Distributed Timeslot Allocation with Crossed Slots in CDMA-TDD Systems

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Abstract

Code division multiple access system with time division duplex (CDMA-TDD) is a promising solution to cope with traffic asymmetry of downlink and uplink in multimedia services. When a rate of asymmetry is different in each cell, CDMA-TDD system may employ crossed slots, where a timeslot is used for different links in cells. However, it may suffer from base station (BS)-to-BS and mobile station (MS)-to-MS interference problem. Zone division scheme is an efficient way to tackle the crossed slot interference by dividing a cell into inner and outer zones and restricting communication in crossed slots only to inner zone. In this paper, we propose distributed crossed slot resource allocation with zone division in multi-cell CDMA-TDD system. Two conditions for crossed slot resource allocation are defined and the bound on the size of inner zone is analyzed mathematically based on the conditions. Relationship between the capacity of crossed slot and the size of inner zone is also analyzed. Then, numerical results of the mathematical analysis are presented, showing that the proposed crossed slot allocation is effective for traffic asymmetry problem.

Keywords

CDMA-TDD, crossed slot, zone division, distributed resource allocation

1. Introduction

Next generation wireless communication systems are expected to support multimedia services with increasing demand for various types of broadband applications. The asymmetry of traffic between downlink (DL) and uplink (UL) is one of the most important features of multimedia communications. Code division multiple access system with time division duplex (CDMA-TDD) is a promising solution to cope with the traffic asymmetry problem [1].

In CDMA-TDD system, DL and UL are separated by different timeslots on the same frequency. It is capable of managing traffic asymmetry by assigning asymmetric number of timeslots to DL and UL according to their traffic loads. However, when the rate of asymmetry is different in each cell, it leads to additional inter-cell interference problem. If adjacent cells independently allocate timeslots, it is likely that some timeslots are used for DL in one cell and for UL in the other cell at the same time. These timeslots are called *crossed slots* [2]. Figure 1 illustrates that BS 2 interferes with BS 1 (BS-to-BS interference) and MS 1 induces interference to MS 2 (MS-to MS interference).

It is reported that BS-to-BS interference substantially decreases the system capacity [3]. MS-to-MS interference may also result in degradation of performance when interfering and interfered MSs are close to the cell boundary [4]. Thus, careful timeslot allocation is necessary in CDMA-TDD system. Yomo and Hara [5] argue that the allocation of timeslots to DL and UL should be synchronized in adjacent cells to minimize the inter-cell interference. However, Haas et al [6] prove that crossed slot does not necessarily suffer from capacity loss. Moreover, recent results have shown that resource allocation with crossed slots outperforms non-crossed slot allocation if an elaborate allocation algorithm is employed [2, 7-13].

Several schemes have been proposed to tackle the crossed slot interference problem. Haas and McLaughlin [8] propose the ‘timeslot opposing technique’ based on the result of [6], where a cell exchanges a DL slot with an UL slot when it reduces inter-cell interference. However, it requires path gain information of all BS-to-BS and MS-to-MS pairs, which is difficult to obtain. In [9], antenna beam forming is adopted to mitigate inter-cell interference. However, it is still too complex to be implemented.

Zone division scheme [2, 10-13] is an efficient approach of allocating crossed slot, where each cell is divided into two zones: inner zone and outer zone. Then, resource of crossed slots is allocated to MSs in inner zone to reduce inter-cell interference. The advantage of the zone division is its simplicity. It requires neither huge path gain information nor complex antenna technique, showing good performance. Jeon and Jeong [2] compare the capacity of crossed slot and non-crossed slot resource allocation in two-cell model and conclude that the crossed slot allocation outperforms non-crossed slot if timeslots are properly allocated. The performance of zone division scheme is also investigated in [11-12] by simulation studies. In [13], an efficient crossed slot resource allocation algorithm is proposed with zone division scheme, but limited to two-cell model.

Resource allocation in multi-cell CDMA-TDD system is investigated in this paper. We propose distributed resource allocation scheme with zone division. It should be noted that the main purpose of zone division is to reduce BS-to-BS and MS-to-MS interference. Thus, the size of inner zone is one of the most important parameters to be determined.

We define two conditions for the multi-cell crossed slot resource allocation. Inter-cell interference from a BS in a cell of DL crossed slot should not exceed that from MSs in a cell of UL regular slot. Also, performance of the cell of DL crossed slot should not be degraded by interference from adjacent cells. Similar conditions are also established in a cell of UL crossed slot. Under these conditions, theoretical bound on the maximum size of inner zone is analyzed mathematically. Moreover, we investigate the tradeoff between capacity of a crossed slot and inner zone size. Implementation issues and numerical results are also presented. The performance of crossed slot is illustrated in terms of increased capacity and reduced blocking probability.

The remainder of this paper is organized as follows. In Section 2, the system model is explained and distributed resource allocation scheme is proposed. In Section 3, the proposed scheme is mathematically analyzed. Numerical results are provided in Section 4. We discuss implementation issue in Section 5, and finally present conclusion in Section 6.

2. System model and timeslot allocation scheme

2.1. CDMA-TDD System model

We consider TD-CDMA technology which is the specification of TDD mode in UMTS Terrestrial Radio Access (UTRA) system. It is a mixture of Time Division Multiple Access (TDMA) and CDMA. Detailed review of TD-CDMA system can be found in [14-15].

Resource of TD-CDMA is defined in time and code domain. The basic resource unit (RU) is one code/timeslot per frequency [16]. We assume that the data rate of an RU is fixed to 8 Kbps by considering spreading factor of 16 and 1/2 rate channel coding. Multiple rate services can be achieved by the code and timeslot pooling of multiple RUs. Since the capacity of CDMA systems is interference limited, the number of allocated RUs in each frame can be different. 15 slots per 10ms frame are recommended with 5MHz channel spacing in UTRA TDD physical layer.

2.2. Distributed timeslot allocation scheme

In this paper, we propose distributed timeslot allocation scheme by which each cell determines whether to use a timeslot for DL or UL. The number of RUs accommodated in each timeslot is also determined by each cell in distributed manner.

The proposed scheme is briefly described below. A radio network controller (RNC) collects DL and UL traffic loads in each cell. Then, it divides the 15 timeslots into DL and UL according to the average traffic loads. This is the RNC guideline of timeslot allocation for its cells. We call this guideline *nominal slot allocation* which cells are recommended to follow. However, some cells may require additional DL or UL timeslots. Thus, it is possible to allocate some timeslots against the nominal slot allocation. If a cell allocates a timeslot to DL (UL) as guided by the nominal timeslot allocation, it is called *DL regular slot* (*UL regular slot*). On the contrary, if a timeslot is allocated to DL in a cell while it is nominally allocated to UL by RNC, it is called *DL crossed slot*. Similarly, *UL crossed slot* is defined as the timeslot that is nominally allocated to DL but is used for UL in a cell. The concept of DL and UL crossed slots is shown in Figure 2 where timeslots 3-6 are DL crossed slots in cell 1 and slots 7-9 are UL crossed slots in cell 2.

The use of timeslots against RNC guideline is caused by deficiency in DL or UL capacity. Since it causes BS-to-BS or MS-to-MS interference, transmission power of cells using crossed slots should be restricted to avoid severe interference problem. The purpose of this study is to make crossed slots behave just like nominal timeslots in terms of interference. In other words, a cell with crossed slots needs to regulate the amount of interference from itself so that other cells do not figure out whether the crossed slot is used in the cell. Also, the performance at the crossed slot should not be degraded by interference from adjacent cells. To achieve this purpose, we define the following conditions for the use of crossed slots.

Condition 1-DL: Inter-cell interference from BS in a cell of DL crossed slot should not exceed that from MSs in a cell of UL regular slot.

Condition 1-UL: Inter-cell interference from MSs in a cell of UL crossed slot should not exceed that from BS in a cell of DL regular slot.

Condition 2-DL: The E_b / N_0 of a MS in a cell of DL crossed slot should exceed the minimum DL E_b / N_0 requirement.

Condition 2-UL: The E_b / N_0 of a BS in a cell of UL crossed slot should exceed the minimum UL E_b / N_0 requirement.

The transmission power of a BS or a MS generally goes up as a receiver is further away from the transmitter. This implies that in order to reduce the interference in a crossed slot, the distance between transmitter and receiver has to be limited to a certain range in a cell. Thus, the usage of crossed slots is restricted to inner zone [2, 10-13]. The maximum size of inner zone is discussed with mathematical analysis in the next section. We will also investigate the tradeoff between the capacity of crossed slots and the size of inner zone. Performance comparison between crossed and non-crossed slot allocations is provided in terms of capacity and blocking probability.

3. Mathematical analysis of crossed slots

By assuming that every cell in the system follows the nominal timeslot allocation, we obtain the maximum number of available RUs in a DL or an UL regular slot which satisfies minimum bit energy to interference and noise ratio (E_b / N_0) requirement. The interference generated from a cell is also calculated for each DL and UL regular slot. Based on the two conditions introduced in Section 2, maximum sizes of inner zones in DL and UL are obtained under the assumption that DL (UL) crossed slot accommodates the same number of RUs in DL (UL) regular slot. Tradeoff between the number of RUs in a crossed slot and the size of inner zone is investigated, followed by capacity and blocking probability analysis of crossed slots.

3.1. Assumptions and notations

The following assumptions are used in order to simplify the mathematical analysis.

- Interference from non-adjacent cells is negligible.
- Path loss is given as $kd^{-\nu}$, where ν is path loss exponent, k is path loss constant, and d is distance between transmitter and receiver.
- The actual shapes of cells are irregular curves due to the shadowing effect [17]. However, we assume circular cell model with radius D as shown in Figure 3 to simplify our analysis. Cells are overlapped in their boundaries to allow for handover margin.
- Inner zone for crossed slots is also assumed to be circular with radius r.
- Every MS is supported with single RU of data rate R. Hereafter, we will not distinguish the number of supported MSs and the number of supported RUs in a cell.

The superscripts *d*, *u*, and *c* denote DL, UL, and crossed slot, respectively.

3.2 Amount of inter-cell interference and the maximum number of MSs

We first analyze a case where a timeslot is used for DL in every cell. We consider a target cell interfered by L adjacent cells. In DL, each MS in the target cell receives different amount of inter-cell interference depending on its location. Thus, we consider a tagged MS t that represents an average case of MSs in DL. To simplify our analysis we assume other MSs follow the average case as MS t. Let s be the distance between target BS and MS t. Since t represents an average case of MSs, it is assumed to be located on the circle of radius s that satisfies $\pi s^2 = \pi D^2 - \pi s^2$, i.e., $s = D/\sqrt{2}$. To obtain the amount of inter-cell interference, we employ polar coordinate where target BS is located at $(0,0)$ and the position of MS t is represented as (s,θ). To simplify our analysis, we assume $\theta = 0$. Let the distance between two BSs be D_{BB}, then the position of BS in adjacent cell j becomes $\left(D_{BB}, \frac{j\pi}{L/2}\right)$, $j = 1 \cdots L$ as shown in Figure 3. D_{jt} denotes the distance between BS in cell j and MS t in the figure. Since cells are overlapped to allow for handover margin, $D_{BB} \le 2D$. Let D_{HO} be the cell radius excluding overlapped region, then by assuming 3dB handover margin [18], we have $10\log_{10} D_{HO}{}^{-\nu} - 10\log_{10} D^{-\nu} = 3\text{dB}$ and $D_{BB} = D_{HO} + D$ as illustrated in Figure 4.

D_{jt} is given by the following equation.

$$D_{jt} = \sqrt{D_{BB}{}^2 + s^2 - 2D_{BB} s \cos\frac{j\pi}{L/2}} \tag{1}$$

Let I_j^d be the interference power that MS t receives from BS in cell j. By denoting transmission power of BS in regular DL slot as P_T^d, we have $I_j^d = P_T^d k D_{jt}{}^{-\nu}$. The total interference power I_{tot}^d that MS t receives from all adjacent cells in DL is given by

$$I_{tot}^d = \sum_{j=1}^{L} I_j^d \tag{2}$$

According to [19], the load factor of the target cell in DL is given as follows.

$$\eta^d = \frac{(1-\alpha)P_T^d k s^{-\nu} + I_{tot}^d}{(1-\alpha)P_T^d k s^{-\nu} + I_{tot}^d + P_N} \tag{3}$$

A cell achieves its pole capacity when the load factor approaches one. However, the maximum allowed loading must be kept clearly below one to ensure stability of the system [19]. Let $\eta^d_{\max}$ be the maximum planned load factor of a DL regular slot in a cell. Then, the transmission power of BS is determined by (3) and maximum power limitation $P^d_{T,\max}$.

$$P_T^d = \min\left(\frac{\eta^d_{\max}}{1-\eta^d_{\max}} \frac{P_N}{(1-\alpha)ks^{-\nu} + k\sum_{j=1}^{L} D_{jt}^{-\nu}}, \quad P^d_{T,\max} \right) \tag{4}$$

,where α denotes orthogonality factor in DL [15].

Let $(E_b/N_0)_t^d$ be the E_b/N_0 value of MS t in DL. Since P_T^d is shared by n^d MSs, it can be expressed as

$$\left(\frac{E_b}{N_0}\right)_t^d = \frac{W}{SR} \frac{P_T^d ks^{-\nu}/n^d}{(1-\alpha)P_T^d ks^{-\nu} + I^d_{tot} + P_N} \tag{5}$$

In the above equation, W and S denote spreading bandwidth and number of timeslots in a frame, respectively. Thus, *W*/*SR* represents the spreading gain of TD-CDMA system in a timeslot. As n^d increases, $(E_b/N_0)_t^d$ becomes worse. The maximum number of MSs in a timeslot, $n^d_{\max}$, can be obtained when $(E_b/N_0)_t^d$ reaches its minimum requirement γ^d.

$$n^d_{\max} = \frac{W}{SR} \frac{P_T^d ks^{-\nu}/\gamma^d}{(1-\alpha)P_T^d ks^{-\nu} + I^d_{tot} + P_N} \tag{6}$$

From now on, let us assume that the timeslot is used for UL in every cell. In UL, MSs in adjacent cells are sources of interference to the target BS. When we consider uniformly distributed MSs, the interference from each adjacent cell is identical. Thus, it is enough to analyze the interference from one adjacent cell and apply the result to others.

We assume that the target BS is located at $(D_{BB}, 0)$ and the BS in the adjacent cell is located at $(0,0)$ as shown in Figure 4. Let us consider an arbitrary MS *m* in the adjacent cell which is located at (a, θ). The transmission power of MS *m*, $P^u_{T,a}$, depends on the distance from its BS. We assume perfect power control such that BS receives the same power from its MSs. Then, the received signal power from MS m should be equal to that from a MS at cell boundary. When we denote the received power from MS m by P_R^u, we have

$$P_R^u = P_{T,D}^u kD^{-\nu} = P_{T,a}^u ka^{-\nu} \qquad (7)$$

From Equation (7), we obtain $P_{T,a}^u = P_{T,D}^u \dfrac{D^{-\nu}}{a^{-\nu}}$.

Let D_{mB} be the distance between MS m and the target BS. Then, $D_{mB} = \sqrt{D_{BB}{}^2 + a^2 - 2D_{BB}a\cos\theta}$. Let $I(a,\theta)$ be the interference power that target BS receives from MS m. Since the transmission power of m is $P_{T,a}^u$, $I(a,\theta) = P_{T,a}^u kD_{mB}{}^{-\nu}$. Also, we define I_a^u as the expected value of $I(a,\theta)$. Then, we have

$$I_a^u = \int_0^D \int_0^{2\pi} I(a,\theta)\frac{a}{\pi D^2}\,d\theta da$$

$$= \frac{P_R^u}{\pi D^2}\int_0^D \int_0^{2\pi} a^{\nu+1}\left(D_{BB}{}^2 + a^2 - 2D_{BB}a\cos\theta\right)^{-\nu/2} d\theta da \qquad (8)$$

where $a/\pi D^2$ is the probability density function of the MS locations [2].

Now, the E_b/N_0 value and load factor in UL are obtained as follows [15, Chap 8].

$$\left(\frac{E_b}{N_0}\right)^u = \frac{W}{SR}\frac{P_R^u}{(n^u-1)P_R^u + Ln^u I_a^u + P_N} \quad \text{and} \quad \eta^u = \frac{n^u(P_R^u + LI_a^u)}{n^u(P_R^u + LI_a^u) + P_N} \qquad (9)/(10)$$

Let $\eta_{\max}^u$ be the maximum planned load factor of an UL regular slot in a cell and γ^u be the minimum E_b/N_0 requirement in UL. The maximum number of MSs in a timeslot, $n_{\max}^u$, is obtained when $(E_b/N_0)^u = \gamma^u$ and $\eta^u \le \eta_{\max}^u$. From (9) and (10), P_R^u is given by

$$P_R^u = \min\left(\frac{P_N}{1-\eta_{\max}^u}\frac{\gamma^u}{W/SR + \gamma^u},\quad P_{T,\max}^u kD^{-\nu}\right) \qquad (11)$$

Then, $n_{\max}^u$ is expressed as

$$n_{\max}^u = \frac{P_R^u\left(\dfrac{W/SR}{\gamma^u}+1\right) - P_N}{P_R^u + LI_a^u} \qquad (12)$$

Let I_{tot}^{u} be the total amount of interference that a BS of UL regular slot receives from MSs in adjacent cells. Then,

$$I_{tot}^{u} = Ln_{\max}^{u} I_{a}^{u} \tag{13}$$

3.3 Bound on the maximum size of inner zone in DL crossed slot

Coverage of DL and UL crossed slots is investigated in Section 3.3 and 3.4 respectively. To have practical bound on the size of inner zone, we adopt the worst case interference scenario throughout the analysis. Though the shadowing effect is important in propagation modeling, what is more important in the size of inner zone for crossed slot is locations of tagged MS and interference sources. The worst case interference will reflect more meaningful coverage of the inner zone and the maximum supportable number of users.

We first consider Condition 1-DL introduced in Section 2.2. We examine a scenario that a target cell employs DL crossed slot and all adjacent cells use UL regular slot. Indeed, every possible case of timeslot usage in adjacent cells can be dealt with by analyzing this scenario. It is because interference from any adjacent cell is regulated below that of UL regular slot by Condition 1-DL. Therefore, some adjacent cells may also employ DL crossed slot rather than UL regular slot.

When a timeslot is used as DL crossed slot in target cell, BS-to-BS interference occurs at adjacent cells as in Figure 1. Thus, Condition 1-DL is a constraint on the transmission power at the target BS. Let $P_{T}^{c,d}$ be the transmission power at BS for DL crossed slot and $I^{c,d}$ be the interference power received at an adjacent BS. Since the distance between two BSs is D_{BB}, $I^{c,d} = P_{T}^{c,d} k D_{BB}^{\ -v}$. By Condition 1-DL, the following inequality should be satisfied.

$$I^{c,d} \le n_{\max}^{u} I_{a}^{u} \tag{14}$$

Now, we consider Condition 2-DL. To consider the worst case, we assume that the target BS is located at $(0,0)$ and tagged MS t at $(r,0)$ on the boundary of inner zone. If $r \ge D_{HO}$, interfering and interfered MSs may be located at the same position, which leads to infinite MS-to-MS interference. Thus, $r < D_{HO}$. MS *t* receives MS-to-MS inter-cell interference from MSs using UL regular slot in adjacent cells. Let us consider adjacent cell *j* whose BS is located at $\left(D_{BB}, \frac{j\pi}{L/2}\right)$. When we denote the distance between MS *t* and BS *j* as $D_{jt}(r)$, it is obtained from Equation (1) by replacing *s* with *r*.

For the worst case MS-to-MS interference, $n_{\max}^{u}$ MSs in cell *j* are assumed to be located at the cell boundary such that they have the shortest distance to the tagged MS *t*. Since $n_{\max}^{u}$ MSs simultaneously transmits in cell *j*, the total amount of interference from cell *j* to MS *t*, $I_j(r)$, is computed by $I_j(r) = n_{\max}^{u} P_{T,D}^{u} k \left(D_{jt}(r) - D\right)^{-\nu}$. Note that $I_j(r)$ is invariant to the loading of target cell. Thus the load factor of DL crossed slot is given by

$$\eta^{c,d} = \frac{(1-\alpha) P_T^{c,d} k r^{-\nu}}{(1-\alpha) P_T^{c,d} k r^{-\nu} + \sum_{j=1}^{L} I_j(r) + P_N} \tag{15}$$

From (14) and load factor constraint $\eta^{c,d} \le \eta_{\max}^{c,d}$, $P_T^{c,d}$ is determined as

$$P_T^{c,d} = \min\left(\frac{n_{\max}^{u} I_a^{u}}{k D_{BB}^{-\nu}},\quad \frac{\eta_{\max}^{c,d}}{1-\eta_{\max}^{c,d}} \frac{\sum_{j=1}^{L} I_j(r) + P_N}{(1-\alpha) k r^{-\nu}} \right) \tag{16}$$

Let $(E_b / N_0)_t^{c,d}$ be the E_b / N_0 value of MS *t* in DL crossed slot. Then, we have

$$\left(\frac{E_b}{N_0}\right)_t^{c,d} = \frac{W}{SR} \frac{P_T^{c,d} k r^{-\nu} / n_{\max}^{d}}{(1-\alpha) P_T^{c,d} k r^{-\nu} + \sum_{j=1}^{L} I_j(r) + P_N} \ge \gamma^{d} \tag{17}$$

MS *t* receives higher inter-cell interference as it approaches the boundary of inner zone. Clearly, it means that the maximum size of inner zone in DL crossed slot, $r_{\max}^{d}$, is obtained when $(E_b / N_0)_t^{c,d}$ reaches minimum requirement γ^{d}.

3.4 Bound on the maximum size of inner zone in UL crossed slot

We assume that $n_{\max}^{u}$ MSs in target cell are served in an UL crossed slot and adjacent cells use

DL regular slots. UL crossed slot generates MS-to-MS interference to MSs in neighbor cells. Severe interference problem may occur if interfering and interfered MSs are closely located at cell boundary. Thus, transmission range of a MS should be restricted by Condition 1-UL.

For the worst case interference scenario, we assume that all $n_{\max}^{u}$ MSs in UL crossed slot are located at the boundary of inner zone such that they have the shortest distance to the tagged MS *t* in adjacent cell of DL regular slot. Let D_{ct} be the distance between target BS and MS *t*, and $I^{c,u}$ be the interference power that MS *t* receives from MSs in target cell. By letting $P_{T,r}^{c,u}$ denote transmission power of a MS in target cell, $I^{c,u}$ is given by $I^{c,u} = n_{\max}^{u} P_{T,r}^{c,u} k (D_{ct} - r)^{-\nu}$. It reaches its maximum when $D_{ct} = D_{BB} - D$, i.e., MS *t* is located at its cell boundary. Since $I^{c,u}$ should not exceed I_j^d by Condition 1-UL, the following condition should be satisfied.

$$n_{\max}^{u} P_{T,r}^{c,u} (D_{BB} - D - r)^{-\nu} \le P_T^d (D_{BB} - D)^{-\nu} \tag{18}$$

The target BS experiences BS-to-BS inter-cell interference from adjacent cells of regular DL slots. Since the transmission power of adjacent BS is P_T^d, the target cell receives inter-cell interference of $L P_T^d k D_{BB}^{-\nu}$ from adjacent cells. The amount of inter-cell interference is fixed regardless of the load of target cell. Thus, the load factor of UL crossed slot, $\eta^{c,u}$, is given by

$$\eta^{c,u} = \frac{n_{\max}^{u} P_{T,r}^{c,u} k r^{-\nu}}{n_{\max}^{u} P_{T,r}^{c,u} k r^{-\nu} + L P_T^d k D_{BB}^{-\nu} + P_N} \tag{19}$$

$\eta^{c,u}$ should be kept below $\eta_{\max}^{c,u}$. Combining this condition with (18), transmission power of a MS in UL crossed slot is determined as

$$P_{T,r}^{c,u} = \min\left(\frac{P_T^d (D_{BB} - D)^{-\nu}}{n_{\max}^{u} (D_{BB} - D - r)^{-\nu}},\ \frac{\eta_{\max}^{c,u}}{1 - \eta_{\max}^{c,u}} \frac{L P_T^d k D_{BB}^{-\nu} + P_N}{n_{\max}^{u} k r^{-\nu}} \right) \tag{20}$$

Let $(E_b / N_0)^{c,u}$ be the E_b / N_0 in UL crossed slot. Then, we have

$$\left(\frac{E_b}{N_0} \right)^{c,u} = \frac{W}{SR} \frac{P_{T,r}^{c,u} k r^{-\nu}}{(n_{\max}^{u} - 1) P_{T,r}^{c,u} k r^{-\nu} + L P_T^d k D_{BB}^{-\nu} + P_N} \tag{21}$$

Similar to DL crossed slot, $(E_b / N_0)^{c,u}$ is a decreasing function of the size of inner zone. From Condition 2-UL, $(E_b / N_0)^{c,u}$ should exceed its minimum requirement. Thus, the maximum size of inner zone, $r^u_{\max}$, is obtained when $(E_b / N_0)^{c,u}$ reaches minimum requirement γ^u.

3.5 Tradeoff between the size of inner zone and the number of MSs in crossed slot

The analyses in Sections 3.3 and 3.4 are based on the assumption that $n^d_{\max}$ and $n^u_{\max}$ MSs are supported in respective DL and UL crossed slots. In this section, we investigate the relationship between the size of inner zone and the number of MSs supported in DL or UL crossed slot.

In DL crossed slots, the transmission power of BS is regulated by Condition 1-DL. Note that it is denoted by $P_T^{c,d}$ and determined by Equation (16). $P_T^{c,d}$ is shared by $n^{c,d}$ MSs within the inner zone. In this case, E_b / N_0 is dependent on $n^{c,d}$ and given by

$$\left(\frac{E_b}{N_0}\right)_t^{c,d} = \frac{W}{SR} \frac{P_T^{c,d} k r^{-\nu} / n^{c,d}}{(1-\alpha) P_T^{c,d} k r^{-\nu} + \sum_{j=1}^{L} I_j(r) + P_N} \tag{22}$$

$n^{c,d}$ can be increased as long as $(E_b / N_0)_t^{c,d} \geq \gamma^d$. Thus, the upper bound of $n^{c,d}$ for a given inner zone radius r, $n^{c,d}(r)$, is determined by

$$n^{c,d}(r) \leq \frac{W / SR}{\gamma^d} \frac{P_T^{c,d} k r^{-\nu}}{(1-\alpha) P_T^{c,d} k r^{-\nu} + \sum_{j=1}^{L} I_j(r) + P_N} \tag{23}$$

MS receives more inter-cell interference in DL crossed slot as the size of inner zone *r* increases, while its received signal power decreases. Thus, a tradeoff exists between $n^{c,d}$ and *r*. It is possible to accommodate more MSs in a cell by reducing the radius of inner zone or to curtail the number of MSs by increasing the size of inner zone.

This tradeoff also exists in UL crossed slots. As *r* increases, MSs in UL crossed slot should reduce their transmission power in order to regulate the inter-cell interference. Note that smaller inter-cell interference can be achieved by reducing number of MSs. Thus, the size of inner zone can be expanded with reduced number of MSs.

The transmission power of a MS in UL crossed slot varies according to the number of MSs.

Let $P_{T,u}^{c,r}\left(n^{c,u}\right)$ be the transmission power of a MS with $n^{c,u}$ MSs. Then, from Equation (20) we have

$$P_{T,r}^{c,u}\left(n^{c,u}\right)=\min\left(\frac{P_T^d (D_{BB}-D)^{-\nu}}{n^{c,u}(D_{BB}-D-r)^{-\nu}},\quad \frac{\eta_{\max}^{c,u}}{1-\eta_{\max}^{c,u}}\frac{LP_T^d kD_{BB}{}^{-\nu}+P_N}{n^{c,u}kr^{-\nu}}\right) \tag{24}$$

From (21), the upper bound of $n^{c,u}$ for a given inner zone radius r, $n^{c,u}(r)$, is given by

$$n^{c,u}(r)\le\left(1+\frac{W/SR}{\gamma^u}\right)-\frac{LP_T^d kD_{BB}{}^{-\nu}+P_N}{P_{T,r}^{c,u}\left(n^{c,u}\right)kr^{-\nu}} \tag{25}$$

3.6 Performance of crossed slot allocation

Assume that nominal allocation in RNC recommends S^d and S^u timeslots to be used for DL and UL in a frame, respectively ($S^d+S^u=S$). A cell of high DL traffic load can employ S^c DL crossed slots with inner zone radius r such that $S^c\le S^u$. Let N^d and N^u denote number of MSs supported by DL and UL. Then, we obtain

$$N^d=S^d n_{\max}^d+S^c n^{c,d}(r)\quad\text{and}\quad N^u=\left(S^u-S^c\right)n_{\max}^u \tag{26}$$

We assume that DL traffic is generated following Poisson process with rate λ^d. Duration of DL call is also assumed to follow exponential distribution with mean $1/\mu^d$. Then, blocking probability of DL traffic, p_b^d, is given by Erlang B loss formula [20].

$$p_b^d=\frac{(\lambda/\mu)^{N^d}\big/N^d!}{\sum_{i=0}^{N^d}(\lambda/\mu)^i\big/i!} \tag{27}$$

Capacity of a cell is given by RN^d and RN^u for DL and UL. As shown in (26), a tradeoff exists between capacity and inner zone size. Let $\Omega^{c,d}(r)$ and $\Omega^{c,u}(r)$ be the number of MSs per area of a cell in DL and UL crossed slots. Then, we have $\Omega^{c,d}(r)=n^{c,d}(r)\pi r^2/\pi D^2$ and $\Omega^{c,u}(r)=n^{c,u}(r)\pi r^2/\pi D^2$. Thus, $C^d(r)$ and $C^u(r)$, capacity per area in DL and UL, are as follow.

$$C^d(r)=R\left[S^d n_{\max}^d+S^c\Omega^{c,d}(r)\right]\quad\text{and}\quad C^u(r)=\left(S^u-S^c\right)n_{\max}^u \tag{28}$$

Note that similar analysis is available to cells employing UL crossed slots.

4. Numerical Results

Analysis in Section 3 is examined by numerical experiments with parameters in Table 1. k and ν represents Okumura-Hata propagation model for urban area with BS height of 30m, MS height of 1.5m, and carrier frequency of 1950 MHz [15]. Noise figure (NF) of 7dB for DL and 3dB for UL is considered to calculate background noise power P_N. When considering thermal noise density of -174dBm, $P_N = -174\text{dBm} + 10\log_{10}(W) + NF$.

From Equations (6) and (12), we obtain number of MSs that are supported in DL and UL regular slots. $n_{\max}^{d}$ and $n_{\max}^{u}$ are shown in Figure 5 for different cell radius. Compared to $n_{\max}^{d}$ which is fixed at 5.15, $n_{\max}^{u}$ varies with the cell radius. When D≤0.77 Km, $n_{\max}^{u} = 4.93$. It diminishes as D increases due to the limited MS transmission power. Number of MSs in UL regular slot is less than 1 when D=1.03Km, which means the coverage of UL is around 1Km. Higher capacity in DL is due to lower E_b / N_0 requirement which reflects better receiver performance of BS than MS.

Figure 6 shows transmission power of a BS and a MS in regular DL and UL slots respectively. As cell size grows, BS transmission power increases without experiencing power limitation up to D = 1.37Km. However, transmission power of a MS reaches its maximum when D≥0.77 Km since it is limited to 200mW. In pico or femto cell environment where BS is not equipped with high power amplifier, DL may also suffer from BS power limitation.

Figure 7 shows the maximum available size of inner zone for DL and UL crossed slots by assuming $n_{\max}^{d}$ MSs in DL crossed slot and $n_{\max}^{u}$ MSs in UL crossed slot. When $D \le 0.77$ Km, we obtain $r_{\max}^{d} = 0.34D$ and $r_{\max}^{u} = 0.45D$. Note that Figure 7 is the result of the worst case interference scenario. Thus the size of inner zone in practical system is expected to be larger than $r_{\max}^{d}$ and $r_{\max}^{u}$. When D ≥ 0.77Km, r/D decreases in DL crossed slot and increases in UL crossed slot. This is because the BS of DL crossed slot reduces its transmission power as in

Condition 1-DL to match reduced inter-cell interference by less $n_{\max}^{u}$. On the contrary, BS of UL crossed slot receives less intra-cell interference as $n_{\max}^{u}$ decreases. Thus, the inner zone coverage is improved at UL crossed slot.

Figure 8 shows tradeoff between the number of MSs and the radius of inner zone in DL and UL crossed slots. The capacity of DL crossed slot exceeds $n_{\max}^{d} = 5.15$ when $r \le 0.34D$. Even 8.9 MSs can be supported in a DL crossed slot if the cell reduces to $r \le 0.23D$. In UL crossed slot more than $n_{\max}^{u} = 4.93$ MSs can be served when $r \le 0.45D$. Note that reducing inner zone radius does not lead to infinite capacity because of background noise. Figure 9 shows $\Omega^{c,d}(r)$ and $\Omega^{c,u}(r)$. UL crossed slot shows better capacity per area than DL crossed slot. It is because DL crossed slot receives very high MS-to-MS interference according to the worst case scenario. In the figure, the maximum of $\Omega^{c,d}$ is 0.64 MSs when $r = 0.30D$ and that of $\Omega^{c,u}$ is 1.18 when $r = 0.39D$.

Finally, we examine the performance of crossed slot allocation. Suppose a nominal slot allocation with $S^{d} = 8$ and $S^{u} = 7$. Then, capacities of nominal allocation are 329.88 Kbps and 275.86 Kbps in DL and UL respectively. If a cell requires larger DL or UL capacity, high blocking probability is inevitable under the nominal slot allocation. Figure 10 shows improved blocking probability by DL crossed slot. By employing 3 crossed slots, we can reduce blocking probability by nearly 20% when 300 calls are generated in an hour. Cell of high UL traffic can also be benefited by adopting UL crossed slots. $C^{d}(r)$ and $C^{u}(r)$ are shown in Figure 11 where rectangular area represents the capacity of a cell under nominal slot allocation and gray area illustrates enhanced capacity per area by crossed slots with $r = 0.30D$ in DL and $r = 0.39D$ in UL. Note that crossed slots cannot extend the DL and UL capacities simultaneously. The capacity increase in one link accompanies the capacity loss in the other link. However, it can improve resource utilization of a cell when DL and UL have high asymmetry in traffic load.

5. Implementation Issue

For practical implementation of the proposed crossed slot allocation, a BS requires geographic information of its MSs. Only MSs within the inner zone can be supported in the crossed slots. For that purpose geometry factor [15, p.361] is recommended in determining the location of a MS. Geometry factor of a MS, which is $I_{or}/I_{oc}+N_0$, represents the ratio of total received power from own cell (I_{or}) to total interference from other cells and noise ($I_{oc}+N_0$). It is obvious that the region of high geometry factor is appropriate to inner zone.

Let $G(x)$ be the geometry factor of a MS whose distance from its BS is *x*. Without shadowing effect, $G(x)$ is given by

$$G(x)=\frac{P_T^d kx^{-\nu}}{k\sum_{j=1}^{L}\left(D_{BB}{}^2+x^2-2D_{BB}x\cos\frac{j\pi}{L/2}\right)^{-\nu/2}+P_N} \tag{29}$$

A MS is expected to be located in the inner zone if its measured geometry factor is higher than $G(r)$. This measurement will be useful for a BS to allocate crossed slots to its MSs.

6. Conclusion

The resource allocation in multi-cell CDMA-TDD system is investigated in this paper. We propose a distributed resource allocation scheme. RNC determines nominal slot allocation by which each timeslot is allocated to DL or UL. Each cell then allocates timeslots to DL or UL under the nominal slot allocation. If a cell requires more DL or UL timeslots, allocation of crossed slots is inevitable. Since crossed slots may degrade the system performance due to severe BS-to-BS and MS-to-MS inter-cell interference, we restrict the use of crossed slots to inner zone of a cell.

The basic concept of the proposed resource allocation is to restrict the amount of inter-cell interference from crossed slots such that other cells do not figure out whether the crossed slot is used or not in the cell. For this purpose, we define two conditions of using crossed slots: BSs or

MSs with crossed slots should not excessively interfere with entities in other cells, and entities using crossed slots should not be damaged by interference from other cells. Based on the two conditions, the maximum size of inner zone is determined by taking the worst case interference scenario into account. First, we determine the maximum transmission power of DL (UL) crossed slot from the condition that it should not exceed that of UL (DL) regular slot. Then, the maximum size of inner zone is determined such that the load factor does not exceed its planned maximum. We also investigate the tradeoff between the capacity of crossed slot and the size of inner zone.

Numerical results of the mathematical analysis are presented. Size of inner zone is calculated according to the cell radius. Tradeoff is examined between the capacity and inner zone coverage. The performance of crossed slot allocation is illustrated with increased data rate and reduced blocking probability by allowing flexible resource allocation to DL and UL.

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Figures and Tables

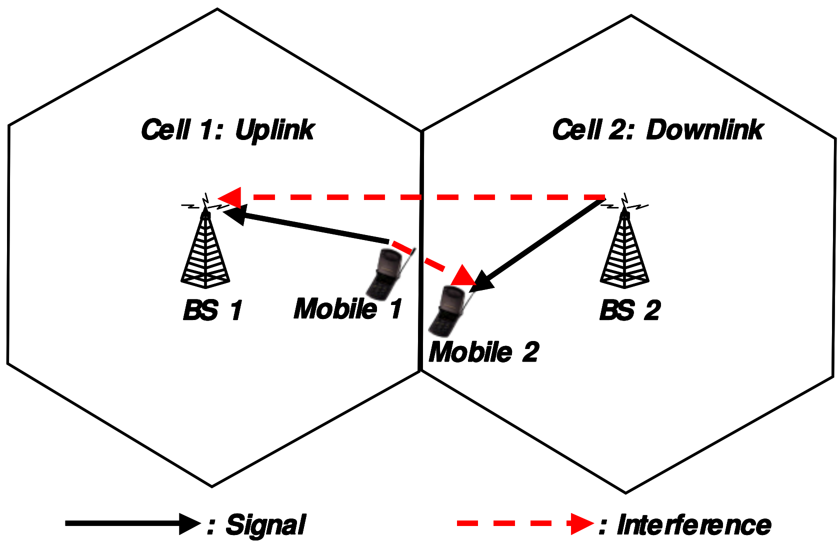

Figure 1. Crossed slot interference problem

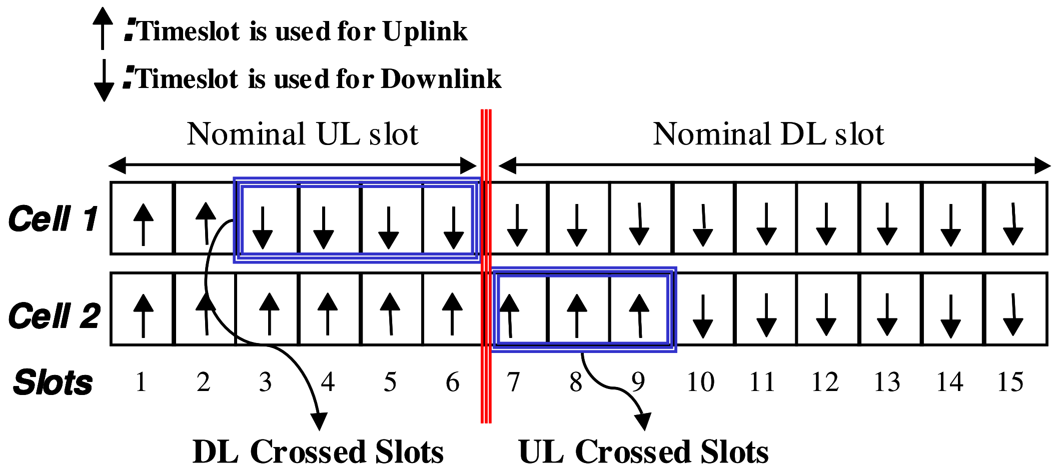

Figure 2. DL and UL crossed slots

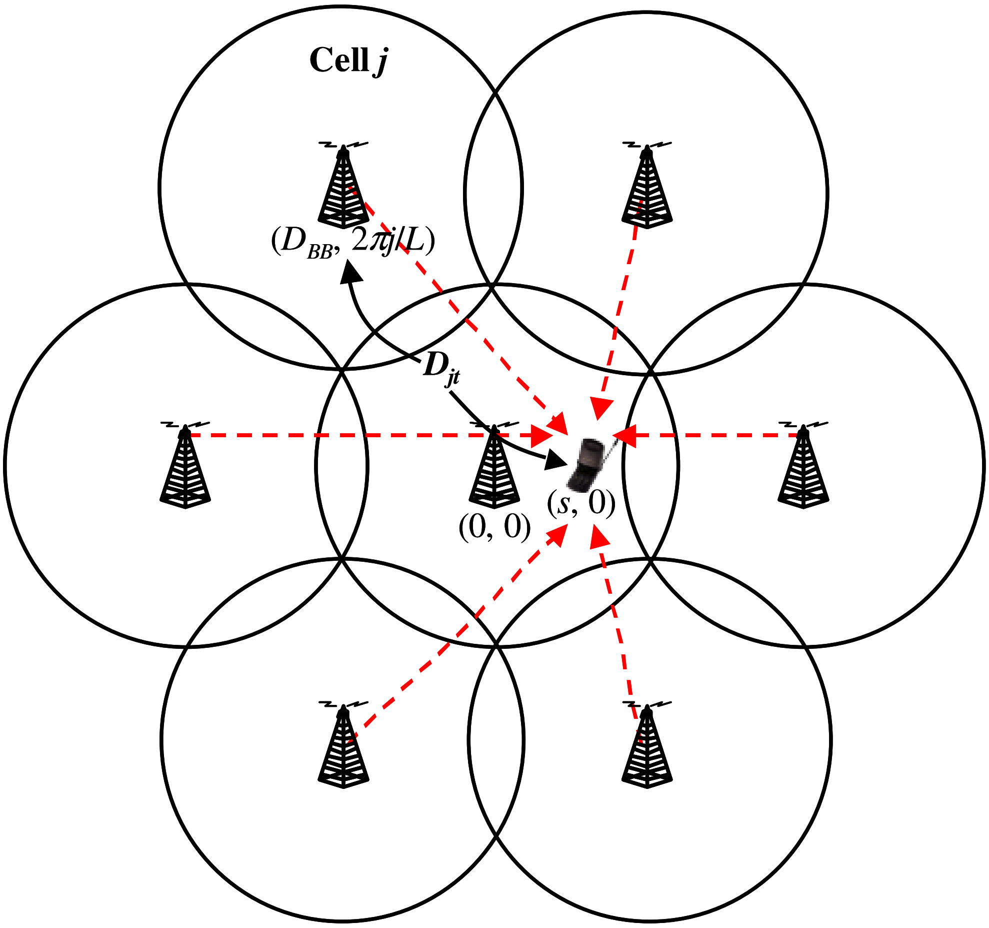

Figure 3. Inter-cell interference in DL regular slot

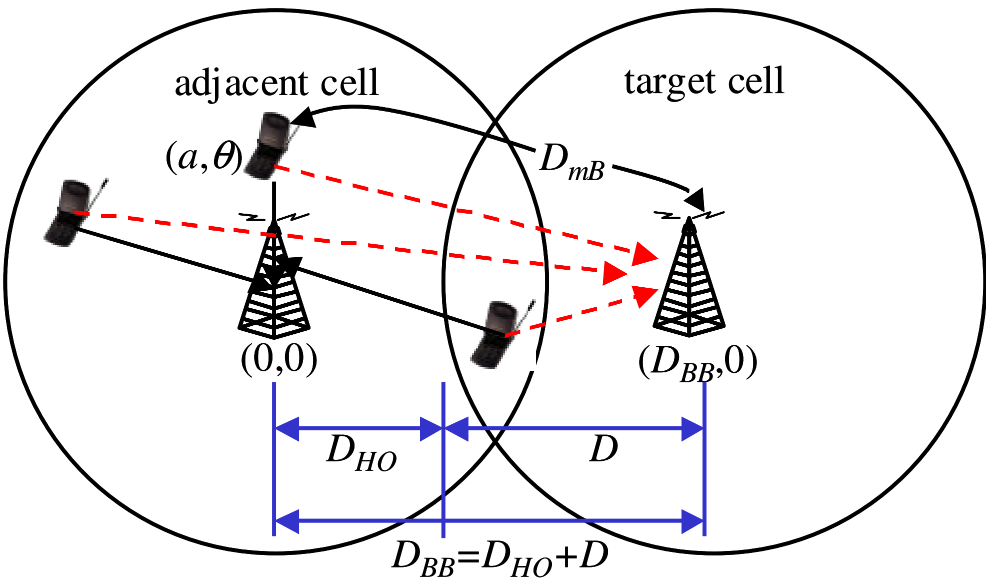

Figure 4. Inter-cell interference in UL regular slot

Table 1. Parameters used in numerical experiments

Parameters	Values
W	3840 Kbps
R	8 Kbps
S	15
L	6
P_N	DL: -101.2 dBm / UL: -105.2 dBm
ν	3.5
k	-137.4 dB
α	0.5
γ^d	7 dB
γ^u	5 dB
$\eta_{\max}^d$, $\eta_{\max}^u$, $\eta_{\max}^{c,d}$, $\eta_{\max}^{c,u}$	0.7
$P_{T,\max}^d$	10 W
$P_{T,\max}^u$	200 mW

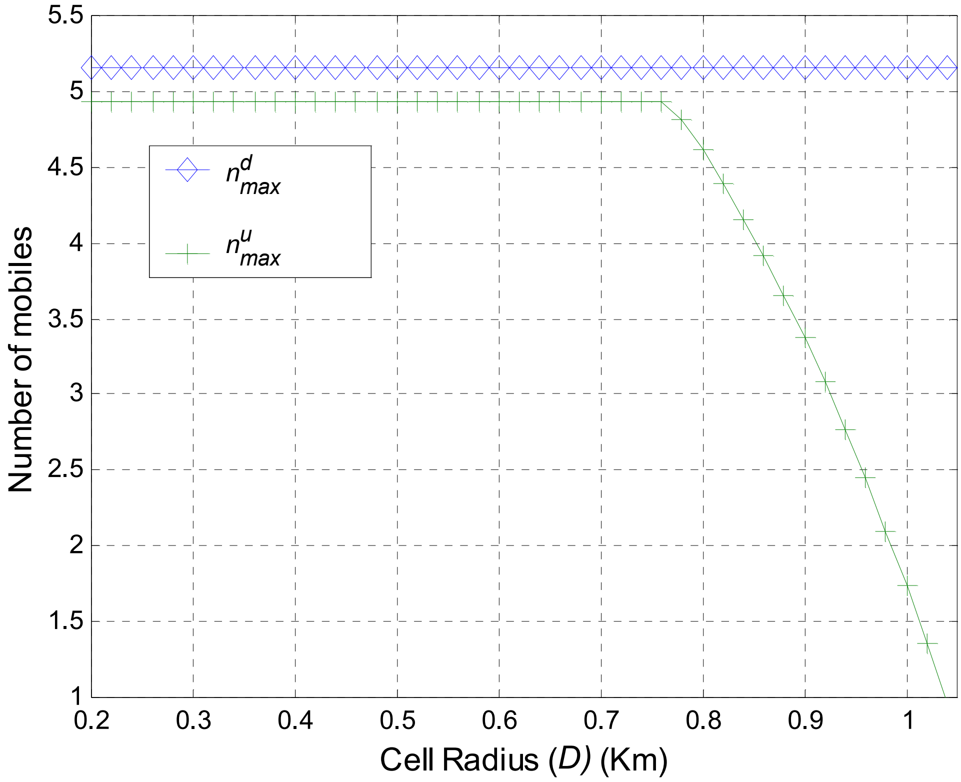

Figure 5. $n^d_{\max}$ and $n^u_{\max}$ in DL and UL regular slots

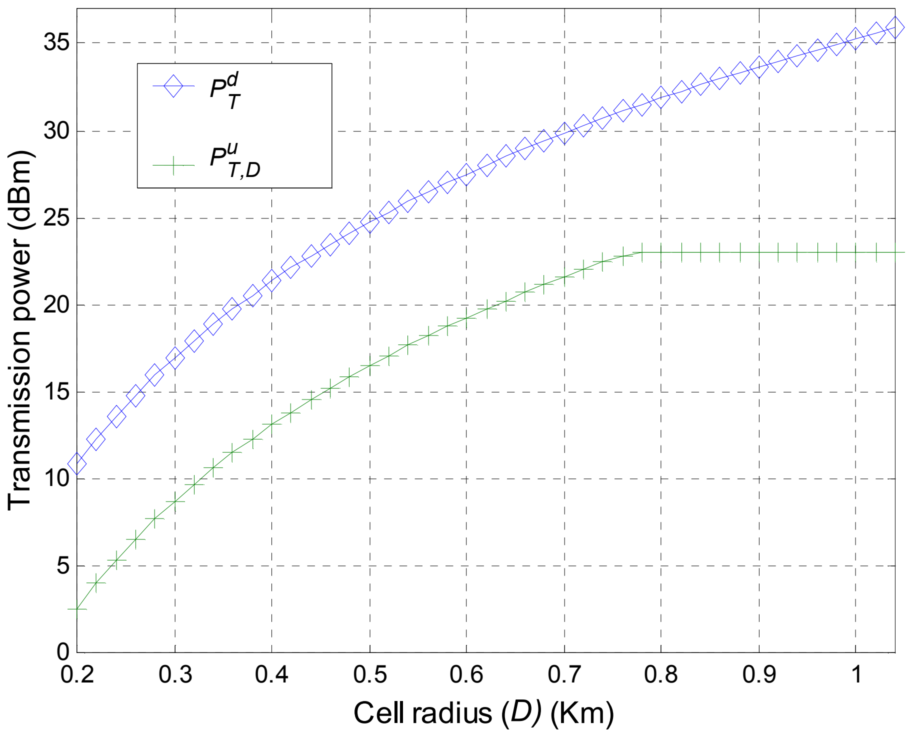

Figure 6. P^d_T and $P^u_{T,D}$ in DL and UL regular slots

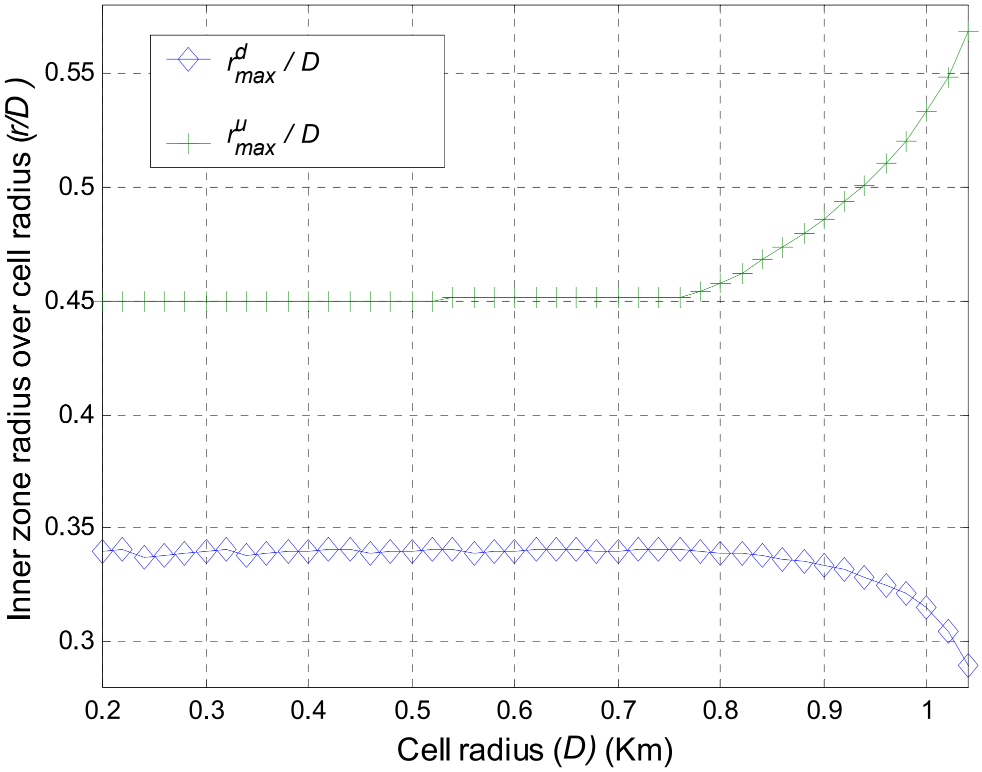

Figure 7. Normalized radius of inner zone in DL and UL crossed slots

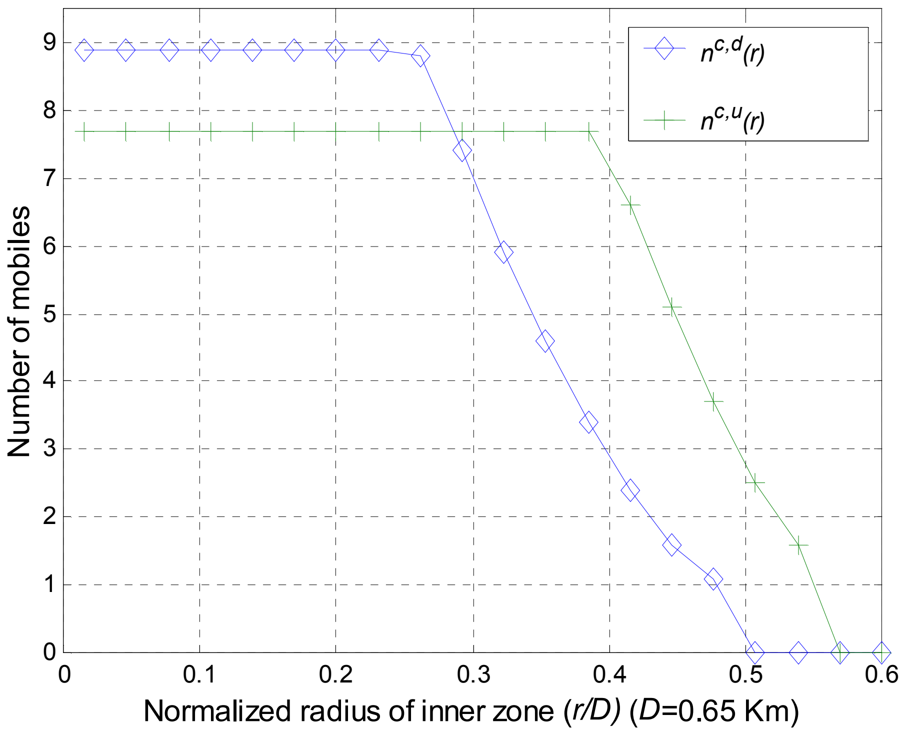

Figure 8. Tradeoff between the capacity and the size of inner zone in DL and UL crossed slots

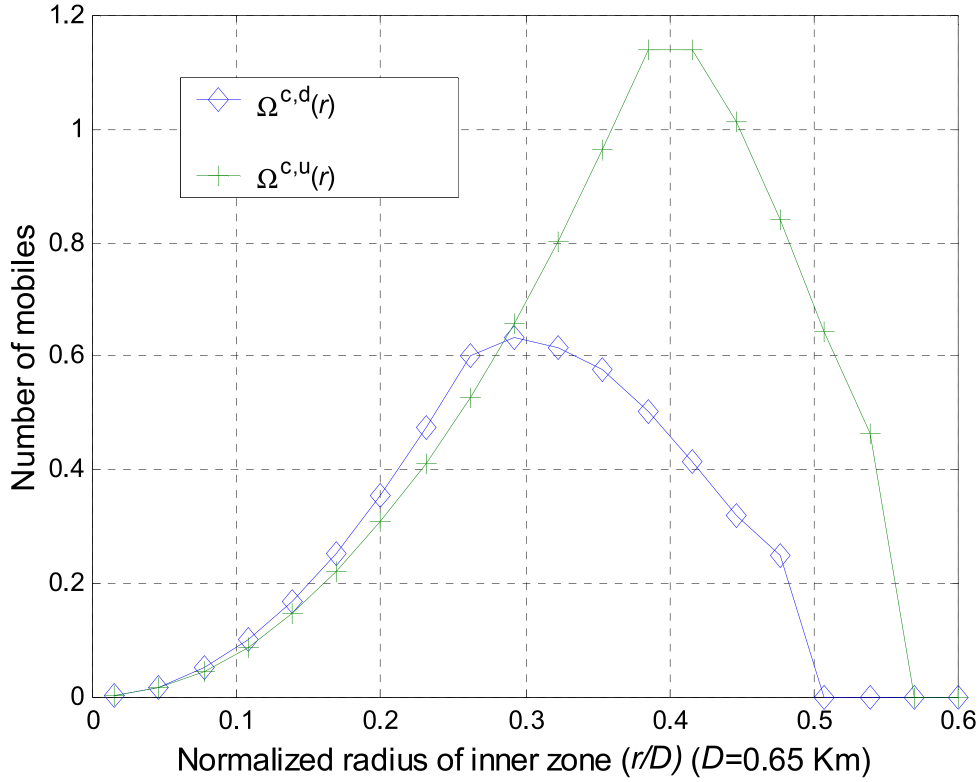

Figure 9. Number of MSs per area of a cell

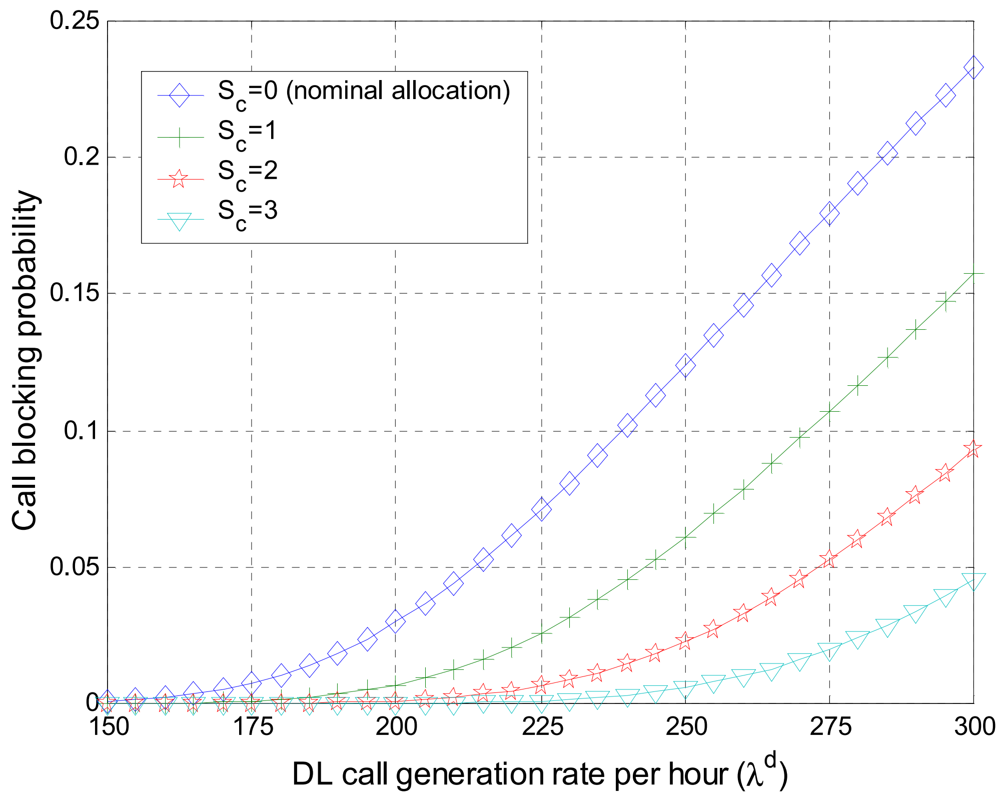

Figure 10. Blocking probability in DL (μ^d =10 minutes)

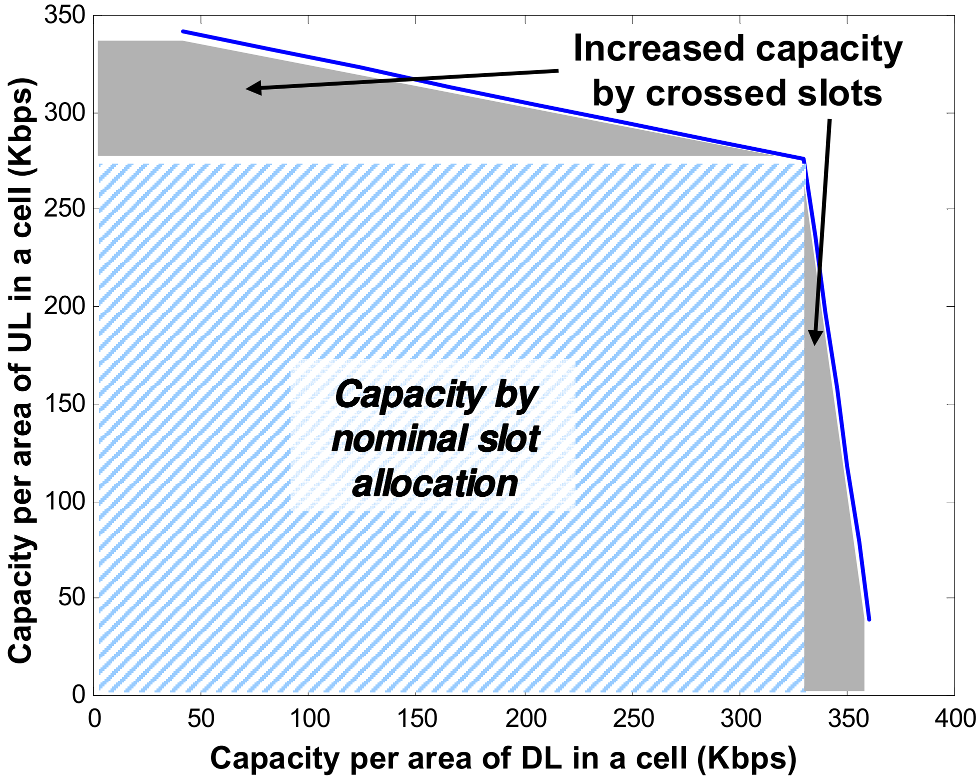

Figure 11. Increased capacity per area by crossed slots