Distributed and centralized architectures for relay-aided cellular systems

Invited Paper

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***Abstract*— In this paper we propose a two-step distributed scheduling algorithm for relay-assisted cellular networks where a given user can be either served by the base station or by a relay, in a opportunistic way. Such a distributed approach allows a reduced feedback signaling with respect to the centralized case, especially when a simple scalar feedback is not sufficient for estimating the channel quality. As a result of the reduced feedback signaling requirements the system becomes more scalable, as new relays can be deployed where required without need of a careful network planning. We study the effectiveness of the proposal by means of a multicell simulator.**

***Index Terms*— Cellular, multihop, relays, scheduling.**

I. Introduction

In the last years wireless relay networks have attracted much attention, since they can provide better coverage and/or higher network throughput, and hence improve the overall system performance [1], [2], [3], [4], [5]. When multiple relays are available, they can be further exploited to obtain macroscopic diversity, multiplexing gain. In other words, they can be utilized to further combat fading and improve coverage, link quality and system capacity. Different relaying protocols have been widely studied to improve the spectral efficiency and system performance. These relaying protocols are designed mainly for the amplify-forward (AF), the decode-forward (DF) and compress-and-forward (CF) relay systems. The relays are often assumed to be half-duplex, since full-duplex relays are difficult and expensive to implement. This, however, generates a pre-log factor 1/2 for the overall system throughput and may therefore limit the achievable spectral efficiency.

Recently, a big effort has been spent on relay-assisted infrastructure based networks due to the potential improvements in system performance provided by relays [6], [7], [8], [9], [10]. The main factors that limit the gain achievable in relay-aided cellular systems are:

- The relay to base station link, that must be able to support the amount of data of all the users associated to a given relay.
- The efficient exploitation of the spatial reuse, by enabling multiple users to be served at the same time by different relays without degrading the performance of individual users.
- The effect of the interference, that can limit the relay gains if an appropriate coordination is not introduced in the system, by means of centralized or distributed-cooperative algorithms.
- The effect of the feedback overhead, especially in centralized solutions that require an estimate of the channel state information at the base station side.

References [8] and [9] tackle some of these issues. In [8] a centralized downlink scheduling scheme is proposed, that guarantees the stability of the user queues for the largest set of arrival rates and achieves a significant gain with respect to the case of a system without relays. In [9] the capacity benefits of in-band backhaul relaying for cellular networks is studied under the assumption of a common maximum rate achievable by all the users in the network and of orthogonal separation of resources between base station to relays links and base station/relays to users links. Simulation results show the benefit of the proposal with respect to the base line without relays.

In this paper we focus our attention on a distributed relay scheme for downlink transmissions, where a given user can be either served by the base station or by a relay (up to two hops are considered). We motivated the study of a distributed relay scheme as it requires a reduced amount of feedback with respect to the centralized case, especially when multiple antennas are deployed in each node and a simple scalar feedback is not sufficient. As a result of the reduced feedback requirements the system is more scalable, as new relays can be deployed where needed. Moreover, by moving the processing towards the relay side, local cooperation between relays becomes possible. Like in the centralized case considered in [8] (and differently from [9] where the notion of maximum common rate is used) we guarantee user-fairness by making scheduling decisions based on the state of the users' queues and on the estimate of instantaneous signal to interference-plus-noise ratios (SINRs). Also, differently from [9], we do not assume an orthogonal separation of resources between base station to relays links and base station/relays to users links. The proposed technique works in two phases. In the first phase the base station makes its scheduling decisions for that time slot taking into account the channel conditions and the relays and users' queue states. The selected destination could be either a relay or an user. In the second phase each relay, if it had not been scheduled by the base station in the first phase, schedules a user taking into account channel conditions and

queue states.
We study the performance of the proposal by means of a multicell simulator.

The paper is organized as follows. In Section II we briefly review the centralized algorithm proposed in [8]. In Section III we present our proposed technique. In Section IV we describe the system simulator used to assess the performance. Finally, in Section V we give some simulation results.

II. Centralized Scheduling Algorithm

In this section we give a brief overview of the centralized scheduling algorithm proposed in [8]. Differently from [8], we consider at most 2-hop communications, i.e. the relays can not exchange information. The set of all transmitters is denoted as $\mathcal{T} = \{1, \ldots, N+1\}$, corresponding to the N relays and the single base station (BS). Similarly, the set of all users is denoted as $\mathcal{M} = \{1, \ldots, K\}$. The total number of links, including the links from the BS to mobiles and relays, and links from relays to mobiles, is given by

$$L = N + K + NK \tag{1}$$

Due to the transmission and reception constraints specified above the actual number of feasible links may be less than L. We use ϕ to denote an arbitrary set of simultaneously active links, and Ω to denote the set of all feasible ϕ. Note that Ω can have at most $2^L - 1$ elements as there are at most $2^L - 1$ possible nonempty sets of simultaneously active links. Number all links in the system (whether feasible or not) from 1 through L. A link l is an ordered pair consisting of an origin (the base or a relay), denoted $orig(l)$, and a destination (another relay or a user), denoted $dest(l)$.

Given a set ϕ of simultaneously active links, we denote by $R_l(t;\phi)$ the transmission rate from origin to destination on link $l \in \phi$ at the start of time frame t. For simplicity, the transmission rates are computed from Shannon's formula as

$$R_l(t;\phi) = \log_2\left(1 + SINR_{orig(l)}^{dest(l)}(t)\right)\,[bits/sec/Hz] \tag{2}$$

where $SINR_{orig(l)}^{dest(l)}(t)$ is the SINR at the destination of this link when receiving from the origin of this link, assuming that all other simultaneously active links (i.e., all other members of ϕ) are interfering. The notation for the rate therefore includes, as a parameter, the set ϕ of simultaneously active links during time frame t.

Let $Q_{BS}^j(t)$ for $j \in \mathcal{M}$ and $Q_{rs,i}^j(t), \forall i$ for $j \in \mathcal{M}$ denote the size of the queues at the base station for mobile user j in the cell and at the i-th relay node for mobile user j, respectively, at the start of time frame t. Let us define $D_l(t;\phi)$ as in (3), where the first case corresponds to the base transmission to one of the mobile users, the second case corresponds to the base transmission to i-th relay and the last case is the transmission from i-th relay to one of the mobile users.

The optimal set $\phi(t)$ of simultaneously active links for the next time frame is selected from Ω as follows:

$$\hat{\phi}(t) = \arg\max_{\phi\in\Omega} \sum_{l\in\phi} D_l(t;\phi) \tag{4}$$

If more than one ϕ achieves the maximum in (4), one of them is chosen arbitrarily. If a link l between the base station and the i-th relay is chosen to be active in time frame t, the user whose packets will be transmitted over this link is

$$j_l^*(t) = \arg\max_{j\in\mathcal{M}} \left\{\max\{Q_{BS}^j(t) - Q_{rs,i}^j(t), 0\}\right\}. \tag{5}$$

III. Decentralized Scheduling Algorithm

In this section we propose a distributed two-phase scheduling algorithm. In the first phase the base station makes its scheduling decisions for that time slot taking into account the channel conditions and the relays and users' queue states. The selected destination could be either a relay or a user. In the second phase each relay, if it had not been scheduled by the base station in the first phase, schedules a user taking into account channel conditions and queue states. We observe that, as in the centralized scheduling case, base station and non-receiving relays transmit at the same time, allowing full spatial reuse. Unlike in the centralized case, here a transmitter set is activated without taking into account the interference generated to the scheduled receivers.

Following the same notations used in Section II, the description of the first phase (relays and users' scheduling at the base station side) can be given as follows. The total number of links that the base station considers, the links from the BS to the users and the relays, is given by

$$L = N + K. \tag{6}$$

We define $D_l(t)$ as

$$D_l(t) = \begin{cases} R_l(t) Q_{BS}^j(t), & \text{if } j = dest(l) \in \mathcal{M} \\ R_l(t) \max\limits_{j\in\mathcal{M}} \left\{\max\{Q_{BS}^j(t) - Q_{rs,i}^j(t), 0\}\right\}, & \\ \quad \text{if } dest(l) = \mathrm{RS_i} \end{cases} \tag{7}$$

where the first case corresponds to the transmission to a user, whereas the second case corresponds to the transmission to the i-th relay. The optimal active link for the next time frame is selected as follows:

$$l^*(t) = \arg\max_{l=\{1,\ldots,L\}} D_l(t) \tag{8}$$

If a link l between the base station and the i-th relay is chosen to be active in time frame t, the user whose packets will be transmitted over this link is given by

$$j_{l^*}^*(t) = \arg\max_{j\in\mathcal{M}} \left\{\max\{Q_{BS}^j(t) - Q_{rs,i}^j(t), 0\}\right\}. \tag{9}$$

The description of the second scheduling phase (users' scheduling at the relays' side) can be given considering the i-th relay as follows. Let us define $D_{l_i}(t)$ as

$$D_{l_i}(t) = R_{l_i}(t; l^*(t)) Q_{rs,i}^j(t), \quad dest(l_i) \in \mathcal{M}, \tag{10}$$

where $R_{l_i}(t; l^*(t))$ is the rate for the link l_i taking into account the scheduling decision of the base station. The optimal active link for the next time frame is selected as follows:

$$l_i^*(t) = \arg\max_{dest(l_i)\in\mathcal{M}} D_{l_i}(t). \tag{11}$$

$$D_l(t;\phi) \;=\; \begin{cases} R_l(t;\phi)Q^j_{BS}(t) \quad \text{if } orig(l)=\text{BS and } j=dest(l)\in\mathcal{M} \\ R_l(t;\phi)\max\limits_{j\in\mathcal{M}}\left\{\max\{Q^j_{BS}(t)-Q^j_{rs,i}(t),0\}\right\}, \quad \text{if } orig(l)=\text{BS and } dest(l)=\text{RS}_\text{i} \\ R_l(t;\phi)Q^j_{rs,i}(t), \text{ if } orig(l)=\text{RS}_\text{i} \text{ and } j=dest(l)\in\mathcal{M} \end{cases} \tag{3}$$

We repeat the same procedure for each relay. We note that for the case of distributed scheduling each relay needs to feedback to the base station only an update of queue values. Unlike in the centralized case, a feedback concerning the channel state information is not required. We emphasize that a feedback concerning the channel state information can require a considerable amount of bits, especially when multiple antennas are deployed at base station, relay or user side and a scalar feedback is not sufficient to estimate the SINR of a given link.

IV. Simulation Setup

A system simulator has been developed with 7 base stations and wraparound for a downlink transmission. The N relay nodes are uniformly placed in the cell with a half cell radius distance from the base station. The K users are dropped with uniform probability inside each cell (see Fig.-1 for an example of a multi-cell setup with 7 base stations, $N = 6$ and $K = 30$ in each cell). All the nodes are assumed to have a single omni-directional antenna. The channel model includes path-loss, shadowing, rice fading for the base stations to relay links and Rayleigh fading from the base station to users and relays to users links.The path-loss is simulated according to the COST 231 model [11] for a small to medium-sized city, given by

$$\begin{aligned} PL(\text{dB}) \;&=\; 46.3 + 33.9\log_{10}(f_c) - 13.82\log_{10}(h_b) - \\ &\quad a(h_r) + (44.9 - 6.55\log_{10}(h_b))\log_{10}(d) \end{aligned}$$

where f_c is the carrier frequency in MHz, d is distance between the transmitter and the corresponding receiver in km; h_b and h_r are the base station antenna height and the mobile user antenna height above the ground level in meters, respectively. $a(h_r)$ is a correction factor for the mobile antenna height based on the size of the coverage area, given by

$$a(h_r) \;=\; (1.1\log_{10}(f_c) - 0.7)\,h_r - (1.56\log_{10}(f_c) - 0.8)\,.$$

A new packet arrives at the base station for each user with equal probability and independently at each time frame with packet length following an exponential distributed with mean μ [bits/sec/Hz] which is the same for all users. We define the the total average arrival rate $\mu_{TOT} = K\mu$ (i.e., the overall system load). The main parameters used in the simulations are specified in Table-I.

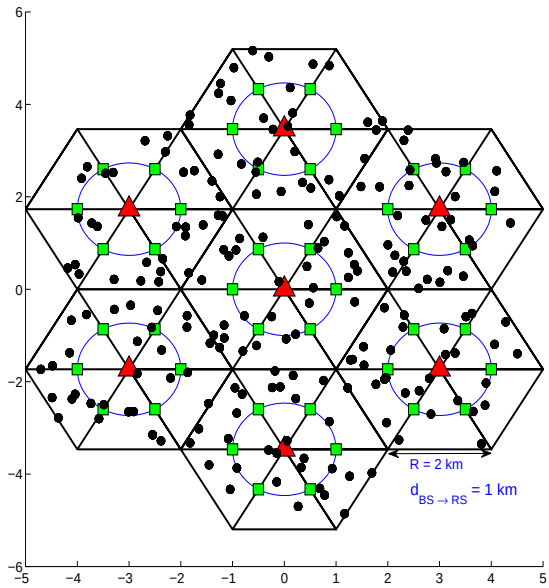

Fig. 1. Multi-cell hexagonal layout, R = 2 km, $d_{BS\rightarrow RS} = 1$km with N=6 RSs and uniformly distributed K = 30 MSs.

TABLE I
Simulation Parameters

Cell layout	Hexagonal (7 cells wraparound)
Cell radius, R	2 km
BS to RS distance, $d_{BS\rightarrow RS}$	1 km
RSs per cell	$N = 6$
MSs per cell	$K = 30$
Antenna Type	Omni-Directional
BS, RS and MS heights	10m, 3m and 1.5m, respectively
Carrier Frequency, f_c	1900 MHz
Thermal noise power, N_0	-121 [dBm]
TX power (BS), P_{bs}	$[35, 40, 45, 50]$ [dBm]
TX power (RS), P_{rs}	35 [dBm]
Rician fading factor	8 [dB] (only for BS to RS links)
Log-normal Shadowing	0 [dB] mean and $\sigma_{sh} = 8$ [dB] (BS to RS) 0 [dB] mean and $\sigma_{sh} = 2$ [dB] (BS to MS and RS to MS)
Packet arrivals	1 [packet/sec/Hz] (constant)
Packet size	exponentially distributed with mean $\mu_{TOT} = \frac{1}{K}[0.1, 0.5, 1, 2, 4, 6, 8, 10]$ [bits/packet]

V. Numerical Results

Figure 2 shows the average cell throughput [bps/Hz] vs base station transmit power [dBm], for $N = 6$, $K = 30$ and for two different values of total packet arrival rate μ_{TOT}. We consider three set of curves: the solid blue line represents the performance of the centralized algorithm, the dashed red

line represents the performance of the distributed algorithm and the dotted green line represents the performance of a system without relays. We firstly observe that the gap between centralized and distributed schemes is small when the total packet arrival rate is small, while it grows as function of the total packet arrival rate. This is due to the fact that the distributed scheme is limited by the intracell interference. For the same reason, the gap between centralized and distributed schemes gets smaller as a function of the base station transmit power: for a low transmit power the percentage of users served by the relays is bigger. We also observe that both the centralized scheme and the distributed schemes outperform the scheme without relays for average to high transmission power. On the other hand, at low transmission power and for a high total packet arrival rate value, the conventional scheme outperforms the distributed one in terms of average cell throughput: we will see from Figure 4 that such a loss in terms of average cell throughput corresponds to a fairer per-user rate allocation.

Figure 3 shows the total average cell throughput versus the total packet arrival rate μ_{TOT} for BS transmit powers $P_{bs} = \{40, 50\}$ [dBm]. We observe that for a low traffic value the performance of the three schemes are similar. For average traffic values the two relay-based schemes give an advantage with respect to the no-relay case. For high traffic values the distributed scheme becomes interference limited for lower values of μ_{TOT} than the centralized scheme as it suffers of both intracell and intercell interference, while the centralized one only of intercell interference.

Figure 4 shows the sorted long-term average user rates for $R = 2$ km, $d_{BS \to RS} = 1$ km, $P_{bs} = \{40, 50\}$ [dBm], $P_{rs} = 35$ [dBm], $\mu_{TOT} = \{4, 8\}$ [bps/Hz], with $N = 6$ relay stations (RSs). The main message of Figure 4 is that the proposed scheme is fairer in terms of long-term average user rate and gives a substantial improvement with respect to the conventional scheme without relays.

VI. Conclusions

We proposed a distributed relay scheme for downlink transmissions, where a given user can be either served by the base station or by a relay, in a opportunistic way. Such a distributed approach, allow a reduced feedback with respect to the centralized case, especially when a simple scalar feedback is not sufficient for estimating the channel quality. As a result of the reduced feedback requirements the system becomes more scalable, as new relays can be deployed where needed without need of a careful network planning. The proposed technique works in two phases. In the first phase the base station makes its scheduling decisions for that time slot taking into account the channel conditions and the relays and users' queue states. The selected destination could be either a relay or an user. In the second phase each relay, if it had not been scheduled by the base station in the first phase, schedules a user taking into account channel conditions and queue states. We study the performance of the proposal by means of a multicell simulator. The distributed approach performs quite near the centralized one when the cell load is not too high. Future studies will improve the performance in the interference limited region by means of multiple antenna processing and local cooperation between nodes.

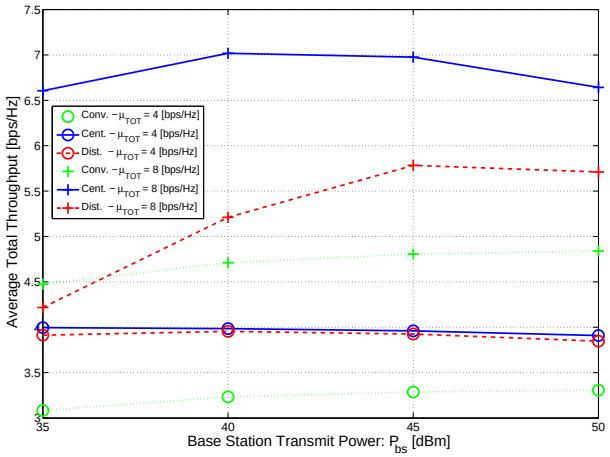

Fig. 2. Total Average throughput versus BS transmit power, P_{bs}, for total packet arrival rate $\mu_{TOT} = \{4, 8\}$ [bps/Hz], $R = 2$ km, $d_{BS \to RS} = 1$ km, $P_{rs} = 35$ [dBm] with $N = 6$ RSs and $K = 30$ mobile stations (MSs).

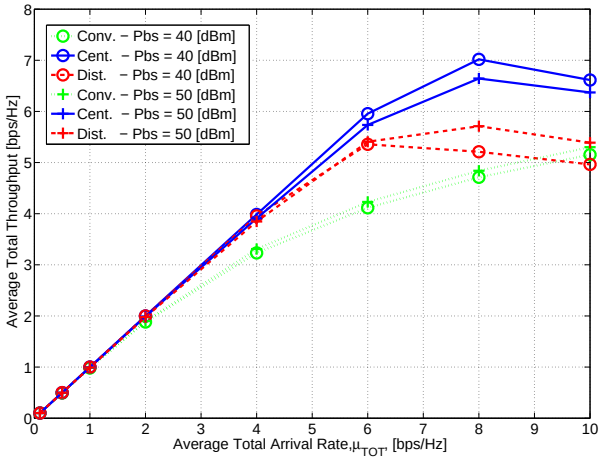

Fig. 3. Total Average throughput versus total packet arrival rate μ_{TOT} for BS transmit powers $P_{bs} = \{40, 50\}$ [dBm], $R = 2$ km, $d_{BS \to RS} = 1$ km, $P_{rs} = 35$ [dBm] with $N = 6$ RSs and $K = 30$ MSs.

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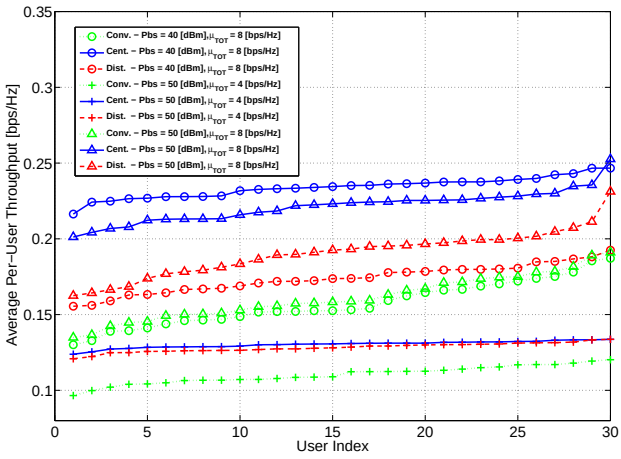

Fig. 4. Sorted average user rates for $R = 2$ km, $d_{BS \to RS} = 1$ km, $P_{bs} = \{40, 50\}$ [dBm], $P_{rs} = 35$ [dBm], $\mu_{TOT} = \{4, 8\}$ [bps/Hz], with $N = 6$ RSs.

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