Congestion Relief in CDMA Cellular Networks using Multihop Inter-Cell Relay

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Abstract—**Multihop communication has been proposed in cellular networks to overcome some inherent limitations. Congestion relief is amongst the promised gains. In this paper, the concept of inter-cell relay, which uses multihop communication to divert calls from heavy loaded cells to less loaded adjacent cells, is introduced. We show that using inter-cell relay, the number of supported calls inside a congested cell can be significantly increased. We devise two approaches for congestion relief based on the conditions of the network, to maximize the number of supported calls inside a congested cell. The distribution-based approach determines the number of extra hops for inter-cell relay based on call distribution. On the other hand, the delay sensitive approach assumes that the number of extra hops for inter-cell relay is limited by calls quality of service requirements. By imposing a limit on the number of extra hops, the approach decides the number of inter-cell relayed calls and the number of calls connected to the congested BS. Our results illustrate the benefits gained from inter-cell relay in congestion relief. We demonstrate that inter-cell relay can decrease congestion of a cell by fully utilizing the available resources in surrounding cells.**

Keywords-CDMA; Multihop; Congestion relief; Cellular; QoS

I. INTRODUCTION

Third Generation (3G) wireless networks have adopted Wideband Code Division Multiple Access (WCDMA) technology. Despite the advances achieved, cellular networks will still suffer inherent limitations on capacity and coverage. WCDMA-based networks are interference limited, which means that their capacities are affected by usage, and mobility of users. Various proposals have been made to overcome this limitation including enhanced functionalities for radio resource management overseeing admission [1] and power control [2].

However, a solution that has been gaining prominent attention is that of exploiting the advances made in the area of multihop wireless relay. Accordingly, the concept of Multihop Cellular Networks (MCNs) has been proposed to overcome drawbacks like congestion, load imbalance and dead spots [3].

Some efforts have been devoted toward investigating the different aspects of MCNs. Different proposals have been suggested [4], [5]. Other works attended to the operational requirements of MCNs, like channel assignment and resource utilization [6], [7]. In our previous work, we showed that using multihop communication in CDMA cellular networks can increase network capacity [8] and reduce consumed energy [9].

In [10], we introduced the inter-cell relay concept, where calls originating inside one cell are diverted to less loaded adjacent base stations (BSs). Inter-cell relay can be used for congestion relief or load balancing. In this paper, we further explore the gains that can be achieved in congestion relief through inter-cell relay. In single-hop cellular networks, calls are rejected in a congested cell even if adjacent cells are underutilized and have unused resources. In multihop cellular networks, inter-cell relay can be used to facilitate diverting the load from the congested cell to its less loaded adjacent BSs, decreasing the probability of congestion. Towards identifying the capacity gains of congestion relief, interference analysis is performed. We show the possible increase in the number of supported calls inside the congested using inter-cell relay based on resulting interference. We also present two congestion relief approaches to maximize the number of supported calls inside a congested cell based on network conditions. The first approach, *distribution-based congestion relief*, decides the number of extra hops used for inter-cell relay based on call distribution inside cell. The second approach is *delay sensitive congestion relief*. The delay sensitive approach is based on the fact that the number of allowed extra hops for inter-cell relay may be limited by the quality of service (QoS) requirements of calls. Imposing the limit on the number of extra hops, the approach tries to maximize the number of supported calls by varying the number of calls inter-cell relayed to adjacent cells and the number of calls connected to the BS of the congested cell. We illustrate that inter-cell relay can be used to increase the number of supported calls inside a congested cell. Our results show that the number of calls supported inside a congested cell can be doubled. We also demonstrate that the devised congestion relief approaches can be used to fully utilize available resources in adjacent BSs, increasing the number of accepted calls inside the congested cell to almost 4 times the number of calls accepted in single-hop case.

The remainder of the paper is organised as follows. Section 2 introduces the models used in the analysis. In section 3, inter-cell relay is introduced along with the formulas, to quantify interference when applying inter-cell relay. In section 4 congestion relief using inter-cell relay is analyzed. The potential gains achieved in congestion relief are emphasized by introducing two approaches to maximize the number of supported calls inside a congested cell. Section 5 concludes.

II. SYSTEM MODEL

We adopt a multi-hop CDMA cellular network model similar to that in [9]. Hexagonal cells with six neighboring cells are considered. Each Cell is divided into k co-centric discs with equal widths centered at BS. Discs are numbered 0 to k - 1 with the inner-most disc being disc 0. An example cell with four

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discs is shown in Figure 1. Single-hop network is represented by the special case with one disc. The radius of a cell is denoted D, r_i represents the outer radius of disc i. and L is the distance between two adjacent BSs.

The analysis is performed for a single uplink slot. Only MTs inside the inner-most disc are allowed to communicate directly with BS. MTs in the rest of the discs have to relay data through MTs in next disc closer to BS. Our model is generic and can be used in time division duplex (TDD) or frequency division duplex (FDD). Hence the results are considered to be per time slot per frequency band. Calculations are done on circular cells, which is a good approximation [11]. All MTs and BSs use omni-directional antennas. We assume that perfect power control is performed in all hops [9].

We consider a 19-cell cluster. To simplify discussion, and without loss of generality, we adopt the following tagging convention. We define a target cell, which is the cell in the center of the cluster. This is the main cell in our analysis. Cells, which are adjacent to the target cell, are called 1st tier (B1) cells. Cells, which are adjacent to 1st tier cells but not the target cell, are called 2nd tier (B2) cells. A target cell, its 1st tier B1 cells and 2nd tier B2 cells are shown in Figure 2. The number of calls in target cell, B1 cell and B2 cell are denoted N_{Tg}, N_{B1} and N_{B2}, respectively.

For interference analysis, a signal propagation model is needed. We use the lognormal attenuation model, which is widely accepted in the analysis of CDMA-based networks [12]. In this model, the power of a received signal can be given by

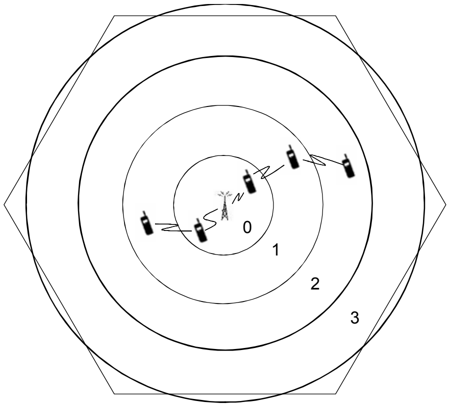

Figure 1. A cell with 4 discs

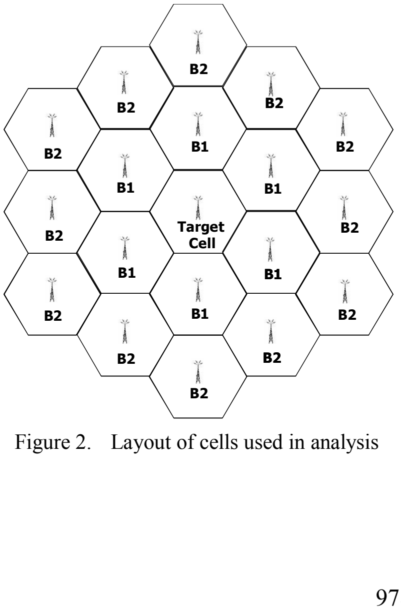

Figure 2. Layout of cells used in analysis

$$S_r = S_{tr} d^{-m} 10^{\xi/10} \tag{1}$$

where S_{tr} is the transmission power, d is the distance from transmitter to receiver and ξ represents shadowing effects. m is the path-loss. Shadowing effect does not depend on distance travelled by signal. Accordingly, shadowing effects are ignored in the analysis of this paper.

III. INTER-CELL RELAY

In traditional single-hop cellular networks, MTs residing inside the area of one cell have to connect to the BS of the same cell. MTs are not allowed to utilize available resources in adjacent cells. When a congested cell is adjacent to a less loaded cell, it could be beneficial to allow calls inside congested cell to use available resources in the less loaded cell.

In our previous work, we introduced the concept of inter-cell relay. Inter-cell relay means diverting calls originating from MTs inside a heavy-loaded cell to BSs of adjacent cells for the purpose of either congestion relief or load balancing [10]. We considered the layout shown in Figure 2. The target cell is assumed to be heavy loaded (Congested) and the rest of the cells are lightly loaded. Calls from MTs inside the target cell are inter-cell relayed to BSs of B1 cells to allow more calls to be accepted inside the area of the target cell.

A scheme, that determines which calls to be inter-cell relayed, needs to be devised. Calls are relayed to neighboring B1 BSs from MTs, which are in the transmission range of MTs inside the coverage area of B1 cells. The distance between these MTs and the supporting BS has to be less than $D + r_0$, where r_0 is the radius of the innermost disc and the transmission range of MTs. MTs with relayed calls are naturally inside the area of the target cell and outside the cell area of the supporting BS. Therefore, MTs, that lie inside the intersection area between the target cell and a disc centered at a supporting BS with inner disc D and outer disc $D + r_0$, can inter-cell relay their calls. This intersection area is referred to as the relaying area. The rest of the target cell is non-relaying area. One sector of the target cell, with its relaying and non-relaying areas, is shown in Figure 3.

Based on this arrangement, a new interference component is introduced at the target BS and supporting BSs. The new component is the interference resulting from the inter-cell relayed calls.

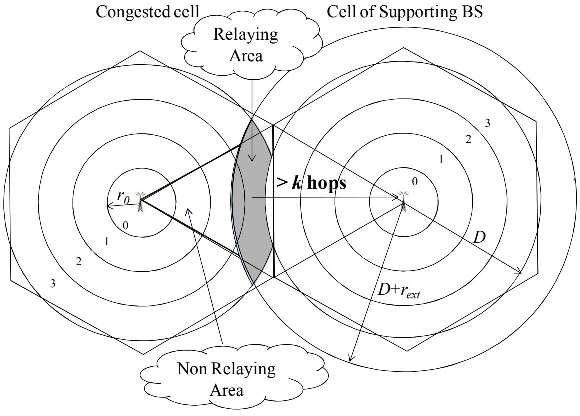

Figure 3. Relaying and non-relaying area in target cell

In [10], we derived interference formulas at the target BS and each of the supporting BSs as follows.

The interference at the target BS consists of three components, which are intra-cell, inter-cell and relaying interference. Intra-cell interference results from all active transmitters inside the target cell and is represented as

$$I_{IntraTgBS} = \sum_{i=0}^{k-1}\left[N_{NR\_i} * I_{Intra\_NRA\_hopi}\right] \tag{2}$$

$$I_{Intra\_NRA\_hopi} = \begin{cases} S_R & i = 0 \\ \dfrac{1}{NRSA(i)} \displaystyle\int_{-\pi/6}^{\pi/6}\int_{r_{i-1}}^{r_i} S_i(r) r^{-m+1} drd\,\theta & \\ & 1 \le i \le k \\ given \quad \sqrt{r^2 + L^2 - 2Lr\cos(\theta)} > D + r0 & \end{cases}$$

where N_{NR_i} and $I_{Intra\_NRA\_hopi}$ are the number of calls and the intra-cell interference caused by a single-hop inside the non-relaying area of disc *i,* respectively. S_R is the required power of received signal and *NRSA*(*i*) is the non-relaying area per sector of disc *i*. $S_i(r)$ is the function of transmission power of MT in disc *i*, which is at a distance *r* from BS [8].

Inter-cell interference is the interference resulting from calls originating inside adjacent B1 cells and all its hops. Inter-cell interference at the target BS is expressed as

$$\begin{aligned} I_{InterTgBS} &= \frac{N_0 S_R}{A(0)} \int_0^{2\Pi}\int_0^{r_0} \frac{r^{m+1}}{\left(r^2 + L^2 - 2Lr\cos(\theta)\right)^{\frac{m}{2}}} drd\,\theta \\ &+ \sum_{i=1}^{k-1}\left[\frac{N_i}{A(i)} \int_0^{2\Pi}\int_{r_{i-1}}^{r_i} \frac{S_i(r)r}{\left(r^2 + L^2 - 2Lr\cos(\theta)\right)^{\frac{m}{2}}} drd\,\theta\right] \end{aligned} \tag{3}$$

where N_i is the number of transmitting MTs in disc *i* of B1 cell and *A*(*i*) is the area of disc *i.* The last interference component, known as relaying interference, results from calls originally inside the target cell but inter-cell relayed to adjacent BSs, with all their hops. Relaying interference at the target BS is given by

$$I_{relayingTg\ BS\_1} = N_R \sum_{i=0}^{k} I_{relaying\_hopi} \tag{4}$$

$$I_{relaying\_hopi} = \begin{cases} \dfrac{S_R}{SA(0)} \displaystyle\int_{-\pi/6}^{\pi/6}\int_0^{r_0} \frac{r^{m+1}}{\left(r^2 + L^2 - 2Lr\cos(\theta)\right)^{m/2}} drd\,\theta & i = 0 \\ \dfrac{1}{SA(i)} \displaystyle\int_{-\pi/6}^{\pi/6}\int_{r_{i-1}}^{r_i} \frac{S_i(r)r}{\left(r^2 + L^2 - 2Lr\cos(\theta)\right)^{m/2}} drd\,\theta & 0 < i < k \\ \dfrac{1}{RA} \displaystyle\int_{-\pi/6}^{\pi/6}\int_D^{D+r_0} \frac{S_i(r)r}{\left(r^2 + L^2 - 2Lr\cos(\theta)\right)^{m/2}} drd\,\theta & \\ & i = k \\ given \quad \sqrt{r^2 + L^2 - 2Lr\cos(\theta)} < D & \end{cases}$$

where N_R is the number of calls relayed to one adjacent BS, and $I_{relaying\_hopi}$ is the interference resulting from one hop of the relayed call inside disc *i* of B1 cell. *SA*(*i*) is the sector area of disc *i* and *RA* is the relaying area per B1 BS. Total interference at target BS is the sum of all three components.

Interference at any of the supporting BSs also consists of three components. The first component is the intra-cell interference resulting from calls originating inside the supporting cell with all its hop and is given by

$$I_{IntraBS} = N_0 S_R + \sum_{i=1}^{k-1}\left[\frac{N_i}{A(i)} \int_0^{2\pi}\int_{r_{i-1}}^{r_i} S_i(r) r^{-m+1} drd\,\theta\right] \tag{5}$$

The second component is the inter-cell interference. Each supporting B1 cell has 6 adjacent cells which are 3 B2 cells, 2 B1 cells and the target cell. The inter-cell interference from each B2 cell resembles inter-cell interference caused at the target BS and can be represented by (3). The inter-cell interference coming from the target cell is similar, with the integrations limited to non-relaying area only, yielding

$$I_{InterSBS\_Tg} = \sum_{i=0}^{k-1} N_{NR\_i} I_{InterSBS\_Tg\_hopi} \tag{6}$$

$$I_{InterSBS\_Tg\_hopi} = \begin{cases} \dfrac{1}{NRSA(0)} \displaystyle\sum_{s=0}^{5}\left[\begin{matrix} \displaystyle\int_{(2s-1)\pi/6}^{(2s+1)\pi/6}\int_0^{r0} \frac{r^{m+1}}{r^2 + L^2 - 2Lr\cos\theta} drd\theta \\ given \quad \sqrt{r^2 + L^2 - 2Lr\cos(\theta - (2s\pi/6))} > D + r_0 \end{matrix}\right] & i = 0 \\ \dfrac{1}{NRSA(i)} \displaystyle\sum_{s=0}^{5}\left[\begin{matrix} \displaystyle\int_{(2s-1)\pi/6}^{(2s+1)\pi/6}\int_{r_{i-1}}^{r_i} \frac{S_i(r)r}{r^2 + L^2 - 2Lr\cos\theta} drd\theta \\ given \quad \sqrt{r^2 + L^2 - 2Lr\cos(\theta - (2s\pi/6))} > D + r_0 \end{matrix}\right] & 1 \le i < k \end{cases}$$

where $I_{InterSBS\_Tg\_hopi}$ is the inter-cell interference per hop coming from the non-relaying area of disc *i* of the target cell.

Inter-cell interference coming from other adjacent B1 cells is more involved. The adjacent B1 BSs can also be supporting inter-cell relayed calls from the target cell. Inter-cell interference coming from one B1 cell consists of two components, which can be expressed as

$$I_{InterSBS\_B1} = I_{InterBS\_1} + N_R \sum_{i=0}^{k} I_{InterSBS\_relayed\_hopi} \tag{7}$$

$$I_{InterSBS\_relayed\_hopi} = \begin{cases} \dfrac{S_R}{SA(0)} \displaystyle\int_{\pi/6}^{\pi/2}\int_0^{r_0} \frac{r^{m+1}}{\left(r^2 + L^2 - 2Lr\cos(\theta)\right)^{m/2}} drd\,\theta & i = 0 \\ \dfrac{1}{SA(i)} \displaystyle\int_{\pi/6}^{\pi/2}\int_{r_{i-1}}^{r_i} \frac{S_i(r)r}{\left(r^2 + L^2 - 2Lr\cos(\theta)\right)^{m/2}} drd\,\theta & 0 < i < k \\ \dfrac{1}{RA} \displaystyle\int_{\pi/6}^{\pi/2}\int_D^{D+r_0} \frac{S_i(r)r}{\left(r^2 + L^2 - 2Lr\cos(\theta)\right)^{m/2}} drd\,\theta & \\ & i = k \\ given \quad \sqrt{r^2 + L^2 - 2Lr\cos(\theta)} < D & \end{cases}$$

where $I_{InterBS\_1}$ is the first component of the inter-cell interference from B1 cell, which results from calls originating inside the B1 cell and is defined by (3). $I_{InterSBS\_relayed\_hopi}$ is the inter-cell interference resulting from one hop of each call relayed from the target cell to B1 BS.

The last interference component at the supporting BS is the relayed interference, which results from inter-cell relayed calls from the target cell to the supporting BS, where interference is calculated. Summing over all hops of relayed calls, the relayed interference at a supporting BS can be expressed as

$$I_{relayedSBS} = N_{R\_0} \sum_{i=0}^{k} I_{relayedSBS\_hopi} \tag{8}$$

$$I_{relayedSBS\_hopi} = \begin{cases} S_R & i = 0 \\ \dfrac{1}{SA(i)} \displaystyle\int_{-\pi/6}^{\pi/6}\int_{r_{i-1}}^{r_i} S_i(r) r^{-m+1} drd\,\theta & 1 \le i \le k-1 \\ \dfrac{1}{RA} \displaystyle\int_{-\pi/6}^{\pi/6}\int_D^{D+r_0} S_i(r) r^{-m+1} drd\,\theta & \\ & i = k \\ given \quad \sqrt{r^2 + L^2 - 2Lr\cos(\theta)} < D & \end{cases}$$

where we assume that B1 cells are numbered 0 to 5 and the BS where interference is calculated is B1 cell number 0. N_{R_0} is then the number of calls relayed to the supporting BS in consideration and $I_{relayedSBS\_hopi}$ is the interference resulting per hop *i* per relayed call.

The detailed derivation can be found in [10].

IV. CONGESTION RELIEF

Having presented inter-cell relay and analyzed the resulting interference, the potential gains that can be achieved using inter-cell relay need to be investigated. Toward this end, we explore the possibility of achieving congestion relief by using inter-cell relay.

In the analysis, we consider the cell layout in Figure 2. We assume that the target cell is heavily loaded, while all other cells are lightly loaded with available resources. It is required to support as many calls as possible inside the area of the target cell to prevent or at least decrease call rejection (i.e. congestion). The number of calls is limited by the experienced interference. Each call has a pre-determined minimum quality, which has to be achievable for a call to be accepted. The quality of calls in this paper is taken to be a certain data rate at a granted maximum bit error rate (BER). BER can be maintained below a certain value by keeping the bit energy to interference ratio (E_b/I_0) above certain threshold (τ). E_b/I_0 is calculated from the Signal to Interference Ratio (SIR) by dividing the power of the desired signal by the allocated data rate (R) and the interference power by the bandwidth (W). By forcing the bit energy to interference ratio to stay above the threshold (τ) at all BSs, a limit on the number of supported calls can be obtained. Using the formulas for interference at the target BS, an upper bound on the density of calls inside the target cell can be obtained as

$$\rho_{Tg} \leq \frac{{}^{W}\!/_{\tau R} + 1 - 6 * N_B * I_{InterTgBS\_call}}{6\sum_{i=0}^{k-1}\left[NRSA(i) * I_{Intra\_NRA\_hopi}\right] + 6 * RA * \sum_{i=0}^{k} I_{relaying\_hopi}} \tag{9}$$

Interference level has to be kept below threshold also at the supporting BSs, which yields another upper bound on the density of calls inside the target cell as

$$\rho_{Tg} \leq \frac{{}^{W}\!/_{\tau R} + 1 - N_B I_{IntraSBS\_call} - 5 N_B I_{InterBS\_call}}{2RA\sum_{i=0}^{k} I_{InterSBS\_relayed\_perhop\_i} + \sum_{i=0}^{k-1} NRSA(i) I_{InterSBS\_Con\_perhop\_i} + RA\sum_{i=0}^{k} I_{relayedSBS\_perhop\_i}} \tag{10}$$

For illustration purposes, and without loss of generality, we consider a case where all cells other than the target cell have the same number of calls (N_B) and that calls are uniformly distributed over the area of each cell. We also assume one class of service with parameters defined in Table 1.

TABLE I. PARAMETERS USED IN CALCULATIONS

Path Loss	*m*	4
Frequency Band	*W*	1.22 MHz
Data Rate	*R*	9.6 Kbps
Max. Bit Error Rate	BER	10^{-3}
E_b/I_0 Threshold	τ	5 (7 dB)

Based on the two upper limits in (9) and (10), the number of calls that can be supported inside the target cell is plotted in Figure 4. In these calculations, all neighboring cells (B1 and B2 cells) are assumed to be almost half loaded (10 calls per cell, based on the calculation under uniform distribution of calls among the whole cell as shown in [8]).

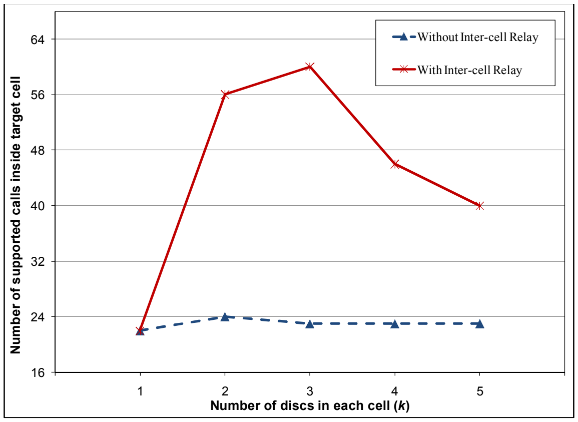

Figure 4. Number of supported calls inside target cell with and without inter-cell relay

From Figure 4, it can be seen that inter-cell relay can be used to increase the number of calls that can be supported inside a congested cell. Using inter-cell relay, the available resources in lightly loaded cells can be used by calls inside a congested cell. The number of supported calls can be more than doubled using inter-cell relay. We remark here that the special case with 1 disc represents the single-hop cellular case, where inter-cell relay is not applied.

It can be noticed that the number of supported calls first increases with increasing the number of discs inside each cell, then decreases. The decrease occurs because of the shrinking of the relaying area. As the number of discs increases, the area of each disc decreases, decreasing the relaying area inside the target cell (Figure 3), resulting in less potential calls for inter-cell relaying. Despite this, the number of supported calls is almost doubled using inter-cell relay with all number of discs. It has to be remarked that the bound with lower value has to be forced at any time to guarantee the quality of all calls.

Based on the results in Figure 4 and the interference levels at the target BS and supporting BSs, it is observed that the resources at supporting BSs are still underutilized in some cases. To fully utilize resources of supporting BSs, two approaches can be devised. The first approach is increasing the relaying area by allowing more than one extra hop for inter-cell relay. In the second approach, the density of supported calls can be increased inside the relaying area of the congested cell. In other words, the number of inter-cell relayed calls is increased to make use of available resources of supporting BSs. The first approach is applicable when there is a certain call distribution inside the target cell. On the other hand, the second approach is suitable when the service is delay sensitive. This implies that there is a limit on the number of allowed hops. In this case, it may not be possible to increase the relaying area beyond a certain point. Instead, more calls can be accepted inside the relaying area, if any is available. The two approaches are illustrated in the following subsections.

A. Distribution-based Congestion Relief

The distribution-based approach is based on the idea that there is usually a certain call distribution inside the cell and the goal is to maximize the number of supported calls based on the specific distribution. In this approach, the relaying area is varied by changing the number of extra hops for inter-cell relay (Figure 3), to support as many calls as possible inside the area of the congested cell.

Using multiple extra hops for inter-cell relay results in slight modifications in the interference formulas at the target and supporting BSs. For intra-cell interference at the target BS and inter-cell interference coming from the target BS at the supporting BS, expressed by equations (2) and (6), respectively, only the conditions are modified to account for multiple extra hops, by multiplying the width of the disc (r_0) by the number of extra relaying hops (n).

Formulas for interference at the target and supporting BS resulting from relayed calls have to account for multiple extra hops for inter-cell relay, by adding the interference from the extra hops. Hence, the summations in equations (4) and (8) are extended to $k+n-1$ terms, where n is the number of extra hops. The same modification applies for inter-cell interference at a supporting BS resulting from another supporting cell, expressed by (7). The modified formulas are not shown here due to space limitation.

The number of extra hops for inter-cell relay has to be less than the number of discs originally inside cells. Otherwise, the relaying area will be too large and will cover the whole area of the target cell. In the example in Figure 3, the number of extra hops for inter-cell relay is limited to 3. If 4 extra hops are used, the relaying area will extend beyond the BS of the target cell, which means that the resources of the target BS cannot be used and will be wasted. In the results below, it will be shown that the number of extra hops that yields the maximum number of calls is usually less than the number of discs per cell.

As an illustrative example, we consider a uniform distribution of calls inside the target cell and calculate the maximum number of calls that can be supported inside the area of the target cell. All other cells are again half loaded (10 calls per cell). The number of supported calls inside the area of the target cell is tabulated in Table 2 for different number of discs per cell and different number of extra hops for inter-cell relay. The row with zero extra hops represents the case when no inter-cell relay is performed. The results in Table 2 show the potential gains that can be achieved by inter-cell relaying calls from a congested cell to adjacent less loaded BSs. Inter-cell relay can increase the number of accepted calls inside a congested cell.

TABLE II. NUMBER OF CALLS IN TARGET CELL WITH DIFFERENT NUMBER OF EXTRA HOPS FOR INTER-CELL RELAY DISTRIBUTION-BASED CONGESTION RELIEF

Number of extra hops (n)	Number of discs per cell (k)				
	1	2	3	4	5
0	22	24	23	23	23
1	/	56	60	46	40
2	/	/	48	70	80
3	/	/	/	41	55
4	/	/	/	/	37

It can be noticed that the number of supported calls increases with the increase of the number of extra hops till a certain point, then starts decreasing. This is the number of extra hops that achieves the highest number of supported calls and should be used under these conditions. At this point, the resources of the supporting BSs are fully utilized and no more calls can be inter-cell relayed. Further increase in the number of extra hops (i.e. extending relaying area) results in higher interference from inter-cell relayed calls at the target BS, because of inter-cell relaying calls, which are closer to the target BS. The interference increase at the target BS results in a decrease in the number of calls supported by the target BS, without an increase in the number of inter-cell relayed calls. Accordingly, the total number of supported calls inside the area of the target cell decreases.

B. Delay Sensitive Congestion Relief

In this approach, the maximum number of extra hops for relaying is limited by calls delay QoS requirements. Based on the pre-determined number of extra hops for inter-cell relay, it is required to maximize the number of supported calls inside the congested cell by determining the number of calls to be inter-cell relayed to the supporting BSs and the number of calls to be supported by the BS of the congested cell.

The number of calls supported by either the BS of the congested cell or the supporting BSs can be varied by changing the density of calls inside the non-relaying and relaying areas of the congested cell. This can then be formulated as an optimization problem. Due to space limitations, we will only show the case, where all neighboring cells have the same number of calls. The decision variables are the call densities inside non-relaying and relaying areas, which are denoted ρ_{NR} and ρ_R, respectively. The constraints are obtained by keeping the interference level below thresholds at target and supporting BSs, which yields the two constraints (11) and (12) shown on the top of next page.

Also, the densities have to be positive or zero. We force the densities to be above zero, hence the condition

$$\rho_{NR} \quad , \quad \rho_R > 0 \tag{13}$$

The goal of the optimization problem is to maximize the total number of calls inside the area of the congested cell. Consequently, the objective function of the optimization problem can be given by

$$\max_{\{\rho_{NR},\rho_R\}} \{\rho_{NR} * NRAT + 6 * \rho_R * RA\} \tag{14}$$

where $NRAT$ is the total non-relaying area inside the congested cell and RA is the relaying area per one neighboring BS, which is shown in Figure 3.

As an illustrative example, we consider the case when only one extra hop for inter-cell relay is allowed due to the nature of calls in the network. The number of calls that can be supported inside the area of the target cell is plotted in Figure 5. From the results, it can be seen that by increasing the number of relayed calls, the available resources in lightly loaded cells can be fully used. The number of accepted calls inside the area of the target cell can be increased and can reach 5 times the number of supported calls without inter-cell relay.

$$6\rho_{NR}\sum_{i=0}^{k-1}\left[NRSA(i)*I_{Intra\_perhop\_NRA\_i}\right]+6\rho_{R}RA\sum_{i=0}^{k}I_{relaying\_perhop\_i}\leq W/_{\tau R}+1-6N_{B}I_{InterConBS\_call} \tag{11}$$

$$\rho_{NR}\sum_{i=0}^{k-1}NRSA(i)I_{InterSBS\_Con\_perhop\_i}+\rho_{R}RA\left(\sum_{i=0}^{k}I_{relayedSBS\_perhop\_i}+2\sum_{i=0}^{k}I_{InterSBS\_relayed\_perhop\_i}\right)\leq W/_{\tau R}+1-N_{B}I_{IntraSBS\_call}-5N_{B}I_{InterBS\_call} \tag{12}$$

The numbers are so high because the bottleneck is avoided. The bottleneck is the resource availability in the BS of the congested cell. By relaying more calls to adjacent cells, the load on the congested BS is distributed among the adjacent BSs. This can be further illustrated by the comparison between the number of inter-cell relayed calls and the calls connected to the target BS. In the 2-disc case in Figure 5, the total number of supported calls inside the area of the target cell is 85 calls, which are divided into 79 inter-cell relayed calls and only 6 calls connected to the BS of the target cell. Dividing the total inter-cell relayed calls among the 6 adjacent supporting BSs, 13 calls are inter-cell relayed to each supporting BS. Hence, each supporting BS supports 23 calls in total, which is the maximum number of calls that can be supported by a BS under uniform distribution. The resources of the supporting BSs are fully utilized. On the other hand, only 6 calls are supported by the target BS avoiding the bottleneck.

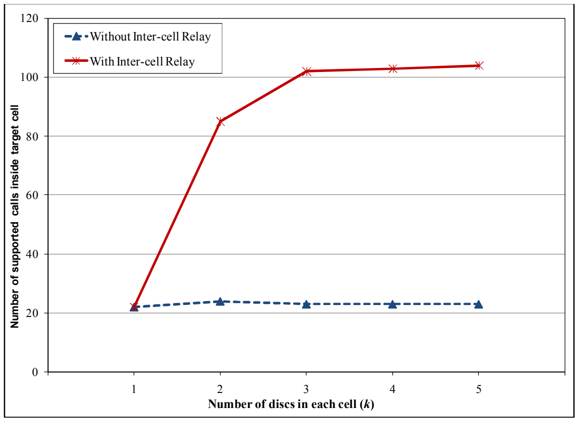

Figure 5. Number of supported calls inside target cell Delay Sensitive Congestion Relief

The two congestion relief approaches discussed in this paper illustrate the benefits gained from using multihop communication in congestion relief using inter-cell relay. The results show that the number of calls inside a congested cell can reach more than 4 times higher than the number of calls accepted in single-hop case. It can also be remarked here that decreasing energy consumption can be taken into consideration when determining the number of extra hops for inter-cell relay and the number of relayed and non-relayed calls.

V. CONCLUSION

In traditional single-hop cellular networks, congestion sometime occurs in a cell, even if adjacent cells are lightly loaded with available resources, resulting in underutilization of network resources. Using multihop communication, inter-cell relay, which entails diverting calls originating in one cell to BSs of adjacent cells, can be performed. Inter-cell relay can be used for congestion relief.

In this paper, congestion relief using inter-cell is studied in multihop CDMA cellular networks. We show the potential increase in number of supported calls inside a congested cell as a result of inter-cell relaying calls to adjacent less loaded BSs. Based on network conditions, two approaches are devised for congestion relief to maximize the number of supported calls. The distribution-based approach varies the relaying area inside the congested cell, while the delay sensitive approach decides the number of calls to be inter-cell relayed and the number of calls to be connected to the congested BS, based on the constraint on the relaying area size. Our analysis demonstrates that both approaches can better utilize available resources in adjacent BSs. We show that the number of calls inside the congested cell can be increased to more than 4 times the number of calls that can be supported without the use of inter-cell relay. Our results emphasize the potential benefits that can be gained by congestion relief using multihop inter-cell relay.

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