ABSTRACT

Relays are used to forward data from the source to the destination. There are scenarios wherein a relay is the only means for the data to reach the destination. In this paper, we will focus on scenarios wherein one or more relays are used to forward data to the destinations when the destination is already in the coverage area of the source. This latter scenario has been studied under the term cooperative relaying, as a scheme that primarily aids in improving the throughput within a given coverage area. Our goal is to take previously postulated studies and evaluate achievable cooperative relaying gains in more realistic settings. In discussing the gains, we first identify the practical constraints and study the implications of adding such constraints on the gains that can be extracted from cooperative relaying.

Index Terms— Cooperative systems, Diversity methods, Land mobile radio cellular systems

1. INTRODUCTION

We consider a multi-hop cooperative relay system deployed as part of a cellular system. The benefits of multi-hop relaying in mobile wireless environments have previously been studied in [1]. Conventionally, relaying methods use a hierarchical arrangement of infrastructure stations to enable data from the source to reach the destination. In cellular downlink, source is the base-station (BS) and destination is the mobile station (MS); the BS and relay stations (RS) are considered infrastructure stations deployed by the operator. We use the term conventional relaying to describe a singular unidirectional flow from one infrastructure station to the next till the destination. Alternatively, schemes where multiple infrastructure stations transmit in-tandem to the MS to take advantage of the broadcast nature of the wireless medium fall under the umbrella of cooperative relaying. These multiple transmissions when coherently combined at the destination provide what is known as the cooperative diversity gain. Numerous cooperative schemes are proposed in [2], [3], [4] and references there-in.

The techno-economic arguments on the advantages and disadvantages of having regenerative relays, which are relays that process the data before forwarding, in a cellular system, are in [5]. Relevant to the current discussion is the first cellular relay standard, the IEEE 802.16j system [6] that specifies the architecture and operation of an OFDMA based mobile multi-hop relaying system. A concise summary of communication framework of the IEEE 802.16j system in [7] will form the basis of our simulations and conclusions in this paper.

Fig. 1. (a) Tree based cellular relay architecture (b) Cooperation in a tree-based cellular architecture

We consider a hierarchical set-up shown in Fig. 1a, where relays are arranged in a tree like hierarchy with the base station at the top of the hierarchy. Practical considerations constrain the permitted communication links in cellular architectures. In time division duplex (TDD), uplink and downlink are time separated and cannot be mixed without causing serious performance degradation. Therefore, communications between peer stations shown as links 3 and 5 in Fig. 1a are not allowed in TDD systems. Communication happens only on the edges of the tree. Further, to facilitate clear discussion, we define relay link as the communication between two infrastructure stations and access link as communication between an infrastructure station and a mobile station. System level evaluations that show scenarios where conventional relaying provides throughput gains in an OFDMA based relaying system is described in [1]. In this paper, we focus on understanding the system-level gains produced by adding cooperative relay links to conventional relaying systems. We first adapt existing literature on cooperative relaying to the downlink of a half-duplex TDD cellular system. Using system level simulations that model the IEEE 802.16 system, we then quantify the gains of cooperative relaying protocol and compare it to the conventional relaying case where no cooperation is used. The objective of this paper is to identify real-world constraints that impede wide-spread adoption of cooperative relaying. The rest of the paper is organized as follows: In Section 2, we briefly review the existing literature
on cooperative relaying and frame the problem in the context of the cellular system under consideration. In Section 3, we describe the simulation set-up and present simulation results to validate our claims, followed by conclusions in Section 4.

2. RELATED WORK

Cooperative relaying can be realized by simply allowing additional access links to the already existing access link in Fig. 1a. As shown in Fig. 1b, the presence of links 5 and 6 to MS-1 from BS and RS-2 respectively signal cooperative diversity transmission. Addition of one more link (either 6 or 5 or both) in addition to improving signal to interference noise ratio (SINR) at MS-1 also allows diversity gain when coherent processing is used, as has been demonstrated in [2][4]. However, it is not clear how these SINR gains at individual MSs contribute to the overall system gain. The gains due to cooperative relaying at the network level are contrasted with a frequency re-use scheme that also reduces interference and is already in wide use in cellular systems.

A popular cooperative relaying scheme is adaptive decode and forward (AdDF) [4] where the RS transmits cooperatively to an MS only when the signal to noise ratio of the BS-RS link exceeds a set threshold. System level evaluation of AdDF relaying scheme when contrasted with conventional relaying that uses frequency reuse-6 showed that AdDF produced no improvement in system throughput but a reduction in the variance of system throughput [8]. Another cooperative relaying scheme is virtual MIMO [3]. Virtual MIMO leverages coordinated diversity transmissions from multiple infrastructure stations that when coherently combined at the MS provide diversity gains at the MS. We consider synchronized transmission from multiple BS just like virtual MIMO but do not impose a particular MIMO scheme like the Alamouti transmit diversity scheme. The transmission to the MSs identified for cooperative transmission will be a simultaneous synchronized transmission from all infrastructure stations. The MSs receiving the transmission will see a composite channel from all infrastructure stations. The challenges in identifying the MSs that qualify for this type of cooperative transmission and the added complexities that such transmission will bring are identified in Section 3.1. This simple cooperative scheme is used to isolate the gains due to cooperation while keeping other factors like latency, scheduling issues, feedback overheads and control signaling overheads comparable between conventional and cooperative schemes.

3. SIMULATION SET-UP

The system level simulation is a set-up with 19 cells separated spatially by a pre-set inter-site distance. Each cell contains 3 sectors. Two relays are inserted above roof tops (ART) at a distance of 3/8th the cell radius as shown in Fig. 2. The assumptions on BS and ART RS transmit parameters are as given in Tables 1, 3, 4 and 6 of the IEEE 802.16m Evaluation Methodology document [9].

A simulation run consists of the following procedure: 5000 mobile stations are dropped uniformly in one sector of the center-cell. The received power at each MS from all sectors of BSs and RSs is computed. This received power is an attenuated version of the transmitted power due to path loss and shadowing. If the BS and RS height is fixed at 15m above the average rooftop and a carrier frequency of 2GHz is used, then the path loss $PL(dB)$ is given by

$$PL(dB) = 128.1 + 37.6 \log(R),$$

where $R$ is the distance in (Km) from the transmitted to receiver. Shadowing factor is assumed to have a log normal distribution with a standard deviation of 8dB. Site-to-site shadowing correlation of 0.5 is also assumed. Let $\gamma_i$ denote the fading term containing both propagation loss and path loss from each infrastructure station $i$ whose transmit power is $P_i$. The received power at the MS is then denoted as $P_r = \gamma_i P_i$. The SINR at each $MS_j$ is defined as,

$$SINR_{MS_j} = \frac{\sum_{i \in \mathcal{D}} \gamma_i P_i}{\sum_{j \in \mathcal{D}} \gamma_j P_j + N} = \frac{\sum_{i \in \mathcal{D}} \gamma_i P_i}{\sum_{j \in \mathcal{D}} \gamma_j P_j + N}$$

where $\mathcal{D}$ denotes the set of desired powers, $\mathcal{D}$ denotes the set of powers from interfering infrastructure stations and $N$ is the additive thermal noise. At every MS, the received powers are arranged in a descending order from the highest to the smallest. The largest power may not necessarily be from the cell that is closest to the MS because shadowing makes proximity irrelevant. For example, an MS in sector-1 can see a larger received power from any of the other sectors or RSs in the 19 cells than the one closest to it. The MS is said to be connected to the infrastructure station that contributes to the highest received power. However, the desired and interfering powers at the MS that contribute to the SINR expression in (2) depends on the type of transmission scheme used. We consider 4 different schemes as described below:

**Fig. 2.** A 19 cell cellular layout with 3 sectors per cell and 2 ART RSs per sector.
• In direct transmission, the sets $\mathcal{D}$ and $\overline{\mathcal{D}}$ consists of only base stations. There is only one BS that contributes to the desired signal.

• In conventional relaying, an MS receives data only from the infrastructure station to which it is connected. There is only one desired signal; the size of the set $\mathcal{D}$ that contains both BS and RSs is 1. The received powers from other BSs and relays are considered interference and belong to set $\overline{\mathcal{D}}$.

• In distributed MIMO cooperative relaying, the MS receives data from more than one infrastructure station. The infrastructure stations that participate in cooperative relaying belong to set $\mathcal{D}$, while the rest belong to set $\overline{\mathcal{D}}$. The size of set $\mathcal{D}$ is greater than 1.

• In conventional relaying with re-use 3, only one third of all infrastructure nodes operate in the same frequency partition. The size of set $\mathcal{D}$ is 1 while the size of set $\overline{\mathcal{D}}$ is reduced to a third compared to that of conventional relaying with full reuse.

A measure of the dynamic range of SINRs seen in the cell is given by the cumulative distribution function (CDF). So, for each of the techniques mentioned earlier, we compute the SINRs at each MS and plot the cumulative distribution function. The CDF of the measured SINR at MSs in the sector is a good measure of the expected coverage, since most services require a minimum SINR to guarantee quality of service. With proper scaling, the SINRs are also indicative of achievable sector throughput when linear processing is used.

### 3.1. Cooperative Relaying Scheme

It is well known that cooperative relaying schemes like distributed MIMO show improvement only when the received powers from infrastructure stations that cooperate are nearly equal [3]. In cellular networks, only a small percentage of MSs those are equidistant from more than one infrastructure station benefit from cooperation. Among this small percentage of users, imposing an equal power constraint is impractical because shadowing makes it a probabilistic rarity. Therefore, we relax this equal power constraint; in that, we allow infrastructure stations to transmit cooperatively as long as largest powers are from the RSs and BS sector-1 in which the MSs are dropped. For the arrangement shown in Fig. 1b, cooperative transmission is allowed only when the largest three received powers are from BS, RS-1 and RS-2. This scheme requires that not only the MS be proximal to BS sector-1 but also be connected to either sector-1 or RS-1 or RS-2. However, we observed that, on an average, only 1.25% of the 5000 MSs in the sector qualify for the 3-node cooperative transmission. Additionally, when 2-node cooperation is allowed, the percentage of MSs that benefit from cooperative transmission increases to 17%. 2-node cooperative transmission is allowed only when the two largest powers are a pair from the trio of BS-sector-1, RS-1 and RS-2. A scatter plot that shows the distribution of MSs in Sector-1 is shown in Fig. 3a. The number of MSs participating in 3-node cooperation represents a small fraction of users in the cell compared to the number of MSs that qualify for 2-node cooperation as shown in Fig. 3a.

Thus, this cooperative scheme classifies the MSs in the network into three groups: 1. Those that participate in a 3-node cooperation, 2. those that participate in a 2-node cooperation and 3. those that do not participate in any cooperation. This classification allows optimum use of cooperation while admitting practical considerations of the network. References to cooperative relaying in the paper refer to this network-based MS classification scheme.

The CDF of the SINRs under the 4 schemes - direct transmission, conventional relaying with full reuse, cooperative relaying and conventional relaying with reuse-3 are plotted in Fig. 3b. The inter-BS distance was assumed to be 1732m which is a typical macro deployment. As observed, when the BS and RS transmit powers are equal (36dBm), adding RSs improves SINR over direct transmission thus improving the overall coverage. The improvement is drastic for MSs in the least 5 percentile which is the statistics MSs located at the edge of BS sector-1 where SINRs improve by as much as a 1dB. Compared to conventional relaying, the improvement due to cooperative relaying is very small, about 0.1dB over the entire dynamic range. This is largely due to the small percentage of users who qualify for cooperative transmission. However, a dramatic improvement of about 4dB in SINR is observed for users in the 5th percentile over conventional reuse-1 relaying when a reuse-3 scheme is deployed. Note that the available bandwidth in the reuse-3 scheme is 1/3 of the reuse-1 scheme. Thus, adding cooperative relaying while boosting SINRs at individual mobile stations, does not translate to big coverage improvements when studied at the system level. We now briefly look at issues that affect implementation of cooperative schemes.

**Message Overhead Implications:** Cooperative relaying in a tree hierarchy requires centralized scheduling while conventional relaying can handle distributed scheduling. Centralized scheduling causes an increase in the volume of control messages since grants for all MSs in the cell now emanate from the BS. Though the feedback overheads can be said to be comparable, the increase in control overhead may be costlier to implement. Higher processing gains with closed loop schemes could improve cooperative diversity gains beyond those offered by conventional relaying in cellular systems. However, closed loop schemes require tighter coordination than the open loop schemes between the MS and cooperating nodes that increases both the feedback overhead as well as the control overhead. The contrast between costs and benefits is not clear for closed loop cooperative schemes.
• **Mobility Considerations:** System level set up considers only stationary MSSs. We drop users in a fixed location and observe their long-term fading characteristics. However, in practice, MS mobility is another big factor that affects system performance. MSs' movement changes prevailing channel conditions requiring frequent updates from the mobile station. Such frequent updates will add to the feedback load in the system. One way, increased feedback is avoided in practice is by distributing the data to the mobile station over sub-carriers in the entire bandwidth by randomly permuting sub-carriers with the unique cell-identification (cell-ID) number of the connected cell as the seed. Since all BSs and RSs follow this procedure using their cell-ID as the seed for random permutation, the interference is randomized and the average interference seen by the data at the MS does not vary widely. However, such a scheme finds limited application here since it requires coordinated transmission between BS and RSs.

### 4. CONCLUSIONS

This paper is an initial foray in characterizing the cost-benefit trade-off of adding cooperation in cellular relaying system. We use a system level set-up modeling ART RS deployment in cellular networks. For an open-loop virtual MIMO scheme when only long term fading characteristics are considered, we show that cooperation produces little improvement in coverage. Considerations of mobility and signaling overhead only add to the complexity of the system. The analysis is elementary. However, there is a clear void in existing literature that addresses the issues we raise in the paper. We are currently working on an extended version of this paper that rigorously quantifies the cost-benefit tradeoff of incorporating cooperation in cellular systems. We hope that our efforts would make the context clear for a cooperative relaying scheme in cellular systems.

### 5. REFERENCES


