

Minimizing Co-Channel Interference in Wireless Relay Networks

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Abstract

The use of multi-hop relaying in cellular networks is considered a key technique for increasing data transmission rates and maximizing coverage in fourth generation (4G) wireless systems. With relaying, data destined for a mobile terminal will be relayed to a wireless relay station nearest the terminal rather than being transmitted from a more distant base station. Selection of the best relay route and relay station is essential in maximizing the data capacity and coverage of such a network. This paper presents an algorithm whose purpose is to find the best relay or set of relays from which to transmit considering two simultaneous goals: use the best propagation path from the relay to the intended data recipient (the target mobile), and minimize interference created in mobiles affected by the relay (victim mobiles). Many interference avoidance algorithms concentrate on reducing the transmit power to the minimum required to achieve a given minimum signal-to-noise ratio at the mobile. It is shown in this paper that consideration of both the target mobile's location, and locations of victim mobiles results in a lower probability of outage for all mobiles in the network.

I. INTRODUCTION

There has been increasing interest in multi-hop relaying concepts to increase the coverage and capacity of a cellular network (see [1], [2], [3] for example). In fact, the Institute of Electrical and Electronics Engineers (IEEE) approved a revised version of the 802.16 standard [4] in 2004, which included an option for fixed mesh topology support (mesh is their term for a relay network). In a relay network, there exist numerous relay stations (RSs) that will participate in delivering data from the network access point (AP) to the mobile terminal (MT). Each RS would normally cover a region (a subcell) with diameter 200-500 metres (compared to cell diameters of 2-5 kilometres in conventional cellular systems) [1]. This has two primary advantages: the radio propagation paths are shortened so the path loss is lowered, and the path essentially can be routed around obstacles to mitigate the effects of shadowing. It has been shown by these researchers that despite the additional radio spectrum requirement for the relay hops, there is an overall increase in network capacity.

At the outset, this paper considers the downlink of fixed relay stations (FRSs). Since there will be a large number of FRSs in a network, they must be inexpensive and simple in order for such a network to be economically feasible. The intelligence of the network would therefore reside in the AP, which would control traffic and numerous FRSs within a fairly large diameter (comparable perhaps to the diameter of a macrocell in a conventional system). The AP would be responsible for selecting the best FRS or FRSs for transmission to a given mobile, and the best relay-hop route (via FRSs) to the MT. Most research to date has considered the selection of only the single closest FRS (in terms of path loss to the target MT) for transmission. This paper is concerned with selecting the best single FRS or set of FRSs, and calculating transmit powers to minimize co-channel interference between FRS subcells. Advantages gained are: additional degrees of freedom in FRS selection, the possibility of using diversity or distributed multiple-input-multiple-output (MIMO) techniques, and additional reduction of shadowing by intervening structures.

The location of each mobile under control of a particular AP will be known by that AP, as will information concerning path loss from FRSs to mobiles. The algorithm proposed by this paper calculates optimal transmit powers (downlink) from FRSs considering both path loss information for the target mobile and the relative positions of potential victims of interference from the FRSs under consideration.

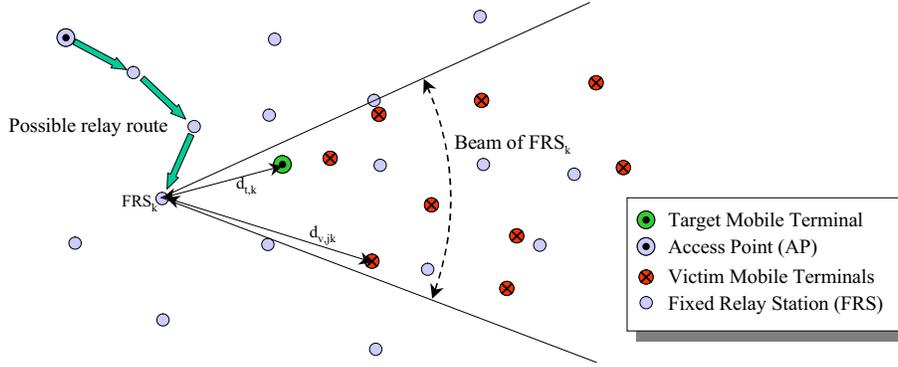


Fig. 1. Generic system model.

II. SYSTEM MODEL

Fig. 1 shows a generic system model, with numerous FRSs under control of a single AP as potential candidates for transmission to the target MT. There exists a transport route (thick green arrows) carrying data to the selected FRSs, and there are possible access paths from the FRSs to the target mobile (for clarity, only one such path is shown in the figure). The algorithms presented in this paper are primarily concerned with the access paths - selecting the most appropriate set of FRSs from which to transmit. Routing from the AP to the selected FRSs follows as a separate problem. Routing in relay networks has been investigated by many researchers.

The normalized path gain from each FRS_k to the target MT is

$$\gamma_{t,k} = \zeta_{t,k} d_{t,k}^{-\beta}, k = 1, 2, \dots, b \quad (1)$$

where $\zeta_{t,k}$ is a random variable modeling multipath fading, β is the path loss coefficient, $d_{t,k}$ is the distance from the target MT to FRS_k , and b is the number of FRSs considered as potential candidates.

With P_k as the transmit power from FRS_k , the total normalized power received at the MT is

$$P_r = \sum_{k=1}^b \gamma_{t,k} P_k \quad (2)$$

The receiver will require a minimum received power, P_{min} , to meet the bit error rate requirement. This results in the constraint

$$P_{min} = \sum_{k=1}^b \gamma_{t,k} P_k \quad (3)$$

Each FRS_k will cause interference I_k for a set of victim MTs, S_k . The victim MTs (in TDMA, those using the same time slot as the target mobile, or in CDMA, those using the same spreading code as the target mobile) in the set will be determined by the distance of the victims from FRS_k and the angle and direction of the antenna beam.

$$I_k = \sum_{j \in S_k} \gamma_{v,jk} P_k = P_k \sum_{j \in S_k} \gamma_{v,jk} \quad (4)$$

where

$$\gamma_{v,jk} = \zeta_{v,jk} d_{v,jk}^{-\beta}, k = 1, 2, \dots, b \quad (5)$$

is the path gain between victim mobile j and its interference source (FRS_k), $d_{v,jk}$ is the distance from FRS_k to victim mobile j , and $\zeta_{v,jk}$ is a random variable modeling shadow fading.

The total normalized interference caused by all FRSs is given by

$$I_{total} = \sum_{k=1}^b I_k = \sum_{k=1}^b \sum_{j \in S_k} \gamma_{v,jk} P_k \quad (6)$$

Solving for P_k in (4) and substituting into (3), we have

$$P_{min} = \sum_{k=1}^b I_k \frac{\gamma_{t,k}}{\sum_{j \in S_k} \gamma_{v,jk}} \quad (7)$$

$$= \sum_{k=1}^b I_k \frac{\gamma_{t,k}}{\gamma_{v,k}} \quad (8)$$

where

$$\gamma_{v,k} = \sum_{j \in S_k} \gamma_{v,jk} \quad (9)$$

Before describing the proposed algorithms, it is necessary to describe two algorithms which will serve as the benchmarks for comparison. The following two benchmark algorithms have been adapted from [5], since they were intended for a similar system, and are fair comparisons to the proposed algorithms.

A. Benchmark Algorithm: Single Antenna Selection (SAS)

A simple algorithm for determining transmit powers P_k , $k = 1, 2, \dots, b$ minimizes the total transmit power

$$P_{total} = \sum_{k=1}^b P_k \quad (10)$$

subject to constraint (3). This results in a linear programming problem, the solution to which simply selects the FRS that corresponds to the largest $\gamma_{t,k}$. For simplicity, and with no loss of generality, assume the $\gamma_{t,k}$ are ordered $\gamma_{t,1} > \gamma_{t,2} > \dots > \gamma_{t,b}$. The result then is $P_1 = P_{min}/\gamma_{t,1}$, and $P_k = 0$ for $2 \leq k \leq b$.

Another way of formulating this result is

$$P_k = \frac{\gamma_{t,k}^\alpha}{\sum_{l=1}^b \gamma_{t,l}^{\alpha+1}} P_{min}, \alpha \rightarrow \infty \quad (11)$$

By minimizing (10), this algorithm expects to minimize interference averaged over all possible co-channel MT distributions. For a particular MT distribution, however, the interference is not necessarily minimized.

B. Benchmark Algorithm: Generalized Power Control (GPC)

The above algorithm results in only one FRS transmitting at one time. However, it would be beneficial to allow more than one to transmit in order to take advantage of multiple antenna techniques. The author of [5] presented a simulcast system similar to that described herein, and proposed to improve upon the above algorithm by introducing an adaptation parameter $0 \leq \kappa \leq 1$ in the following manner

$$P_k = \left(\frac{\gamma_{t,k}^\alpha}{\sum_{l=1}^b \gamma_{t,l}^{\alpha+1}} \right)^\kappa P_{c1}, \alpha \rightarrow \infty \quad (12)$$

where P_{c1} is a scaling factor. In general, this results in $P_k \neq 0 \forall k$. It was found in [5] that $\kappa = 0.5$ gave the lowest probability of outage, and gave a 2 dB improvement in carrier to interference ratio (CIR) compared to the Single Antenna Selection algorithm.

C. Proposed Algorithm: Selective Transmit (ST)

The goal here is to choose the P_k values that minimize the total interference in (6) subject to the constraint (3). The solution selects the single FRS corresponding to the highest $\gamma_{t,k}/\gamma_{v,k}$ which can be expressed as

$$P_k = \frac{(\gamma_{t,k}/\gamma_{v,k})^\alpha}{\sum_{l=1}^b (\gamma_{t,l}/\gamma_{v,l})^{\alpha+1}} \frac{P_{min}}{\gamma_{v,k}}, \alpha \rightarrow \infty \quad (13)$$

By minimizing (6), this algorithm will perform better since it takes into account additional known information: the paths to co-channel MTs that are victims of interference from each FRS.

D. Proposed Algorithm: Simulcast (SC)

Once again, it is desirable to allow more than one FRS to transmit simultaneously, so the ST algorithm is modified to include an adaptation parameter $0 \leq \kappa$. The resulting solution is

$$P_k = \left(\frac{(\gamma_{t,k}/\gamma_{v,k})^\alpha}{\sum_{l=1}^b (\gamma_{t,l}/\gamma_{v,l})^{\alpha+1}} \right)^\kappa P_{c2} \quad (14)$$

where P_{c2} is a scaling constant. Again, the general solution has $P_k \neq 0 \forall k$.

The adaptation parameters κ and α have been investigated. The optimum results (lowest outage probability) are obtained when $\kappa = 1/\alpha$ with any $0.1 \leq \kappa \leq 1$. The outage probability becomes worse when $1 \leq \kappa$.

III. SIMULATION DESCRIPTION

To show the efficacy of the proposed algorithms via simulation, a system considering three potential FRSs ($b = 3$) was considered. Structuring the network with a regular FRS distribution results in the system shown in Fig. 2. $b = 3$ is a convenient number to use since it gives good diversity gain - increasing this number beyond three has decreasing return. It also results in a neat equilateral triangle subcell tessellation. (For Manhattan type layouts, $b = 4$ is useful, resulting in a square pattern.) For simplicity, only the closest sets of interference victims are shown in the figure. The three FRSs closest to the target mobile are considered as candidates for transmission to that mobile. FRSs use beam steering (or beam forming) and channels can be reused in each triangular cell. For this simulation, 60° sectoring has been assumed, as required to cover an equilateral triangular cell.

Numerous sets of random mobile locations have been generated and the four algorithms run on each set. The CIRs for each algorithm have been calculated and the results analyzed. To investigate different system loading, sets have been generated with different "mobile probabilities" (probability that a channel is in use by a victim MT in a subcell): 10%, 70%, 90%, 100%. Path loss coefficients (β s) used are 3.5, 4.0, 4.5, and 5.0.

Not included in the results are factors such as handoff gain, coding gain, and spread spectrum processing gain. It is expected that all algorithms tested will benefit similarly so the relative performance results are valid. All four algorithms simulated for the results presented here have been subjected to the same system model and parameters, and are thus compared on a fair basis.

IV. SIMULATION RESULTS

A useful quantity to analyze when modeling random phenomena in radio networks is the cumulative distribution function (cdf) of the carrier-to-interference ratio (CIR). The cdf value on the vertical axis gives the probability that the CIR falls below the value on the horizontal axis, so one can directly read the probability of outage for a given CIR requirement (the protection ratio).

Fig. 3 shows the cdfs for the two benchmark algorithms and the proposed algorithms with several mobile probabilities (i.e the probability that a mobile is using a channel in subcells outside of the target

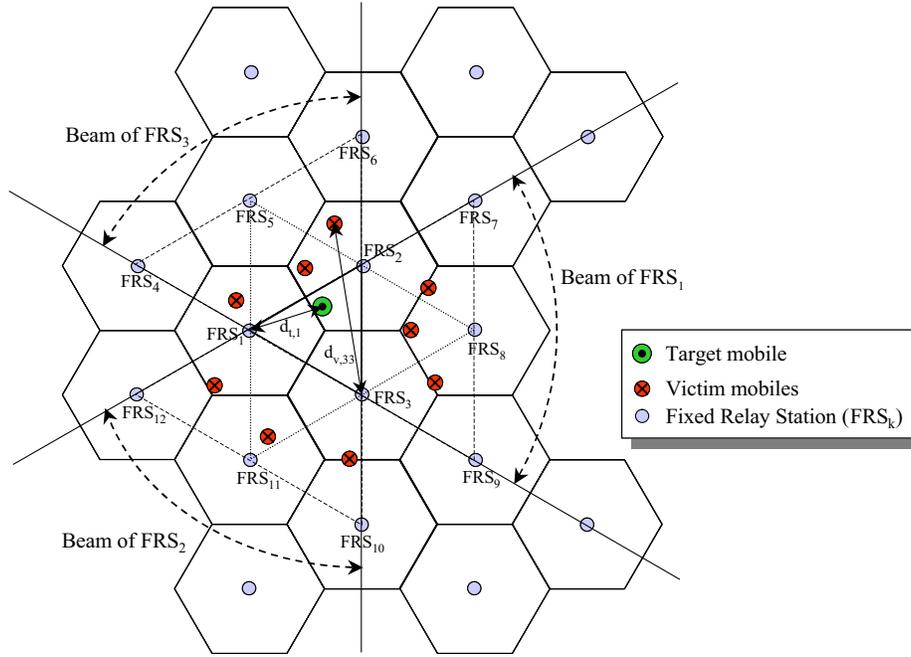


Fig. 2. Simulation system model - example with $b = 3$.

subcell), and a fixed path loss coefficient $\beta = 4.0$. As expected the SC algorithm out-performs the other ones under all circumstances, and both ST and SC algorithms show the best improvement when the mobile probability is low (i.e. a lightly loaded system). This is because both of these algorithms take advantage of unused channels by favouring selection of, or increasing the transmit power of, an FRS pointing in the direction of subcells with channels not in use.

Fig. 4 shows the cdfs for the algorithms, with dependency on β for a fixed mobile probability of 70%. Fig. 5 shows the probability of outage for the algorithms, for a CIR requirement (protection ratio) of 12 dB.

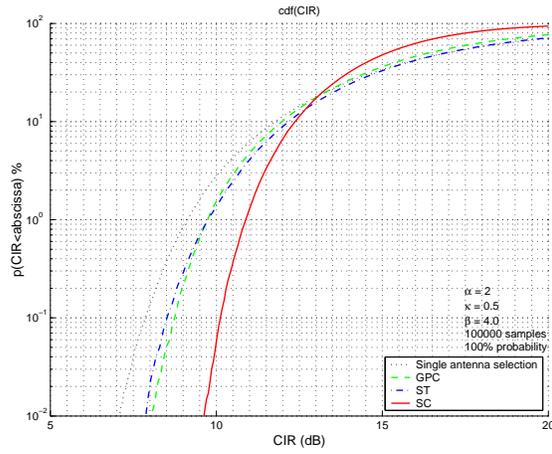
Table I shows the average CIRs (dB) for the simulation runs. Note that the average CIR was not necessarily increased with the proposed algorithms - in some cases it is slightly reduced. However, the improvement shows in the shape of the cdf of the CIR, which was drastically steepened below the average CIR. So for a given CIR requirement, the probability of outage is greatly reduced using the proposed algorithm.

V. DISCUSSION

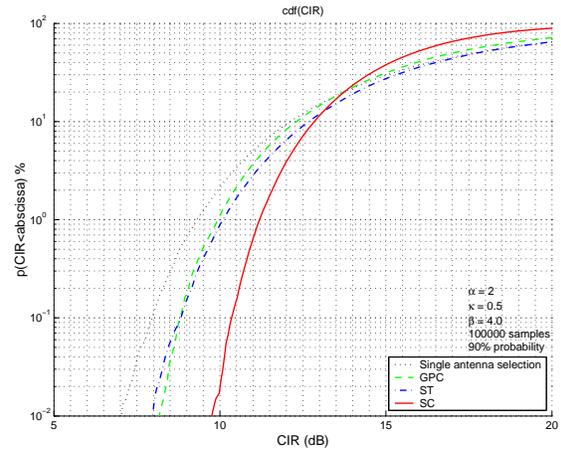
Algorithm Implementation

Estimation of the FRS to target MT channels is necessary for any algorithm. However, for the proposed algorithms, channels between FRSs and victim mobiles must also be considered. The number of estimated channels required will depend on the number of tiers of interference to be considered in the algorithm. With the triangular system example shown above, three FRS-to-target MT estimations are required, and nine FRS-to-victim MT estimations are required for first tier interference consideration. So it would appear that the channel estimation work is quadrupled (12 total estimations vs three).

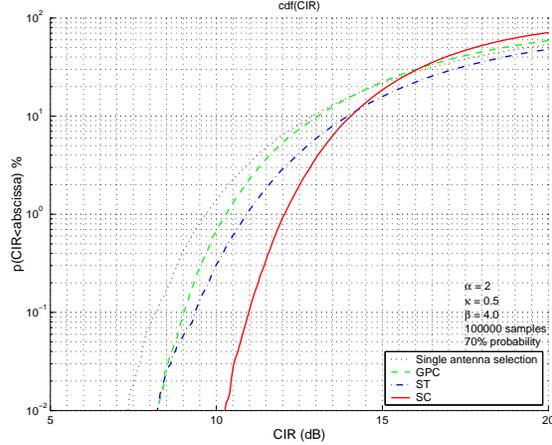
On the other hand, for determining hand-off between subcells, what is considered a FRS-to-victim MT path in one cell, is the same as a FRS-to-target MT path in another cell. So in fact much of the required channel information will already be available in the network, and the workload is really no different than that of any other algorithm. It is just a matter of sorting the known channel information appropriately.



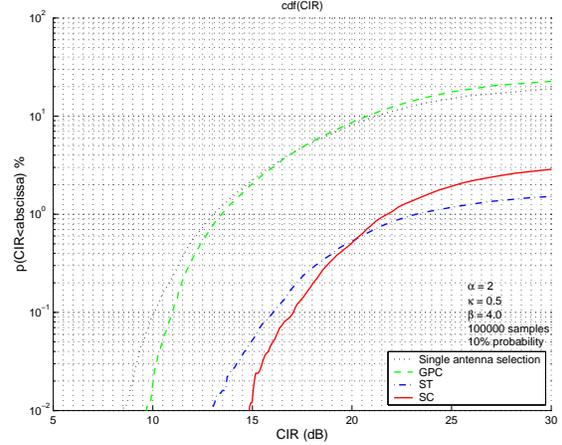
(a) Mobile channels occupied with 100% probability



(b) Mobile channels occupied with 90% probability



(c) Mobile channels occupied with 70% probability



(d) Mobile channels occupied with 10% probability

Fig. 3. Comparison of the four algorithms: path loss coefficient $\beta = 4.0$, various mobile probabilities.

		$\beta = 3.5$			
prob	SAS	GPC	ST	SC	
10%	23.1	23.0	35.1	34.6	
70%	14.7	14.6	15.6	14.8	
90%	13.6	13.5	14.0	13.1	
100%	13.2	13.1	13.3	12.5	

		$\beta = 4.0$			
prob	SAS	GPC	ST	SC	
10%	25.3	25.2	38.0	37.0	
70%	16.8	16.8	17.9	17.0	
90%	15.8	15.7	16.2	15.3	
100%	15.3	15.2	15.6	14.7	

		$\beta = 4.5$			
prob	SAS	GPC	ST	SC	
10%	27.3	27.3	40.3	39.3	
70%	18.9	18.8	20.1	19.2	
90%	17.9	17.8	18.4	17.5	
100%	17.4	17.3	17.7	16.9	

		$\beta = 5.0$			
prob	SAS	GPC	ST	SC	
10%	29.4	29.3	42.5	41.6	
70%	20.9	20.9	22.2	21.3	
90%	19.9	19.8	20.5	19.6	
100%	19.4	19.3	19.8	19.0	

TABLE I
AVERAGE CIR (DECIBELS) FOR THE ALGORITHMS.

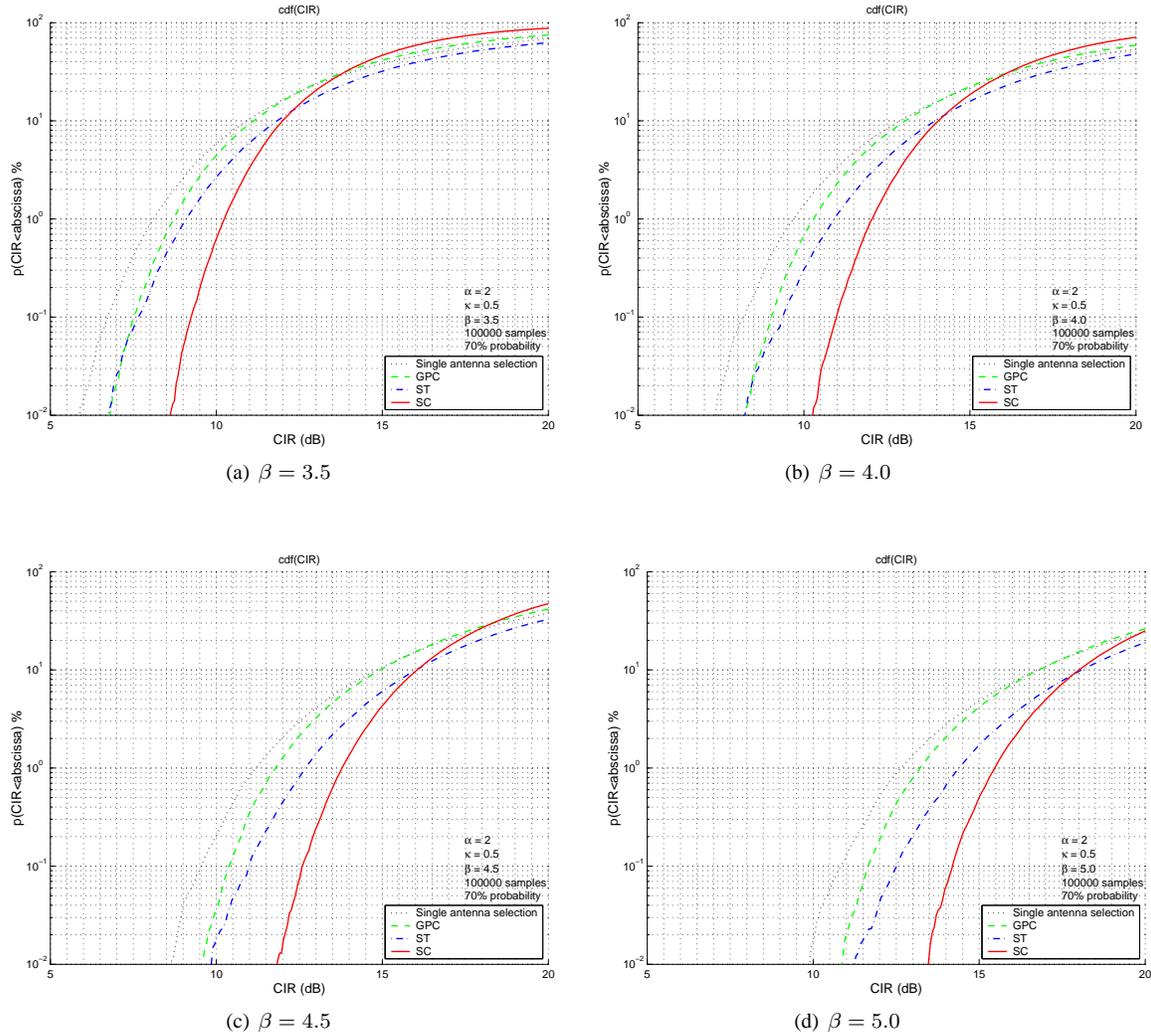


Fig. 4. Comparison of the four algorithms: 70% mobile probability, various path loss coefficients (β).

VI. CONTINUING WORK

MIMO Application

The results of this research can be applied to multiple antenna techniques. It has been shown (see [6] and [7] for example) that virtual antenna arrays (VAAs), which use distributed antennas as MIMO arrays, significantly increase the capacity of a network. However, in the authors' analyses, the optimal grouping of antennas in the array was assumed as known. Determining the optimal set of antennas to use is key in the operation of the VAA technique, and it is believed that the algorithms proposed in this paper address this problem. Continuing research will look at the capacity of networks combining our algorithms with VAA.

A promising avenue of research is combination of multiple-FRS selection in a relay network with beamforming. As discussed in [8] and [9], joint power control and optimal beamforming (JPCOB) can result in greatly increased network capacities. With MIMO beamforming and knowledge of locations of potential interference victims, the transmit beams can be directed toward the target mobile and away from victims. It is intended to apply the algorithms of this paper to these ideas in order to achieve greater

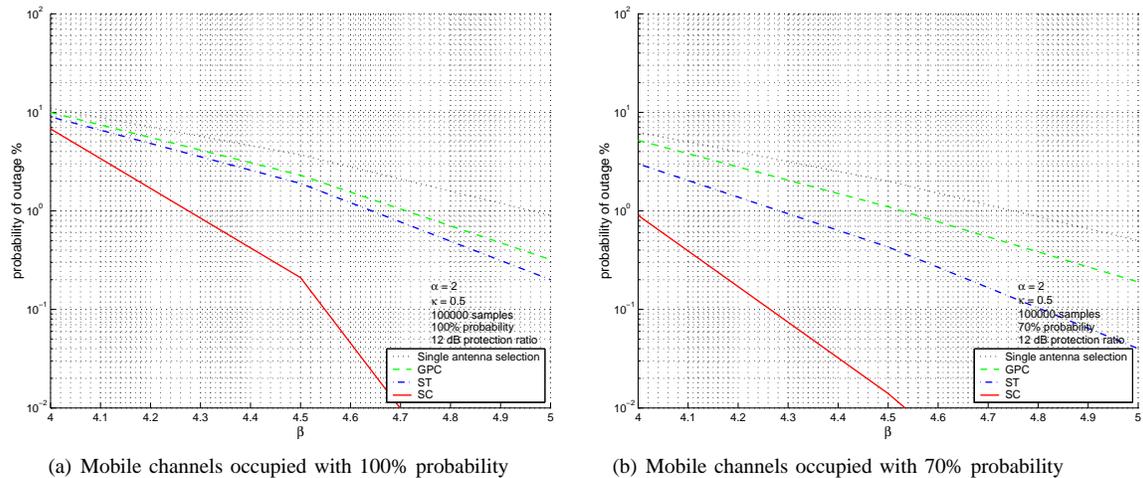


Fig. 5. Comparison of the four algorithms: probability of outage vs β for a CIR of 12 dB (protection ratio).

capacities.

VII. CONCLUSIONS

It has been shown that a significant improvement in the outage probability can be achieved in a multihop relay network by allocating downlink transmit powers considering the channels of target mobiles and potential victims of interference. A non-linear algorithm has been introduced that allows the determination of transmit powers from multiple relay sites, facilitating the use of multiple antenna techniques.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge funding for this work provided by the Natural Sciences and Engineering Research Council (NSERC) of Canada, TRILabs, Alberta Informatics Circle of Research Excellence (iCORE), and the Canadian Council of Professional Engineers (CCPE).

REFERENCES

- [1] R. Pabst *et al.*, "Relay-based deployment concepts for wireless and mobile broadband radio," *IEEE Commun. Mag.*, vol. 42, pp. 80–89, Sept. 2004.
- [2] J. Jun and M. Sichertiu, "The nominal capacity of wireless mesh networks," *IEEE Commun. Mag.*, vol. 41, pp. 8–14, Oct. 2003.
- [3] N. Esseling, B. Walke, and R. Pabst, *Fixed Relays For Next Generation Wireless Systems*. New York, USA: Springer Science & Business Media, Inc., 2005, ch. 5, pp. 71–91.
- [4] *Air Interface for Fixed Broadband Wireless Access Systems*, IEEE Std. 802.16-2004.
- [5] S. Zurbes, "Power control in simulcast digital cellular radio networks," in *Proc. PIMRC 1997*, vol. 3, Sept. 1997, pp. 887–891.
- [6] M. Dohler, J. Dominguez, and H. Aghvami, "Link capacity analysis for virtual antenna arrays," in *Proc. VTC 2002-Fall*, vol. 1, Sept. 2002, pp. 440–443.
- [7] M. Dohler, A. Gkelias, and H. Aghvami, "Throughput of distributed-MIMO multi-stage communication networks over non-ergodic channels," in *Proc. VTC 2004-Spring*, vol. 3, May 2004, pp. 1737–1741.
- [8] G. Pinero *et al.*, "Downlink power control and beamforming for a cooperative wireless system," in *Proc. PIMRC 2004*, vol. 2, Sept. 2004, pp. 974–978.
- [9] F. Rashid-Farrokhi, L. Tassiulas, and K. Liu, "Joint optimal power control and beamforming in wireless networks using antenna arrays," *IEEE Trans. Commun.*, vol. 46, pp. 1313–1324, Oct. 1998.