Abstract—Relaying, or multihop communications, and multiple transmit antennas represents two key technologies for the achievement of the spectral efficiency targeted by the European IST-4-027756 Project WINNER II. In this paper, a method for dynamic resource partitioning in relay enhanced cells (REC) is proposed. This exploits spatial sharing of time-frequency resources by different radio access points, base station or relay nodes, for their connections to the user terminals. The spatial resource sharing is based on a simple dynamic beamforming approach. A quite significant performance gain is shown with respect to a conventional solution featuring fixed intra-REC sectorization.

I. INTRODUCTION

The EU IST-4-027756 Project WINNER II targets the development of a ubiquitous air interface capable of supporting a large variety of user service requirements in different scenarios, ranging from local area to wide area, while guaranteeing high spectral efficiency [1], [2]. Towards this ambitious aim, two key technologies, multiple antenna transmission and relaying, are gaining increasing attention due to their potential ability in enlarging the coverage area and/or enhancing the achievable capacity.

When multiple transmit and receive antennas are used in a spatial multiplexing mode, multiple data streams can be transmitted over the same time-frequency resources being separated in space, thus leading to higher resource reuse levels and potentially huge capacity gains [3]. If the multiplexed data streams are intended to different users, Space Division Multiple Access (SDMA) is configured. The stream separation is realized by beamforming, i.e., by adequately weighting the signals transmitted by each element of the antenna array in order to establish virtual channels, namely spatial sub-channels [4].

Relaying, or multihop communications, indicate the deployment of relay nodes (RNs) capable of forwarding the traffic between the base station (BS) and the user terminals (UTs). RNs can be integrated into a traditional cellular network either to enlarge the coverage area of a BS, as shown in Figure 1(a), or to increase the capacity, as depicted in Figure 1(b) [5]. Cells where relay-nodes are deployed are referred to as relay enhanced cells (RECs). In RECs, a UT and a BS can be connected to each other either directly or by means of one or more RNs. Therefore, a proper resource partitioning between the BS and its connected RNs has to be implemented. According to the current assumptions of the WINNER project, in a REC, the total time-frequency resources shall be dynamically partitioned into parts used by the BSs for their direct connections to some UTs and parts used, and possibly shared, by the RNs for their connections to the UTs, as well as parts shared by the BSs and its RNs. Moreover, a proper amount of resources has to be assigned for the BS-to-RN links, hereafter referred to as relay links, to feed all the data that has to be transmitted on the RN-to-UT links. The resource partitioning is performed by the MAC (medium access control) at the BS on a longer time scale, on the order of a few milliseconds. A complete MAC layer is assumed then to be implemented at each RN for the scheduling of the transmissions to its affiliated UTs on a shorter time scale, on the order of less than 1 ms. Hence, each RN can be seen as controlling a separate sub-cell within the REC [6].

Higher spectral efficiency can be achieved when spatial reuse schemes are applied, thus allowing different RN-to-UT links and/or BS-to-UT links to share the same chunks in an SDMA fashion. However, the application of a traditional fixed sectorization in each sub-cell with a static frequency
In this paper we propose a strategy for flexible and dynamic spatial resource sharing within a REC. The basic idea is that users links assigned to the same serving RAP (radio access point) being this the base station and the relay nodes, which generate similar interference patterns are grouped together. These groups, which are called beams, are the entities considered by the BS during the resource partitioning. More specifically, the BS selects the beams from different RAPs which are sufficiently spatially uncorrelated, so that they can share the same time-frequency resource in spatial domain without generating too high inter-beam interference. The selection procedure in the beam grouping uses an estimate of the inter-beam interference and of the average beam transmission rate that can be achieved with a specific resource allocation to the group of beams. The same beam rate evaluation can also be used for estimating the amount of chunks which should be granted to allow a certain bit rate according to the user requirements. The implementation of this approach requires a number of different procedures, such as the user affiliation, the creation of the beams, the inter-beam interference estimation and the resource partitioning between first and second hop, i.e. between relay links and RN-to-UT links.

The remainder of the paper is organized as follows. In Section II, the considered system model is briefly introduced. Section III first explains the basic idea of dynamic spatial resource sharing in RECs more thoroughly; it then describes some insights of the signaling protocol underlying the user affiliation. Section IV presents some simulation results. Finally, conclusions are drawn in Section V.

II. SYSTEM MODEL

The MAC frame structure currently considered within the WINNER project [8] is depicted in Figure 2. The long-term resource partitioning is assumed to be carried out on a super-frame basis, where a super-frame has a duration of 5 ms. This consists, in the basic case, of 8 frames of 0.7 ms each, for both the TDD and the FDD mode.

OFDM (Orthogonal Frequency Division Multiplexing) based transmission is assumed with 1024 sub-carriers over each band and guard interval of 3.2 µs. The basic time-frequency resource unit is defined as a rectangular area, named chunk, comprising 12 OFDM symbol periods and 8 sub-carriers. Each frame extends over 2 chunks in time domain and 128 chunks in frequency domain.

The deployment scenario is the Base Coverage Urban scenario defined in [9], in which a single isolate urban-area cell with a radius of 500 meters is considered. The BS and six RNs are located above rooftop and have arrays with 4 antenna elements, while the UTs have a single omnidirectional antenna. Connections up to two hops long are considered.

The channel model for the RAP-to-UT links is the WINNER C2 channel specified in [10]. However, since the focus in this paper is on long-term resource partitioning at the BS, where only long-term channel state information (CSI) is available, only the path-loss and the shadowing parameters of the channel model C2 are considered. The relay links are LoS (Line of Sight) links since the RNs are fixed and above roof-top.

For the first hop, beamforming based SDMA is assumed with up to three concurrent relay links. The second hop also uses beamforming in order to reduce the interference to other nodes, but only a single transmission per RAP is allowed on every chunk. More specifically, TDMA based Grid of Beam (GoB) is used [11]. Link adaptation is assumed with uncoded M- QAM modulation, with $M \in \{2, 4, 16, 64\}$. The SNR (signal-to-noise ratio) required for the reception of $c$ bits/symbol is given by $SNR(c) = \frac{c}{\gamma} \cdot \frac{2^{c-1}}{e}$, where the target BER (Bit Error Rate) is $P_e = 10^{-3}$ and $\gamma(P_e) = 12.1157$ [12]. Uniform and constant transmission power with no adaptive power allocation is assumed.

III. PROPOSED APPROACH

The proposed strategy enables a dynamic sharing of chunks in spatial domain by different RAPs by exploiting a simple beamforming approach. The basic idea is illustrated in Figure 3. In a first step, each RAP locally builds groups of spatially correlated UT links affiliated to it, which generate similar interference patterns to other sub-cells. These groups have been called “beams”, since they can be seen as representing a single logical beam for the RAP. In a second step, a centralized grouping of spatially uncorrelated beams is performed at the BS. For example, with reference to Figure 3, the groups of beams with the same pattern are considered sufficiently uncorrelated and are allowed to share a chunk. It is to be noted that the beam configuration is not necessarily as regular as in Figure 3, but it is dynamically adapted to the actual user distribution and traffic patterns in order to minimize the intra-REC interference. Groups of beams can be partially overlapping, i.e. a beam can belong to more than one group. Provided that information on the allocation in
adjacent REC is available, the inter-cell interference can also be considered when forming the beams and deciding on their resource sharing.

In the following, the procedures involved in the two main steps of beams creation and beams grouping are first described. A procedure is then proposed for allocating resources to beams considering also the balancing between first and second hops.

A. User Affiliation and Beams Creation

User affiliation refers to the procedure used for deciding whether a user should be served by the BS or through one or more RNs, while beams creation represents the grouping of active users into beams at each RAP. The ultimate goal is that of assigning each UT to a serving RAP/beam pair in a dynamic way on a short-term basis, e.g. on a frame-basis. During the normal system operation, however, the user distribution and traffic patterns do not usually change significantly. Hence, the beams configuration can be assumed to vary only on a long-term basis, e.g. a few superframes, and the affiliation of new users can be independently managed based on the existing beam structure. Even under this assumption, different and sometimes contrasting requirements have to be considered in performing the user affiliation. For example, in some circumstances a user could experience a better channel towards a certain relay node, but the BS could opt for another assignment yielding a slightly lower channel quality for the user but better interference levels in the cell. The decision whether to affiliate a UT to one or another RAP might also depend on load balancing considerations. If, e.g., a beam has a significantly lower load with respect to the other beams of its group, the spectrum assigned to that group will not be fully exploited. Therefore, from a network capacity perspective, it might be more convenient to affiliate a new UT to that beam, although, from a single-link capacity perspective, it would be more convenient to affiliate it to another one.

In order to verify the validity of the proposed dynamic spatial resource sharing, we restrict here our attention to user-affiliation and beam creation procedures considering only channel-based metrics. Table I shows some possible channel-based user-affiliation criteria (the link names refer to those in Figure 4), which differ in the considered parameters and in whether the whole link or only the last-hop quality is taken into account. The choice of the criterion should be based on a trade-off between the quality of the decision it enables and the required amount of computational and signaling overhead.

For the dynamic beam creation we resort to a distributed approach, i.e. each RAP independently creates its own beams. More specifically, we use the tree-based algorithm proposed in [13]. The algorithm starts with each user in a different group. At each step all possible pairs of groups are checked and those maximizing a certain metric are merged. The algorithm stops when no group can be created whose required amount of computational and signaling overhead.

![Figure 4. User affiliation modes in a REC. Mode 1 indicates the direct connection to the BS (link $L_1$), while Mode 2 is the relayed connection (links $L_{21}$ and $L_{22}$).](image)

![Example of beams configuration using dynamic resource sharing](image)

### Table I

<table>
<thead>
<tr>
<th>Metric</th>
<th>Last hop only</th>
<th>Whole link</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>$d(L_1) &gt; d(L_{21})$</td>
<td>$d(L_1) &gt; d(L_{21}) + d(L_{22})$</td>
</tr>
<tr>
<td>Pathloss</td>
<td>$PL(L_1) &gt; PL(L_{21}) + PL(L_{22})$</td>
<td>$PL(L_1) &gt; PL(L_{21}) + PL(L_{22})$</td>
</tr>
<tr>
<td>Capacity or throughput (bit/sec/Hz)</td>
<td>$C(L_1) &lt; C(L_{21})$</td>
<td>$C(L_1) &lt; \frac{1}{2} (C(L_{21}) + C(L_{22}))$</td>
</tr>
</tbody>
</table>

In Figure 4, the inter-cell interference to the users served by a certain relay node, but the BS could opt for another assignment yielding a slightly lower channel quality for the user but better interference levels in the cell. The decision whether to affiliate a UT to one or another RAP might also depend on load balancing considerations. If, e.g., a beam has a significantly lower load with respect to the other beams of its group, the spectrum assigned to that group will not be fully exploited. Therefore, from a network capacity perspective, it might be more convenient to affiliate a new UT to that beam, although, from a single-link capacity perspective, it would be more convenient to affiliate it to another one.

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\[ r = \frac{\sum_{i} \sum_{j} (x_i - \bar{x})(y_j - \bar{y})}{\sqrt{\sum_{i} (x_i - \bar{x})^2} \sqrt{\sum_{j} (y_j - \bar{y})^2}} \]
where \( d \) is the distance between the \( L \) antenna elements, \( \lambda \) is the wavelength, \( \theta_1 \) and \( \theta_2 \) are the DoAs (Direction of Arrival) for the signals of users 1 and 2, respectively.

### B. Signaling for RAP/Beam Affiliation

When a new UT becomes active, it sends an initial ranging request (RNG-REQ), e.g. in the RACH (random access channel). As soon as a RN successfully decodes the ranging message, it informs the BS sending also the quantized power level of the received RNG-REQ and the quantized estimated DoA of the user. Once the BS becomes aware of the new user, either because it has decoded the RNG-REQ itself or because it has been informed about it by one or more RNs, it is able to decide to which RAP/beam the UT should be affiliated. It then sends a ranging response message (RNG-RSP) to the user through the assigned serving RAP/beam pair and updates the list of existing links.

When the signal level for a user drops below a certain threshold or when interference mitigation considerations should require it, the BS can order an intra-REC handover, resulting in a change of the user’s serving beam or RAP/beam pair.

### C. Beams Grouping

The proposed beam grouping approach uses as metric the estimate of the achievable beam transmission rate. It starts with an empty group, and at each step it adds the beam allowing the highest overall throughput increase. It stops when another beam would decrease the throughput due to excessive interference.

In order to estimate the achievable beam rate, a measure of the inter-beam interference has to be derived first. The computation of the inter-user interference levels for all the users in all the beams would be extremely computational demanding. Moreover, two problems arise in doing this. The first is that the use of beamforming complicates the estimation of the interference between different links. The second is that the actual user within the beam scheduled by the single RAP for transmission on a short-term basis is not known at the BS when it carries out the long-term resource partitioning among RAPs within its REC. We therefore propose a simplified approach which models the interference experienced by a beam when another one is transmitting in terms of maximum or average inter-user interference as

\[
\rho_{1,2} = \begin{cases} 
\frac{1}{\exp(\frac{2\pi^2}{\lambda^2} \sin(\theta_1) - \sin(\theta_2))} & \text{for } \theta_1 \neq \theta_2 \\
1 & \text{for } \theta_1 = \theta_2 
\end{cases}
\]

for (1)

transmitting and \( I_{i,j} \) is the interference experienced by user \( i \) when user \( j \) is transmitting. This value is estimated based on the transmission power and the spatial correlation between the users, as expressed by (1).

The inter-beam interference is considered as a Gaussian random noise to the users of each beam. When multiple beams transmit on the same resources, the different interference levels sum up. The resulting overall inter-beam interference, together with the user’s long-term channel quality information, is used to derive an estimate of each user’s SINR (signal-to-noise-plus-interference ratio). For example, the average beam rate of the beam \( A \) when allocated together with beams \( B, C \) and \( D \) can be expressed as

\[
R_{A/B,C,D} = \frac{\sum_{i \in A} d_i}{\sum_{i \in A} f(x) \sum_{j \neq i} (x_i + I_{i/B} + I_{i/C} + I_{i/D})}
\]

for (4)

where \( d_i \) denotes the \( i \)-th user data-rate request, \( S_i \) its received signal power, and \( f(x) \) is a function mapping the SINR value to the achievable user transmission rate. It should be noted that the short-term scheduling at the single RAP based on instantaneous CSI allows a certain multi-user diversity gain. This factor can be taken into account in (4) as a single-user SINR gain, whose value depends on the number of users in the beam.

### D. Resource Partitioning

The procedures described so far are used by the resource partitioning procedure, which actually assigns the chunks to the beams. We propose a resource partitioning algorithm which aims at maximizing the overall cell throughput while guaranteeing that, for each allocated chunk, the resources assigned to the first and second hop are balanced. This procedure is hereafter denoted as chunk-by-chunk balancing (CCB), and it is depicted in Figure 5. Before the actual allocation begins, the relay links are grouped in disjoint sets, whose number depends on the system characteristics, e.g. on the number of antennas at the BS. At the beginning of each iteration of the CCB algorithm, the BS identifies the beam group with the highest overall throughput by applying the beam grouping procedure described in Section III-C and proceeds with allocating resources to it. For each allocated chunk, it checks whether the resources already assigned to the relay-links serving the beams in that group are enough to feed them. If not, it gives them the allocation they need and proceeds to the next chunk, until one of the beams in the group has been completely served. When this occurs, a new beam grouping procedure is initiated and the CCB allocation procedure is applied to the new beam group.

The algorithm is computationally quite simple, but it manages to ensure that at every step the allocations on the first hop are enough to forward the amount of data corresponding to the capacity of the second hop allocation. It further allows a significant throughput gain, by always selecting the best available group of beams. It is however sub-optimal in that the initial groups of relay links remain fixed, independently of the
beam group composition at each iteration. This might imply that, at some iteration, a group of relay links is assigned more resources than actually needed, e.g., because not all the relay links serve the beam group that is being granted resources. However, an adaptive grouping of the relay links according to the composition of the beam group would also lead to suboptimal solutions. In fact, the dynamic feeds groups would have to be created according to the instantaneous requirements, without any guarantee that the resulting decision would be optimal with respect to the final beams allocation.

IV. SIMULATION RESULTS

The proposed strategy has been assessed by means of simulations against a more conventional approach, in which the sub-cell of each RAP is subdivided into six fixed sectors and spatially compatible sectors of different sub-cells are dynamically identified and let share the same chunks. The scenario and the system parameters described in Section II have been assumed for the simulations. The transmit power is 46 dBm at the BS, 40 dBm at the RNs and 24 dBm at the UTs. The BS and the RNs are equipped with arrays of 4 antennas, while the UTs have a single omnidirectional antenna. Up to 3 relay links are allowed to share a chunk in SDMA fashion, while links affiliated to the same RAP/beam pair cannot share a chunk because of their high spatial correlation. All the transmissions are assumed to make use of beamforming towards the target node.

The users are affiliated to their serving RAP based on the expected capacity of their last-hop links, and the dynamic beam creation is performed according to the tree-based algorithm described in Section III-A. The selected criterion is the maximization of the minimum correlation between the users, which our preliminary tests showed to outperform the maximum-average correlation metric. This result is explained by the higher inter-user correlation in the resulting beams and, consequently, the better inter-beam interference patterns.

Both for the case of fixed intra-sub-cell sectorization and the case of dynamic beam creation, the procedure explained in Section III-C has been used to group spatially compatible sectors/beams. In particular, the inter-beam interference estimation is based on the maximum inter-user interference, according to (2). This guarantees that the performance of the resulting allocation will be at least as good at the estimated one. In both cases, then, the CCB algorithm of Section III-D has been adopted for the resource allocation.

The resulting performance is evaluated in terms of aggregated downlink end-to-end cell throughput and of fairness. In calculating the aggregated cell throughput the rate of a beam is considered only if its corresponding first hop has been assigned a sufficient amount of resources. This allows to take the effect of unbalanced allocations for the first and the second hop into account. In fact, an exceeding capacity allocated on any of them implies either that some transmitted data cannot be forwarded within one superframe, or that some chunks are wasted because no data is available for transmission.

The fairness is evaluated through the Jain’s fairness index [15], whose value in an N-users cell ranges from 1 (full fairness) to 1/N (fully unfair, i.e. one user receives all the resources).

We assume 800 uniformly distributed users in the cell with the same bit-rate requirements. Simulations have been run by considering different requirements per user, ranging from 100 to 1000 kbit/sec. This enables a better granularity in varying the offered traffic, with respect to varying the number of users for a fixed bit-rate requirement. The results are averaged over multiple user positions and channel realizations.

Figure 6 plots the cell throughput for the considered scenarios. For both the case of fixed sectorization and of dynamic beams the throughput increases linearly until the cell saturation point is reached (at around 260 kbit/sec/user) and slows down afterwards. It is to be observed that, while for a fixed sectorization the throughput almost saturates around 260 Mbit/sec, for the dynamic beams it keeps increasing almost-linearly, although at a lower rate. The higher throughput is due to the higher flexibility offered by the dynamic beam creation in selecting spatially compatible transmission for the resource partitioning. Moreover, it should be noted that the throughput increase after the saturation point is due to the fact that users with better channel conditions are favored. This can be seen in Figure 7, where the results on fairness are plotted. This approach can be advantageously applied, e.g., in case of best-effort only traffic. Indeed, in this case the main goal is the maximization of the overall cell throughput. It is then reasonable to allocate most resources to the users with best channel conditions, while letting other users wait for their channel to improve. In order to still provide some fairness it is possible, e.g., to set a timeout which forces the algorithm to schedule the delayed users even if their channel is still unchanged. Finally, from Figure 7, it can be inferred that the proposed dynamic approach manages to achieve better performance also from the point of view of fairness.
results refer to the case of uniform user and traffic distribution within the cell. A larger gain is expected in the case of non-uniform distribution, in which the flexibility offered by the dynamic beam creation can be fully exploited. Moreover, no upper bound on the cell throughput has been provided here, since the focus of this paper is on the potential of the proposed method with respect to the fixed sectorization. Further effort will be made to obtain analytical bound on the achievable performance as well as to investigate resource partitioning procedures guaranteeing higher level of fairness among users.

V. CONCLUSIONS

A method has been proposed to implement dynamic resource partitioning in a relay enhanced cell. Multiple transmit antennas are exploited at the BS and the RNs to enable spatial sharing of time-frequency resources by different RAP-UTs links. The method is composed of two main steps. In the first step, referred to as beam creation, spatially correlated links affiliated to each RAP are locally grouped together, in order to form a sort of logical “beams”. In the second step, denoted as beam grouping, the BS selects beams of different RAPs which are sufficiently spatially uncorrelated to let them share the same time-frequency resources. Procedures for user affiliation, beam creation and beam grouping have been proposed. Based on that, a procedure for resource partitioning has been derived, which also considers the balancing between the allocation to the first and second hop.

Simulation results have shown that the proposed method enables a significant performance gain, both in terms of overall cell throughput and fairness, with respect to a more conventional approach, in which each sub-cell is sub-divided into fixed sectors and spatially compatible sectors are dynamically identified. It should be noted however, that the performance

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REFERENCES