Coverage Enhancement Through Peer-to-Peer Relaying in Cellular Radio Networks[1]

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***Abstract* — We consider a TDMA cellular multihop network where relaying – via wireless terminals that have a good communication link to the base station – is used as a coverage enhancement technique. Provided that the subscriber density is not very low, relaying via wireless terminals can have a significant impact on coverage, capacity, and throughput. This is mainly due to the fact that the signals only have to travel through shorter distances and/or improved line-of-sight paths. In this work, we investigated the effects of various relaying node selection (essentially a routing issue) and relaying channel selection schemes, as well as the effects of transmit power control, on system performance (these three selection/control schemes constitute the three major radio resource management decisions in peer-to-peer relaying in cellular networks). Our results show that with some modest intelligence incorporated in the relaying node selection scheme, the system coverage can be improved significantly through two-hop relaying. Furthermore, this improvement is observed to be fairly insensitive to the relaying channel selection scheme used, which is a plus in implementation. It is also observed that, as long as the number of wireless terminals in a cell is not very low, a minimal relaying node power level is sufficient to obtain most of the coverage enhancements.**

***Index Terms* — Cellular multihop networks, relaying, cellular ad hoc networks, opportunity-driven multiple access, mesh networks, ubiquitous coverage, location techniques.**

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I. INTRODUCTION

Peer-to-peer relaying technology originates in packet radio networks in tactical communications [1]. At present, this type of network has evolved into ad hoc networks where the main purpose is to provide an on-demand communication medium among wireless nodes[2] belonging to some organization (such as dispatch/emergency/conference service, law enforcement, etc.) without relying on an existing infrastructure or service provider [2]. This is achieved by relaying the signals through one or more intermediate node(s), depending on the distance separation between the source and the destination node [1],[2].

In a cellular radio system, the conventional form of relaying is facilitated via repeaters, which are used to extend the coverage to dead spot regions such as convention centers, tunnels, and freeways [3]. This form of relaying is carried out in analog format, whereby the multiplexed signals received on the so-called "donor antenna" are amplified and sent to the "distribution antenna", from which they are forwarded to the area to be covered. The forwarding is done "blindly" and without any signal processing; hence, as the signal is amplified, so is the noise.

Relaying can be performed in digital format as well, in which case the received signals are first demodulated and detected, and thus cleaned from noise and interference (as much as possible), and then re-encoded and re-modulated before forwarding; this process is sometimes referred to as "decode-and-forward relaying" [4],[5] or "regenerative relaying" [6]. Thus, when digital form of relaying is employed, there is no noise propagation from one hop to the next; however there is a danger of detection error propagation [4],[5]. It should be borne in mind that for delay sensitive traffic, such as voice, the digital form of relaying may not be suitable due to the incurred delay. Meanwhile, other traffic types, which are less sensitive to delay and which require large bandwidth to accommodate high data rates, would require

[2] In this paper, the terms "node", "wireless terminal", and "subscriber", are used interchangeably.

the digital form of relaying in order to prevent the noise propagation and thus to minimize the error rate. We consider only digital relaying in this paper. Although this form of “intelligent” relaying has not been previously deployed in cellular networks, the interest is growing in both academia and industry [7]-[11].

In conventional cellular networks, radio resource management deals mainly with the following three assignment problems: base station assignment, channel assignment, and transmit power assignment. In view of this, our objective is to investigate the sensitivity of relaying systems to relaying node selection (routing), relaying channel selection, and relaying node power level selection and control.

Routing is very crucial and challenging in ad hoc networks. Routing protocols must be power-aware, robust, and resilient to changes in the network topology; and these protocols should achieve all of these goals without excessive overhead. Routing in cellular multi-hop networks, on the other hand, is likely to be much more manageable, mainly due to the presence of a central node (which is the common source in the downlink and the common destination in the uplink) with much more functionality and intelligence, namely, the base station. Nevertheless, routing (relaying node selection) is still a non-trivial issue in cellular multi-hop networks since there will often be many candidate relaying nodes for a node that requires relaying assistance and not choosing the optimal relaying node can have potential impacts on the overall network performance. In this paper we only consider the downlink in two-hop cellular networks.

Whenever relaying is performed, an additional channel (which is referred to as the “relaying channel” in this paper) will be required for the second hop in order to avoid self-interference at the relaying terminal. One strategy would be to reserve channels exclusively for relaying purposes. This is a conservative approach since each two-hop link will cost (in radio resources) the equivalent of two users to the system provider, which is obviously not desirable, especially in busy systems. If no channels are reserved for relaying, on the other hand, the system can search for a vacant channel whenever there is need for relaying, and relaying is performed only when such a vacant channel is available. One may develop other such strategies as well. In this paper we adopt an aggressive strategy: relaying is performed by always employing the already used channels in that cluster. This strategy will be desirable (if it works) since the terminals with poor links will be served without consuming any extra radio resources (excluding the control overhead). But the channel reuse pattern (in a fixed channel assignment scheme) will clearly be violated when this strategy is employed, and therefore there exists the danger of creating excessive co-channel interference. If that happens, one or more other terminals in the same co-channel set may be adversely affected. Now, if those affected terminals also initiate relaying processes for themselves in some other co-channel sets, they may as well bring down some further other users. This may lead to a chain reaction which may cause instability and may eventually bring down the entire system!

We considered the downlink of a loaded cellular TDMA system with the above described aggressive channel reuse scheme for the second hop (from relaying node to the node that requires relaying assistance). We investigated two types of systems, noise-limited and interference-limited types, which correspond to cell sizes 2 km and 400 m (square layout), respectively.

Various relaying node and relaying channel selection schemes, with and without power control, are considered. In all relaying channel selection schemes, the selection is performed among the channels already used in the adjacent cells within the same cluster. With this strategy, no channel is used twice in the same cell, but some channels are used more than once in the same cluster (and in the limiting case a particular channel can be used in all cells).

Mobility is not considered in this paper.

II. RELAYING NODE AND RELAYING CHANNEL SELECTION SCHEMES

We present various relaying node selection schemes based on three routing metrics in increasing order of complexity: random, distance-based, and pathloss-based. We also present two relaying channel selection schemes. In our modeling, first the relaying node selection is performed for each node that requires relaying assistance, and the relaying channel selection process then follows (i.e., the two selection processes are sequential).

Choosing a relaying node solely based on the physical distance will not be as effective as choosing one based on the pathloss (because of the shadowing effects); however, location-based relaying node selection schemes are attractive as they can be carried out quite simply with the aid of location techniques. Due to U.S. Federal Communications Commission's (FCC) E911 mandatory requirements, all upcoming cellular systems will have the capability of locating the wireless terminals [12]. FCC requires an accuracy of 50 meters in 67% of calls and 150 meters in 95% of calls and it is expected that the future systems will operate with even a better accuracy. For instance, it is stated in [13] that the assisted GPS method, one of the three location techniques specified for 3G UTRAN (Universal Terrestrial Radio Access Network), can achieve an accuracy of under 20 meters in 67% of calls.

With the location information, relaying node selection can be carried out simply and quickly by the base station for the node that requires relaying assistance. In fact, location-based routing has already been proposed for ad hoc networks in order to reduce the routing overhead and to maintain a small routing table at the mobile nodes [14]-[16]. In cellular multi-hop networks, the presence of the base station will simplify the implementation of the location-based routing schemes.

In the simulations which employ location-based relaying node selection, we assumed perfect location knowledge. It has to be noted that although an accuracy of 50 meters may be sufficient for the proper implementation of the location-based relaying node selection schemes in the noise-limited 2x2 km cells, such an accuracy, or that of even 20 meters, is likely to be insufficient in the interference-limited 400x400 meter cells. Therefore, our results for the location-based relaying node selection schemes are optimistic.

In this paper, the small-scale multi-path fading effects are excluded during the relaying node and channel selection processes since it would be impractical to perform inter-relaying node and inter-relaying channel hand-offs based on multi-path conditions. However, after the relaying node and channel are selected, the effects of multi-path fading are included in the coverage simulations.

A. Relaying Node Selection

A.1 Selection Based on Physical Distance

In the following, we investigate three relaying node selection schemes in a two-hop relaying network: the first is a scheme that makes the selection based on the shortest overall path; the second is based on the path with the least longest hop out of all the candidate paths; and the third is based on the shortest relaying hop (i.e., second hop which is peer-to-peer) among the candidate relaying nodes.

Let N denote the set of candidate relaying nodes defined as the nodes which have an adequate link to the base station in a two-hop relaying network (see (11) for the definition of adequate link). Let d_{n1} and d_{n2} be the distances associated with the first (between the base station to the candidate relaying node) and the second (between the candidate relaying node to the relayed node) hop, respectively, along the n^{th} route, where $n \in N$.

Then, the selected route, r_s, is determined as follows in each selection scheme:

- Shortest Total Distance Selection:

$$r_s = \arg \min_{all\ n \in N} (d_{n1} + d_{n2}) \tag{1}$$

- Least Longest Hop Selection:

$$r_s = \arg \min_{all\ n \in N} (\max(d_{n1}, d_{n2})) \tag{2}$$

• Shortest Relaying Hop Distance Selection:

$$r_s = \arg \min_{all\ n \in N} (d_{n2}) \tag{3}$$

A.2 Selection Based on Pathloss

As discussed earlier, although it is expected that a relaying node selection based on pathloss will be superior to the one based solely on distance, the pathloss based selection will incur higher signaling overhead (mainly due the pathloss estimation techniques which are not considered in this paper); this disadvantage must be weighted against the additional performance return.

In the following, we investigate three relaying node selection schemes in a two-hop relaying network: the first is a scheme that makes the selection based on the least pathloss in the two combined hops; the second is based on a route that has the lowest bottleneck (in terms of pathloss); and the third is based on the least pathloss in only the second hop (which we call the relaying hop).

Similar to the notations used in the previous section, let PL_{n1} and PL_{n2} denote the pathlosses in dB associated with the first and the second hop, respectively, along the n^{th} route, where $n \in N$. Then, the selected route, r_s, is determined as follows in each selection scheme:

• Minimum Total Pathloss Selection:

$$r_s = \arg \min_{all\ n \in N} (PL_{n1} + PL_{n2}) \tag{4}$$

• Least Maximum Pathloss Selection:

$$r_s = \arg \min_{all\ n \in N} (\max(PL_{n1}, PL_{n2})) \tag{5}$$

• Minimum Relaying Hop Pathloss Selection:

$$r_s = \arg \min_{all\ n \in N} \{PL_{n2}\} \tag{6}$$

Fig. 1 illustrates a cell with a base station, a relayed node, and three candidate relaying nodes. Associated with each candidate relaying node, there is a candidate path (route), marked as I, II, and III in Fig. 1. Path I, corresponds to the minimum relaying hop pathloss selection, path II corresponds to the minimum total pathloss selection, and path III corresponds to the least maximum pathloss selection scheme.

There will be as many candidate paths (routes) as the number of nodes that have a good link with the base station (i.e., candidate relaying nodes). In practice, however, each node that requires relaying assistance should limit its candidate relay nodes set to only a few in order to minimize the routing overhead.

A.3 Random Selection

Finally, random selection is considered for comparison purposes:

- Random Selection:

$$r_s = \underset{all\ n \in N}{\mathrm{rand}}(n) \tag{7}$$

B. Channel Selection

The multiple access scheme considered here is TDMA where a channel is uniquely identified by a timeslot and a frequency carrier. Given that the bandwidth is scarce, our model assumes no reserved channels for relaying purposes. Hence, when a channel is needed for relaying, it is selected among the already used channels in the adjacent cells. By doing so we run a risk of creating too much interference that could lead to service interruptions at some already active links. To minimize this risk, power control may be necessary. In the following, two relaying channel selection schemes are presented.

Let γ_i^c be the signal-to-interference ratio (SIR) experienced 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 will also use channel *c* for relaying purposes (i.e., B_c is the augmented co-channel set for channel *c*). Then,

$$\gamma_i^c = \frac{G_{ji} P_j^c}{\sum_{k \in B_c, k \neq j} G_{ki} P_k^c}, \tag{8}$$

where G_{ji} is the pathloss between the relayed node *i* and the relaying node *j*, and P_j^c is the transmitted power of the relaying node *j*. Similarly, G_{ki} is the pathloss between the relayed node *i* and a co-channel base station *k* whose channel is being probed for reuse, and P_k^c is the corresponding base station transmit power. Also, let *L* denote the set of all channels in the adjacent cells (within the cluster of the subscriber which needs relaying assistance). Then, a channel, l_s, is selected as follows:

- Maximum SIR Selection (first scheme):

$$l_s = \arg \max_{all\ c \in L} (\gamma_i^c), \tag{9}$$

- Random Selection (second scheme):

$$l_s = \underset{all\ c \in L}{\text{rand}}(c) \tag{10}$$

Two remarks have to be made for the maximum SIR selection scheme (9). First, although the relaying channel selection is performed based on SIR, the outage is determined taking the thermal noise into account as well, i.e., outage is calculated according to SINR (signal-to-interference-plus-noise ratio) as described in the next section (refer to (11)). Second, it should be noted that the relaying node selection based on SIR (or, for that matter, based on SINR) experienced only at the relayed node is suboptimal, since such a selection is not taking into account the impact of the additional reuse of a channel on the other nodes in the same co-channel set. However, any further SIR checks in the co-channel set are intentionally avoided to prevent excessive control signaling.

Fig. 2 shows a basic configuration of the 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, and $c_{i,j}$ represents the j^{th} channel conventionally used in cell i. The 4-cell cluster and the relay path are drawn in bold. Similar to Fig. 1, the base stations are represented by triangles, and the relaying nodes and the relayed nodes by towers. The numbers attached to the base stations identify the sets of co-channel cells prior to the incorporation of relaying. With relaying incorporated, the cell in which the relayed node is located becomes a co-channel cell as well to the adjacent cell whose channel is selected to be reused for relaying purposes. Once a channel from an adjacent cell is selected for reuse in a certain cell, it is tagged, i.e., another relaying node within that same cell cannot select this channel to reuse once again (however, another relaying node in another cell in the same cluster can select that channel for relaying).

III. SIMULATION MODEL

We consider the downlink of a TDMA urban cellular network where two-hop relaying is used whenever there does not exist a sufficiently good direct link between a base station and a wireless terminal.

Our propagation model consists of distance-dependent attenuation with a propagation exponent of 4, lognormal shadowing (standard deviation 10 dB), and flat Rayleigh fading. The same pathloss model is used between a base station and a wireless terminal, and between one wireless terminal and another. The simulation area consists of 6x6 square cells with wrap around edges. The cluster size is chosen to be 4. Two different cell sizes are considered, 400x400 meters and 2x2 km, to represent interference-limited and noise-limited environments. Omnidirectional antennas are used at both base stations and wireless terminals.

The carrier frequency is taken to be 2.5 GHz and the transmission bandwidth 2 MHz. The thermal noise is also considered at the receiver, with a noise figure of 8 dB. Due to the large bandwidth and noise figure assumptions, the digital form of relaying is used throughout. We considered only two-hop relaying with single-class traffic where every wireless terminal has the same SINR requirement of 10 dB.

Simulations are run both with and without transmit power control for comparison. Whenever power control is employed, a “snapshot” 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, whichever comes first.

The nodes within a cell are placed randomly according to a two-dimensional uniform distribution. The number of channels available in each cell is assumed to be equal to the number of (active) wireless terminals; that is, all the cells are assumed to be fully loaded before relaying, and therefore, a relaying channel has to be chosen among the already used channels in the adjacent cells. Each relaying 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.

The simulation process consists of the following steps:

1) Set the number of subscribers (nodes) per cell, S.
2) Place the subscribers randomly across the network while maintaining S subscribers per cell. Each subscriber is given service through the closest base station. Assign an independent lognormal shadowing component between each subscriber and its base station.
3) Determine whether each subscriber has a sufficiently good link with its base station or not. Towards that end, collect 100 SINR samples for each subscriber with each sample undergoing independent

Rayleigh fading (note that all of the 100 samples have the same lognormal shadowing component). Execute a snapshot power control (if this simulation corresponds to a case with power control) before recording each SINR sample. For a given subscriber, if 95% or more SINR samples turn out to be above the 10 dB threshold, i.e., if

$$\Pr[SINR \geq 10\ dB] \geq 95\%, \quad (11)$$

then classify that subscriber as one having a sufficiently good link with its base station (such a subscriber does not require relaying; indeed, it constitutes a candidate relaying node for those subscribers which need relaying assistance). Otherwise (i.e., if the complement of (11) is true), classify it as a subscriber that has a poor link and therefore that subscriber will require relaying assistance).

4) For all subscribers that require relaying assistance, choose a relaying node and a relaying channel according to the algorithms specified in Section II (note that the multi-path fading is not taken into account in both relaying node and relaying channel selection schemes).

5) With relaying incorporated, collect once again 100 SINR samples for each subscriber, incorporating independent Rayleigh fading in each sample (also, incorporating snapshot power control if this is a simulation with power control). For subscribers which are served by their base stations through a single-hop, use (11) to determine whether the links are sufficiently good; and for those subscribers whose signals are delivered in two-hops, use the following criterion:

$$\Pr[\{SINR_1\ \&\ SINR_2\} \geq 10\ dB] \geq 95\%. \quad (12)$$

In the above, subscripts 1 and 2 correspond to the first and second hops, respectively. In the SINR calculation, take into account the interference created as a result of relaying (an independent Rayleigh fading and a lognormal shadowing component are associated with all the interference links).

Record the number of subscribers that have good links, according to (11) or (12) as appropriate, only in the four cells that constitute the innermost cluster in the 9-cluster wrap around network.

6) Repeat steps 2)-5) for a total of 1000 times. The fraction of subscribers that have good links, out of the total number of 4 (number of cells in the innermost cluster) x *S* (number of subscribers per cell) x 1000 (number of runs) subscribers observed, yields the desired coverage value.
7) Go to step 1) and repeat steps 1)-6) for various *S* values.

IV. SIMULATION RESULTS

For the results shown below, the maximum base station transmit power used for any mobile node is 1 W (30 dBm). Figs. 3 and 5 show the results for the case with no power control, while the remaining figures 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 with power control for a 2x2 km cell where the relaying node maximum transmit power is a parameter that ranges from 100 mW up to 1 W. In this case the system coverage is low when relaying is not considered. With relaying the performance only improves gradually (i.e., at the highest subscriber density, 64, the system coverage improvement due to relaying increases from approximately 31% to 49% as the relay node maximum transmit power is increased from 100 mW to 1 W, respectively). This is the case of a noise-limited system where the performance only increases gradually with increasing relaying node maximum power.

On the other hand, Fig. 6 (where the cell size is reduced to 400x400 m) shows much greater improvements from relaying, and besides, these improvements are achieved with significantly lower maximum relaying node transmit power levels. For instance, at a subscriber density of 64 and a maximum relaying node transmit power of 20 mW, the system coverage due to relaying is increased to approximately 95%, which corresponds to a much more significant improvement from that of Fig. 4. It is important to note that for an interference-limited system as in the case of Fig. 6, the performance improvement starts to saturate rapidly at higher relaying node maximum transmit power levels. This can be observed in Fig. 6 where the curves for the 1 W and 2 W maximum relaying node transmit power cases practically overlap.

Fig. 7 compares the results for the different relaying node selection schemes based on the distance selection metric, corresponding to shortest total distance selection, shortest relaying hop distance selection, and least longest hop selection schemes. The shortest relaying hop distance selection scheme offers the best performance improvement, with a coverage increase from approximately 70% without relaying to 90% with relaying, at a subscriber density of 64 and a maximum relaying node transmit power of 20 mW. Using this selection metric, it can be observed that further improvement can still be obtained with increased maximum relaying node transmit power levels.

Fig. 8 compares the results for the different relaying node selection schemes based on the pathloss (corresponding to minimum total pathloss selection, minimum relaying hop pathloss selection and least maximum pathloss selection), as well as based on random selection. As expected, if we compare the results of Fig. 8 to Fig. 7, for the same the selection algorithm, those based on the pathloss show superior performance to those based on the distance. Fig. 8 also shows that choosing a relaying node on a random basis (without any intelligence incorporated) offers almost no improvement (i.e., the maximum achievable coverage is 72% with relaying irrespective of the subscriber density). On the other hand, with some intelligence incorporated (as in the former three cases) the system coverage increases from moderately to strikingly (i.e., coverage ranging from 79% for minimum total pathloss selection, to 95% for least maximum pathloss selection, to 97% for minimum relaying hop pathloss selection, at a subscriber density of 64 and the maximum relay node transmit power of 20 mW).

Moreover, from Fig. 8 we can observe that at a low maximum relaying node transmit power (20 mW) the minimum relaying hop pathloss selection scheme is slightly superior to the least maximum pathloss selection scheme (97% system coverage versus 95%); while, at a higher power (1 W) the reverse is true (approximately 98% versus 97%). The reason for this is that when there is a power constraint at the relaying node, the link between it and the node that is being relayed to dictates the quality of service at the relayed node, and since the latter scheme (least maximum pathloss selection) does not always choose the best link from among the relay hops, it is therefore inferior to the former.

Fig. 9 compares the results for the two channel selection schemes. Surprisingly, it seems that with a good relaying node selection scheme (least maximum pathloss selection as presented in Fig. 9), the system coverage improvement is rather insensitive to the channel selection schemes as can be witnessed by only a slight increase in performance improvement between the random selection and the maximum SIR selection scheme.

Fig. 10 compares the worst-case performance to the best-case performance. The worst-case performance occurs when both relaying node and relaying channel are selected randomly, and in the absence of power control. The best-case performance is obtained with the combination of maximum SIR selection and minimum relaying hop pathloss selection schemes, for a low relaying node maximum transmit power (20 mW), and with the combination of maximum SIR selection and least maximum pathloss selection schemes, for a higher relaying node maximum transmit power (1 W).

Finally, Fig. 11 offers a perspective on how the subscriber density impacts the range of maximum relaying node transmit power levels required to achieve a maximum attainable coverage improvement at that particular subscriber density. As can be observed, at a low subscriber density (below 16) we see that the cut off maximum relaying node transmit power is approximately 30 dBm (1 W) before the performance improvement starts to saturate; while, at the high subscriber density (above 32), the cut off is approximately 24.8 dBm (300 mW). What this reveals is that at a reasonably high subscriber density, the maximum achievable coverage improvement can be obtained at fairly low relaying node maximum transmit power levels.

Since the results in this paper are mainly based on simulations, below we provide a 95% confidence interval test for one particular set of simulations corresponding to the following scenario: 400x400 m cell size, power control, and no relaying. The results of this set of simulations yield the coverage statistics *C* given in Table 1 (which are already plotted in Fig. 5).

Subscriber Density	8	16	24	32	40	48	56	64
Cov.(*C*)	0.54	0.51844	0.51396	0.52375	0.51525	0.51656	0.51714	0.51656

Table 1. Coverage statistics for the no relaying case (Fig. 5, bottom curve).

Since a uniform distribution was assumed for the subscriber density within each cell, the coverage should also be uniform across all the subscriber densities in table 1 when there is no relaying. Thus, at each subscriber density (each is simulated using a different random number generator), the coverage statistic can be treated as an independent observation.

Let $\hat{C}$ denote the sample mean (or the point estimator) for all the above coverage statistics which can be computed as $\hat{C}$ =0.5202. Then, the estimated variance of $\hat{C}$ can be computed as follows:

$\hat{\sigma}^2(\hat{C}) = \frac{(0.54-0.5202)^2 + ... + (0.516563-0.5202)^2}{7\times 8} = 0.000009052$, where 8 and 7 in the denominator are the total number of observations and the degrees of freedom (*f*), respectively, as defined in [17]. The standard error of $\hat{C}$ =0.5202 is obtained from $\hat{\sigma}^2(\hat{C})$ by taking its square root (see [17] for the definition of standard error): $\text{s.e.}(\hat{C}) = \hat{\sigma}(\hat{C}) = 0.003$.

The 95% confidence interval for C is found from the following expression: $\hat{C} \pm (t_{0.05/2,7} \times \hat{\sigma}(\hat{C}))$, where $t_{0.025,7}$ can be obtained from Table A.5 in [17] as 2.36. Therefore, the 95% confidence interval for the coverage statistics given in Table 1 turns out to be $0.513 \leq C \leq 0.527$. In other words, with 95% confidence, the coverage without relaying (Fig. 5, bottom curve) lies between 51.3% and 52.7%.

V. DISCUSSIONS AND CONCLUSIONS

In this study we investigated whether there is a potential benefit from employing digital relaying in a fully loaded cellular system. Our results show that relaying can have a significant impact on the coverage. The degree of improvement depends on the density and maximum transmit power level of potential relaying nodes. In small cells (interference-limited system), the coverage improvement due to relaying is dramatic (Fig. 6). However, this dramatic increase is obtained only with the use of power control. Moreover, with power control, this performance improvement is obtained even without extra channels reserved for relaying purposes since the additional interference due to relaying is confined to within the vicinity of the relaying/relayed node pair and thus kept at a minimal level.

Furthermore, as expected the relaying node selection schemes based on the pathloss offer a superior performance to those based on the distance (Fig. 8 vs. Fig. 7). Although in both selection metrics, the same selection scheme produces a different performance result. For the pathloss-based selection schemes (Fig. 8), it is observed that in order to obtain a maximum achievable improvement, it is important to properly choose a relaying node selection scheme in accordance to the resource constraint at the relaying node (i.e., with a power constraint at the relaying node, choose the minimum relaying hop pathloss selection over the least maximum pathloss selection; otherwise choose the latter over the former).

Moreover, certain relaying node selection schemes are sensitive to the subscriber density, while others are not. For instance, from Fig. 8 the minimum total pathloss selection scheme offers only a slight increase in performance improvement, and the random selection scheme offers no increase at all, as the subscriber density increases.

As for the channel selection schemes, as long as some intelligence is incorporated in the relaying node selection scheme, the performance improvement is not greatly affected by the different selection schemes (Fig. 9). Hence, it is probably wise to put more effort into the relaying node selection and less into the channel selection, while not incurring too much overhead. For instance, a combination of shortest relay hop selection and maximum SIR channel selection offers a balanced trade-off between performance improvement and complexity overhead (Fig. 8).

The only case where we observe a performance degradation due to relaying is when both the relaying node and channel selection are carried out on a random basis and no power control is used (Fig. 10). This is so because in our model we assume the same air interface for both the base station link (first hop) and the relay link (second hop) – after all we are trying to integrate relaying seamlessly into an already existing cellular system – and as a consequence of being careless, excessive co-channel interference results. If a different air interface from the base station link is used for the relay link, however, the performance due to relaying cannot be worse than the case without relaying. In such a case, relaying can only enhance (regardless of the relaying node or channel selection schemes), but not degrade the coverage performance.

Finally, based on the results in Fig. 11 it can be concluded that the higher the subscriber density, the less transmit power it is required of the relaying mobile terminals since a reasonably good relaying node selection scheme can be applied in order to assign the best relaying/relayed node pair, which will in turn have a positive effect on the system coverage improvement.

It is envisioned that relaying in a cellular system not only can be a promising coverage enhancement technique, but it can also be used towards improving the system throughput by combining it with adaptive modulation techniques (i.e., to increase the data rate for an individual mobile node per given channel bandwidth). It has been observed that adaptive modulation techniques are most beneficial when used in a situation where the channel conditions are good the majority of the time [18]-[20]. Such a situation is expected in a relaying scenario and as such an adaptive modulation technique can be combined to offer a high link spectral efficiency without sacrificing the BER (Bit Error Rate) or considerable transmit power.

Nonetheless, there still remain open issues that require further investigations. These issues concern fixed- versus mobile-terminal-relay station, two-hop versus multi-hop relaying, and mobility and handoff management as nodes move in and out of cells. The advantages that fixed-relay station relaying have over mobile-terminal-relay station relaying is that it does not rely on or consume the resources of the subscriber terminals since the relay stations are usually owned by the provider, and furthermore in a highly mobile environment it is probably more manageable. However, when extended to multi-hop relaying, fixed-relay station relaying has a disadvantage in that it requires more stations to be added, which in turn incurs more costs and overheads. With mobile-terminal-relay station relaying, multi-hop relaying can be easily extended without incurring additional overheads. In fact, since mobile-terminal-relay station relaying is envisioned as an opportunity to increase the coverage whenever it arises, it and fixed-relay station relaying can exist in tandem.

Finally, for practical purposes, a system wide relay-capable cellular network is only 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 leads to a question of how long an average relay session should last before a handoff occurs as a result of the battery drain of the relaying mobile terminal. As such, there ought to be some type of compensation for the node whose resources are being consumed for the benefit of others.

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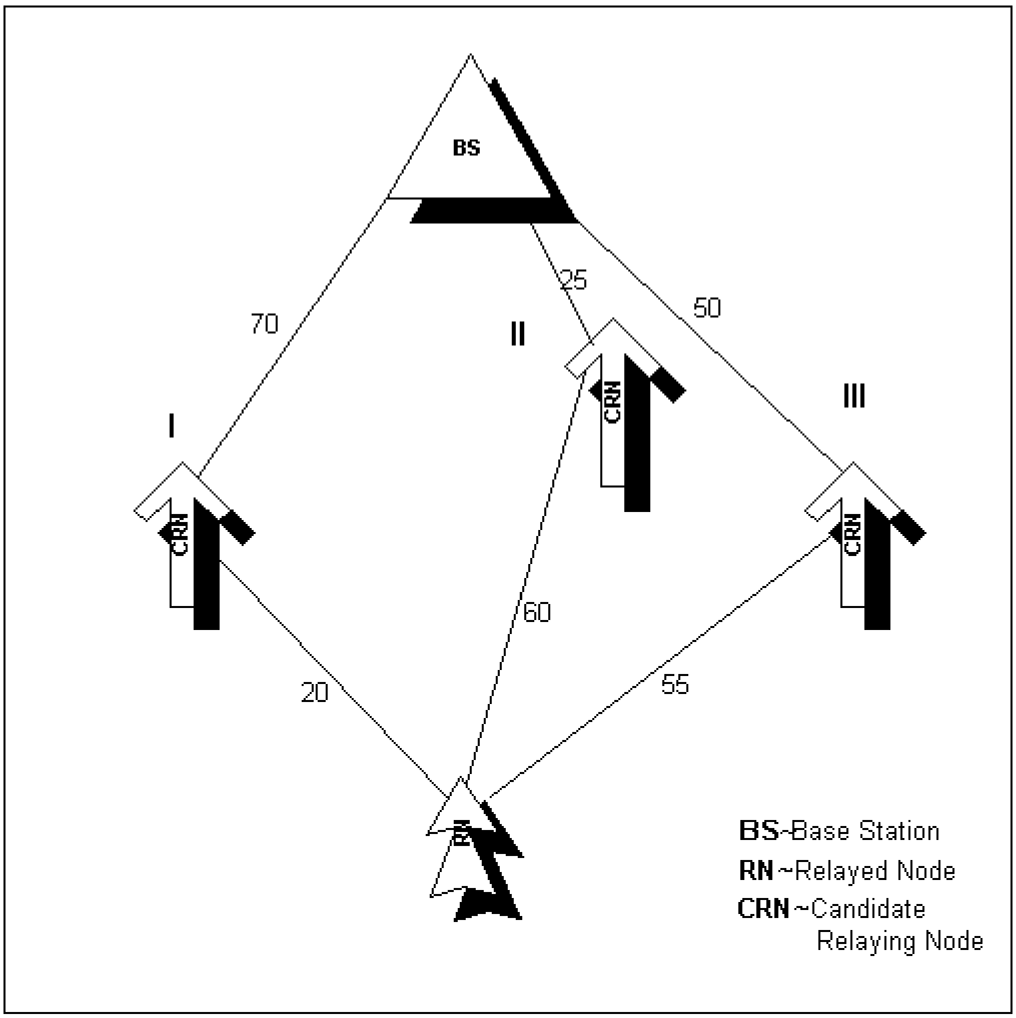

Fig. 1. Illustration of three possible routes based on three different relaying node selection schemes (the numbers attached to the edges indicate the pathlosses in dB).

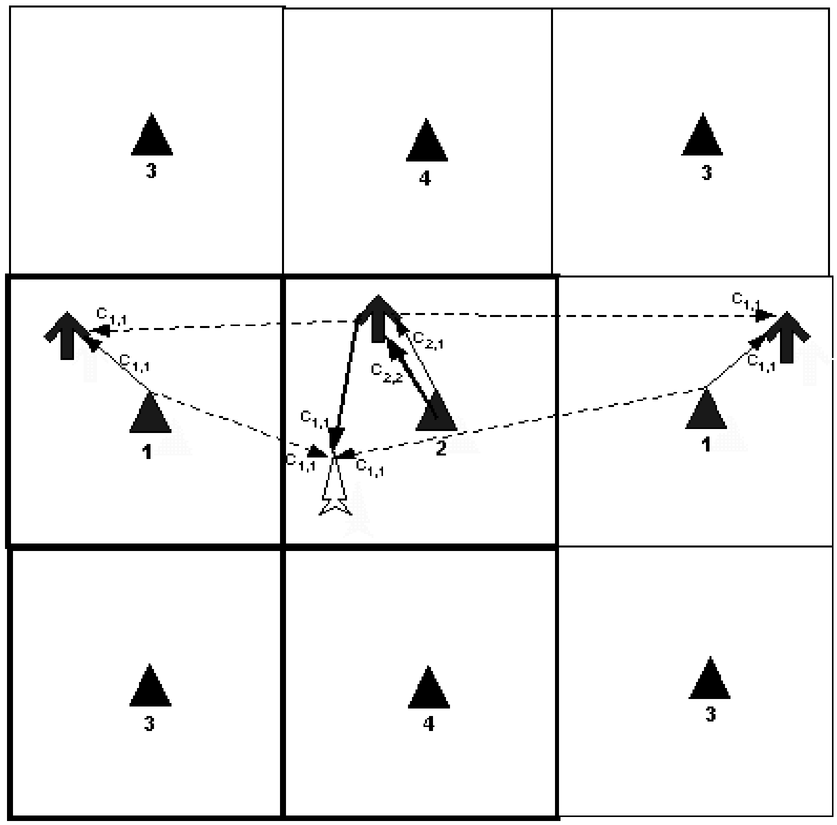

Fig. 2. Basic configuration of co-channel links when channels from an adjacent cell are probed for reuse for relaying in a 4-cell clustered system.

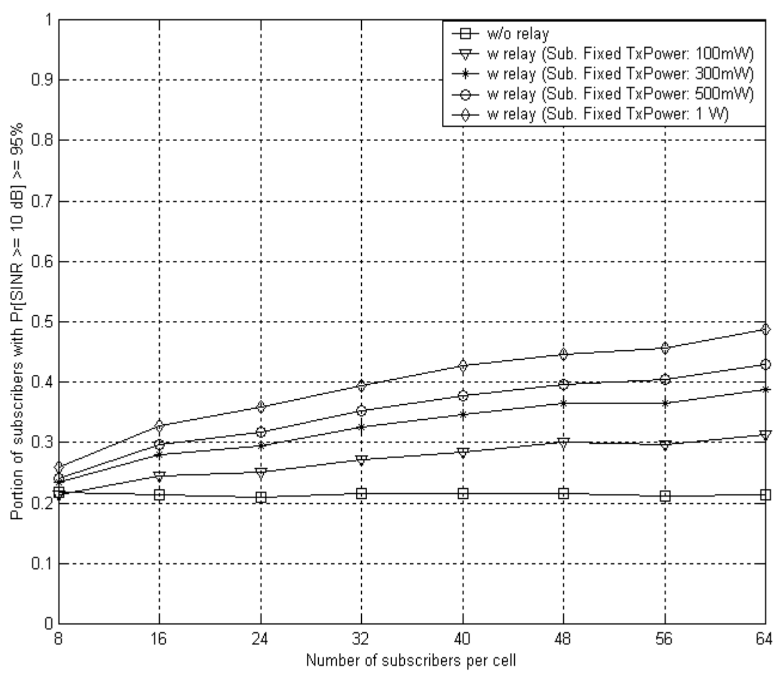

Fig. 3. User Coverage vs. Number of subscribers per cell (for 2x2 km cell size, No Power Control, least maximum pathloss selection, Maximum SIR Channel Selection Scheme).

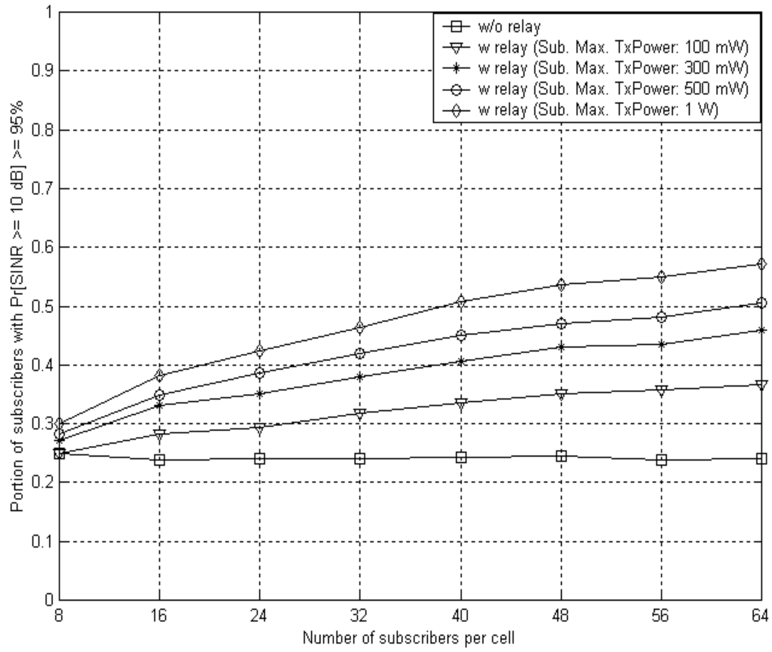

Fig. 4. User Coverage vs. Number of subscribers per cell (for 2x2 km cell size, Power Control, least maximum pathloss selection, Maximum SIR Channel Selection Scheme).

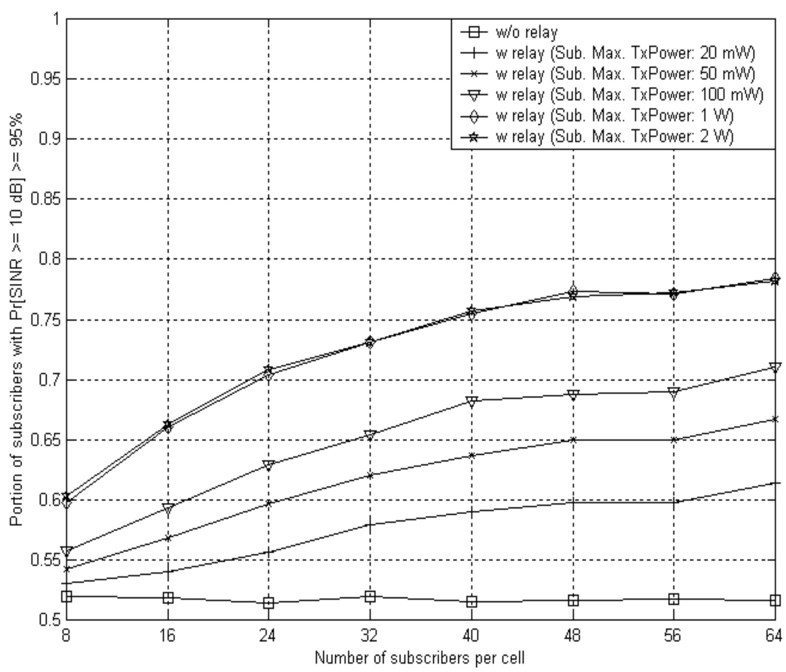

Fig. 5. User Coverage vs. Number of subscribers per cell (for 400x400 m cell size, No Power Control, least maximum pathloss selection, Maximum SIR Channel Selection Scheme).

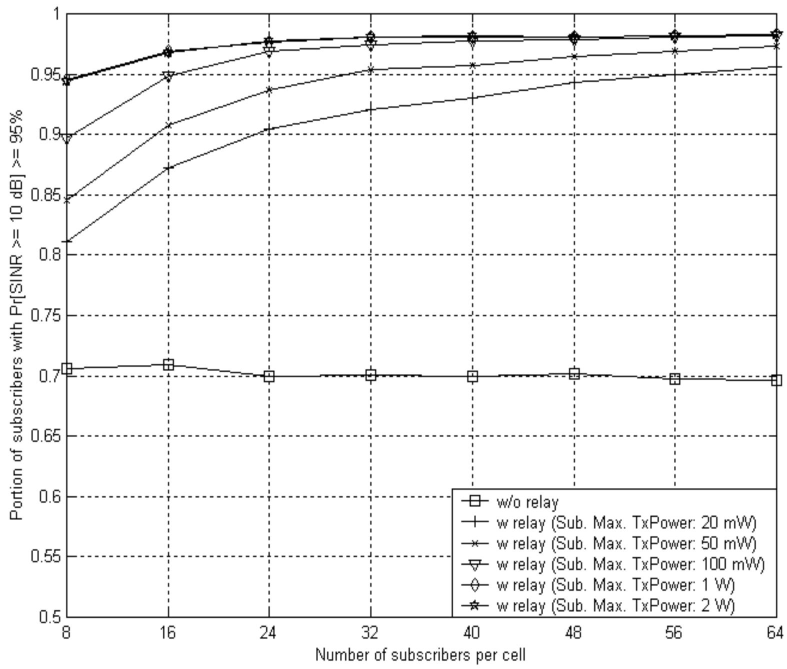

Fig. 6. User Coverage vs. Number of subscribers per cell (for 400x400 m cell size, Power Control, Least Maximum Pathloss Selection, Maximum SIR Channel Selection Scheme).

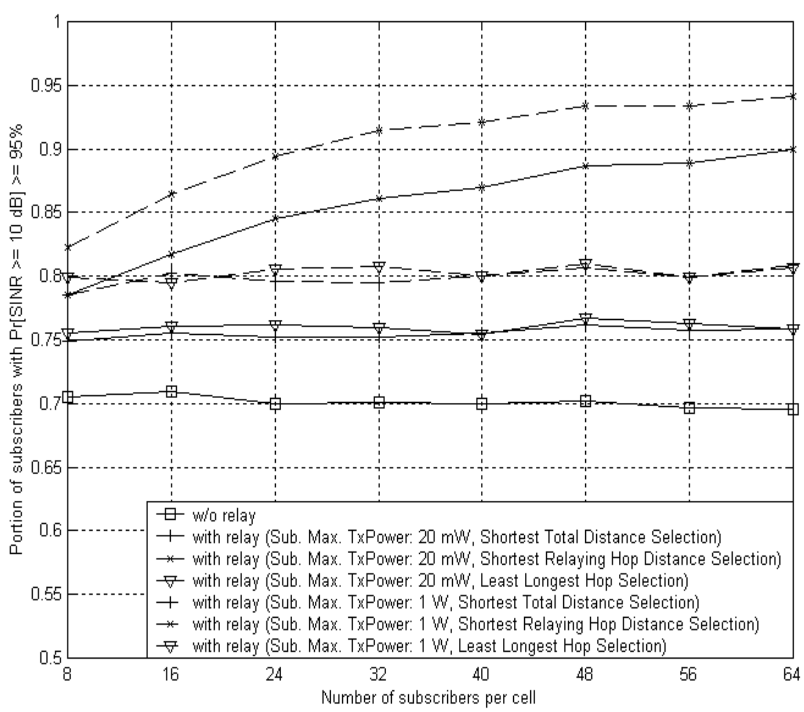

Fig. 7. User Coverage vs. Number of subscribers per cell (for 400x400 m cell size, Power Control, Distance-based Path Selection, Maximum SIR Channel Selection Scheme).

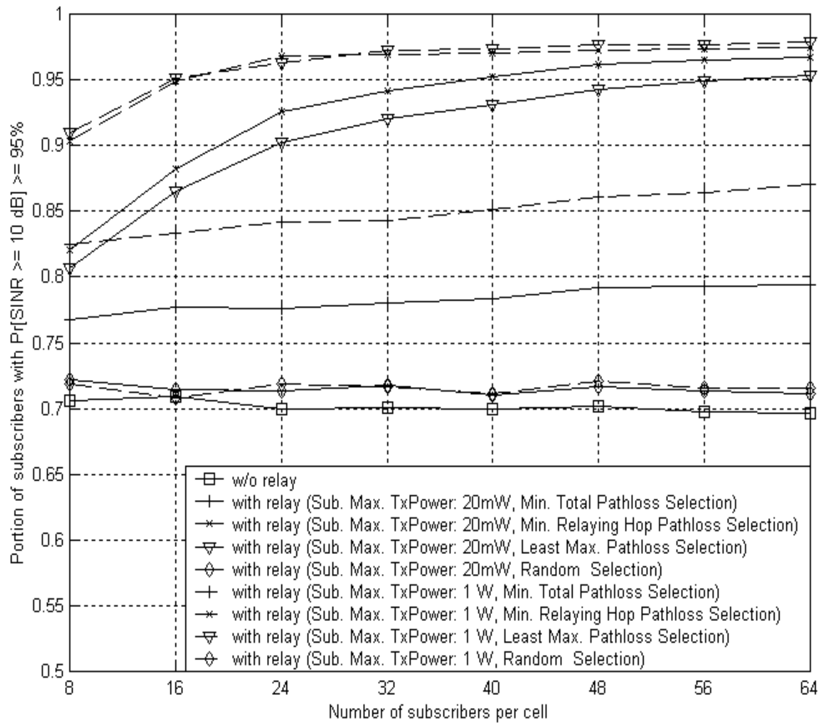

Fig. 8. User Coverage vs. Number of subscribers per cell (for 400x400 m cell size, Power Control, Pathloss-based Path Selection, Maximum SIR Channel Selection Scheme).

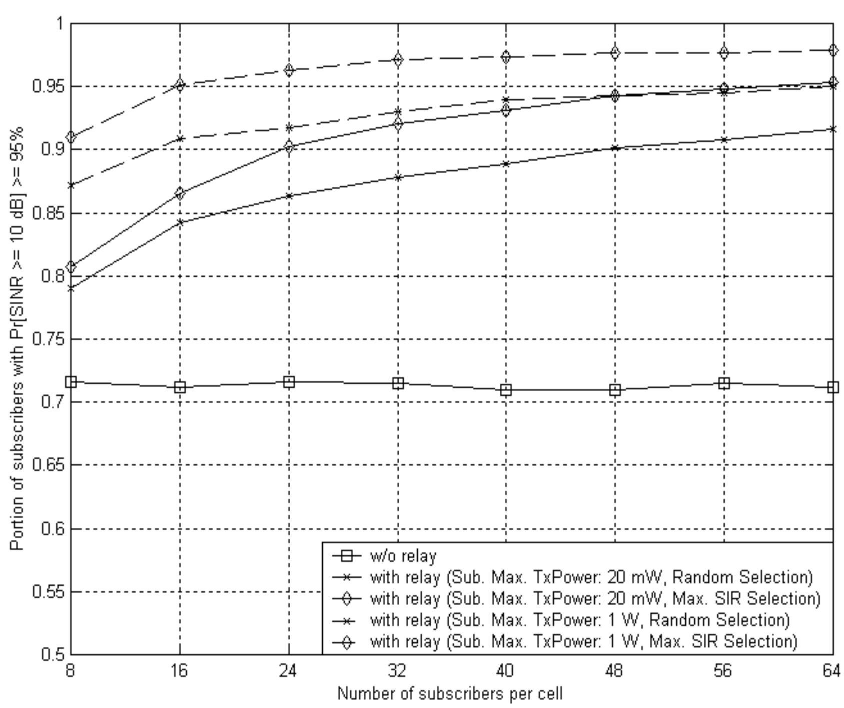

Fig. 9. User Coverage vs. Number of subscribers per cell (for 400x400 m cell size, Power Control, least maximum pathloss selection, Both Channel Selection Schemes).

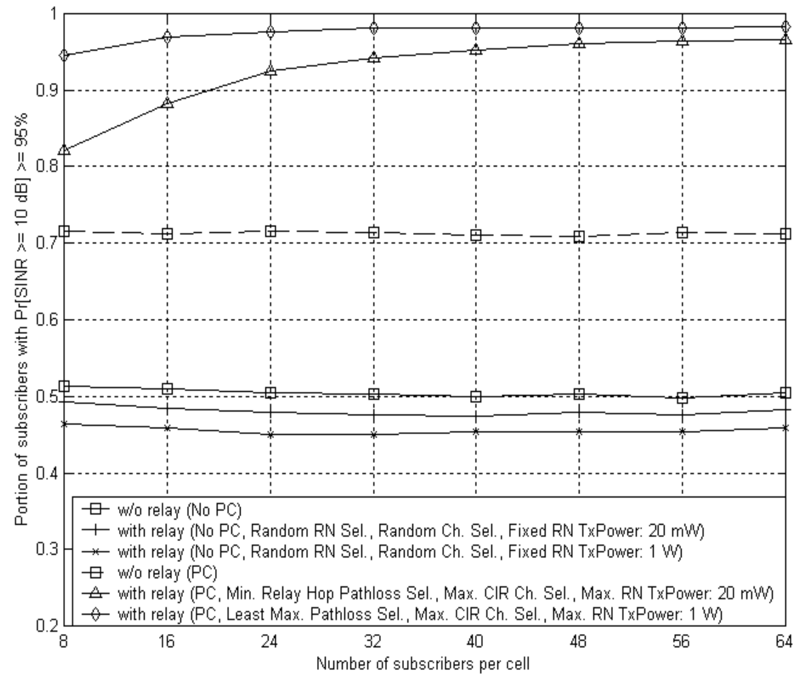

Fig. 10. Worst-case versus best-case performance (for 400x400 m cell size).

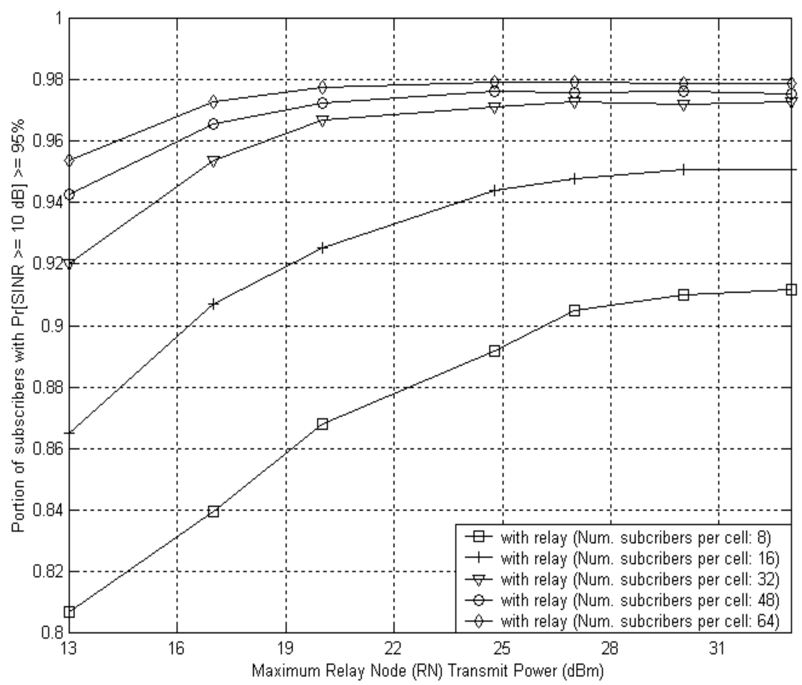

Fig. 11. User Coverage vs. Max. RN Transmit Power (Power Control, Least Maximum Pathloss Selection, Maximum SIR Channel Selection, 400x400 m cell size).