad-hoc networks, relay-based networks, and sensor networks [4–6]. Distributed channel allocation schemes for wireless local area networks (WLANs) are also an active topic of current research [7,8]. In addition, cognitive radio (CR) networks have gained increasing importance, and the problem of resource allocation in CR networks is being widely investigated [9–14].

CR, ad-hoc, and sensor networks are distributed in nature. However, distributed resource allocation has also been implemented in infrastructure based networks where MTs are connected to a central base station (BS). In fact, several standards for 3G CDMA cellular networks, e.g., 1xEV-DO [15,16], have introduced mechanisms that give MTs greater independence in making transmission decisions best matched to their applications, e.g., deciding when to transmit and at what rate. The cdma2000 1xEV-DO Revision A [16] enables various traffic types to achieve latency targets by allowing them to benefit from high uplink spectral efficiency and advanced packet scheduling strategies. The uplink channel rate control algorithm for cdma2000 is presented in [17], where transition from one rate to another is performed by MTs in a probabilistic manner, and the optimization of the transition probabilities is treated in [18,19].

In state-of-the-art and next generation wireless communications systems, orthogonal frequency division multiple access (OFDMA) is adopted as the accessing scheme, e.g., in the UMTS long term evolution (LTE) and WiMAX. In OFDMA, a set of orthogonal subcarriers are grouped into a set of subchannels, where each subchannel consists of a fixed number of consecutive subcarriers [20,21]. Centralized OFDMA resource allocation is widely investigated in the literature, e.g., [22–25]. Therefore, it is interesting to investigate distributed resource allocation schemes over OFDMA. In [26], we presented a distributed resource allocation scheme over OFDMA with collaboration between the MTs. Collaboration is performed via the exchange of quantized channel state information (CSI), and each MT uses the exchanged CSI to perform distributed resource allocation.

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In this work, a distributed OFDMA resource allocation scheme without MT collaboration is presented. The proposed scheme is based on sorting the OFDMA subchannels according to their CSI levels, then transmitting over each subchannel in a probabilistic manner. The transmission probabilities depend on the CSI over each subchannel: the better the channel quality is on a given subchannel for a certain MT, then the higher the chances are for that MT to transmit on that subchannel. The proposed scheme is subdivided into a reservation phase and a transmission phase. Collisions may occur in the reservation phase, but not in the transmission phase.

Although the proposed method is applicable to both the uplink and downlink directions, we will focus on the uplink in this paper. In fact, the increase in demand for delay-sensitive applications with symmetric data rate requirements such as wireless gaming, video telephony, and voice-over-IP, has mandated the need for efficient uplink scheduling algorithms in state-of-the-art wireless communications systems. However, the downlink implementation of the proposed approach will be briefly discussed.

The paper is organized as follows. The system model is presented in Section 2. The proposed distributed scheduling scheme is discussed in Section 3. In Section 4, relevant schemes that will be compared to the proposed approach are summarized. Simulation results are presented and analyzed in Section 5. Some practical aspects and potential extensions of the proposed scheme are discussed in Section 6. Finally, Section 7 concludes the paper.

2. System model

The system studied consists of a single central controlling device (CCD) covering an area of interest. Although we will use the term CCD throughout the manuscript, a CCD can represent in practice: a BS serving a small coverage area, a remote antenna or remote radio head (RRH) in a distributed BS system, an access point (AP) in a local area network, a central controller in a cognitive radio (CR) network, or a femto BS inside a house or building. The proposed approach can be applied to an outdoor scenario by considering a wireless communication system consisting of a single cell where a central BS is connected to several CCDs spread over the cell area such that each CCD is allocated a subset of the subchannels available at the BS. The subsets of subchannels allocated to CCDs are mutually exclusive; i.e., no subcarrier can be used by more than one CCD within a single cell. In this work, we investigate the performance of the proposed scheme within the range of a single CCD due to the orthogonality of the subcarrier allocations.

2.1. Throughput calculations

We consider a single cell uplink OFDMA system with K MTs and N subcarriers to be allocated. For each MT k and subcarrier i, the transmit power, channel gain, and total noise power are respectively denoted by $P_{k,i}$, $H_{k,i}$, and $\sigma^2_{k,i}$. The signal-to-noise ratio (SNR) is given by

$$\gamma_{k,i} = \frac{P_{k,i} \cdot H_{k,i}}{\sigma^2_{k,i}} \quad k = 1, \ldots K; \quad i = 1, \ldots, N \tag{1}$$

The peak power constraint of MT k is given by:

$$\sum_{i=1}^{N} P_{k,i} \leqslant P_{k,\max} \quad k = 1, \ldots, K \tag{2}$$

This means that the power spent by the MT over all its allocated subcarriers should be lower than its maximum transmission power $P_{k,\max}$.

Total rate of MT k is defined as follows:

$$R_k = \sum_{i=1}^{N} R^d_{k,i}(\gamma_{k,i}) \tag{3}$$

where $R^d_{k,i}$ is the discrete rate of MT k over subcarrier i. Conversely to continuous rates, which can take any non-negative real value according to the Shannon capacity formula $\log_2(1+\gamma_{k,i})$, discrete rates represent the quantized bit rates achievable in a practical system as follows:

$$R^d_{k,i}(\gamma_{k,i}) = \begin{cases} r_0, & \eta_0 \leqslant \gamma_{k,i} < \eta_1 \\ r_1, & \eta_1 \leqslant \gamma_{k,i} < \eta_2 \\ r_2, & \eta_2 \leqslant \gamma_{k,i} < \eta_3 \\ \vdots & \vdots \\ r_{L-1}, & \eta_{L-1} \leqslant \gamma_{k,i} < \eta_L \end{cases} \tag{4}$$

where η_l represents the SNR target in order to achieve the rate r_l with a predefined BER. Note that in the limit, we have $r_0 = 0$, $\eta_0 = 0$, and $\eta_L = \infty$. Consequently, the sum-rate of the system is given by:

$$R_{\text{tot}} = \sum_{k=1}^{K} \sum_{i=1}^{N} R^d_{k,i}(\gamma_{k,i}) \tag{5}$$

3. Distributed scheduling scheme

3.1. Proposed scheme

The proposed scheme is a novel method to perform distributed resource allocation over OFDMA. It consists of allowing MTs to compete over transmission slots, or transmission time intervals (TTIs), over all the available subchannels. It is shown in Fig. 1.

Each frame of duration N_{TTI} is subdivided into three phases: a pilot transmission and channel estimation phase of duration 1 TTI, a reservation phase of duration 1 TTI, and a transmission phase of duration $N_{\text{TTI}} - 2$, with each TTI having a duration T. The approach can be described as follows:

- The CCD transmits a pilot signal over the available subchannels. Each MT measures the received pilot power and estimates its CSI over each subchannel.
- Each MT sorts its subchannels in decreasing order of CSI.
- In the reservation phase, there are $N_{\text{TTI}} - 2$ small reservation slots over each subchannel. Each MT goes sequentially through its subchannels, sorted in decreasing order of CSI. It decides to transmit over a subchannel i with a probability $p_T(k,i) = f(\text{Rank}(k,i))$, where $\text{Rank}(k,i)$ is the position of i in the sorted list of subchannels and $f(\text{Rank}(k,i))$ is a function of $\text{Rank}(k,i)$. It indicates that the transmission probability is selected as function of the rank of i in the sorted list. If the MT decides to transmit, it randomly selects one of the $N_{\text{TTI}} - 2$ small reservation slots over that subchannel and transmits a reservation signal in that slot.
- The MT estimates its achieved rate on the selected slot. If it is not sufficient to achieve its target rate, it moves to the next subchannel and repeats the same operation. When it goes through all subchannels without achieving its target rate, it moves back to the first subchannel and repeats the process, until it achieves its target rate or until a maximum number of allowed slots is reserved.
- At the end of the reservation phase, the CCD transmits an Ack message containing $N_{\text{sub}} \times (N_{\text{TTI}} - 2)$ bits, representing the reservation slots over all subchannels, with N_{sub} the number of subchannels. When a reservation was successfully made on a given TTI over a certain subchannel, the corresponding bit is set to 1. When a collision has occurred during the reservation