MULTI-USER DIVERSITY IN MULTI-HOP CELLULAR NETWORKS

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ABSTRACT

In this paper we study multi-user diversity in the downlink of single-hop and multi-hop cellular networks. We also propose a base-station coordinated relaying method in a multi-hop cellular network to overcome the fundamental limitations on the average achieved throughput per-user. In the proposed method, multi-user diversity is induced in a 2-hop forwarding scheme and then exploited to improve per user achieved data throughput. We show that using the proposed method, the downlink throughput per-user is significantly increased.

1 INTRODUCTION

A fundamental characteristic of wireless communications is the time variations of wireless channel. An important means to mitigate the destructive effects of wireless channel time variations is *diversity*, where the basic idea is to improve the system performance by creating several independent signal paths between the transmitter and the receiver.

In a wireless cellular network with multiple users, *multi-user diversity* is provided by having independent time-varying wireless channels between the base-station and different users in the cell coverage area (see Fig. 1.a). The multi-user diversity gain arises from the fact that, in a system with many users whose channels vary independently, there is likely to be a user with a "very good" channel at any time. System throughput is then maximized by allocating the shared channel resource at any time to the user that can best exploit it [1], [2].

In this paper, we first study multi-user diversity gain for average per-user throughput in a single-cell system. We consider a time domain scheduling scheme that exploits multi-user diversity by transmitting to the user with maximum channel gain in each time instant. We then show that for such method the main limiting factors are: number of users in the cell coverage area, base-station maximum transmit power, its maximum supported transmit bit-rate, and the average maximum channel gain.

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We then consider multi-user diversity in multi-hop cellular networks with mobile relays. Multi-hop cellular networks are a promising combination of the dynamics of mobile ad-hoc networks and the reliability of cellular networks [3]. In multi-hop cellular networks, the data-units are transmitted to the destination through relays. By utilizing such transmission method an immediate advantage is the opportunity of exploiting multi-user diversity in each hop.

To exploit the multi-user diversity in a multi-hop network, a relaying method is proposed in [4]. In this method, multi-user diversity is exploited in each hop by selecting the next relay based on the instantaneous channel quality. However, the transmission to only one relay reduces the opportunity of finding a good channel between the selected relay and the next relay.

In this paper, we propose a base-station coordinated relaying policy, Induced Multi-User Diversity Relaying (IMDR). IMDR uses the broadcast feature of wireless channel to induce multi-user diversity through a two-phase process. In the first phase, data-units are broadcasted by the base-stations with its maximum bit-rate. Some users in the cell coverage area are likely to receive the data-units. These users, acting as relays in the second phase, wait until the occurrence of a "good channel" to transmit data-units into the destination with maximum bit-rate. Transmitting to multiple relays in the first phase induces multi-user diversity into the system that can be exploited in the second-phase.

2 SYSTEM MODEL

We consider a single-cell 2-hop data communication system with unit cell-coverage area. Base-station is located at the center of the cell and its maximum transmit power is P_{max}. Air interface is based on Direct Sequence Coded Division Multiple Access (DS-CDMA) with chip-rate of W and maximum supported bit-rate of R_{max}.

Data-units can be transmitted directly from the base-station to the users, or they can go through one other mobile users serving as relays. There are n mobile users, indexed by i, distributed uniformly in the cell coverage area. Mobile users are able to receive, temporarily save and relay data-units in the same frequency band of base-station transmission. We assume each user has an infinite buffer to store relay data-units. Each data-unit has infinite delay tolerance and includes the identity of the destination user. Each user in the coverage area broadcasts a pilot signal to indicate its identity. This pilot signal is also utilized by other entities for channel estimation.

The wireless channel gain between the base-station and the ith user at time instant t is given by the process $\{g_i(t)\}$. We assume that the process $\{g_i(.)\}$ is stationary and ergodic. Moreover, for different users in the cell coverage area, the corresponding channel processes are assumed to be independent and identically distributed (i.i.d.).

At any time instant t, a resource allocation policy, Π, manages the data transmissions from the base-station to relays, or relays to destination users. For a resource allocation policy, Π, $\Gamma_i^{\Pi}(t)$ is the *achieved downlink throughput of user* i at time t, that is the number of bits received by users i at time t. For a resource allocation policy Π, we define *feasible long-term achieved per-user downlink throughput*, $\Gamma^{\Pi}(n)$, if for every i,

$$\liminf_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T}\Gamma_i^{\Pi}(t) \geq \Gamma^{\Pi}(n). \quad (1)$$

$\Gamma^{\Pi}(n)$ is a random quantity and it depends on the various factors including, base-station maximum transmit power and maximum supported bit-rate, number of users in the cell coverage are and their corresponding random channel condition. Definition of (1) is similar to that of presented in [5] for ad-hoc networks.

3 MULTI-USER DIVERSITY

To exploit multi-user diversity in a single-hop cellular network, a time domain resource allocation policy, $\Pi_{\mathcal{D}}$, is used, in which, at each time, maximum base-station transmit power, P_{max}, is allocated to a user i^* where,

$$i^*(t) = \arg\min\{g_i(t)\}. \quad (2)$$

Therefore the aggregated interference due to simultaneous transmission to other users in the cell coverage area is simply eliminated. However, selecting $i^*(t)$ only based on the channel condition may results in an unfair resource allocation . Some corrective scheduling methods are usually used to resolve the fairness issue (see e.g, [6], [7]). Since in this paper our focus is on the multi-user diversity gain, we simply consider a long-term fairness requirement in which $\liminf_{T\to\infty}\frac{1}{T}\sum_{t=1}^{T}\Gamma_i^{\Pi}(t)$ for all user is the same, that is a direct consequence of the independent and identically distributed wireless channels across the different users in the cell coverage area.

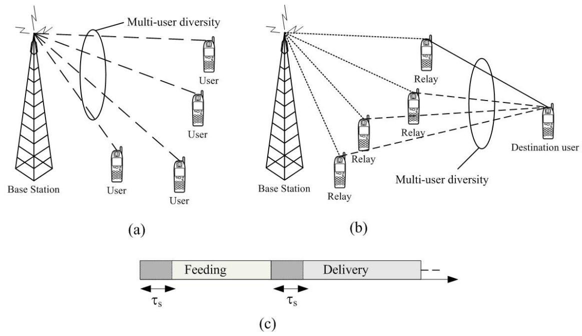

Fig. 1: Multi-user diversity (a), IMDR for single relay (b), and IMDR two-phases (c).

In order to exploit multi-user diversity, according to $\Pi_{\mathcal{D}}$, data-units have to be delayed until the channel becomes "very good" relative to other users. Therefore, the time-scale of channel variations that can be exploited by $\Pi_{\mathcal{D}}$, is limited by the delay tolerance of the corresponding application.

It is shown that for resource allocation policy, $\Pi_{\mathcal{D}}$, the overall system throughput performance is significantly higher than that of simultaneous transmission [1]. The greater the number of users in the cell coverage area, the greater is the probability of occurrence of a good channel, which results in a greater improvement in the base-station downlink throughput. However, the achieved downlink throughput per-user is still limited by the maximum base-station transmit power, its maximum transmit bit-rate, and cell coverage area, thus limited by fundamental architectural constraints.

For transmission with rate $R_i(t)$ bits/s to user i, the basic bit-energy to the interference-plus-noise spectral density constraint should be satisfied. Thus

$$\frac{W}{R_i(t)}\frac{P_{max}g_i(t)}{N_0} \geq \rho_i(t), \quad (3)$$

where N_0 is the background noise spectrum density, and $\rho_i(t)$ is the minimum required bit-energy to the interference-plus-noise spectral density for reception the data transmission with bit-rate $R_i(t)$. For a user i that is selected for transmission, using (3) we write,

$$R_i(t) \leq \xi_0 W g_i(t) \quad (4)$$

where $\xi_0 = \left(\max\{\rho_i(t)\}N_0\right)^{-1}P_{max}$. Therefore, for user i,

$$\liminf_{T\to\infty}\frac{1}{T}\sum_{t=1}^{T}\Gamma_i^{\Pi_{\mathcal{D}}}(t) = \liminf_{T\to\infty}\frac{1}{T}\sum_{t=1}^{T}a_i(t)R_i(t) \quad (5)$$

where $a_i(t)$ is the selection indicator; $a_i(t) = 1$, if user i is selected for transmission at time t, and 0 otherwise. Summing (5) over all users, we have

$$\Gamma^{\Pi_{\mathcal{D}}}(n) \leq \frac{\xi_0 W}{n} \liminf_{T\to\infty} \frac{1}{T} \sum_{i=1}^{n} \sum_{t=1}^{T} a_i(t) g_i(t) \quad (6)$$

$$= \frac{\xi_0 W}{n} \liminf_{T\to\infty} \frac{1}{T} \sum_{t=1}^{T} g_{i^*}(t). \quad (7)$$

Eq. 7 shows that the downlink throughput per-user is bounded by the values of $g_{i^*}(t)$.

To increase multi-user diversity gain, in [6] multiple transmit antennas are used to induces large and fast channel fluctuations, i.e., greater $g_{i^*}(t)$. Also in a multiple-cell scenario, the independent time variations of the channels between a user and the neighboring base-stations is introduced in [8] as a new dimension in multi-user diversity. This form of diversity is exploited by joint base-station assignment and packet scheduling, which results in greater $g_{i^*}(t)$ and thus greater multi-user diversity gain per-user.

4 MULTI-USER DIVERSITY IN MULTI-HOP CELLULAR COMMUNICATION

In multi-hop cellular networks, there is an opportunity to exploit multi-user diversity in each hop. Here, we consider a 2-hop cellular system (Fig. 1.b). In the first hop, between the base-station and the relay, the base-station transmits with its maximum bit-rate. Data-units are received by m users in the cell coverage area. These users act as relays for the communication in the next hop. In the second hop, a relay transmits a data-unit to its corresponding destination upon observing strong channel. Since by this scenario we *induce* multi-user diversity through generating independent paths between the destination user and m relays we name it Induced Multi-user Diversity Relaying (IMDR). A brief description of IMDR in the simplest case is presented in the followings.

The proposed scenario, $\Pi_{\mathcal{I}}$, has two phases: the *feeding phase* and the *delivery phase*. These two phases occur sequentially in time (Fig. 1.c). The time-span of each phase is assigned based on the network traffic and the communication environment characteristics. In each phase, τ_s seconds of each time-slot is considered for signalling purpose.

Feeding Phase: In the feeding phase, data-units are broadcasted by the base-station with the maximum bit-rate and maximum transmit power. Any user which receives a data-unit in the feeding phase acts as a relay in the delivery phase. The selection of the order of transmission of the queued data-units in the base-station is managed by a higher-layer functionality. If the destination user, is among those users who receive data-units in the feeding phase, it sends a received acknowledge signal, R-ACK, to the base-station. Consequently, the base-station broadcasts a data release signal, D-REL, and all other relays release that data-unit.

Delivery Phase: In the delivery phase, base-station is kept inactive and only the transmissions from the relays to the final destinations are allowed. Each relay continuously tracks the quality of the wireless link to the neighboring users as well as their identity. If a relay is able to achieve a transmission bit-rate, greater than or equal to a system parameter R_0, over the channel to the destined user, that relay transmits the data-units to the destination user. Medium access control can be either a contention-based method or a base-station coordinated non-contention based method. Upon successful transmission, destination user sends an R-ACK signal to the base-station. Consequently, the base-station broadcasts a D-REL signal and other relays release that data-unit. If the base-station does not receive R-ACK corresponds to a data-unit in a predefined time interval, τ_{max} seconds, that data-unit is considered lost and a D-REL signal is broadcasted by the base-station. That data-unit may be considered for retransmission in a later time.

Note that, in the feeding phase data-units are fed with the highest bit-rate into the users in the cell coverage area. Therefore, the base-station time is only allocated for transmission with the highest bit-rate. For a large number of users in the cell coverage area, it is likely that some users have a channel state that supports the base-station highest bit-rate.

In the delivery phase, we exploit multi-user diversity by transmission only on the channels with the highest achieved bit-rate. Note that in practice the transmit bit-rate may be adjusted based on the channel status which is fed back into the base-station by the users. An intelligent directional relaying based on the location of the users can also be considered for more improvement in the total throughput.

In IMDR, we also utilize the benefits of cellular architecture through utilizing the base-station knowledge of cell-wide channel state information for medium access coordination in the delivery phase. The parameters τ_{max}, the time span of each phase, and R_0 can be also adjusted by the base-station or an upper-layer mechanism based on different environmental factors and/or traffic demand.

In IMDR for $R_0 \geq R_{max}$, and large number of users in the cell coverage area, n, it is simple to show that

$$\Gamma^{\Pi_{\mathcal{I}}}(n) \leq \frac{\xi_1 W}{n} \breve{g}, \quad (8)$$

where ξ_1 is defined similar to ξ_0 in (7) correspond-

Table 1: Simulation Parameters.

Parameter	Value
Physical layer	Based on UMTS
Cell radius	100 m
Base-stations transmit power	10 W
Standard dev. of log-normal fading	8 dB
Bckground noise density	-174.0 dBm/Hz
Propagation loss exponent	4
Time-slot length	10 ms
Minimum required E_b/I_0	2 dB

ingly. In (8), we assume that within the interval $[1,\ T]$ for $T \to \infty$, the data-units transmitted to the relays will be delivered to the users. $\check{g}$ is the minimum time-average value of $g_i(t)$ between the base-station and a relay that is needed for transmission with the maximum bit-rate, note that

$$\liminf_{T\to\infty} \frac{1}{T} \sum_{t=1}^{T} g_{i^*}(t) < \check{g}, \tag{9}$$

which directly results in $\Gamma^{\Pi_{\mathcal{I}}}(n) > \Gamma^{\Pi_{\mathcal{D}}}(n)$. In other words, using IMDR, the achieved average throughput per user is increased.

5 SIMULATION RESULTS

We simulate a single-cell DS-CDMA system based on UMTS standard [9] with n active users. Users are uniformly distributed in the cell coverage area. The simulation parameters are presented in Table 1. To show the effect of multi-user diversity, we consider three different systems: in System I, for each user the base-station transmits data-units in first-come-first-serve fashion using a time domain scheduling scheme i.e., each user at a time instant. In System II, data-units are scheduled based on $\Pi_{\mathcal{D}}$. Transmission in System III is based on $\Pi_{\mathcal{I}}$, with a non-contention based medium access method in the delivery phase.

We normalize the average achieved throughput of Systems II and III by the average achieved throughput of System I. Fig. 2 illustrates the normalized average achieved throughput versus number of users in the cell coverage area. The difference between the throughput gains of System II and III indicates the achieved multi-user diversity gain resulting from exploiting the induced multi-user diversity by IMDR. A s it is expected, this gain is increased by the number of users. Note that normalized throughput curve will saturate because of the base-station total throughput constraint.

6 CONCLUSION

In this paper we studied the multi-user diversity in the downlink of single-hop and multi-hop cellular networks. For a 2-hop cellular network with mobile relays, we proposed a base-station coordinated relaying method, induced multi-user diversity relaying. IMDR is a two-phase process in which multi-user diversity is induced in the first phase through forwarding the data-units into a number of relays, and then exploited in the next step through transmission on the best link between the relays and the destination users. We showed that using the proposed method, per-user throughput is significantly increased.

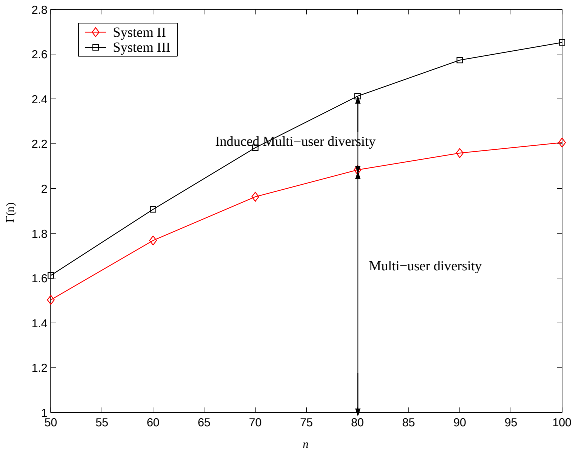

Fig. 2: Normalized average achieved throughput versus the number of users.

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