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PFS-based Resource Allocation Algorithms for an OFDMA System with Multiple Relays

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Abstract— We address the problem of radio resource allocation in the Downlink (DL) of a cellular system with multiple Relay Stations (RS), based on Orthogonal Frequency Division Multiple Access (OFDMA) transmission technology. The design of efficient resource allocation algorithms for such a system is crucial, in order to exploit the potential capacity and coverage increase offered by the relays. We propose different resource allocation algorithms which provide excellent throughput/outage trade-off with low complexity and minimized amount of Channel State Information (CSI). The simulation results show the benefits of our algorithms, for various number of relays and for different user distributions.

I. INTRODUCTION

One of the major goals of the 4th Generation (4G) wireless system is to provide higher data rates over larger areas in a cellular system. Orthogonal Frequency Division Multiplexing (OFDM) transmission technology is a very promising candidate for the physical layer of the 4G system, due to its high achievable spectral efficiency by bit loading and inherent robustness against inter-symbol interference caused by frequency-selective fading. There has also been an increasing focus on the relaying technology which has the potential to enhance the data rates in remote areas of the cell while keeping a low cost of infrastructure. However, to fully exploit this potential gain in capacity and coverage, many challenges are left to the radio resource allocation. Hence, the problem of resource allocation and scheduling for relay-aided cellular systems has been a flourishing topic for investigation [1] [2] [3]. Some works on resource allocation for OFDMA relay systems can be found in the literature [4] [5], but to the best of the authors' knowledge, there has been little work on specific resource allocation schemes for multiple access in a relay-aided cellular system based on OFDMA technology. Thus, our goal is to design allocation algorithms for such a system, which can enhance both capacity and coverage, but with reasonable degree of complexity. We have proposed such algorithms for a system with one relay in [6], and for multiple relays in [7]. One of the key points of these algorithms is that they are designed in such a way that reduces the algorithm complexity and required amount of Channel State Information (CSI). However, the algorithms in [6] are only designed to maximize the system throughput and [7] considers only a specific case of multiple relays in

the cell. It was shown in [6] [7] that the proposed algorithms outperformed the conventional Max CSI algorithm without relays in terms of both throughput and outage. In this work, we further improve these algorithms to provide proportional fairness and compare them with the conventional Proportional Fair Scheduling (PFS) algorithm without relays. Furthermore, we evaluate these algorithms under more general conditions by varying the number of relays and user distributions. The simulation results show the efficiency of our algorithms under various conditions and the excellent trade-off realized between throughput and outage probability.

II. SYSTEM MODEL

We focus on the Downlink (DL) transmissions from a Base Station (BS) to Mobile Stations (MS) or Relay Stations (RS) in a single cell, where users feed back to the BS their CSI on every subchannel, defined as a group of adjacent subcarriers. We use a Discrete Adaptive Modulation (DAM) model, applied per subchannel, for each user, where the rates [1, 2, 4, 6, 8] [b/s/Hz] corresponding to the modulations [BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM] are supported when the link Signal-to-Noise-Ratio (SNR) is above their respective predefined SNR thresholds [−5, 13.6, 20.6, 26.8, 32.9] [dB]. The SNR thresholds from QPSK to 256-QAM are determined for a target Bit Error Rate (BER) of 10^{-6} for uncoded M-QAM symbols in flat fading channels with a known fixed gain, based on [8] [9]. For SNRs below 13.6dB, BPSK is used, and there is no transmission below −5dB. The BS is surrounded by multiple RS, as depicted in Fig. 1. The RS are placed at a distance of 0.8km from the BS, where the cell radius is 1km. As in [6], we consider the frame structure depicted in Fig. 2, where the BS and each RS transmissions are divided in time. Within the frame of length T_F , T_{BS} denotes the time allocated to the BS-subframe where transmissions from the BS occur, and T_{RS} the time allocated to each RS_j -subframe where transmissions from the RS occur. Since the interference between opposite RS can be assumed low, they are allocated the same subframe in a parallel manner, as shown in Fig. 2. When there are $I = 6$ relays, there are 3 groups of opposite RS: (RS_1, RS_4) , (RS_2, RS_5) and (RS_3, RS_6) . We assumed that in the BS-subframe, each subchannel can be allocated to a BS-MS link or a BS-RS link, and T_{BS}, T_{RS} can be adapted frame to frame.

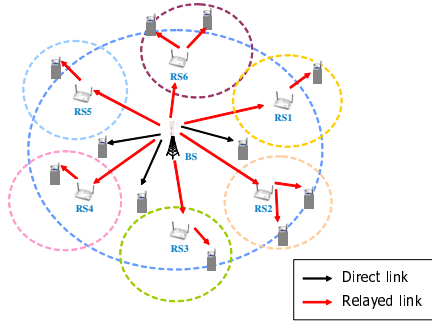


Fig. 1. Cellular System with Multiple Relays, $I = 6$ relays

The algorithms are optimized for the two-hop scenario. The packets of a relayed user queued at the BS will require at least two frames to arrive to destination: one from BS to RS, the second from RS to MS.

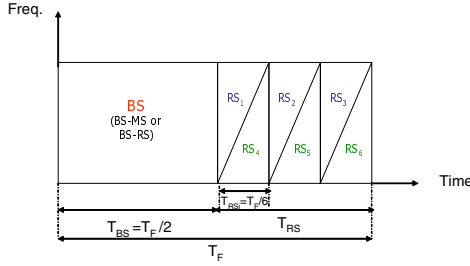


Fig. 2. Frame Structure with Parallel RS Transmissions, time division

We assume here that each MS is attached to one access point at a time, among the BS and the RSs. As in [6], the path selection is performed first, based on the long-term average user SNR in order to limit the algorithm complexity and required amount of CSI. The achievable AM levels corresponding to the long-term average SNR of the direct and relayed links are compared for each user, and the path allowing the best achievable rate is chosen. The allocation algorithms are performed once each user has been linked to a path.

III. RESOURCE ALLOCATION ALGORITHMS

A. Basic Algorithm

The proposed algorithms can be termed as *relay-aided centralized*, which aim at realizing a good trade-off between throughput and outage performance. As shown in [6], they are designed in such a way that minimizes the complexity and the required CSI, as opposed to the optimal algorithm for which the BS requires the CSI of all users, all subchannels and all links, which becomes very large as the numbers grow. The required CSI is reduced in our algorithms, since the CSI for RS-MSs are only required at that particular RS because it makes its own subframe allocation. Then, the RS forwards only a minimal information to the BS about the allocated users, as explained in [6]. Below, we briefly

recall the main steps of these algorithms, but with a slight modification in the allocation of the BS-subframe (Step 3) which provides a huge improvement compared to the usual Proportional Fair Scheduling (PFS) algorithm, as shown in the simulation results.

- 1) *Allocation of each RS_j -subframe by each RS:* Each subchannel is allocated to the user with the best $\phi_{k,n}$, but with queued packets, to ensure that the allocated capacity will be used, thereby increasing throughput. $\phi_{k,n}$ is defined as

$$\phi_{k,n} = \frac{r_{k,n}}{\frac{\bar{\beta}_k(i-1)}{R}}, \quad (1)$$

where R is the minimum data rate requirement and $r_{k,n}$, the instantaneous rate of user k on subchannel n . $\bar{\beta}_k(i-1)$ is the past average rate allocated to user k at frame i over a window of p frames and is updated after every frame allocation (as in PFS)

$$\bar{\beta}_k(i) = \frac{p-1}{p} \times \bar{\beta}_k(i-1) + \frac{1}{p} \times \sum_{n=1}^N c_{k,n} r_{k,n}(i), \quad (2)$$

where N is the total number of subchannels, $c_{k,n}$ is equal to one if subchannel n was allocated to user k and zero otherwise, so $\sum_{n=1}^N c_{k,n} r_{k,n}(i)$ is the sum of allocated rates to user k in the current frame i . With the metric ϕ , users whose achieved throughput is far from the rate requirement and with higher instantaneous CSI are prioritized. The users having a higher $\phi_{k,n}$ than the allocated one but without packets queued at RS are represented by the set U_{Req} .

- 2) *RSs send request message to BS:* This message contains
 - the IDs of the users in U_{Req} for which packets are requested,
 - the order of these users in terms of ϕ -metric, e. g., the maximum $\phi_{k,n}$ over all n for user k in U_{Req} (needed to determine the priority of the packets sent on the BS-RS link, see Step 3)
 - the value of $\bar{\phi}_{max}$, defined as the maximum value of the ϕ -metric for the relayed users in U_{Req} , averaged over the subchannels (see Step 3).
- 3) *Allocation of BS-subframe made by BS, based on the requests by RSs:* BS allocates (tentatively) each subchannel to the best direct user. The BS-RS subchannels are allocated as follows. If U_{Req} is non empty, the scheduler calculates the number of subchannels n_{BR} required to send all the packets queued at the BS of the users in U_{Req} . As mentioned in section II, all the BS-RS subchannels are allocated with the same rate, corresponding to their average SNR level. Thus, any n_{BR} subchannels among all N subchannels can be chosen for the BS-RS transmission. Whereas in [6], the subchannel allocation between the direct users and the BS-RS links was based on the rate metric, a new criterion based on the ϕ -metric is introduced to ensure a fair distribution of subchannels. For each user in U_{Req} , the average ϕ -metric over the RS-MS subchannels is determined, and the maximum average ϕ -metric is denoted $\bar{\phi}_{max}$. In each subchannel,

the ϕ -metric of the initially allocated direct user is compared with $\bar{\phi}_{max}$, and the subchannel is allocated to the link with the highest value. This gives y subchannels allocated to the BS-RS link. But not all y subchannels may be required, so we compare y with n_{BR} .

- a) If $y < n_{BR}$, the y subchannels are not enough for all the packets, e.g., some remain at the BS queue. To decide which packets to send on the BS-RS link, the RS-MS users for which packets were required are ordered by ϕ (only this order needs to be fed back to BS, not the ϕ values nor the CSI since these are not needed at the BS). Packets are allocated from the best RS-MS users, until all y subchannels are filled.
- b) If $y > n_{BR}$, all y subchannels are not needed for the BS-RS link since there are less queued packets. Only the n_{BR} worst subchannels for direct users are allocated to the BS-RS link, and the remaining $y - n_{BR}$ subchannels to the best direct users.

B. Multiple Relay Allocation Algorithms

We propose two algorithms which both use the initial algorithm presented above, namely the *Multiple-RS Parallel with Activation* (MRPA) algorithm and the *Multiple-RS Adaptive Activation* (MRAA) algorithm. In the MRPA algorithm, the initial frame is as shown in Fig. 2. The difference of the present algorithms compared to those in [6] mainly arises from step 3), where the subchannel allocation between the BS-RS and BS-MS links is based on the ϕ metric instead of the rate metrics, allowing for an increased level of fairness. The concept of *Long-Term RS-Activation* is introduced, where, if after the path selection, 2 opposite RS in the same group are not activated (for example, RS_1 and RS_4), their corresponding subframe is removed and the frame is redivided in time among the remaining RS groups. After this initial phase fixing the frame, the algorithm above is applied. For MRAA algorithm we have in the initial frame $T_{BS} = T_F/2$ and the RS-subframe is equally divided in time between all the relays, without frequency reuse, resulting in a RS_j -subframe length of $T_F/2/I$. Here the *Per-Frame RS-Activation* is performed on top of the *Long-Term RS-Activation*. Basically, the *Long-Term RS-Activation* phase removes all RS_j -subframes for relays which were not selected by any user during path selection (based on long-term channel qualities), and the *Per-Frame RS-Activation* phase removes all the relays which decrease the overall throughput for the current frame, hence based on the instantaneous channel qualities (see [6] for more details). Thus, compared to a completely fixed allocation, the MRPA algorithm improves the resource utilization by removing the RS-subframes of relays without any user, and redistributing them to the "activated" relays. The aim of MRAA algorithm is to further improve the achieved throughput, by discarding in each frame the relays which do not enhance the overall throughput.

IV. NUMERICAL RESULTS

The simulations are made over 150000 sets of channel realizations, where user locations are kept constant for a fixed

number of channel realizations, then regenerated. The path loss model in [10] is used for the three links: BS-MS, BS-RS and RS-MS. Log-normal shadowing with 0dB mean and 8dB standard deviation is assumed for the BS-MS links, and 6dB standard deviation for the RS-MS links. The multipath fading channel model in [11] is used. The BS power and RS power are fixed to 20 Watts and 5 Watts. Given the subframe, there is equal power distribution in each subcarrier. There are 48 subcarriers and 12 subchannels, each composed of 4 contiguous subcarriers. The frame duration is fixed to 12ms. Packets arrive at the BS queue following a Poisson process. The reference algorithms described in [6] are used: the *RS-Max Full Buffer* algorithm for the throughput upper bound, and the *Optimized Outage* algorithm for the outage lower bound. In these algorithms, we take the ideal assumption that the time division between BS/RS transmissions is optimized per subchannel, to ensure the bounds. In the *RS-Max Full Buffer* algorithm, the user with the best achievable rate is allocated among all choices of users and links, in each subchannel. Similarly, *Optimized Outage* algorithm allocates in each subchannel the user with the best ϕ metric among all choices of users and links. As our algorithms are PFS-based, they are also compared with the *PFS* algorithm without relays, where the user with the best ϕ metric is allocated in each subchannel.

A. User Generation in the cell

In this work, we have considered two different user distributions: uniform distribution and distribution towards cell edge. Since one of the major goals is to support more users located in the cell edge, it is of great interest to consider such a distribution. The edge distribution model is derived from [12], e.g., *clustering to the edge of the cell*. The cell is divided into square bins as shown in Fig. 3, which are each attributed a certain probability to be selected, P_x , for $x \in [1..16]$. To generate more users towards the edge compared to the center, the bin probability increases as the distance from the bin center to the BS increases. The bins sharing the same center to BS distance are characterized by the same bin probability. In this case, 3 regions can be defined where each region corresponds to bins of equal probability, namely:

- the central area C regrouping bins 6, 7, 10 and 11,
- the closer edge area E_1 regrouping bins 2, 3, 5, 8, 9, 12, 14 and 15,
- the further edge area E_2 regrouping bins 1, 4, 13 and 16.

Users are allowed to be generated anywhere in the whole square grouping the 16 bins, including outside the hexagonal cell. The user generation is carried out similarly as described in [12]. First, a bin is selected by sampling the CDF of the bin probabilities with a uniformly distributed random number between 0 and 1. Then, a user is generated randomly within the selected bin area.

Once users are generated either uniformly or towards the edge, each user is attached to the BS or one of the RS, following the path selection mentioned in section II. After that the resource allocation is performed. The path selection is renewed each time the average user SNR changes.

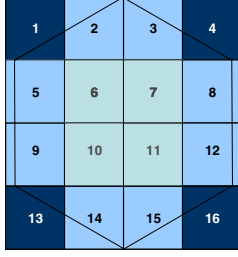


Fig. 3. Hexagonal cell divided into bins, for generating the user distribution towards cell edge, case of multiple relays

B. Performance Metrics

Two performance metrics are used: system goodput and outage probability. The goodput γ in [b/s/Hz], where the overhead for CSI feedback is included, is defined as

$$\gamma = \tau \times \frac{n_{data}}{n_{data} + n_{OH}}, \quad (3)$$

where τ is the throughput, n_{data} the number of OFDM symbols in the frame carrying data and n_{OH} the number of symbols carrying the CSI, assuming QPSK modulation.

The system outage is defined as the probability that the allocated user rates \bar{r}_k are lower than a reference rate R , where \bar{r}_k is averaged over $p = 100$ frames. The system outage probability P_{out} is expressed as

$$P_{out} = \frac{\sum_{s=1}^S K_s}{K \times S}, \quad (4)$$

where K_s denotes the number of users in outage for the sample s and S is the total number of samples, $K_s = \text{Card}\{k, \bar{r}_k < R\}_s$, where Card denotes the number of elements in the set.

With the frequency reuse carried out in *MRPA*, some subchannels are used at the same time, so the opposite relays transmitting in parallel interfere with each other. The effect of this interference is taken into account in the simulations.

Results for goodput and outage probability are plotted for varying number of relays, $I = 3, 6, 8, 12$, with $K = 20$ users. For the outage probability, the target rate is fixed to 100 kbps. In these evaluations, the amount of resource used for the preambles and the user mapping information vary with the number of relays. The impact of these control fields is taken into account in the overall throughput. Simply, there is one preamble per relay which occupies one OFDM symbol, $n_{pre} = 1$. In case of frequency reuse by opposite relays, their corresponding preambles also reuse the frequencies. The DL mapping information consists of the ID of the allocated user (or relay for the BS-RS link), for each subchannel. Denoting n_{MAP} the number of OFDM symbols used for the DL mapping, the goodput is determined as

$$\gamma = \tau \times \frac{n_{data}}{n_{data} + n_{OH} + (N_{RS} + 1) \times (n_{pre} + n_{MAP})}, \quad (5)$$

where N_{RS} is the number of non-overlapped, activated RS_j -subframes.

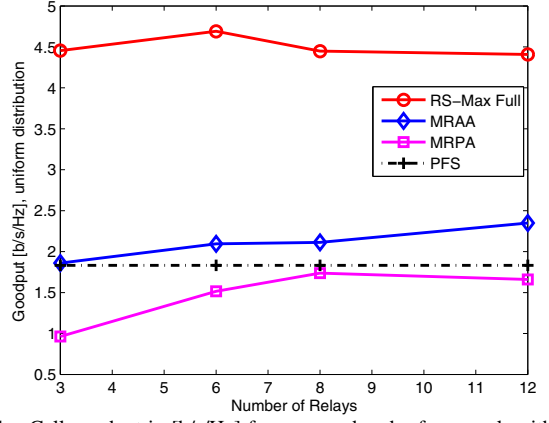


Fig. 4. Cell goodput in [b/s/Hz] for proposed and reference algorithms with varying number of relays, uniform user distribution

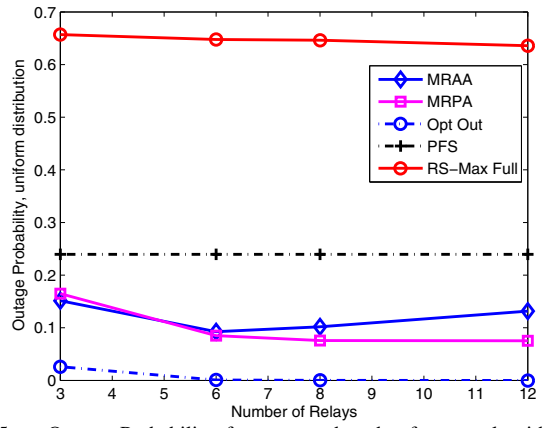


Fig. 5. Outage Probability for proposed and reference algorithms with varying number of relays, uniform user distribution

Figs. 4 and 5 show the system goodput and outage performance for uniform user distribution, respectively. The goodput and outage of *PFS* algorithm remain constant since it is independent from the number of relays. The goodput decrease of *RS-Max Full Buffer* in Fig. 4 for $I = 8, 12$ is due to the increased amount of signalling with the higher number of relays. For *Optimized Outage*, the outage at $I = 6$ is already so low that increasing the number of relays does not provide noticeable improvement. However, note that *Optimized Outage* is an infeasible scheme so that the difference with the actual optimal scheme is smaller. *MRPA* achieves the best outage performance for all number of relays and outperforms *PFS*, but its best goodput occurs for $I = 8$ relays. Its goodput decreases from $I = 8$ to $I = 12$ because the time allocated to each RS_j -subframe becomes very small at $I = 12$. The worst performance of *MRPA* happens at $I = 3$ as there is no frequency reuse. Thus, there is a large improvement for $I \geq 6$. *MRAA* outperforms *PFS* in terms of both goodput and outage, for all number of relays. It can be seen from Fig. 4 that the goodput of *MRAA* increases with the number of relays, even though the amount of signalling increases as shown in (5), which indicates the robustness of the proposed scheme to increasing signalling overhead. At the same time, the outage probability of *MRAA* increases as the number of relays grows

for $I \geq 8$, since this algorithm is designed to allocate in each frame, the relays which increase the overall throughput. Still, the outage performance of *MRAA* at $I = 12$ is considerably lower than the one of *PFS*. When users are distributed towards the edge, an interesting point is that the performance of all the algorithms is generally degraded for all number of relays, as observed in Figs. 6 and 7. While the outage lower bound of *PFS* is largely degraded, the outage of the proposed algorithms is only slightly lower than with uniform user distribution, pointing out their robustness against varying user distributions. The gain in goodput of *MRAA* compared to *PFS* is even higher than with uniform distribution, and *MRPA* also outperforms *PFS* for $I = 6$, while achieving the best outage for all I .

The simulations with different number of relays in the cell showed the efficiency of the proposed algorithms, which are robust to varying number of relays and to different user distributions. Under the considered assumptions, the optimal number of relays differ depending on the algorithm. *MRPA* achieves its best performance for $I = 8$, for both user distributions. For *MRAA*, $I = 8$ also achieves the best compromise between goodput and outage, but $I = 12$ offers the best goodput level while considerably reducing the outage probability compared to the conventional *PFS* algorithm. Interestingly, continuously increasing the number of relays may not be the best solution even when there are more users in the cell edge, since, for example, the goodput of *MRPA* is affected by the increasing amount of signalling overhead as more and more relays are activated and less resource is allocated to each RS_j -subframe. As the number of relays increase, the goodput of *MRAA* improves but not the outage since more RS_j -subframes are not allocated.

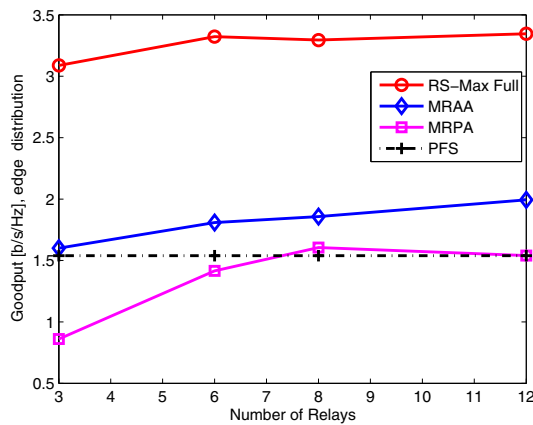


Fig. 6. Cell goodput in [b/s/Hz] for proposed and reference algorithms with varying number of relays, users distributed towards cell edge

V. CONCLUSION

This work investigated the problem of resource allocation for a relay-aided cellular system based on OFDMA. The proposed algorithms are designed to provide both throughput and outage probability improvements with low complexity, while the required signalling information is minimized compared to the optimal solution. The simulation results showed that they achieved an excellent outage/throughput trade-off compared

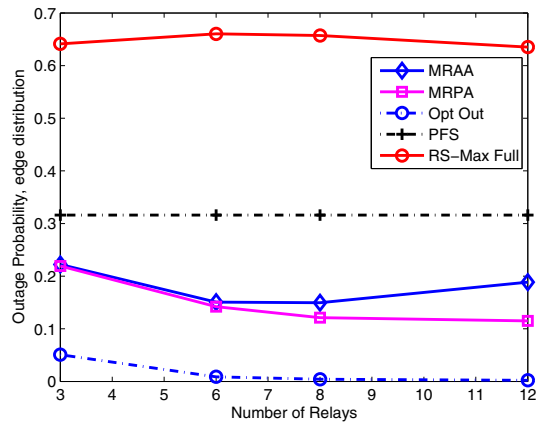


Fig. 7. Outage Probability for proposed and reference algorithms with varying number of relays, users distributed towards cell edge

to reference algorithms, and outperformed the well known conventional *PFS* algorithm. Moreover, simulations under different user distributions and various number of relays showed the robustness and efficiency of the proposed algorithms.

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