



Identifying the capacity gains of multihop cellular networks

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ABSTRACT

Claims for the advantages of applying multihop relay in CDMA cellular networks have been widely accepted in the literature. However, such claims have yet to be closely examined. In this paper, capacity increase in CDMA cellular networks through multihop relay is quantified. As CDMA networks are interference-limited, interference has to be analyzed to estimate the system capacity. Toward this end, we derive formulas to calculate interference experienced in multihop CDMA cellular networks by both base stations and mobile terminals. The formulas are generic and applicable whether or not power control is exercised between mobile terminals. The capacity of multihop CDMA cellular network is compared to that of single hop CDMA cellular network to verify the claimed advantage. We demonstrate that a 23% capacity increase is achieved when relaying with power control. We also extend the work to illustrate the effect of call distribution on the capacity of the cell and its neighbors – both in the single and multiple hop cases. Furthermore, we ascertain that call distribution inside a cell hardly affects the capacity of adjacent cells when using multihop relay. This specific advantage overcomes the inherent capacity degradation caused by near border calls, which is the biggest burden on the capacity of single hop CDMA cellular networks. To the best of our knowledge, this effort is the first of its kind in this area.

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1. Introduction

The adoption of a Wideband Code Division Multiple Access (WCDMA) system and its evolutions by the Third Generation Partnership Project (3GPP) responds to an ever increasing demand for multimedia applications and maintainable service during user mobility. However, WCDMA systems are inherently interference-limited, which means that their capacities are affected by usage, positions and mobility of the systems' users. Various proposals have been made to overcome this limitation including enhanced functionalities for Radio Resource Management (RRM) overseeing admission [1] or power control [2], and propos-

als for adaptive coverage responding to congestion and hotspot instances [3].

However, a solution that has recently been gaining prominent attention involves exploiting the advances made in the area of multihop wireless relay. Instead of Mobile Terminals (MTs) directly connecting through the access gateways, i.e. Base Stations (BSs), MTs are indirectly connected through other network elements. These elements can be either dedicated Relay Stations (RSs), mostly with fixed positions and substantial power supply, or other MTs offering their capabilities in term of transmission or processing powers. Relaying can be performed either in-band, i.e. direct and indirect access made using the same access technology, or out-of-band, in which case two or more access technologies are utilized. In all cases, the resulting hybrid architecture, called Multihop Cellular Networks (MCNs) [4], stands as a viable solution not only to enhance the capacity of 3G networks, but also to extend their coverage to deadspots, and increase their resilience

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to instances of congestion, failure or emergency. Fig. 1 schematizes the general advantages of MCNs over regular, i.e. single hop, cellular networks.

Much work has been devoted to investigating the different aspects of MCNs. Early proposals such as Qiao and Wu's iCar [5] and Lin and Hsu's MCN-b and MCN-p [6] outline the main architectures utilizing dedicated RSs for respectively, in-band and out-of-band MCNs. Architectures utilizing MTs for in-band relay includes Sawfat's A-Cell [7] and Yamao et al.'s Hop Station [8]. Other works attended to the operational requirements of MCNs. For example, Riyami et al. [9] and Tam et al. [10] investigate channel assignment and resource utilization schemes for in-band TDD-WCDMA systems with MTs. Tam et al. [11] also offered schemes for load balancing and congestion relief. In [12], Safwat builds on his A-Cell proposal offering an RRM framework comprising modules for call admission control, channel assignment and scheduling. Le and Hossain [4] offer a brief survey of MCNs and propose a resource allocation scheme with power and rate control components for out-of-band MT relay. Showing a further advantage of MCNs, Cho et al. [13] display enhancements in handoff management with the assistance of RSs. As user compensation is an essential element for MCNs, proposals such that of Lindstrom and Lungaro [14] have been sought to ensure simultaneously provider's profitability and user satisfaction. Finally, and towards the vision of All-IP wireless, Cavalcanti et al. [15] investigate the general issues relevant to implementing IP-based MCNs.

Despite the many studies, however, the claimed advantages of MCN have never been rigorously quantified. Such quantification is unavoidable if serious frameworks for RRM functionalities are to be realized. This is especially the case in CDMA systems where interference affects the capabilities of the network in a dominant manner. The objective of this work is hence to quantify, through rigorous analysis, the total interference experienced by BS and relaying MTs in multihop CDMA cellular networks. Specifically, our contributions in this work are as follows.

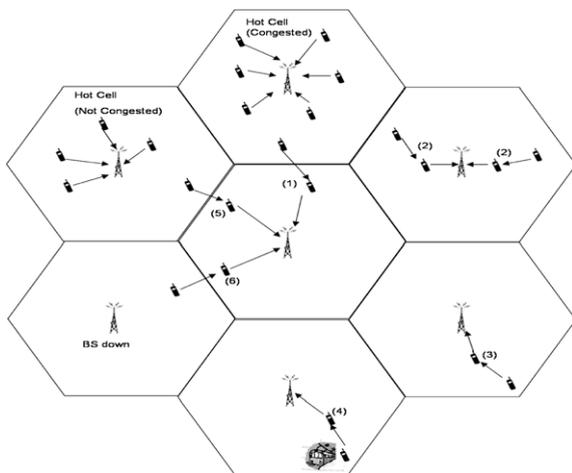


Fig. 1. Multihop relay to solve cellular networks drawback (1) Congestion, (2) Interference, (3) Higher data rate for distant MTs, (4) Dead spots, (5) Load balance and (6) BS failure.

First, we derive formulas for in-band multihop relay in CDMA networks that are generic in their application in the sense that: (a) they are not based on a specific underlying algorithm for channel assignment or scheduling; (b) they are applicable whether or not power control is exercised between the relaying MTs; and (c) they accommodate any user/nodal distribution. The second contribution is the offered computational framework for investigating the capacities of MCNs. While in this work we focus on in-band MT-based relay, the framework presented accommodates the use of either RSs or MTs, or both, and can be applied to environments with mixed access technologies. Third, we verify the claimed advantages of applying multihop relay in cellular networks and identify the operational instances where it is most needed. To the best of our knowledge, this work is the first of its kind in the area.

In this paper, we analyze and quantify the potential capacity increase associated with the use of multihop communication in CDMA cellular networks. Such capacity increase depends on the resulting interference. For this reason, we begin by analyzing the interference in multihop CDMA cellular networks and derive formulas to calculate interference at the BSs as well as at the relaying MTs. These formulas are used to estimate the network capacity. The capacity of MCN is then compared to that of single hop cellular networks. We show that using multihop relaying (in a generic, non-optimized setting) can achieve a 23% increase in capacity when using power control in all hops. We also show that a 10% increase is possible even with power control only applied in the last hop before the BS. The analysis is further extended to accommodate uniform and non-uniform call distributions. We show the effect of call distribution on the capacity of the network, and highlight scenarios where multihop communication is deeply needed and most rewarding, i.e. when the density of active terminals increases at cell borders.

The remainder of this paper is organized as follows. In Section 2, the models used in the analysis are introduced, including the network and propagation models. In Section 3, interference analysis is presented. General formulas to quantify interference are derived and then modified to represent different scenarios of transmission power and call distribution. Section 4 provides numerical results to illustrate the possible capacity increase and show the effect of call distribution. Section 5 concludes the paper.

2. The system models

2.1. The network model

We consider a CDMA cellular network with hexagonal cells, with each cell neighboring 6 other cells. Each cell is also virtually divided into k -concentric discs centered at the cell's BS. The discs have equal width and are numbered 0 to $k - 1$, with disc 0 being the innermost disc. At any given time, an MT is associated with only one of the discs based on the MT's distance from the BS. This distance can be estimated from the power of the received pilot signal at the MT. When multihop relay is used, only the MTs residing inside disc 0 are allowed to communicate directly

with BS in one hop. All other MTs, i.e. MTs within the cell but residing outside the innermost disc, must use multihop relay to communicate with the BS. MTs residing in disc n ($0 < n < k$) communicate with the BS by relaying their data through MTs in disc $n - 1$. This setup limits the number of hops to a maximum of k hops. An example of a cell with four discs is shown in Fig. 2, where two MTs are communicating with the BS through multihop relay. The special case when a cell has only 1 disc represents the single hop case.

In this paper, all MTs and BSs are assumed to use omnidirectional antennas. It is also assumed that MTs are dense enough that an MT in an arbitrary disc n can always find within its transmission range another MT in disc $n - 1$ to relay its data.

Utilizing a scheme for power control involves adjusting the transmission power of transmitting MTs based on how far they are from their receiving element, whether it is the BS or another MT. Power is adjusted to preserve the battery life of the transmitting MT while maintaining the power at the receiving end above a predefined threshold. This threshold, denoted S_r , dictates the minimum power required for correct reception. Two cases for MTs' transmission power are considered in this paper:

- (1) Fixed Transmission Power: In this case, power control is applied only for MTs inside the innermost. All other MTs use fixed transmission power.
- (2) Complete Power Control: In this case, power control is applied at all hops. As in case (1), the BS oversees power control in the innermost disc. However, for all other discs MTs exercise power control in their transmission independently from the BS.

Both cases are studied in Section 3.2.

We adopt a generic model that can be applied in either TDD or FDD networks. The results obtained in this paper are considered to be per time slot, per frequency-band. The analysis considers an uplink slot in which data flow

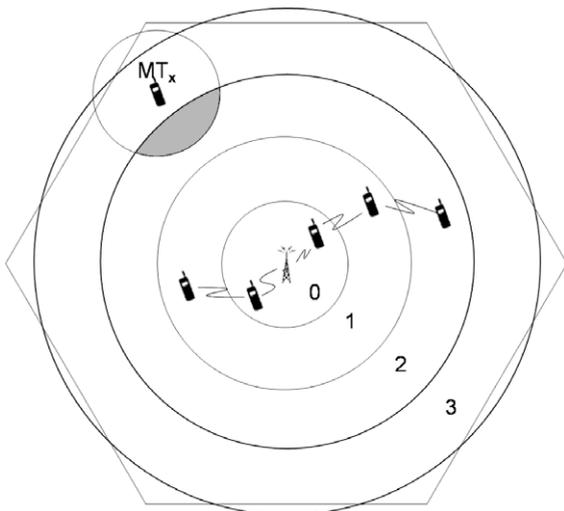


Fig. 2. A cell with 4 discs.

from MTs to the BS. The usage of omnidirectional antennas in multihop communication makes the uplink case and downlink case very similar. Expanding this analysis to include the downlink case needs only a slight modification to consider the BS transmission. This is a subject of future work.

2.2. Propagation model

In general, the capacity of CDMA networks depends on the actual interference experienced during network operation. In order to quantify interference in multihop CDMA networks, a reasonable model for signal propagation is needed. In this analysis, we use the lognormal attenuation model, widely accepted for use in the analysis of CDMA networks. In the model, the power of a signal attenuates proportionally to the product of the m th power of the distance travelled and a lognormal component representing shadowing effects. The power of a received signal, S_r , is then calculated by

$$S_r = S_{tx} d^{-m} 10^{\xi/10}, \quad (1)$$

where S_{tx} is the transmission power of the signal, d is the distance travelled by the signal and ξ is shadowing effect in dB. The path loss power, denoted m , usually varies between 2.7 and 5.0. The typical value of m is 4, which is the value used throughout this paper. Variable ξ is normally distributed with zero mean and a standard deviation of σ , varying between the values of 5 and 12 and independent from the distance. The shadowing effect does not depend on the distance signals travel and is usually estimated using expectations that can be shown to be scalar [16]. Accordingly, the effects of shadowing will be ignored in our analysis.

3. Interference analysis

Studying the capacity of Time Division Multiple Access (TDMA) or Frequency Division Multiple Access (FDMA) networks is relatively easier than in CDMA networks, as in the latter capacity depends on the actual interference experienced during the network operation. An integral factor in this operation is the ratio of the power of the desired signal to the power of interference at receiver, commonly known as the signal to interference ratio (SIR). SIR must be maintained above a certain threshold; a decrease in the SIR, invariably indicating an increase in the interference levels, results in a decrease in a CDMA network's capacity. CDMA networks are hence described as "interference-limited". Consequently, studying interference is crucial in analyzing the capacity of multihop CDMA cellular networks.

In this section, we derive formulas to calculate interference in multihop CDMA cellular networks. We consider an uplink slot. In single hop networks, the BS is the only entity receiving signals inside the cell during an uplink slot. However, in multihop networks the relaying MTs and the BS may be receiving data. Therefore, interference must be considered at both the BS and at the relaying MTs.

Interference in cellular networks is composed of intra-cell interference and inter-cell interference. Intra-cell interference results from signals transmitted from inside the same cell, while inter-cell interference results from signals originating in neighboring cells.

3.1. Fundamental interference formulas

We begin by deriving formulas for interference at the BS. Intra-cell interference at the BS is the total power of all signals received at the BS originating inside the cell, excluding the desired signal. The interference from a single MT_x, denoted I_x , at the BS is expressed as

$$I_x = S_x d_x^{-m}, \quad (2)$$

where S_x is the transmission power, and d_x is the distance between MT_x and the BS in consideration. From (2), it can be seen that the resulting interference decreases as the distance between the source and the receiver increases. The total intra-cell interference, denoted $I_{IntraBS}$, is the sum of (2) over all MTs transmitting inside the same cell. This summation results in the expression

$$I_{IntraBS} = \sum_x S_x d_x^{-m} \quad (3)$$

and can be further divided into summations over each disc separately, yielding

$$I_{IntraBS} = \sum_{i=0}^{k-1} \sum_x N_i S_x d_x^{-m}, \quad (4)$$

where N_i is the number of all MTs transmitting inside disc i . Each inner summation represents total interference from a certain disc. To calculate this summation, the average interference from one MT inside this disc is calculated by integrating over the disc's area and then multiplied by the number of transmitting MTs inside the disc. Applying this to (4) yields

$$I_{IntraBS} = \sum_{i=0}^{k-1} \left[N_i \int \int_{A(i)} S_x d(x,y)^{-m} f(x,y) dx dy \right], \quad (5)$$

where $A(i)$ is the area of disc i and $f(x,y)$ is the distribution of MTs inside disc. While hexagonal cells are assumed, integrations are performed on circular cells using polar coordinates. This has been shown to be a reasonable approximation in [17]. Transforming to polar coordinates results in the following form

$$I_{IntraBS} = \sum_{i=0}^{k-1} \left[N_i \int_0^{2\pi} \int_{r_{i-1}}^{r_i} S_x r^{-m+1} f(r,\theta) dr d\theta \right], \quad (6)$$

where r_i is the outer radius of disc i and r_{-1} is zero. The innermost disc is different from other discs. In the two cases considered in this paper, power control is always assumed to be exercised inside the innermost disc. This means that signals from MTs inside the innermost disc are always received at the BS with a predefined power S_R . Therefore, we split the summation in (6) into two parts. The first part is the first term only and represents interference from the innermost disc and the second part is the remainder of terms and represents interference from discs

1 through $(k-1)$. This splitting results in the following form

$$I_{IntraBS} = N_0 S_R + \sum_{i=1}^{k-1} \left[N_i \int_0^{2\pi} \int_{r_{i-1}}^{r_i} S_x r^{-m+1} f(r,\theta) dr d\theta \right]. \quad (7)$$

Next, we calculate inter-cell interference at the BS. Only first tier neighboring cells are taken into account in this calculation. In the multihop case, MTs use multiple hops to reach BSs, i.e. MTs utilize limited transmission power and their effect on farther cells is negligible. However, considering only the first tier is uncommon in the single hop case, where usually the second tier is also involved in the computation [16]. Despite this consideration, which certainly favors the single hop case, the advantages of multihop cellular networks remain evident as will be shown below. Each cell has six neighbors. The interference from each neighbor at the BS is the same as they are equidistant. It hence suffices to calculate the interference from one cell and multiply it by 6.

The interference from one neighboring cell, denoted $I_{InterBS-1}$, is the summation of interference from all its active MTs. The same steps used in intra-cell interference are applied here, with two differences. The first term in (7) is completely different since the signals from MTs inside the innermost disc of neighboring cells are received with power S_R at neighboring BSs. These signals are received at the BS of consideration with power S_{BS} , which is calculated by

$$S_{BS} = S_R \left(\frac{d_i}{d_j} \right)^m, \quad (8)$$

where d_i is the distance from the MT to its serving BS and d_j is the distance to the BS in consideration. To get the interference from the innermost disc of the neighboring cell, Eq. (8) is integrated over the area of the disc and multiplied by the number of transmitting MTs inside the disc.

For the other discs, the difference lies in the distance between the MTs and the BS in consideration. In deriving the formula for intra-cell interference, the BS was assumed to be at the origin with the concentric discs centered at the BS. This makes the distance between any interfering MT and the BS simply the radius (r) of the polar coordinates of the MT. Here, the neighboring BS becomes the new origin of computation, making the BS of consideration at point $(L, 0)$, where L is the distance between two neighboring BSs. Hence, the distance between the interfering MT and its serving BS is r and the distance between the interfering MT and the BS in consideration is $(r^2 + L^2 - 2Lr \cos(\theta))^{1/2}$. Applying these differences to (7), yields

$$I_{InterBS-1} = N_0 S_R \int_0^{2\pi} \int_0^{r_0} \frac{r^{m+1}}{(r^2 + L^2 - 2Lr \cos(\theta))^{\frac{m}{2}}} f(r,\theta) dr d\theta + \sum_{i=1}^{k-1} \left[N_i \int_0^{2\pi} \int_{r_{i-1}}^{r_i} \frac{S_x r}{(r^2 + L^2 - 2Lr \cos(\theta))^{\frac{m}{2}}} f(r,\theta) dr d\theta \right]. \quad (9)$$

The total interference at BS, denoted by I_{T-BS} , is the sum of intra-cell interference and inter-cell interference and can be expressed as

$$I_{T_BS} = I_{IntraBS} + 6I_{InterBS_1}. \quad (10)$$

We derive interference at relaying MTs in a similar way to interference at the BSs. A fundamental difference is that interference at the MTs depends on the position of relaying MT, which determines the distance to the serving BS and its neighboring BSs. Interference at relaying MTs is calculated based on their distance to their serving BS.

Both intra-cell interference and inter-cell interference at relaying MTs can be represented by the formula for inter-cell interference at the BS, i.e. Eq. (9), with slight adjustments. In intra-cell interference calculation, the serving BS is at the origin. The relaying MT is at a distance b from the BS, i.e. point $(b, 0)$. Applying these adjustments the intra-cell interference at a relaying MT a distance b from its BS, denoted by $I_{IntraMT}$, can be calculated by

$$I_{IntraMT} = N_0 S_R \int_0^{2\pi} \int_0^{r_0} \frac{r^{m+1}}{(r^2 + b^2 - 2br \cos(\theta))^{\frac{m}{2}}} f(r, \theta) dr d\theta + \sum_{i=1}^{k-1} \left[N_i \int_0^{2\pi} \int_{r_{i-1}}^{r_i} \frac{S_x r}{(r^2 + b^2 - 2br \cos(\theta))^{\frac{m}{2}}} f(r, \theta) dr d\theta \right]. \quad (11)$$

The inter-cell interference at a relaying MT differs from that at the BS because the first tier neighboring BSs are not equidistant from the relaying MT in consideration. This necessitates calculating the inter-cell interference from each neighboring cell separately. For calculating inter-cell interference at a relaying MT, the neighboring BS is assumed at the origin. The relaying MT is at a distance b from its serving BS, and a distance b_n from the neighboring BS. This distance b_n is calculated for each neighboring BS n . Modifying (9), the inter-cell interference from one neighboring BS n , denoted $I_{InterMT_n}$ at a relaying MT a distance b from its serving BS is given by

$$I_{InterMT_n} = N_0 S_R \int_0^{2\pi} \int_0^{r_0} \frac{r^{m+1}}{(r^2 + b_n^2 - 2b_n r \cos(\theta))^{\frac{m}{2}}} f(r, \theta) dr d\theta + \sum_{i=1}^{k-1} \left[N_i \int_0^{2\pi} \int_{r_{i-1}}^{r_i} \frac{S_x r}{(r^2 + b_n^2 - 2b_n r \cos(\theta))^{\frac{m}{2}}} f(r, \theta) dr d\theta \right]. \quad (12)$$

The total interference at a relaying MT, denoted I_{T_MT} , is then the sum of intra-cell interference and inter-cell interference from all neighboring cells and can be expressed by

$$I_{T_MT} = I_{IntraMT} + \sum_{n=1}^6 I_{InterMT_n}. \quad (13)$$

3.2. Transmission power

Having derived the basic interference formulas at the BS and relaying MTs, further investigation of certain variables is required. First, the value of the transmission power for MTs has to be determined. As described in Section 2.1 above, two cases are considered for MTs transmission power. The calculation will be affected by the values of the transmission powers of MTs residing outside the innermost disc since the BS oversees power control of MTs inside the innermost disc. Consequently, the terms for the innermost disc will remain unchanged.

The fixed transmission case is easy to deal with. All MTs outside the innermost disc use a predetermined fixed transmission power denoted S_{TR} . This value is constant and can be used to replace S_x in all the interference formulas derived above. However, determining the value S_{TR} is based on the width of the discs. The value must guarantee that signals transmitted by MTs at the outer edge of a disc can reach the next disc with a power of at least S_R . The value of the constant transmission power can then be determined by

$$S_{TR} = S_R r_0^m, \quad (14)$$

where r_0 is the radius of the innermost disc, and also the width of all discs.

The power control case where power control is applied at all hops is not as straightforward. MTs outside the innermost disc do not use fixed transmission power. Instead, their signals are received with a constant power, S_R , at their intended receivers. This means that MTs use variable transmission power based on the distance to their receivers. The controllable transmission power would be continuously determined for each MT. Using (1), the transmission power of a transmitting MT, denoted S_{tx} , can be calculated by

$$S_{tx} = S_R d_{tx}^m, \quad (15)$$

where d_{tx} is the distance between an MT and its intended receiver. In order to calculate the average transmission power of an MT, Eq. (15) has to be averaged over all possible positions of its receiver.

For MTs outside the innermost disc, receivers can be anywhere in the intersection area between their transmission range and the next disc closer to the BS. This area is shown with the shaded area in Fig. 2 for MT_x . Transmission range is the area around the transmitting MT, where the power of its transmitted signal is at least S_R . The transmission range depends on the maximum transmission power of an MT, denoted S_{MAX} , which is set such that a signal sent from an MT at the outer edge of a disc can reach the next disc with power S_R . Hence, S_{MAX} is equal to S_{TR} used in the fixed transmission case. This means that the transmission range of any MT is a circle centered at this MT with radius r_0 . Therefore, the average transmission power of a certain MT depends on the width of discs and the position of MT with respect to disc edges. Here, we calculate the average transmission power as a function of the distance from the BS.

If MT_x is in disc n and is a distance d_x from the BS, its average transmission power, denoted S_{av} , can be calculated by

$$S_{av} = \frac{S_R}{A_{int}} \int_0^{2\pi} \int_{r_{n-2}}^{r_{n-1}} r (r^2 + d_x^2 - 2rdx \cos(\theta))^{m/2} dr d\theta \quad \text{such that } \sqrt{r^2 + d_x^2 - 2rdx \cos(\theta)} \leq r_0, \quad (16)$$

where A_{int} is the intersection area between transmission range of MT_x and disc $(n-1)$. The condition in (16) guarantees that the receiver resides inside the transmission range of transmitting MT_x .

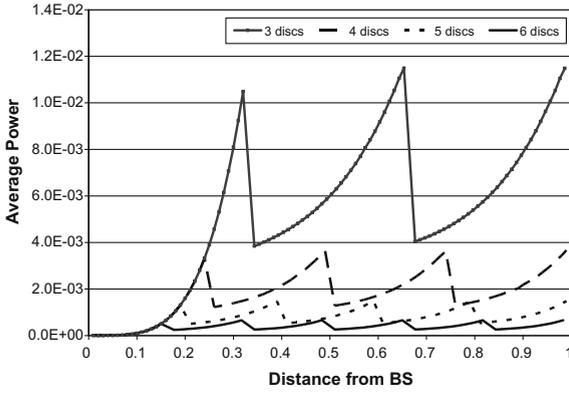


Fig. 3. Average transmission power of MTs.

Fig. 3 shows the average transmission power of MTs, normalized by S_R , as a function of distance from the BS. The figure shows different plots for different numbers of discs. To simplify exposition, we will assume that the cell radius is unity.

From Fig. 3, it can be seen that the average transmission power of an MT increases as the distance from the BS increases. This increase ends when the MT reaches the outer edge of a disc. At that point, the average transmission power drops drastically then starts increasing again. MTs inside the innermost disc only have one possible receiver, the BS. The required transmission power increases as the MT becomes farther from the BS, so that the signal reaches BS with power S_R . For other discs, as the MT moves away from the outer edge of the closer disc, the MT's average transmission power increases as the distance to candidate receivers increases. Also note that at the outer edge of each disc the average transmission power is almost S_{MAX} . We remark that as the number of discs gets larger, the average transmission power becomes more uniform. In contrast, for a small number of discs the variation in the average transmission power significantly increases. This observation indicates the necessity of exercising global power control when using a small number of discs.

Using curve fitting, a function $S_i(r)$ for average transmission power as a function of distance from BS can be obtained for each disc. This function is used to replace S_x in interference calculations.

3.3. Call and MTs distribution

All interference formulas derived above have a distribution function $f(x, y)$ and number of MTs in disc i , N_i . Both values need to be determined to perform the computation. We first study the case with uniform call distribution, then study the more complicated case with non-uniform call distribution. In both cases, the transmitting MTs are assumed to be uniformly distributed over the area of the disc they reside in. Based on this assumption, the intra-cell interference formula and the inter-cell interference formula at BS can be respectively modified as follows

$$I_{IntraBS} = N_0 S_R + \sum_{i=1}^{k-1} \left[\frac{N_i}{A(i)} \int_0^{2\pi} \int_{r_{i-1}}^{r_i} S_x r^{-m+1} dr d\theta \right], \quad (17)$$

$$I_{InterBS_1} = \frac{N_0 S_R}{A(0)} \int_0^{2\pi} \int_0^{r_0} \frac{r^{m+1}}{(r^2 + L^2 - 2Lr \cos(\theta))^{\frac{m}{2}}} dr d\theta + \sum_{i=1}^{k-1} \left[\frac{N_i}{A(i)} \int_0^{2\pi} \int_{r_{i-1}}^{r_i} \frac{S_x r}{(r^2 + L^2 - 2Lr \cos(\theta))^{\frac{m}{2}}} dr d\theta \right]. \quad (18)$$

Eq. (18) can be used to represent intra-cell interference and inter-cell interference at a relaying MT, by respectively replacing L by b and b_n .

It is noteworthy that there is a variable N_i in every term in all interference formulas. As mentioned earlier, N_i is defined as the total number of transmitting MTs inside disc i . This total number includes MTs transmitting their own data, MTs relaying others' data and MTs doing both. This number is the factor that differentiates the uniform call distribution case from the non-uniform one. In both cases, this number can be divided into MTs transmitting their own data, denoted N_{oi} and additional relaying MTs, denoted N_{Ri} .

In the uniform call distribution case, the number of MTs transmitting their own data in each disc can be determined by the ratio of the disc area to the area of the whole cell. Hence, number of MTs sending their own data in disc i is

$$N_{oi} = \frac{N_T}{A_T} A(i), \quad (19)$$

where N_T is the total number of calls originating in each cell and A_T is the cell area. The number of additional relaying MTs is dependent on the ability of MTs sending their own data to relay others' data as well. Consequently, the number of additional relaying MTs in disc i (N_{Ri}) is the percentage α ($0 \leq \alpha \leq 1$) of signals transmitted by MTs in disc $(i+1)$ that cannot be relayed by MTs sending their own data in disc i . By recursion, the number of additional relaying MTs in disc i can be given by

$$N_{Ri} = \alpha N_{i-1} = \frac{N_T}{A_T} \sum_{n=i+1}^{k-1} \alpha^{n-i} A(n). \quad (20)$$

The total number of transmitting MTs in disc i then becomes

$$N_i = N_{oi} + N_{Ri} = \frac{N_T}{A_T} \sum_{n=i}^{k-1} \alpha^{n-i} A(n). \quad (21)$$

In the case of non-uniform call distribution, the call distribution inside a cell is varied by changing the number of calls originating from each disc. This is done by defining a weight vector $W_n = (w_{n0}, w_{n1}, \dots, w_{n(k-1)})$ where w_{ni} represents the weight for each disc i and $\sum_{i=0}^{k-1} w_{ni} = 1$. The number of MTs transmitting their own data in disc i hence becomes

$$N_{oi} = w_{ni}^* N_T \quad (22)$$

and the number of additional relaying MTs is just the percentage α ($0 \leq \alpha \leq 1$) of signals transmitted by MTs in disc $(i+1)$, which cannot be relayed by MTs sending their own data in disc i . The weight vector is varied from

$(1, 0, 0, \dots, 0)$, which means that all calls originate inside the innermost disc to $(0, 0, \dots, 0, 1)$, where all calls are inside the outermost disc. In between, the concentration of calls gradually shifts from around the BS toward the cell borders. The special case of uniform distribution can be represented by the weight vector through dividing the area of each disc by the total cell area.

4. Numerical results and discussion

In this section, we display numerical results for the interference formulas derived above and discuss our findings.

4.1. Capacity increase under uniform distribution

First, the capacity of a multihop CDMA cellular network is compared to that of a single hop network under uniform call distribution. Using the above formulas, the total interference at the BS or MT, denoted I_T , can be expressed as a function of N_T and S_R in the form of

$$I_T = C_k N_T S_R, \quad (23)$$

where C_k can be defined as the average interference caused per original call and is dependent on the number of discs. C_k is the total interference normalized by $(N_T * S_R)$. Neglecting thermal noise, SIR can now be expressed as

$$SIR = \frac{S_R}{C_k N_T S_R - S_R}. \quad (24)$$

According to the IS-95 standard [18], the bit energy to interference density ratio (E_b/I_0) must be maintained above a certain threshold τ to guarantee a given bit error rate (BER), e.g. for IS-95 $\tau = 5$ (7 dB) for BER of 10^{-3} . The value of E_b/I_0 can be calculated from the formula of SIR by dividing the power of the desired signal by the data rate R , and the interference by the bandwidth W [19]. Substituting in (24) and keeping E_b/I_0 above threshold τ , an upper bound on N_T is obtained as

$$N_T \leq \frac{W/\tau R + 1}{C_k}. \quad (25)$$

If the interference at the BS is used, this upper bound can be defined as the maximum number of simultaneous calls that can be supported by this BS.

It should be clear that the maximum number of allowed simultaneous calls originated in each cell is dependent on C_k . Decreasing C_k increases the maximum number of simultaneous calls and hence increases the practical capacity. For this reason, C_k is plotted against the number of discs in Fig. 4. The values obtained in the case of power control are compared to the case with no power control. The special case with 1 disc represents the case of single hop CDMA cellular network.

In these results, it is assumed that all MTs are transmitting with the same data rate and with a continuous bit stream. This setup means that MTs sending their own data cannot relay other's information, which results in the percentage of additional relaying MTs (α) to be 1. Substituting

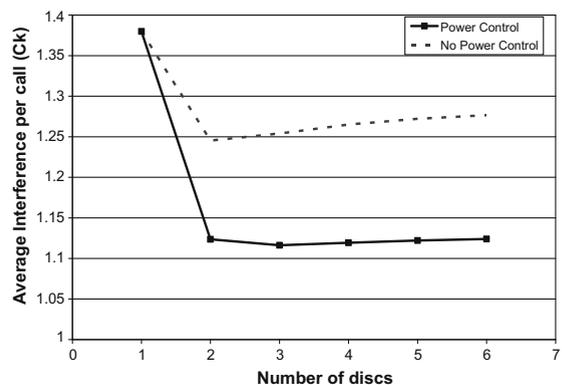


Fig. 4. Average interference (C_k) per call.

with α equals 1 in (21), the total number of transmitting MTs when call distribution is uniform becomes

$$N_i = \frac{N_T}{A_T} \sum_{n=i}^{k-1} A(n) = \frac{N_T}{D^2} (D^2 - r_{i-1}^2), \quad (26)$$

where D is the radius of the cell, and is taken to be unity here.

From Fig. 4, it can be seen that using multihop relay in cellular networks decreases the average interference per call. More calls can hence be simultaneously accepted in each cell, increasing the total capacity of the network. It can also be noticed that the average interference first decreases and then increases as the number of discs increases. This can be explained by the fact that 100% additional relaying MTs are used. The large number of additional relaying MTs results in an increase in interference with the increase in number of discs. Despite the excessive number of additional relaying MTs, a decrease in the total interference is still achieved, resulting in an increase in the total number of original calls in each cell. The percentage increase in the number of calls can be obtained from (25) and is plotted in Fig. 5. Again, the same two cases are plotted in the figure. Obviously, power control results in higher increase in the total number of calls. From the results, it can be seen that a 23% increase in number of calls over single hop networks can be achieved using power control, even with no increase in data rate and with 100% additional relaying MTs.

The above results show that MCNs can achieve higher capacity than single hop ones. To achieve this increase, proper operation of relaying procedure has to be guaranteed. For relaying MTs to correctly forward others' data, they first have to correctly receive this data. The same idea applies here. The ratio E_b/I_0 at relaying MTs has to be kept above the threshold τ . To ensure this, the number of maximum calls allowed per cell is calculated using (25). The values used for W and R are 1.22 MHz and 9.6 Kbps, respectively. These are the values used in IS-95 standards [18]. Using these values, the ratio E_b/I_0 at relaying MTs is calculated and plotted against their distance from the BS in Fig. 6. This is done for the two cases with power control only at the last hop and with power control at all hops.

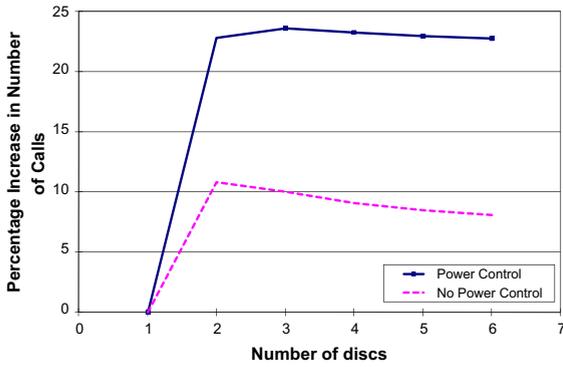


Fig. 5. Percentage increase in number of simultaneous calls.

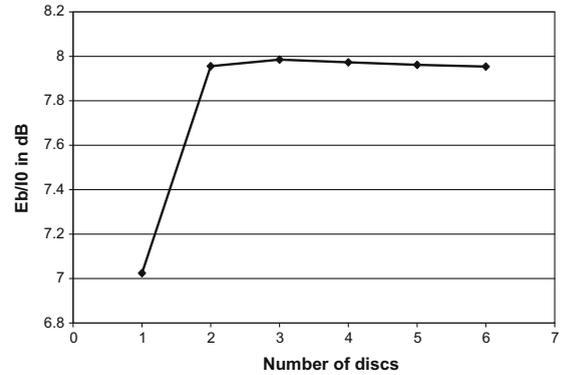


Fig. 7. Bit energy to interference density ratio (E_b/I_0) with power control using same number of calls as single hop.

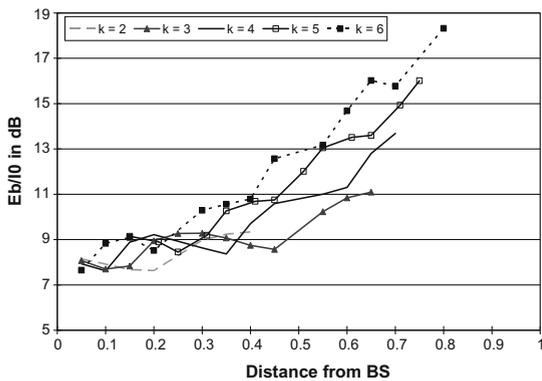


Fig. 6. Bit energy to interference density ratio (E_b/I_0) at relaying MTs with complete power control.

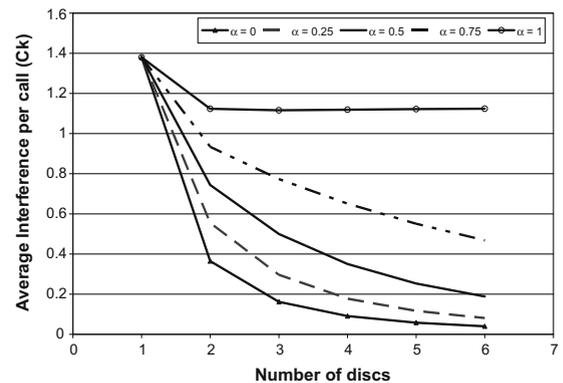


Fig. 8. Average interference per call (C_k) with different percentage of additional relaying MTs (α).

We only show the results from the case with complete power control to save space.

Recall that there are no relaying MTs in the outermost disc. The graphs do not show E_b/I_0 inside these discs. Fig. 6 shows that E_b/I_0 at relaying MTs is kept above the threshold ($\tau = 7$ dB), guaranteeing proper relay.

To investigate the possibility of increasing data rates, the maximum number of calls that can be handled in the case of single-hop is used in the multihop case. Using this number, E_b/I_0 is calculated. The values of E_b/I_0 are plotted in Fig. 7. It is obvious that using multihop relay decreases total interference, resulting in higher E_b/I_0 values. This increase in E_b/I_0 can be used to achieve higher data rates. Higher data rates allow MTs sending their own data to relay others' data as well, decreasing the number of transmitting MTs and reducing interference per call originator – ultimately enhancing network capacity. This effect can be examined by decreasing the value of the percentage of additional relaying MTs. The value C_k is plotted against number of discs in Fig. 8. Different graphs are for different values of α . As expected, decreasing the percentage of additional relaying MTs decreases the average interference per original call. This results in an increase in the total capacity of the network. It is worth noting here that α and the data rate are mutually dependent. Decreasing α decreases inter-

ference and hence increases the achievable data rate. Meanwhile, increasing the data rate allows more active MTs sending their own data to relay others' data, decreasing the percentage of additional relaying MTs even more. In Figs. 7 and 8, again we only show results from the case with complete power control to save space.

4.2. Examining the effect of call distribution

In all the above results, a uniform call distribution over the cell area was assumed. Here, we investigate the effect of call distribution inside the cell on network capacity. The call distribution inside a cell can have an effect on the capacity of the cell itself or the capacity of its neighboring cells.

To simplify the discussion, and without loss of generality, we adopt the following tagging convention. First we define a target cell. This is the main cell in the analysis. Cells adjacent to the target cells are called 1st tier neighboring cells (B1). Cells adjacent to 1st tier cells but not the target cell are called 2nd tier cells (B2). A target cell and its 1st tier (B1) cells and 2nd tier (B2) cells are shown in Fig. 9. The number of calls in target cell, B1 cell and B2 cell are denoted N_{Tg} , N_{B1} and N_{B2} , respectively.

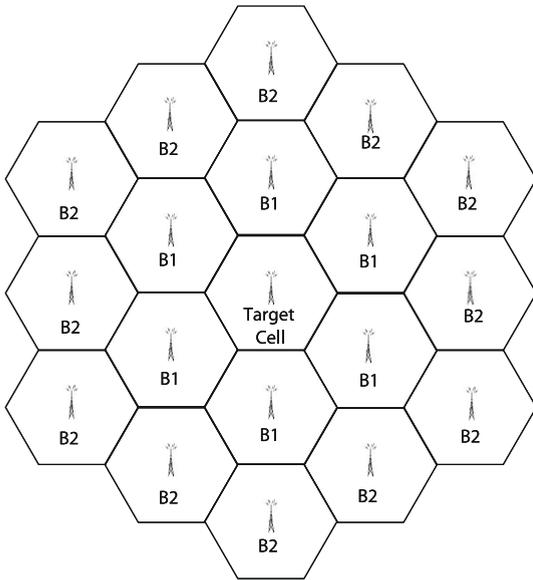


Fig. 9. Layout of cells used in non-uniform call distribution analysis.

The call distribution inside a cell is varied by changing the number of calls originating in each disc. This is done by changing the weight vector previously defined. In the results calculated here, the cells are divided into 4 discs; accordingly, the weight vector has 4 elements. The weight vectors used in the calculation below are shown in Table 1, and they are varied from $W_1 = (1, 0, 0, 0)$, which means that all calls originate inside the innermost disc, to $W_{10} = (0, 0, 0, 1)$, where all calls are inside the outermost disc. In between, the concentration of calls gradually shifts from around the BS toward the cell borders. Weight vector W_8 (shaded row in Table 1) is the special case representing uniform distribution, i.e. weight vector is calculated by dividing the area of each disc by the total cell area.

We begin by investigating the effect of call distribution inside a cell on the capacity of the cell itself. Call distribution inside the target cell is assumed to be non-uniform, while call distribution is uniform in the rest of the cells. The maximum number of calls that can be supported in the target cell is calculated for different distributions represented by weight vectors in Table 1.

The number of transmitting MTs in each disc of the target cell has to be derived to accommodate the non-uniform

call distribution. In each disc, there are $w_{ni}N_T$ MTs transmitting their own data (original calls) in addition to additional MTs relaying data from outer discs. Assuming all MTs transmit at the same rate, relaying MTs are considered different than MTs transmitting their own data. Applying these assumptions, the number of transmitting MTs in disc i becomes

$$N_i = w_{ni}N_{Tg} + \sum_{l=i+1}^{k-1} N_l = N_{Tg} \sum_{l=i}^{k-1} w_{nl} \tag{27}$$

Interference is then calculated at the BS of the target cell. Intra-cell interference is calculated using (17), with N_i defined as in (27). B1 cells have N_{B1} calls uniformly distributed over their areas. Hence, inter-cell interference is calculated using (18), with N_i defined as in (26) but with N_T replaced by N_{B1} . Using the same argument as above, the upper bound on the number of simultaneous calls supported in the target cell is

$$N_{Tg} \leq \frac{W/\tau R + 1 - 6N_{B1}I_{Inter_U}}{I_{Intra_n}} \tag{28}$$

where I_{Inter_U} is the average inter-cell interference resulting from one call under uniform distribution and I_{Intra_n} is the average intra-cell interference caused by one call under non-uniform distribution defined by weight vector W_n . The maximum number of calls that can be supported in the target cell is plotted in Fig. 10 when B1 cells are heavily loaded and in Fig. 11 when B1 cells are lightly loaded. The number of calls supported in the single-hop case is also shown. Graphs show two different data rates (4 Kbps and 8 Kbps) and the two cases of fixed transmission power and per-hop power control.

The load of B1 cells is determined based on the previous uniform calculations. An upper bound on the number of supported calls was calculated for the single hop case. Cells are heavily loaded when number of calls equals the upper bound (22 and 44 calls for data rates of 8 Kbps and 4 Kbps, respectively). The same value is used in single hop and multihop for comparison. Cells are lightly loaded when the number of calls is 10. Note that this is just a sampler value, which is much lower than the upper bound in all cases.

Table 1
Weight vectors for non-uniform call distribution.

Weight vector	Disc 0	Disc 1	Disc 2	Disc 3
W_1	1	0	0	0
W_2	0.8	0.2	0	0
W_3	0.7	0.2	0.1	0
W_4	0.5	0.5	0	0
W_5	0.5	0.3	0.15	0.05
W_6	0.25	0.25	0.25	0.25
W_7	0.1	0.2	0.3	0.4
W_8	0.0625	0.1875	0.3125	0.4375
W_9	0.05	0.15	0.3	0.5
W_{10}	0	0	0	1

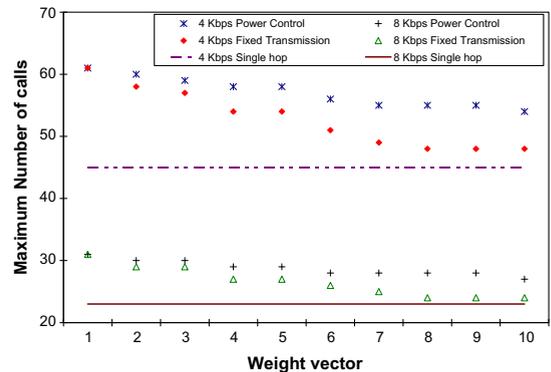


Fig. 10. Upper bound on number of calls in the target cell with heavily loaded neighboring cells.

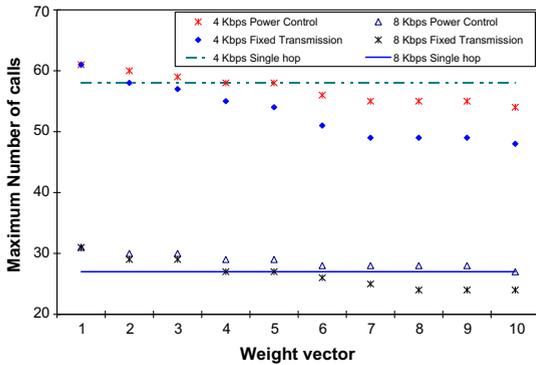


Fig. 11. Upper bound on number of calls in the target cell with light loaded neighboring cells.

To compare the multihop case to the single hop case, conditions have to be similar. When assuming non-uniform distribution in the latter case, the cell area is still divided into discs. In each disc a certain number of calls originate based on the weight in each disc, although they all communicate directly with the BS.

It can be seen that the distribution of calls affects cell capacity when using multihop communication. The location of the call determines the number of hops needed to reach the BS. As the call gets closer to the BS, a lower number of hops is needed which results in less interference. This effect is obvious when all calls reside inside the innermost disc. At this point, all calls reach BS in one hop, thus reaching the maximum capacity of the cell as shown in the case with weight vector W_1 . When calls originate near the border of the cell, they require the maximum number of hops to reach the BS resulting in high interference. This can be seen in the case with weight vector W_{10} , where all calls originate in the outermost disc. In this situation, the capacity of the cell is minimized. Comparing Figs. 10 and 11, we can see that the load in neighboring cells has negligible effect on cell capacity in the multihop case due to the short distances signals have to travel.

The situation is different in the single hop case. It is observed that the capacity of the cell is constant despite the change in call distribution. Power control at BS means all calls are received at BS with the same power S_R . This eliminates the effect of call location on intra-cell interference. From Figs. 10 and 11, it is observed that the load in neighboring cells greatly affects the cell capacity in the single-hop case.

Comparing the two cases, it is observed that the network in the multihop case always has higher capacity when neighboring cells are heavily loaded (Fig. 10). When the load in neighboring cells is light (Fig. 11), the capacity of multihop is still higher than that of the single-hop case when calls are close to the BS due to the high inter-cell interference. When the concentration of calls moves toward the cell border, intra-cell interference dominates in the multihop case and becomes higher than the inter-cell interference in the single-hop case. This results in higher capacity in the single-hop case. Such a finding seems to contradict the widely accepted claim that it is better to

use multihop communication in cases when calls originate near cell borders. We remark though that this observation is only true when neighboring cells are lightly loaded. Also, it has to be noted that only the effect of this non-uniform call distribution on the capacity of the cell itself has been considered. Its effect on the capacity of neighboring cells has to be taken into consideration when comparing the two cases. Also, 100% additional relaying MTs are assumed in these results.

To further investigate such an effect, we now consider scenarios where all calls originate from one disc. Such scenarios may result in events with a large number of people at one place, e.g. concert, game, etc. To simulate this, we set the weight vector of one disc to 1 and all other values to 0. The maximum number of calls that can be supported in each disc for different data rates is shown in Fig. 12. As mentioned earlier, the maximum number of calls in the single-hop case does not change with call distribution. A high load was assumed for neighboring cells. The multihop case is plotted for the same two rates (8 Kbps and 4 Kbps). The horizontal lines represent the maximum number of calls supported in the single hop case (dotted for 4 Kbps and solid for 8 Kbps).

From the results in Fig. 12, it can be seen that the capacity of the multihop case is always higher than that of single-hop when neighboring cells are heavily loaded, regardless of call distribution. It should be noted that whether or not power control is exercised between MTs does not affect the outcome when all calls reside inside the innermost disc, as power control is always applied on the last hop to BS. We can then conclude that call distribution affects the capacity of the cell in multihop networks but not in single hop ones.

The situation is reversed, however, when we study the effect of call distribution in one cell on the capacity of adjacent cells. We assume that the target cell has uniform call distribution and B1 cells have non-uniform call distribution. Call distribution in the 6 B1 cells is the same. The capacity of the target cell is then calculated.

In the calculations below, only the 4 scenarios where all calls are concentrated in one disc are considered. This means that one value in the weight vector is 1, while all other values are 0. The intra-cell interference is calculated

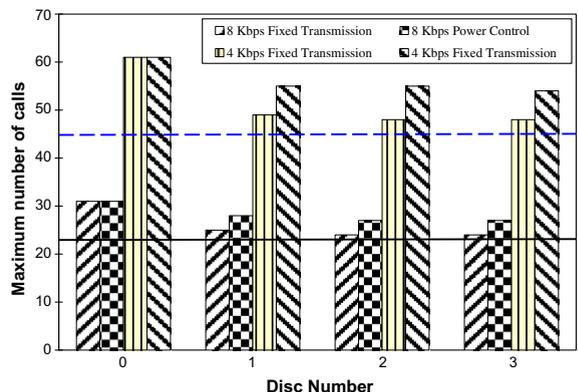


Fig. 12. Maximum number of calls that can be supported in each disc.

using (17) with N_i represented by (26) with N_T replaced by N_{Tg} . Equation for inter-cell interference has to accommodate the non-uniform distribution assumed in adjacent cells. This is done by using (18) with N_i defined by (27) and replacing N_T by N_{B1} . Using a minimum threshold τ for E_b/I_0 , the upper bound on number of supported calls in target cell is

$$N_{Tg} \leq \frac{W/\tau R + 1 - 6N_{B1}I_{Inter-n}}{I_{Intra-U}}, \quad (29)$$

where $I_{Inter-n}$ is the average inter-cell interference resulting from one call under non-uniform distribution defined by weight vector W_n and $I_{Intra-U}$ is the average intra-cell interference caused by one call under uniform distribution. The upper bounds on number of supported calls in the target cell are calculated and are shown in Table 2 for 8 Kbps data rate under heavily and lightly loaded neighboring cells. The first column in Table 2 indicates the disc where all calls in neighboring cells originate.

The results in Table 2 show that call distribution in neighboring cells hardly affects cell capacity in the multihop case, especially when per-hop power control is exercised. This is explained by the short distances signals have to travel in the multihop case, decreasing the required transmission power and making the inter-cell interference insignificant compared to the intra-cell interference. From the last two columns in Table 2, it is clear that cell capacity in single-hop CDMA-based cellular networks is highly affected by call distribution in neighboring cells. The cell capacity can be significantly reduced if all calls are at cell border. In this situation, calls are almost midway between their serving BS and the adjacent BS. An MT needs to use the maximum transmission power to reach its serving BS, and will also reach the BS of the adjacent cell with almost same power, severely decreasing capacity of the adjacent cell. The maximum number of supported calls can be decreased by 17 calls resulting in 136 Kbps (17 calls \times 8 Kbps) decrease in cell throughput per time slot when calls in neighboring cells move from near the BS to cell border. The capacity of this cell is effectively reduced by half. In fact, when calls are concentrated in outermost discs, the multihop cellular case with power control achieves twice the capacity of the single-hop case. This also supports the argument made earlier about multihop networks being more appropriate for calls near cell borders.

Finally, we study the effect of call distribution in the target cell on its neighboring cells. We assume that target cell has non-uniform call distribution, while the rest of cells have uniform distribution. In order to find the effect

of non-uniform call distribution in the target cell on the capacity of adjacent B1 cells, the upper bound on number of calls in B1 cells is calculated. Since B1 cells are similar, it suffices to evaluate capacity in any of them. Each B1 cell is adjacent to the target cell, 2 B1 cells and 3 B2 cells. The total interference at the BS of any of these 6 cells in this scenario can then be written as

$$I_T = N_{B1}I_{Intra-U} + 3N_{B2}I_{Inter-U} + 2N_{B1}I_{Inter-U} + N_{Tg}I_{Inter-n}, \quad (30)$$

where the first term represents intra-cell interference, the second term represents inter-cell interference from the 3 B2 cells, third term represents inter-cell interference from the 2 B1 cells and the fourth term represents the inter-cell interference from the target cell. Applying the threshold on E_b/I_0 at the BS of the B1 cell, the upper bound on number of supported calls in each B1 cell becomes

$$N_{B1} \leq \frac{W/\tau R + 1 - N_T I_{Inter-n} - 3N_{B2} I_{Inter-U}}{(2I_{Inter-U} + I_{Intra-U})}, \quad (31)$$

Using (31), the maximum number of calls with data rate 8 Kbps supported in each of the neighboring cells (B1 cells) is recorded in Table 3. In these calculations, all cells other than B1 cells are assumed to be highly loaded. The upper bound on the number of calls per cell in single hop case is 22 calls at rate 8 Kbps. This is taken as the number of calls in target cell and B2 cells (i.e. N_T and N_{B2} in (31)). The first column in Table 3 indicates the disc where all calls in neighboring cells originate.

From Table 3, it can be seen that changing the call distribution in one cell does not affect the capacity of surrounding cells in the multihop case, while in the single hop case the capacities of all adjacent cells are affected. It can also be seen that the number of calls is dropped by 3 in each of the 6 adjacent cells (B1 cells) resulting in a decrease of 144 Kbps (6 cells \times 3 calls \times 8 Kbps) in the network throughput per time slot. Furthermore, comparing the same situation in multihop and single-hop cases, a degradation of 336 Kbps (6 cells \times 7 calls \times 8 Kbps = 336 Kbps) can be observed.

We can then conclude that call distribution of a cell hardly affects the capacity of its neighboring cells in multihop CDMA cellular networks, while it can seriously degrade the capacity of neighboring cells in the single hop case, especially if calls tend to originate near the cell borders. This is one of the most rewarding advantages of multihop CDMA cellular networks as they almost eliminate the effect of border calls, maintaining constant capacity in surrounding cells even if all calls are at cell borders.

Table 2

Maximum number of calls that can be supported in the target cell.

Disc	Power control		Fixed trans.		Single hop	
	Light	Heavy	Light	Heavy	Light	Heavy
0	28	28	25	25	31	31
1	28	28	25	24	31	31
2	28	28	24	24	30	28
3	28	28	24	24	23	14

Table 3

Maximum number of calls that can be supported in each B1 cell.

Disc	Power control	Fixed trans.	Single hop
0	28	24	24
1	28	24	24
2	28	24	23
3	28	24	21

5. Conclusion

The claimed advantages of MCNs have thus far been widely accepted, despite lack of rigorous scrutiny. In this paper, and for the first time in the literature, these claims have been closely examined. We quantified the increase in capacity caused by utilizing multihop relay in CDMA cellular networks. Due to the interference-limited nature of CDMA networks, this quantification required calculating the interference at both the BS and relaying MTs. Formulas were derived for two cases covering whether or not power control is exercised between the relaying terminals. It is shown that using multihop relaying (even in a non-optimized setting) can achieve a 23% increase in number of simultaneous calls while using power control, and a possible 10% increase when using fixed transmission power. The analysis is extended to accommodate generalized user distribution to examine the effect of call distribution on the capacity of a cell and its neighbors. It is demonstrated that, unlike in the single hop case, call distribution affects the cell capacity due to variation in number of hops. More critically, we demonstrate how MCNs overcome the disadvantage in single hop networks when network capacity degrades as the user density increases toward cell borders.

In our future work, we plan to further extend the capacity analysis to consider sectorization and directional antennas. We are currently working on performing a detailed analysis of power consumption in multihop CDMA networks. We plan on using the capacity analysis along with the power consumption analysis toward a detailed RRM framework for multihop CDMA cellular networks.

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