Coverage Enhancement through Two-hop Relaying in Cellular Radio Systems

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Abstract — **Digital relaying is a technique that uses certain mobile terminals that have good communication links with the base station to act as relay nodes for those that do not have. With this technique, the signal quality at the destination is expected to improve since the signal only goes through favorable links and, at each intermediate node, the signal is decoded and re-encoded (so that no noise is propagated) before forwarding. One of the major costs of relaying is that additional channels are needed. In this paper, we investigated the effect of using different schemes for selecting channels - among those already used in the adjacent cells - for relaying on performance improvement. Our simulation results show that not only can relaying improve the performance; but also, with power control this improvement is quite insensitive to the channel selection scheme. Furthermore, with small cell radii where there is a potential for high interference level, only a low relay node transmit power is sufficient to improve the system performance significantly.**

I. INTRODUCTION

The concept of relaying is well known. Analog repeaters are sometimes used in a cellular system to help extend coverage to areas that the base station cannot cover [1]. However, these repeaters, in their old analog form, are "dumb" in the sense that they blindly retransmit all the signal received from the base station. Along in this process, not only do they boost the signal but also the noise. Relaying using digital techniques via mobile terminals, as presented here on the other hand, involves the forwarding of a clean signal from one hop to another. Each relay session is expected to be short, carried out only as needed and over a connection-oriented path where, for each session, the relay node and channel used for relaying are selected based on a certain criteria.

Although this form of "intelligent" relaying has not been previously deployed in cellular systems, recently there has been interest in the research community [2,3]. Two issues are studied in this paper: the method of relay node selection and channel selection for relaying purposes. The problem of relay node selection is actually a routing problem and it is particularly important in a system that supports different traffic types. In this type of system, there will be diverse link quality associated with the various links along any route; therefore different routing schemes are expected to produce different performance results and overhead.

The second issue involving the method of channel selection for relaying is, in particular, of interest in what we are proposing. Since our model assumes a system with fully loaded cells and since the spectrum is scarce, no channels will be reserved for relaying purposes. Thus, we propose to reuse channels from the adjacent cells for relaying purposes. By doing so we are resorting to an even denser channel reuse, in addition to an already existing reuse plan. This could pose a potential risk whereby excessive interference is created due to this unplanned frequency reuse; therefore tight power control may be required in order to minimize the co-channel interference.

In this paper, we consider, without loss of generality, only the downlink; similar derivations can be derived for the uplink as well.

II. RELAY NODE/PATH AND CHANNEL SELECTION SCHEMES

For each node that requires relaying assistance, first a relay node is selected and then the channel required by that relay node to communicate with the node that requires assistance is determined. Both the relay node and channel selections are performed based on only large-scale variations (distance attenuation and shadowing); since it would be impractical to perform inter-relay node and inter-channel hand-off based on multipath fading. However, Rayleigh fading is included in the coverage evaluation.

A. Relay Node/Path Selection

Since the path-loss associated with each link varies from location to location, to have an efficient routing algorithm it is necessary to have global path-loss information for all the different links in a given cell. One of the benefits gained from using an efficient routing scheme is power savings and this, in turn, translates into less interference to other co-channel links. However, this benefit must be weighted against the signaling overhead involved.

The following is a scheme that makes a relay node selection based on a route that has the lowest bottleneck in a two-hop relaying network (assuming path-loss information on all the links in a given cell can be readily obtained).

Let N denote the set of candidate relay nodes defined as the nodes which have an adequate link to the BS. Let PL_{n1} and PL_{n2} be the path-losses associated with the first (between the base station to the candidate relay node) and the second hop (between the candidate relay node to the relayed node of interest), respectively, along the n^{th} route, $n \in N$. Then, the selected route, r_s, is:

$$r_s = \arg \min_{all\, n \in N} (\max\{PL_{n1}, PL_{n2}\}) \tag{1}$$

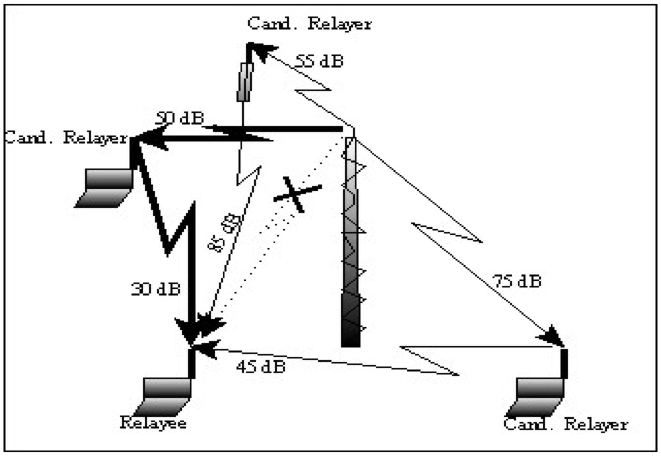

Fig. 1. Relay node/path selection based on MinMax scheme (the numbers attached to the arrows indicate the path-losses).

Fig. 1 provides an example based on (1); note that the selected route, indicated by the links with bold arrows, has the lowest path-loss among the higher ones on each route. Note also that the number of independent routes in this case should correspond to the number of candidate relay nodes. If the number of candidate relay nodes is large, however, the overhead involved in link quality measurements and information exchanges between the base station and the candidate relay nodes, and between each candidate relay node and the relayed node of interest, may be enormous. Therefore, for practical purposes the number of potential relay nodes should be limited.

B. Channel Selection

First of all, the multiple access scheme considered here is TDMA where a channel is uniquely identified by a timeslot and a frequency carrier. Since our model assumes no reserve channels, channels from the adjacent cells will be acquired for relaying purposes. By doing so we run a risk of creating too much interference that could lead to service interruptions at some links. To minimize this risk, tight power control may be necessary. In the following, three schemes are presented among which a trade-off between efficiency and the overhead complexity is involved.

Let γ_i^c be the carrier-to-interference ratio received at the relayed node *i,* on channel *c,* and B_c the set of all base stations that use channel *c* plus the relay node *j* which also uses channel *c* for relaying purposes. Then,

$$\gamma_i^c = \frac{(G_{ji} P_j^c)}{\sum_{k \in B, k \neq j} (G_{ki} P_k^c)}, \tag{2}$$

where G_{ji} is the path-loss coefficient between the relayed node *i* and the relay node *j,* and P_j^c is the transmitted power of the relay node *j*. Similarly, G_{ki} are the path-loss coefficients between the relayed node *i* and each co-channel base station *k* whose channels are being probed for reuse, and P_k^c is their corresponding transmitted power. Then:

- Smart Channel Selection:

$$l_s = \arg \max_{all\, c \in K, K \subset L} (\gamma_i^c), \tag{3}$$

where L is the set of all channels in the adjacent cells, and K is the subset of L which denote the reusable channels. To determine whether a given channel, l, is reusable, a path-loss or link gain matrix of the active links that are associated with this channel plus that of the new candidate relay link is set up; let B_l denote the set of these active links. A maximum achievable γ, $\gamma_{B_l}^*$, is then determined from the largest real eigenvalue of this matrix [4]. If $\gamma_{B_l}^* \geq \gamma_t$ (where γ_t is the threshold value), then there exists a positive power vector such that all the links belonging to the co-channel set of the channel under question can be active simultaneously. Now, from set L the subset K is formed as follows:

$l \in K$, if $\gamma_{B_l}^* \geq \gamma_t$, and $l \notin K$ if $\gamma_{B_l}^* < \gamma_t, \forall l \in L$.

- Semi-Smart Channel Selection:

$$l_s = \arg \max_{all\, c \in L} (\gamma_i^c) \tag{4}$$

- Random Channel Selection:

$$l_s = \text{rand}(L) \tag{5}$$

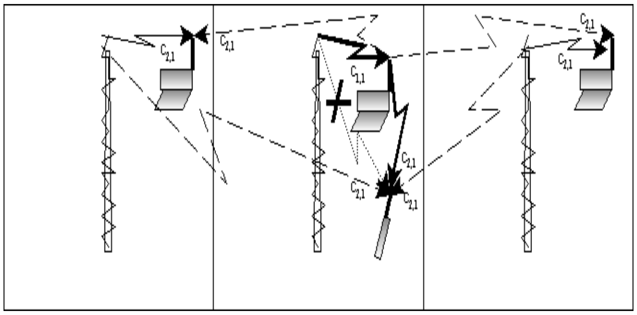

Fig. 2. Basic configuration of co-channel links when channels from an adjacent cell are probed for reuse for relaying.

What makes (3) a "smart" scheme is the fact that each channel is probed first for its effective γ at all the nodes involved, and among those that are acceptable to be reused only the one that results in the highest γ at the relayed node of interest is selected. The Semi-Smart scheme is similar to

(3); the only exception is that the reusability check is not performed. With this scheme, the signaling overhead is reduced quite significantly. However, its performance is expected to be inferior to (3). In (5), the selection is done on a random basis irrespective of the quality of the links affected by the chosen channel. This scheme is very simple and involves very little overhead, but neither the service continuity of the active links nor the service of the relayed node link is guaranteed. Thus, it is expected to provide the worst performance.

Fig. 2 shows a basic configuration of co-channel links when channels from an adjacent cell are probed for reuse. In the figure, the solid arrows represent the desired links, while the dashed arrows represent the interfering links. Due to space constraint, only three co-channel cells are shown.

Furthermore, for all three selection schemes, once a channel from an adjacent cell is selected for reuse in a certain cell, it is tagged, i.e., another relay node from within that same cell cannot select this same channel to reuse simultaneously.

III. SIMULATION MODEL

In our simulation model, we have assumed an urban environment with a propagation exponent of 4, lognormal shadowing (standard deviation of 10 dB), and flat Rayleigh fading. The simulation area consists of 6x6 square cells with wrap around edges. The cluster size is chosen to be 4 and the cell radius is varied from 200m to 1 km. Omnidirectional antennas are used for both the base station and the mobile terminal. The carrier frequency is 2.5 GHz and the transmission bandwidth is 2 MHz. Thermal noise is also considered at the receiver, which has a noise figure of 8 dB. Due to the large bandwidth and noise figure assumptions, it is assumed that decoded relaying as presented in [5] is used throughout.

At present, only two-hop relaying and single-class traffic, where every mobile node has the same SINR threshold requirement of 10 dB has been considered. A "snapshot" power control scheme is used for both relaying and non-relaying cases with a step size of 2 dB. Power updates are performed until the receiver's SINR falls between 10 and 12 dB, or until a maximum of 10 updates are reached, which ever one comes first. Furthermore, all the cells are assumed to be fully loaded, with the mobile nodes distributed randomly and uniformly within the cell. Since we are not committed to any specific channel access scheme at this point, the number of channels available in each cell is presumed equal to the number of subscribers. Moreover, the same path-loss model between the base station to the mobile terminal and between one mobile terminal to another has been assumed. As well, each relay node is assumed to support up to 7 nodes; for practical purposes this number is sufficiently large such that this cap does not have any limiting impact on the performance.

For each subscriber density the simulation is started without relaying. After the determination of the portion of subscribers in each cell that cannot communicate directly with the base station, the remaining portion, by definition, makes up the set of candidate relay nodes. Relaying is then incorporated and the simulation continues for 1000 iterations. Each iteration corresponds to a different subscribers' location position. For each location position, statistics of 100 received SINR are recorded for each subscriber and its coverage (defined as the $\Pr[\mathrm{SINR} \geq 10\,\mathrm{dB}] \geq 95\%$) is evaluated. In the simulation, when subscribers change location, their first priority is to get connected with the base station. Only when they find that they cannot get good communication from the base station will they turn to relaying.

IV. SIMULATION RESULTS

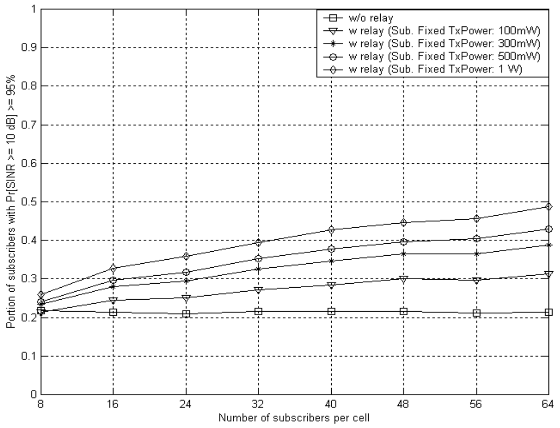

Fig. 3. User Coverage vs. Number of subscribers per cell (for 1 km cell radius, No Power Control, Semi-Smart Channel Selection Scheme).

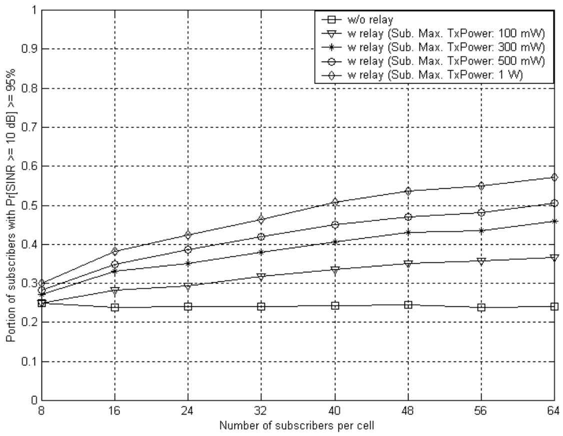

Fig. 4. User Coverage vs. Number of subscribers per cell (for 1 km cell radius, Power Control, Semi-Smart Channel Selection Scheme).

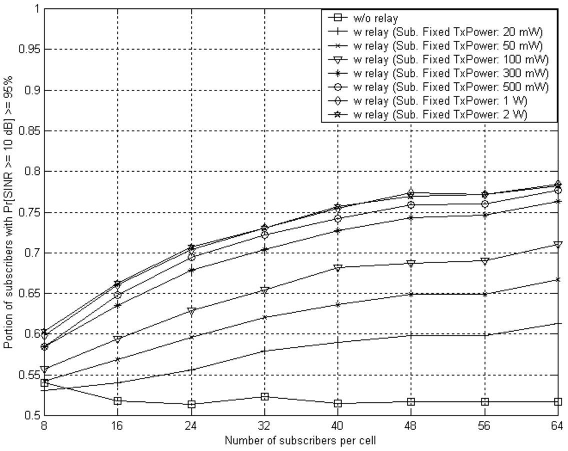

Fig. 5. User Coverage vs. Number of subscribers per cell (for 200m cell radius, No Power Control, Semi-Smart Channel Selection Scheme).

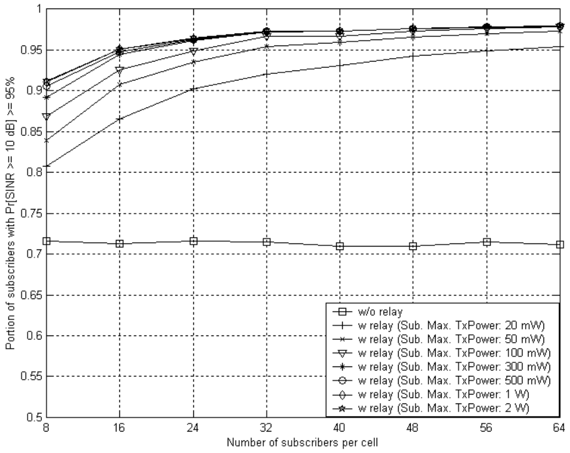

Fig. 6. User Coverage vs. Number of subscribers per cell (for 200 m cell radius, Power Control, Semi-Smart Channel Selection Scheme).

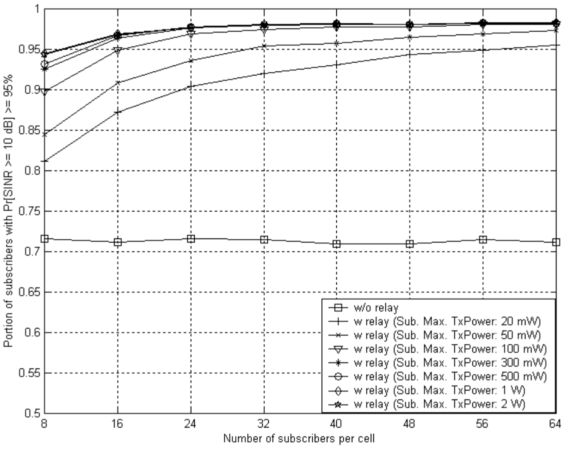

Fig. 7. User Coverage vs. Number of subscribers per cell (for 200 m cell radius, Power Control, Smart Channel Selection Scheme).

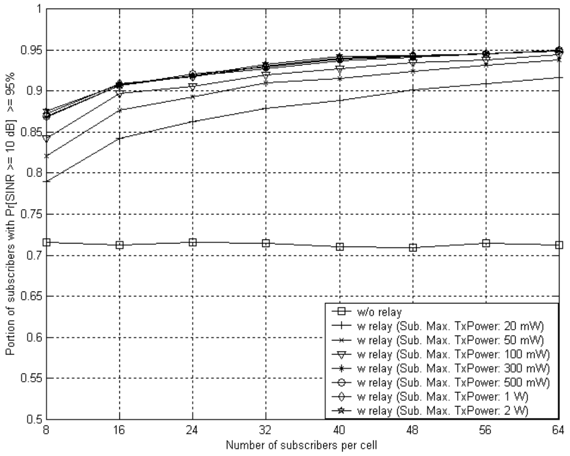

Fig. 8. User Coverage vs. Number of subscribers per cell (for 200 m cell radius, Power Control, Random Channel Selection Scheme).

For both cell radii in the above results, the maximum base station transmit power used on any mobile node is 1 W. Figs. 3 and 5 show the results for the case with no power control, while Figs. 4, 6, 7, and 8 are with power control. Here, it can be observed that the performance improvement with power control is consistently superior to the case with no power control.

Fig. 4 shows the result for a 1 km cell radius where the relay node maximum transmit power is set a parameter that ranges from 100 mW up to 1 W. Here it can be observed that when the user coverage (here defined as the portion of subscribers in a cluster with Pr[SINR >= 10 dB] at least 95% of the time) is low when relaying is not considered, with relaying the performance only improves gradually. This is the case of a noise-limited system where the performance keeps increasing gradually with increasing relay node maximum power.

The result in Fig. 6, where the cell radius is reduced to 200 m, shows a better improvement with significantly lower relay node maximum transmit power. It is important to note that, for an interference-limited system as in this case, higher relay node transmit power does not offer higher performance. This can be observed in all figures with the 200 m cell radius (Figs. 6, 7, 8), where a significant improvement is observed at the 20 mW relay node maximum power level and it starts to saturate at higher power levels.

Surprisingly, it appears that the performance improvement is not very sensitive to the channel selection scheme as this can be witnessed by the similar improvements attained in Figs. 6, 7, and 8.

V. DISCUSSIONS AND CONCLUSIONS

In this study we investigated whether there is a potential benefit from employing relaying in a fully loaded digital cellular system. Our results show that relaying can significantly improve the system performance; and the higher the cell density the better the improvement is. However, this improvement result is obtained based on certain assumptions that require further explanations; and they are provided below:

(1) The number of channels available per cell increases linearly with the number of subscribers. (The reason is we chose to focus on the coverage aspects, rather than the traffic aspects of performance.)

(2) Accurate channel measurements can be obtained so that closed-loop power control can be performed precisely. (This is reasonable provided the channel under consideration is slow fading, where the user speed is expected to be very low (i.e. at pedestrian speed); in fact we did not take into account the Doppler effect due to mobility in our simulations.)

Although it appears that the improvement result is not very sensitive to the channel selection scheme for relaying, if different assumptions are used this result is expected to differ somewhat. Therefore, based on our simulation results, the following conclusions are drawn:

- Even though no extra bandwidth is reserved for relaying purposes, significant returns can be obtained through relaying.
- The return, with the use of power control, increases as the system moves from being noise-limited to interference-limited.
- The difference in returns between using Smart, Semi-Smart, and Random Channel Selection is not very significant; therefore if the overhead complexity involved in Smart or Semi-Smart Selection does not justify the slight increase in performance return, then it may be more advantageous to opt for the Random Selection.

Furthermore, in our model we assume decoded relaying is used throughout. There is a possibility of decoding error being introduced at each hop; therefore Forward Error Correction (FEC) is necessary in order to minimize the Bit Error Rate (BER) at the destination. The use of error protection will, in turn, introduce decoding delay. This delay, however, might not be tolerable for delay-sensitive traffic. Thus, when relaying a certain traffic signal, factors such as number of hops, end-to-end delay, and BER must be factored in.

Thus far in our model we have made restrictions on a two-hop only relay path and the set of candidate relay nodes that are found from within the same cell in which the node requiring relaying assistance is assigned. However, it would be interesting to see how much more improvement can be attained if these restrictions were lifted. Furthermore, the possibility of using different relay node/path selection schemes has not been investigated. It would be interesting to see what kind of impact different selection schemes would have on the system performance such as throughput and end-to-end delay when more number of hops and subscribers of different traffic requirements are introduced into the system. All of these topics are subjects for further investigation.

Finally, although our simulations show promising results there still remain many open issues. Among them is the issue of practicality. For example, a system wide relay-capable cellular network would be feasible if there is a full cooperation among all subscribers. Mobile terminals must remain on as long as there is traffic to be sent or received. This, in turn, opens a very interesting question and that is whether relaying in a cellular system should be enforced only when coverage is needed or it should be carried out as much as possible in an effort to achieve a higher performance. The answer to this question will have an impact on the design of the new terminal devices since if the devices are required to be on for a long duration to serve a relaying purpose, then they must be designed to have long-lasting power.

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