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.

Index Terms

Distributed scheduling, OFDMA, channel reservation, random access, probabilistic transmission

I. 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], [2], [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], [5], [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], [10], [11], [12], [13], [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] and [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], [23], [24], [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.

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 II. The proposed distributed scheduling scheme is discussed in Section III. In Section IV, relevant schemes that will be compared to the proposed approach are summarized. Simulation results are presented and analyzed in Section V. Some practical aspects and potential extensions of the proposed scheme are discussed in Section VI. Finally, Section VII concludes the paper.

II. 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.

A. 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 $\sigma_{k,i}^2$. The signal-to-noise ratio (SNR) is given by

$$\gamma_{k,i} = \frac{P_{k,i} \cdot H_{k,i}}{\sigma_{k,i}^2} \quad k=1, \ldots K; \quad i=1, \ldots, N$$  \hspace{1cm} (1)$$

The peak power constraint of MT $k$ is given by:

$$\sum_{i=1}^{N} P_{k,i} \leq P_{k,max} \quad k=1, \ldots, K$$  \hspace{1cm} (2)$$

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

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Total rate of MT $k$ is defined as follows:

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

(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:

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

(4)

where $\eta_l$ 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:

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

(5)

III. DISTRIBUTED SCHEDULING SCHEME

A. 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 $N_{\text{TTI}}$ 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 $N_{\text{sub}}$ 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 phase, or when no reservation was made, the bit will be set to 0. Hence, if an MT has attempted to reserve a slot and found a 1 in the corresponding bit in the Ack message, it knows that the slot was successfully reserved. If, on the other hand, it finds a 0, it knows that a collision has occurred and hence it refrains from transmission on that slot.

With the proposed approach, collisions occur only in the reservation phase, but not in the transmission phase, which leads to avoiding unnecessary transmissions. Since collision detection is done at the CCD, the MTs do not need to perform channel sensing to hear the transmissions.
of other MTs, as in the 802.11 standard for example. This allows avoiding the hidden terminal problem and leads to more efficient collision detection. Thus, when a collision is detected at a given slot, transmission is avoided in that slot, as shown in Fig. 1 on the sixth reservation slot. The pilot signal transmitted by the CCD at the beginning of each frame allows the MTs to keep their synchronization with the CCD, in addition to being used for CSI estimation.

B. Reservation Approach to Achieve the Target Rates

We consider a scenario with a single CCD and MTs competing for resources to communicate with that CCD by using the proposed distributed resource allocation scheme. MTs are assumed to always have data to transmit as in [27]. Each MT needs to satisfy a target average data rate $R_T$. If the average data rate is not achieved by an MT after a certain number of frames $N_{frames}$, the MT is assumed to be in outage. MTs regulate their transmissions in order to achieve $R_T$ after $N_{frames}$. This is performed as follows. The number of bits that should be transmitted in order to achieve $R_T$ after $N_{frames}$ is given by:

$$N_{b,T} = R_T \cdot N_{frames} \cdot N_{TTI} \cdot T$$

(6)

Denoting by $n_F$ the number of the current frame in a window of length $N_{frames}$, and by $N_{b,n_f}$ the number of bits transmitted in frame $n_f$, the number of previously transmitted bits is expressed as:

$$N^{(p)}_{b,n_F} = \sum_{n_f=1}^{n_F-1} N_{b,n_f}$$

(7)

Consequently, an MT makes enough reservations in frame $n_F$ in order to transmit $N_{b,n_F}$ bits with:

$$N_{b,n_F} = \frac{N_{b,T} - N^{(p)}_{b,n_F}}{N_{frames} - (n_F - 1)}$$

(8)

Hence, an MT attempts to subdivide the remaining $(N_{b,T} - N^{(p)}_{b,n_F})$ bits equally over the remaining $N_{frames} - (n_F - 1)$ frames.

C. Setting the Transmission Probabilities

In this section, we briefly describe the selection of the values of the transmit probabilities $p_T(k,i) = f(\text{Rank}(k,i))$. We select $f(\text{Rank}(k,i))$ as a decreasing function with respect to $\text{Rank}(k,i)$, while keeping $p_T(k,i)$ in the interval $[0, 1]$ since it is a probability measure. Hence,
the transmission probability for MT $k$ is higher on subchannels having better channel conditions. In other words, a better CSI for MT $k$ on a given subchannel indicates that the chances of that subchannel being selected for transmission by MT $k$ are higher.

The simplest choice is to select $p_T(k, i) = p_T$, i.e., set the probabilities to a constant for all MTs and subchannels. In this case, subchannels having better channel conditions are favored only by the sorting process, not the transmission probabilities. On the other hand, letting $f(Rank(k, i)) = p_{T0}/Rank(k, i)$, with $p_{T0}$ a constant, presents a simple straightforward approach to make the transmission probability of MT $k$ on subchannel $i$ vary with its CSI level: a high CSI leads to a lower rank, thus a higher transmission probability. The constant $p_{T0}$ is generally set to a value close to 1, say 0.9 for example, to increase the transmission probability on subchannels higher in the list. Hence, the transmission probability on the first subchannel in the sorted list will be 0.9; the transmission probabilities on the second and third subchannels in the list will be $0.9/2 = 0.45$ and $0.9/3 = 0.3$, respectively, and so on.

More aggressive reservation strategies could use, for example, functions of the form $f(Rank(k, i)) = p_{T0}/[b \log_b(c_2 \cdot Rank(k, i) + c_3)]$, with $b$ the base of the logarithm and $c_1$, $c_2$, and $c_3$ are constants selected such that the value of the transmission probabilities stays within the interval $[0, 1]$. Selecting a logarithmic variation for the probabilities allows these probabilities to decrease slowly with the rank of the subchannel in the sorted list; hence, even when the CSI decreases, the transmission probabilities would generally be higher than the case $f(Rank(k, i)) = p_{T0}/Rank(k, i)$.

On the other hand, a more restrictive approach can use functions of the form $f(Rank(k, i)) = p_{T0}/[c_1 \exp(c_2 \cdot Rank(k, i) + c_3)]$. Selecting an exponential variation for the probabilities allows these probabilities to decrease fast with the rank of the subchannel in the sorted list; hence, when the CSI decreases, the transmission probabilities would generally be lower than the case $f(Rank(k, i)) = p_{T0}/Rank(k, i)$. Thus, the transmissions of each MT will be focused on its subchannels with the best channel conditions.

IV. OTHER RANDOM ACCESS SCHEMES COMPARED TO THE PROPOSED APPROACH

In this section, other random access schemes are described and extended to OFDMA in order to be compared to the proposed approach in the next section.
A. Slotted Reservation Aloha

Aloha is one of the first algorithms for random access [28], [29]. Aloha is commonly studied under a single channel assumption, in which user contention happens over only one channel. In single channel slotted Aloha, MTs transmit packets in fixed length time slots. When more than one MT transmit in the same time slot, collision occurs [20]. To reduce the impact of collisions, reservation Aloha was proposed [28]. In reservation Aloha, the fixed length time slots (as in slotted Aloha) are preceded by small reservation request slots. Requests are transmitted in the minislots using the slotted Aloha random access technique. Hence, collisions occur in the reservation phase, but not in the transmission phase. Reservation Aloha is used in satellite networks, e.g., [30], and in wireless local area networks (WLANs), e.g., [31]. It still attracts recent research attention. For example, priority reservation Aloha over a single channel for applications in vehicle-to-vehicle communication (e.g., audio and video streaming are given higher priorities) is investigated in [32]. Classical Aloha (without reservation) is recently being investigated in the context of underwater acoustic sensor networks [33].

In slotted reservation Aloha, the reservation is over transmission slots in the time domain. All the bandwidth is used for transmission, e.g., [28] and [34]. In this paper, for a fair comparison with the proposed approach, an extension of slotted reservation Aloha to OFDMA is adopted, and it is shown in Fig. 2. Thus, if an MT reserves a certain time slot, it transmits on all subcarriers for the duration of that slot. In addition to using OFDMA in the reserved transmission slots, the extension of Fig. 2 incorporates channel knowledge in the reservation phase. Thus, similarly to the proposed approach, the OFDMA reservation Aloha scheme of Fig. 2 contains a channel

Fig. 2. OFDMA application of slotted reservation Aloha.
estimation phase that allows MTs to estimate the rate they can achieve in a reserved slot.

B. Subchannel Reservation

With OFDMA being widely used in state-of-the-art wireless communications systems, several random access schemes based on OFDMA were presented in the literature [27], [35], [36], [37]. In all these schemes, reservations are made over subchannels, and a single MT is allowed to transmit over a reserved subchannel until the next frame where a new reservation is performed. In this paper, these schemes are extended to accommodate pilot measurement and CSI estimation so that channel knowledge can be used by MTs in the reservation phase. We will refer to this approach as the “subchannel reservation” scheme. It is shown in Fig. 3.

With the proposed approach of Section III-A, reservation is performed on a frequency-time grid, as opposed to classical reservation Aloha where time slots are reserved over the whole bandwidth [28], [32], and as opposed to subchannel reservation [36], [37], where a subchannel is reserved over the whole transmission period of the frame.

V. RESULTS AND DISCUSSION

This section presents the simulation results obtained by comparing the proposed approach to other schemes in the literature, in terms of sum-rate, percentage of MTs in outage, and collision probability.
A. Simulation Model

The simulation model consists of a single CCD with MTs uniformly distributed within its coverage area. Each frame consists of $N_{TTI} = 10$ TTIs, i.e., eight TTIs are used for transmission. Each MT attempts to achieve its target rate, and it is considered in outage if it fails to achieve that rate after $N_{frames} = 100$ frames. The duration of a TTI is considered to be 1 msec, sufficient to transmit 12 symbols over each subcarrier [38]. The results are averaged over 50 iterations of 100 frames each.

The total bandwidth considered is $B = 5$ MHz, subdivided into 25 subchannels of 12 subcarriers each [21]. The maximum MT transmit power is considered to be 125 mW. All MTs are assumed to transmit at the maximum power, and the power is subdivided equally among all subcarriers allocated to the MT. The channel gain over subcarrier $i$ corresponding to MT $k$ is given by:

$$H_{k,i,\text{dB}} = (-\kappa - \lambda \log_{10} d_k) - \xi_{k,i} + 10 \log_{10} F_{k,i}$$  \hspace{1cm} (9)

In (9), the first factor captures propagation loss, with $\kappa$ a constant chosen to be 128.1 dB, $d_k$ the distance in km from MT $k$ to the CCD, and $\lambda$ the path loss exponent, which is set to a value of 3.76. The second factor, $\xi_{k,i}$, captures log-normal shadowing with zero-mean and an 8 dB standard deviation, whereas the last factor, $F_{k,i}$, corresponds to Rayleigh fading with a Rayleigh parameter $a$ such that $E[a^2] = 1$. The SNR thresholds of the various modulation and coding schemes obtained from [39] are shown in Table I.

B. Results with Different Transmission Probabilities

In this section, we consider a cell radius of 500 m and a target rate of 128 kbps. We study the impact of varying the transmission probability. We compare the case of constant transmission probabilities $p_T(k,i) = p_T$, with the cases $p_T = 0.2$, $p_T = 0.5$, and $p_T = 0.7$ being considered, to the case of dynamic transmission probability selection with $f(\text{Rank}(k,i)) = p_{T_0}/\text{Rank}(k,i)$.

We set $p_{T_0} = 0.9$ to increase the probability of selecting the subchannels having the best channel gain.

Fig. 4 shows the collision probability results. For fixed $p_T$, reservations become more aggressive as $p_T$ increases, which leads to a slight increase in collision probability, but the results remain comparable. However, the dynamic scheme leads to considerably better performance since it better exploits the frequency diversity.
TABLE I
DISCRETE RATES AND SNR THRESHOLDS WITH 14 MODULATION AND CODING SCHEMES [39].

<table>
<thead>
<tr>
<th>MCS</th>
<th>$r_l$ (bits)</th>
<th>$\eta_l$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Transmission</td>
<td>0</td>
<td>$-\infty$</td>
</tr>
<tr>
<td>QPSK, $R = 1/8$</td>
<td>0.25</td>
<td>-5.5</td>
</tr>
<tr>
<td>QPSK, $R = 1/5$</td>
<td>0.4</td>
<td>-3.5</td>
</tr>
<tr>
<td>QPSK, $R = 1/4$</td>
<td>0.5</td>
<td>-2.2</td>
</tr>
<tr>
<td>QPSK, $R = 1/3$</td>
<td>0.6667</td>
<td>-1.0</td>
</tr>
<tr>
<td>QPSK, $R = 1/2$</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>QPSK, $R = 2/3$</td>
<td>1.333</td>
<td>3.4</td>
</tr>
<tr>
<td>QPSK, $R = 4/5$</td>
<td>1.6</td>
<td>5.2</td>
</tr>
<tr>
<td>16-QAM, $R = 1/2$</td>
<td>2.0</td>
<td>7.0</td>
</tr>
<tr>
<td>16-QAM, $R = 2/3$</td>
<td>2.6667</td>
<td>10.5</td>
</tr>
<tr>
<td>16-QAM, $R = 4/5$</td>
<td>3.2</td>
<td>11.5</td>
</tr>
<tr>
<td>64-QAM, $R = 2/3$</td>
<td>4.0</td>
<td>14.0</td>
</tr>
<tr>
<td>64-QAM, $R = 3/4$</td>
<td>4.5</td>
<td>16.0</td>
</tr>
<tr>
<td>64-QAM, $R = 4/5$</td>
<td>4.8</td>
<td>17.0</td>
</tr>
<tr>
<td>64-QAM, $R = 1$</td>
<td>6.0</td>
<td>26.8</td>
</tr>
</tbody>
</table>

Fig. 4. Collision probability of the proposed scheme for a target rate of 128 kbps, a cell radius of 500 m and different values of the transmission probability.
Outage results are shown in Fig. 5. For all cases, the percentage of MTs in outage is negligible when the number of MTs is below 30. For 30 MTs in the cell, the cases with $p_T = 0.2$, $p_T = 0.5$, and $p_T = 0.7$, become unstable and lead to 96.13, 91.53, and 99.33% of MTs in outage, respectively. Remarkably, the dynamic approach has exactly 0% of MTs in outage for all the simulated values, even when the number of MTs reaches 30. The sum-rate results, shown in Fig. 6, indicate that the dynamic approach outperforms the fixed transmission probability approach, especially as the number of MTs increases.
Fig. 7. Sum-rate of the different schemes for a cell radius of 500 m and different target rates.

Fig. 6, are comparable for all the studied cases, except for the dynamic scheme in the case of 30 MTs, since it has no MTs in outage. In fact, all MTs achieve their target rate (0% outage), which leads to a sum-rate of 3.93 Mbps, compared to 2.16 Mbps for the case $p_T = 0.5$, where a high outage rate is achieved.

C. Results with Different Target Rates

In this section, we present simulation results for a cell radius of 500 meters and three different target rates: 64 kbps, 128 kbps, and 256 kbps. We use a constant $p_T = 0.5$. Fig. 7 shows the sum-rate results, Fig. 8 shows the percentage of MTs in outage, and Fig. 9 displays the collision probability results. For a small number of MTs (up to four MTs), all schemes perform comparably and all MTs achieve their target data rate. When the number of MTs increases, the reservation Aloha and the subchannel reservation schemes degrade significantly and lose their stability. This is not the case for the proposed scheme which shows better stability when the number of MTs increases. In fact, it is widely known in the literature that Aloha is an unstable algorithm. In [20], it was shown that this unstability property also applies to OFDMA-based extensions of Aloha. Attempts to enhance the stability of single channel slotted and reservation Aloha were made in [34]. Attempts to enhance the stability of multichannel Aloha were presented in [20].
Using the proposed scheme with $R_T = 64$ kbps, all the MTs are served even when the number of MTs reaches 30. With $R_T = 128$ kbps, degradation occurs when the number of MTs exceeds 25, and with $R_T = 256$ kbps, stability is lost when the number of MTs exceeds 20. In fact, when the number of MTs and/or the target data rate increases, more packets need to be
transmitted at the same time in order to achieve the target data rate for all MTs. This leads to an increase in collision probability during the reservation phase, as shown in Fig. 9. Consequently, less transmissions occur during the transmission phase which leads to a sum-rate degradation, as shown in Fig. 7, and hence the number of MTs in outage increases, as shown in Fig. 8.
In this section, we present simulation results for a target rate of 128 kbps and three different values for the cell radius: 250 m, 500 m, and 1000 m. We use a constant $p_T = 0.5$. Fig. 10 shows the sum-rate results, Fig. 11 shows the percentage of MTs in outage, and Fig. 12 displays the collision probability results. Clearly, when the distance increases, the SNR received at the CCD is significantly reduced. This decreases the achievable rate within a reserved time slot. However, the proposed scheme shows significant superiority over the other schemes. For a relatively small number of MTs, the target rate can be achieved even when the distance increases. In fact, enough time slots are available with the proposed scheme to compensate the increase in the distance. When the number of MTs increases, each MT will need a higher number of time slots to compensate the increased distance. This will lead to more collisions in the reservation phase, as shown in Fig. 12. Hence, less transmissions will occur in the transmission phase, which reduces the achieved rate, as shown in Fig. 10, and leads to an increase in the number of MTs in outage, as shown in Fig. 11.

VI. PRACTICAL CONSIDERATIONS

In this section, we discuss some practical considerations related to the proposed scheme and its possible extensions.
A. **Downlink vs. Uplink**

Although the results presented in this paper are for the uplink direction, the proposed approach presented in Section III-A can be applied for both the uplink and downlink. For the downlink direction, the CCD sends pilot signals over the downlink subchannels, and the MTs perform the reservation similarly as in the uplink case. However, the transmission on the reserved subchannels is done from the CCD to the MTs, instead of transmissions from the MTs to the CCD as in the uplink direction.

The results of Section V can be mapped to the downlink scenario without modification, except for the CCD transmit power dedicated to transmit to each MT. The CCD transmit power allocated to each MT should be used instead of the MT transmit power. Otherwise, no additional insights can be derived from downlink results compared to uplink results. In fact, in the special case where the CCD dedicates to each MT a portion of its downlink power equal to the maximum MT uplink transmit power, then the results of Section V would correspond exactly to the downlink scenario, without any modifications.

B. **Collisions and Capture Effect**

With the proposed approach, collisions occur only in the reservation phase, but not in the transmission phase, which leads to avoiding unnecessary transmissions. It should be noted that the proposed approach can be easily modified to accommodate collision resolution and capture effect. With capture effects, even if collisions occur in the contention period, the CCD may be able to detect one of the contending MTs and allow it to use the corresponding transmission slot [35], [36]. In general, the MT that gets the channel with capture effect is the one that has the strongest CSI over the contended subchannel, since the reservation signal it sends is the strongest one received at the CCD [35].

To modify the proposed approach in order to allow capture, the CCD must notify the MT that won the contention. Hence, the CCD can transmit, in the Ack message, the ID of the MT who successfully reserved each slot, and a zero otherwise. Consequently, if more than one MT competed over the same slot, they will know which one won the competition. However, without capture effect, the Ack message can be significantly shortened since only one bit is needed for each slot.
C. Fully Distributed Scenario

Although the proposed approach is distributed and gives MTs a significant role in the resource allocation process, the CCD still has an important role since it transmits the pilot signal and then confirms successful reservations. In a fully distributed scenario without CCD, the proposed approach can still be applied with some modifications:

- The MTs should be aware of the existence of each other so that they can communicate directly. Each MT should be able to know with which other MT it will be communicating.
- In this case, assuming MT A will be sending data to MT B, MT B will send pilot data to MT A, so that the latter could determine the channel quality over all subchannels on the link between MTs A and B. To avoid interference from pilot transmissions of other communicating MT pairs, the pilot sequence of each MT should be encoded using CDMA to maintain orthogonality with respect to the pilot transmissions of the other MTs. Otherwise the CSI estimation will be flawed due to the presence of interference. This represents a significant overhead of the fully distributed scenario compared to the scenario with CCD, where pilot signals are sent only by the CCD and communications are restricted to MT-CCD links only.
- After receiving the pilot signals and extracting the CSI information, MT A will then perform time-frequency slot reservations as described in Section III.
- However, reservation signals in the small reservation slots are not sent to the CCD. Instead, they are broadcasted so that all other MTs can “hear” them and thus know that these slots are reserved by MT A.
- To be able to detect the communications of each other, the MTs should be within a close proximity so that the reservation could be done in a distributed way without the intervention of the CCD. In other words, MTs should be close enough so that the reservation signals sent by an MT could be detected by the other MTs. Thus, MTs would be performing subcarrier sensing in addition to probabilistic transmission.

Assuming the MTs are within a close vicinity so that the method described above can be applied, then the results of the fully distributed scenario would be similar to the scenario with CCD in terms of sum-rate, collision probability, and outage rate. However, a major challenge in the fully distributed scenario is to keep the MTs synchronized so that the reservation and transmission...
phases take place at the appropriate timings in the frame. In addition, in case simultaneous reservations of a certain time-frequency slot occur, then the concerned MTs will not be able to detect the collision, since both would be transmitting the reservation signals at the same time. This will not affect the presented results numerically since capture effects are not considered: collisions in the reservation phase in the presence of a CCD prevent transmissions in the corresponding slot in the transmission phase. In the absence of CCD, collisions in the transmission phase in the same slot will not lead to a modification in the sum-rate results. However, they lead to unnecessary transmissions and waste of power by the MT, compared to the case with CCD.

**D. Extension to a Multiple Cell Scenario**

A multicell scenario consists of several adjacent cells, where each cell consists of the coverage area of one CCD. Reusing the same subchannels in all cells would lead to intercell interference. Hence, in a multicell framework, intercell interference should be taken into account, and efficient techniques to mitigate intercell interference should be adopted.

Several techniques for reusing the radio frequencies are investigated in the literature to limit the effects of intercell interference in multicell scenarios. Static reuse schemes are based on fractional frequency reuse (FFR) where a cell is divided into an inner area with the same frequencies reused in all cells and an outer area where a subset of the frequencies is reused, e.g., [40]. More efficient schemes consist of dynamic frequency reuse where all the frequencies are allowed to be used in all cells and elaborated techniques are applied for interference mitigation or avoidance. In [4], pricing is considered in ad-hoc networks, where each user sets a price for other users to compensate for the interference they are causing. The prices are used as a sort of power control scheme to reduce transmission power. However, users are assumed to transmit on the same carriers and pricing is used for power control and not for scheduling. In [41], multicell uplink OFDMA scheduling is considered. Pricing is imposed by the network and each user performs power control in a distributed manner using the pricing information.

In [26], we considered distributed resource allocation within a single cell with MT collaboration, as opposed to the distributed non-cooperative scheme presented in this paper. In [42], [43], we proposed interference mitigation schemes to be used with the scheduling approach of [26], when implemented in a multicell scenario. The same interference mitigation methods can be used in the scenario without MT collaboration, since they were designed in a way to
be transparent for the MTs performing distributed resource allocation. Thus, they can be used unaltered in both collaborative and non-collaborative resource allocation scenarios. They are briefly described next.

In this section, two levels of cooperation will be considered in the discussions and confusion between them should be avoided:

- **Intracell collaboration**: this refers to the collaboration between MTs inside each cell for the purpose of resource allocation. The approach of [26] is collaborative, and the approach in this paper corresponds to the non-collaborative scenario.

- **Intercell collaboration**: this refers to the collaboration between the CCDs of different cells for the purpose of interference mitigation. The collaborative and non-collaborative intercell interference mitigation techniques of [42], [43] can be applied with any of the distributed intracell scheduling methods discussed above.

In [42], an intercell cooperative scheme was presented, where the CCDs exchange pricing information reflecting the interference levels received on each subchannel. Each CCD used the interference prices received by its neighboring CCDs in order to reduce the transmitted pilot power accordingly. Hence, a subchannel subjected to high interference in neighboring cells will have its corresponding pilot power reduced by the CCD of the interfering cell. The MTs in that cell will measure the reduced pilot power and assume that they have a reduced channel quality on the corresponding subchannel. Thus, the probability of using that particular subchannel gets reduced, which contributes to reducing the interference in the neighboring cells. This approach is completely transparent to the MTs, since they are unaware of the intentional tampering of the pilot transmission levels and are somehow “tricked” in order to reduce the intercell interference level in the network.

The collaborative intercell scheme of [42] can be used both for uplink and downlink transmissions using the proposed distributed intracell scheduling method of this paper. However, for the downlink, a more efficient approach can be used: the pilot levels are not altered, but the interference prices sent by the neighboring CCDs are used to perform pricing-based power control. Thus, the transmit power of the CCD over each subchannel is reduced according to these power prices. Power control is more difficult to implement in the uplink since the power prices on each subchannel need to be communicated to the MTs, which increases the signalling overhead. We proposed such a power control scheme in [43].
In the case of non-collaborative intercell interference mitigation, we proposed a scheme in [43] based on probabilistic interference avoidance. The non-collaborative intercell interference mitigation technique is based on shutting down each subchannel with a probability that increases with the received interference level on that subchannel. Hence, CCDs do not exchange prices reflecting interference levels. Instead, each CCD measures the interference level it receives on each subchannel, and turns that subchannel off with a probability that increases with the interference level. Consequently, pilot transmissions and resource allocation are performed on the subchannels that are still on. This approach is simple and completely transparent to the MTs. In addition, it can be applied for both uplink and downlink transmissions. Furthermore, it leads to good results not only in distributed scheduling scenarios, but also in centralized systems as shown in [44].

The interference mitigation methods presented in [42] and [43] can be applied with the intracell non-cooperative distributed scheduling scheme, proposed in this paper, without any modification. Therefore, they are not repeated here.

E. Application in a Femtocell Scenario

Femtocells are low-cost, low-power, access points that can be overlaid with an existing wireless network [45], [46], [47]. The purpose is to satisfy the demand for high data rates which are expected to grow significantly in the foreseeable future with the proliferation of novel resource demanding applications such as gaming, mobile TV, and social networking. Femtocells are expected to be small and inexpensive plug-and-play devices that can be installed both by the service providers in their network and by the end users at home. The femtocells are devices that can coexist with existing wireless infrastructure and are interconnected by an IP backhaul network through a local broadband connection, such as cable or digital subscriber line (DSL).

The CCD could represent a femto base station installed inside a home by end users. MTs inside the home would then share the OFDMA subchannels using the distributed scheduling approach presented in this paper. Outside the femtocell coverage, the MTs would be connected to a macrocell base station that constitutes part of an OFDMA cellular system. Thus, indoor traffic offloading via femtocells can reduce the load on the external macrocell network, and the proposed approach could play a significant role as a distributed resource allocation scheme in the femtocell coverage area.
In the proposed scheme, the CCD could be part of a cellular network or of a CR network. In a cellular network, the CCD could act as a remote antenna in a distributed base station system (e.g., see [48], [49], [50], and [51]), where the CCD connects the MTs to the central BS in the cell and the BS allocates subchannels to the different CCDs. In a CR network, the CCD could represent a device with higher capabilities than the MT, and it could sense the medium for the presence of primary users and determine the available subchannels and then announce these subchannels to MTs within its coverage range by transmitting the appropriate pilot signals. The MTs would then apply the distributed scheduling approach presented in this paper to dynamically share these free subchannels.

VII. CONCLUSIONS

Distributed uplink scheduling in OFDMA systems was considered. A novel non-collaborative random access scheme for OFDMA systems was presented. 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. Transmission is done in a probabilistic manner, with the probabilities depending on the channel quality on each subchannel.

The proposed approach was compared to other random access schemes in the literature. Several desired target rates were considered, and different cell sizes were investigated. Significant performance enhancements over existing schemes were obtained. The proposed scheme was 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. In all the investigated schemes, collisions occur in the reservation phase but not in the transmission phase. The proposed scheme was shown to support a large number of users before stability is lost, conversely to the other schemes.

The proposed scheme can be applied in a femtocell deployment scenario, in a cognitive radio framework, and in the case of distributed base stations. In addition, it can be integrated in a multicell scenario with intercell interference mitigation techniques implemented transparently to the MTs who can use the proposed approach without modification.
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