Dynamic Resource Allocation for CDMA-TDD Indoor Wireless Systems

Chae Y. Lee and Ki Won Sung

Dept. of Industrial Engineering, KAIST, 373-1, Kusung Dong, Taejon, Korea

Tel: +82-42-869-2916

FAX: +82-42-869-3110

Email: {chae, kwsung}@kaist.ac.kr

Abstract

Future wireless communication systems are expected to provide a broad range of multimedia services that have a significant traffic asymmetry between uplink and downlink. The code division multiple access - time division duplex (CDMA-TDD) system is a promising solution to cope with the problem of traffic asymmetry. However, the TDD system is subject to inter-cell interference compared to frequency division duplex (FDD) system. Since both uplink and downlink share the same frequency in TDD, uplink and downlink may interfere each other especially when neighboring cells require different rates of traffic load. Thus, the resource allocation among cells is an important issue in TDD. In this paper, the resource allocation in the CDMA-TDD is formulated as a mixed integer programming (MIP) problem. A dynamic resource allocation algorithm (DRAA) is provided that effectively solves the traffic asymmetry problem. The MIP problem is also solved by a well-known branch and bound procedure. Both the crossed slot and non-crossed slot allocation are examined and compared to the DRAA. Computational result shows that proposed DRAA gives a good performance as the traffic asymmetry increases between the uplink and downlink.

Keywords

CDMA-TDD, E_b / N_0, dynamic resource allocation, mixed integer programming

1. Introduction

Future wireless communication systems are expected to provide a broad range of multimedia services, where the traffic asymmetry between uplink (UL) and downlink (DL) is significant. In the multimedia traffic environment such as streaming or web services, the DL traffic will be the bottleneck of the system. On the other hand, the uplink traffic may be bursty irregularly when mobiles use the file uploading services. The dynamic change of the traffic asymmetry between UL and DL makes the resource allocation of the future wireless system difficult. The code division multiple access system with time division duplex mode (CDMA-TDD) is a promising solution to cope with the traffic asymmetry problem.

In the Third Generation Partnership Project (3GPP), CDMA-TDD mode has been proposed as one of the standards for IMT-2000. The CDMA-TDD mode of 3GPP, named UTRA-TDD, is based on TD-CDMA technology, which is a mixture of TDMA and CDMA [1, 2, 3, 4]. The resource of TD-CDMA is divided in both time and code domain. The 10 ms frame consists of 15 time slots, each of which supports parallel orthogonal spreading codes up to spreading factor of 16. Each time slot can be allocated to UL or DL in a cell. Thus, the resources required for the asymmetric UL and DL traffic can be easily controlled by the number of UL and DL slots in a frame. More detailed review of TD-CDMA can be found in [5, 6].

The resource allocation in the UMTS version of the CDMA-TDD system is divided into two parts: slow dynamic channel allocation (DCA) and fast DCA [7]. Slow DCA is responsible for the allocation of resources to cells. The slow DCA is typically operated at the radio network controller (RNC). The RNC determines whether a time slot is used for UL or DL in each cell. Any specific timeslot within the TDD frame is available for either the UL or DL transmission. However, an interference constraint should be satisfied when the slow DCA is employed. On the contrary, the fast DCA reallocates resources to bearer services in a cell. The fast DCA algorithms that can be operated at the BSs are investigated in [8, 9, 10, 11]. Most of algorithms determine the priority of each time slot when a bearer service requires resource in the cell. Note that the fast DCA algorithm averages the interference levels of each slot so that none of the slot may suffer from the excessive interference. In this paper, we are interested in the slow DCA algorithm that reflects the dynamic change of traffic loads in the two-cell model. The proposed slow DCA algorithm may well be a complement to any fast DCA algorithm. As an example, the RNC periodically performs the slow DCA according to the estimated UL and DL traffic at each cell. Based on the slow DCA, each BS then reallocates the resources to bearer services.

The number of UL and DL slots in each cell is decided in the slow DCA to resolve the asymmetric traffic. However, the control of the UL and DL traffic in the CDMA-TDD brings about the inter-cell interference problem compared to the traditional frequency division duplex (FDD) system. Since both UL and DL share the same frequency band in the CDMA-TDD, the UL and DL transmission may interfere each other especially when a time slot is used as an UL slot in a cell and a DL slot in an adjacent cell. It is called as the crossed slot problem [12]. An efficient way of preventing serious interference problem in the crossed slot is to divide the area of a cell into two regions. At the crossed slot, the transmission of mobiles in the outer region is prohibited because these mobiles may cause severe interferences to mobiles in an adjacent cell. The region division scheme is proposed in [12] and the performance is investigated in [13, 14] by the simulation studies

The crossed slot in the CDMA-TDD can resolve the traffic asymmetry between cells, however it may cause serious interference problem as discussed above. Thus, whether to allow the crossed slot or not is an important problem in the resource allocation of the CDMA-TDD system. Yomo and Hara [15] argue that timeslots allocated to the UL or DL in a cell are preferred to be used in the same manner in other cells to minimize the inter-cell interference. Non-crossed slot resource allocation algorithms are also proposed in [8, 16]. However, Haas and McLaughlin [17] show a case where the capacity of the crossed slot allocation is higher than that of the non-crossed slot allocation. The argument of [17] coincides with the computational result by Jeon and Jeong [12] in which the system capacity of crossed and non-crossed slot allocation is compared in two-cell model. In this paper, we propose a resource allocation algorithm that efficiently employs the crossed slot depending on the traffic asymmetry between UL and DL.

The objective of the dynamic resource allocation in this paper is twofold. First, we need to satisfy the traffic load in each cell. Secondly, in addition to the traffic load, extra capacity is considered to protect unexpected bearer services in each cell. The resource allocation is formulated as a mixed integer programming (MIP) problem. A dynamic resource allocation algorithm (DRAA) is proposed, which is based on the maximum capacity at each time slot depending on the type of slot in the two cells. Then, the performance of proposed DRAA is compared with the solutions by the crossed slot and the non-crossed allocation.

The remainder of this paper is organized as follows. In Section 2, the system model and the problem is explained. The dynamic resource allocation problem is formulated as a mixed integer programming and the interference requirement of the system is analyzed. A dynamic resource allocation algorithm (DRAA) is proposed in Section 3. Then, the performance of the proposed DRAA is demonstrated in Section 4. The performance is compared with the crossed slot and non-crossed slot allocation procedures. Finally, the conclusion is presented in Section 5.

2. System Model and Problem Description

In the 3GPP, different service needs are supported by a combination of FDD and TDD. The FDD is intended for macro cell environment, while TDD is advantageous for micro and pico cells. The TDD is particularly well suited for environments with high traffic density, indoor coverage, and highly asymmetric traffic [5]. For the simplicity of the analysis, we assume a two-cell model as considered in [12, 14]. The two-cell model is not uncommon when we consider overlaid CDMA-TDD system on FDD to cover the inbuilding area with high traffic intensity. When there exists multiple cells in a building, the locally centralized system can be operated. Cells in the system are partitioned into local clusters such that each cluster covers a number of cells [18]. The inter-cluster resources are allocated in a distributed manner, while the intra-cluster resources are controlled by a centralized allocation algorithm.

In CDMA-TDD system, the resource consists of codes and timeslots. The basic resource unit (RU) for the channel allocation is one code/timeslot/(frequency) [7]. Single frequency allocation is considered in this paper. The data rate of an RU is assumed fixed and multi-rate services, if necessary, can be achieved by the code and time pooling of multiple RUs. The UL (DL) capacity of a cell is defined as the number of RUs allocated to the UL (DL) in a frame.

Let S be the number of slots in a frame, which is defined as 15 in 3GPP specification. Each of the 15 slots within a 10ms frame can be allocated to either UL or DL. Note that if a time slot is once allocated to UL in a cell, the time slot cannot be allocated to DL in the same cell. Thus, we have binary indicator u_{ij} as follows:

$$u_{ij} = \begin{cases} 1, & \text{if slot } j \text{ is allocated to UL in cell } i \\ 0, & \text{if slot } j \text{ is allocated to DL in cell } i \end{cases}$$

A time slot j is the UL slot if $u_{1j} = u_{2j} = 1$. Otherwise, if $u_{1j} = u_{2j} = 0$, the slot j is the DL slot. When slot j is used for UL in one cell and for DL in the other cell, it is referred to as the crossed slot. In Figure 1, for example, time slots 7, 8, and 9 are crossed slots.

Let N_{ij} be the number of RUs allocated to slot *j* in cell *i*. Also, let C_i^u and C_i^d respectively be the UL and DL capacity of cell *i*. Since the capacity of a cell is defined as the number of RUs allocated in a frame, C_i^u and C_i^d is expressed as

$$C_i^u = \sum_{k=1}^{S} u_{ik} N_{ik} \tag{1}$$

$$C_i^d = \sum_{k=1}^{S} (1 - u_{ik}) N_{ik} \tag{2}$$

Let T_i^u and T_i^d be respectively the UL and DL traffic load by the ongoing bearer services in cell *i*. Then, the residual capacities of cell *i* in the UL and DL are defined as $C_i^u - T_i^u$ and $C_i^d - T_i^d$, respectively.

Now our objective is twofold. First, we are interested in allocating RUs to satisfy the UL and DL traffic load in each cell. Secondly, we consider residual capacity in each cell such that the extra capacity is proportional to the current traffic load. By assigning the residual RUs proportionally to the traffic load, the instantaneous system-wide blocking probability can be minimized. Also, the residual capacity will be a good protection to the unexpected bearer services in the hot-spot cells.

The main constraint in the resource allocation in the CDMA system is the E_b / N_0 requirement, E_b / N_0 represents the ratio of the bit energy to noise density, which is obtained by the product of the signal to interference ratio (SIR) and the processing gain in the CDMA system. Let γ_u and γ_d be respectively the E_b / N_0 requirement of the UL and DL slots. Also, let $(E_b / N_0)_{i,j}^{u/d}$ be the E_b / N_0 of slot *j* in cell *i* for UL/DL. We denote z as the minimum ratio of residual capacity to the traffic load. Then, the crossed slot dynamic resource allocation problem is formulated as follows.

$$\text{Maximize} \quad z \tag{3}$$

Subject to

$$z \le \frac{C_i^u - T_i^u}{T_i^u}, \quad z \le \frac{C_i^d - T_i^d}{T_i^d} \quad \text{for all } i \tag{4}$$

$$u_{ij}\left(\frac{E_b}{N_0}\right)_{i,j}^{u} \ge u_{ij}\gamma_u\ ,\ \ (1-u_{ij})\left(\frac{E_b}{N_0}\right)_{i,j}^{d} \ge (1-u_{ij})\gamma_d \quad \text{for all } i, j \tag{5}$$

$$u_{ij} \le 1 \quad \text{for all } i, j \tag{6}$$

$$u_{ij} \text{ and } N_{ij} \text{ are non-negative integer} \tag{7}$$

Note that for the non-crossed slot allocation, the following constraint is added, where each slot is used either UL or DL in the two cells.

$$u_{1j} = u_{2j} \quad \text{for all } j \tag{8}$$

In the above formulation, the E_b / N_0 of the constraint (5) is dependent on the channel model and the result of capacity analysis of the CDMA-TDD system. In this paper, we apply the capacity analysis given in [12].

When a slot is used as the crossed slot, a transmitting mobile in the UL cell may cause a significant interference to a receiving mobile in the DL cell in the worst case, where two mobiles are located close to each other near to the cell boundary as in Figure 2. To prevent the significant interference problem, mobiles that use the crossed slot as the UL transmission is restricted within the inner circle [12, 13, 14, 19] that has the radius of r, where the radius of the cell is given as D.

For the analysis of the E_b / N_0, let P_R be the received signal power at a BS for an RU in UL. Also, let Q_R be the received signal power at an MS for an RU in DL. By assuming the perfect power control, a BS receives the same P_R per each RU from all UL mobiles. Similarly, MSs also have the same Q_R per each RU for all DL services.

Let us denote P_T as the transmission power of an MS that is located in the boundary of inner circle, and Q_T as the transmission power of a BS to the MS that is located in the boundary of a cell. Then by ignoring the fading effect, we have $P_R = r^{-n} P_T$ and $Q_R = D^{-n} Q_T$, where n is the path loss exponent. Note in cellular systems, Q_T is much greater than P_T.

Now, E_b / N_0 is determined by the amount of the received signal power and the interference power, and the interference power is proportional to the number of allocated RUs in each cell. For a specific time slot, three interference situations are possible: a time slot is used as a crossed slot, UL slot, or DL slot. From [12], the E_b / N_0 in each case is expressed as follows. The background noise is ignored.

Case 1: A time slot is used as a crossed slot

Let W and R be the spreading bandwidth and data rate of an RU, respectively. Without loss of generality, we assume slot j is used for UL in cell 1 and for DL in cell 2. Then, the BS in cell 1 receives interference from the BS in cell 2. The distance of two BSs is $2D$. Thus,

$$\left(\frac{E_b}{N_0}\right)_{1j}^{u} = \frac{W}{SR}\frac{P_R}{(N_{1j}-1)P_R + N_{2j}(2D)^{-n}Q_T} \geq \gamma_u \tag{9}$$

In (9), W/SR represents the processing gain of an RU in slot j.

In the DL cell, each MS experiences different other cell interference due to the different location of the MSs. Thus, E_b/N_0 of cell 2 is derived for a mobile located in the worst case position, i.e., the cell boundary. For the target mobile, the other cell interference comes from mobiles in the cell 1. Since the locations of interfering mobiles are different, the mobiles in the cell 1 are assumed to be uniformly located within the inner circle of the cell. Then E_b/N_0 of cell 2 is given by

$$\left(\frac{E_b}{N_0}\right)_{2j}^{d} = \frac{W}{SR}\frac{Q_R}{(N_{2j}-1)Q_R + N_{1j}\overline{IP_t}} \geq \gamma_d \tag{10}$$

In the equation $\overline{IP_t}$ is the expected interference power from a mobile located at arbitrary position of cell 1. By denoting $I(a)$ be the interference from a mobile at position a and $p(a)$ be the probability that the mobile is located at position a. Then, $\overline{IP_t}$ is obtained by $\int_A I(a)p(a)da$, where A is the area of the inner region of cell 1. Detailed analysis on the expected interference is given in [12].

Case 2: A time slot is used as an UL slot

Let ζ be the ratio of the interference from adjacent UL cell to that from the home cell [12]. Then, the E_b/N_0 of cell 1 is given by

$$\left(\frac{E_b}{N_0}\right)_{1j}^{u} = \frac{W}{SR}\frac{P_R}{(N_{1j}-1)P_R + \zeta N_{2j}P_R} \geq \gamma_u \tag{11}$$

E_b / N_0 of cell 2 is obtained by just substituting the cell index in the above equation. $\zeta = 0.06$ is assumed in this paper.

Case 3: A time slot is used as a DL slot

A target mobile is assumed to be located in the cell boundary as in Case 1. Then,

$$\left(\frac{E_b}{N_0}\right)_{1j}^{d} = \frac{W}{SR} \frac{Q_R}{(N_{1j} - 1)Q_R + N_{2j} D^{-n} Q_T} \geq \gamma_d \tag{12}$$

E_b / N_0 of cell 2 is derived in the same way.

From the above E_b / N_0 analysis, it is clear that the constraint (5) is nonlinear. Note that the constraint (4) is also nonlinear. Since the problem with the nonlinear constraint requires a complex nonlinear optimization procedure, we convert the two constraints into linear which is relatively easy to solve. The linear conversion of constraints is given in the Appendix. Now, with the linear conversion the crossed slot dynamic resource allocation given in (3) ~ (7) becomes a mixed integer programming (MIP) problem.

Note that the MIP version of the dynamic resource allocation problem requires too much computational effort to obtain the optimal solutions. As the problem size increases, the MIP could not be solved effectively by the conventional branch and bound technique [20] using the ILOG CPLEX 7.0 optimization software [21]. In problems with high traffic load and link asymmetry, the branch and bound procedure failed to find the optimal solutions even with three hours of running time. Thus, to tackle the dynamically changing traffic load in each cell, we provide a dynamic resource allocation algorithm as a promising solution procedure for real-world problems.

3. Dynamic Resource Allocation Algorithm

To satisfy the asymmetric UL and DL traffic in each cell, we need to determine the number of UL, DL, and crossed slots in the system. We also need to determine the number of RUs for each slot. In our resource allocation, the crossed slot plays an important role in resolving the traffic asymmetry problem. As the UL/DL asymmetry increases, the number of crossed slots increases.

The determination of the number of RUs allocated for each slot in each cell is flexible in CDMA due to the soft capacity. The capacity of a cell is dependent on the amount of the resources allocated to the adjacent cell. Thus we can assign more resources in a cell by decreasing the number of RUs of the adjacent cell.

In this section, we first examine the number of RUs for each type of slot in each cell. Then the determination of the number of UL, DL, and crossed slots in a frame will be considered. To determine the number of RUs for each slot, we focus on the capacity constraints investigated in the previous section. The capacity of a specific time slot is shown in Figure 3, 4, and 5 from equations (9) ~ (12). The parameters used for the E_b / N_0 analysis are given in Table 1. From Figure 3, it is clear that the system capacity of a crossed slot is maximized at the extreme point P_c where the two constraints are crossing. The same is true in Figure 4. The capacity is maximized at P_u when the time slot is used for UL slot in each cell. However, when the time slot is used for DL slot, the maximum capacity P_d can be obtained at any point on the constraint in Figure 5. Thus, the number of RUs at each slot is determined at the extreme points P_c and P_u respectively when the slot is used as crossed and UL slot. When the slot is used as a DL slot, any point on the constraint in Figure 5 can be selected.

To determine the maximum capacity in each case, let us assume $C_1^d \geq C_2^d$ without loss of generality, then it is clear that the crossed slot is used for DL in cell 1, and for UL in cell 2. Also, let us define the following notations.

$x_{ij}{}^{u}$:number of RUs allocated to slot j in cell i at the point P_u if slot j is the UL slot

$x_{ij}{}^{d}$: number of RUs allocated to slot j in cell i at the point P_d if slot j is the DL slot

$x_{1j}{}^{c,d}$: number of RUs allocated to slot j as DL in cell 1 at the point P_c if slot j is the crossed slot

$x_{2j}{}^{c,u}$: number of RUs allocated to slot j as UL in cell 2 at the point P_c if slot j is the crossed slot

When the slot j is used as the crossed slot, the maximum capacity of the crossed slot is obtained by equating the two constraints (9) and (10) as follows.

$$x_{2j}{}^{c,u} + \left(\frac{\delta}{2}\right)^n \frac{Q_T}{P_T} x_{1j}{}^{c,d} = \frac{\bar{I}P_T}{Q_R} x_{2j}{}^{c,u} + x_{1j}{}^{c,d} \leq \frac{W}{SR\gamma} + 1 \tag{13}$$

Equation (13) is obtained under the assumption that $\gamma_u = \gamma_d = \gamma$. From (13), we have

$$x_{1j}^{\ c,d} = \left\lfloor \frac{2^n (D^{-n} Q_T - \bar{I} P_T)}{Q_T (D^{-n} 2^n - \bar{I} \delta^n)} \left(\frac{W}{SR\gamma} + 1 \right) \right\rfloor \text{ and } x_{2j}^{\ c,u} = \left\lfloor \frac{2^n D^{-n} P_T - \delta^n D^{-n} Q_T}{P_T (D^{-n} 2^n - \bar{I} \delta^n)} \left(\frac{W}{SR\gamma} + 1 \right) \right\rfloor \tag{14}$$

where $\lfloor x \rfloor$ means the maximum integer value which does not exceed x.

When the two cells use time slot j for UL transmission, the maximum capacity of slot j is obtained by equating two constraints in Figure 4. Thus, the maximum capacity in the UL slot is obtained when

$$N_{1j} + \zeta N_{2j} = N_{2j} + \zeta N_{1j} \le \frac{W}{SR\gamma_u} + 1 \tag{15}$$

Thus, we have

$$x_{1j}^{\ u} = x_{2j}^{\ u} = \left\lfloor \frac{1}{1+\zeta} \left(\frac{W}{SR\gamma_u} + 1 \right) \right\rfloor \tag{16}$$

Finally, when a timeslot is allocated to DL in the two cells, $x_{ij}^{\ d}$ needs to satisfy the following requirement.

$$x_{2j}^{\ d} = \left\lfloor \frac{W}{SR\gamma_d} + 1 \right\rfloor - x_{1j}^{\ d} \tag{17}$$

Let us denote S_u, S_d, and S_c as the number of UL slots, DL slots, and crossed slots in a frame, respectively. Clearly, $S = S_u + S_d + S_c$ corresponds to the number of timeslots in a frame. The capacity of the two cells, i.e., the number of total RUs allocated to cell 1 and 2, depends on the number of S_u, S_d, and S_c. From Equation (1) and (2), the capacity of two cells is computed as

$$C_1^u = x_{1j}^{\ u} S_u \tag{18}$$

$$C_2^u = x_{2j}^{\ u} S_u + x_{2j}^{\ c,u} S_c \tag{19}$$

$$C_1^d = {x_{1j}}^d S_d + {x_{1j}}^{c,d} S_c \tag{20}$$

$$C_2^d = {x_{2j}}^d S_d \tag{21}$$

Now, to determine ${x_{1j}}^d$ and ${x_{2j}}^d$ that satisfy (17), notice the objective function given in Section 2. Since our objective is to maximize the minimum ratio of residual capacity to the traffic load, the maximization of the objective function is obtained when the following condition is satisfied.

$$\frac{C_1^d - T_1^d}{T_1^d} = \frac{C_2^d - T_2^d}{T_2^d} \tag{22}$$

Using the condition (22) and equations (14), (20) and (21), ${x_{1j}}^d$ is given by

$${x_{1j}}^d = max\left(\left\lfloor \frac{\lfloor W/SR\gamma_d + 1 \rfloor T_1^d S_d - {x_{1j}}^{c,d} T_2^d S_c}{(T_1^d + T_2^d) S_d} \right\rfloor, 0 \right) \tag{23}$$

Also, ${x_{2j}}^d$ is obtained from (17).

Since we have decided the maximum RUs at each slot, we are now interested in the determination of the number of UL, DL, and crossed slots that maximize the objective function. An iterative search algorithm is proposed by starting from the initial solution of S_u, S_d, and S_c. To improve the objective function value, the cell/link that gives the minimum ratio of residual capacity to the traffic load is selected at each iteration. Then a slot is incremented to the link in the cell. Since the crossed slot is assumed to be used as DL in cell 1 and UL in cell 2, when the UL (DL) slot is required in cell 1 (cell 2), the improvement can be achieved only by increasing the UL (DL) slot.

The heuristic search procedure may result in a local optimum, since S_u, S_d, and S_c are updated based on the number of slots obtained in the previous iteration. To prevent the local optimum, the search process is continued even without the solution improvement. When no improvement is obtained for T_{Rep} consecutive iterations, then the algorithm is terminated. For the global optimum, an exhaustive search may be considered in the two-cell model. However, the computational burden required for the solution may well exceed that of the heuristic procedure as the problem size increases.

The steps for the dynamic resource allocation algorithm (DRAA) are proposed as follows.

Step 1: Initialize the number of slots assigned to UL, DL, and crossed slots as $S_u = S_d = S_c$.

Step 2: Compute C_1^u, C_1^d, C_2^u, and C_2^d as in Equations (18) ~ (21).

Step 3: Compute the objective function and select the cell/link that gives the minimum objective function value.

Step 4: In each case, update S_u, S_d, and S_c to the direction that leads to the larger objective function value of the two candidate solutions.

When the DL of the cell 1 is the minimum: ($S_u - 1$, $S_d + 1$, S_c) or ($S_u - 1$, S_d, $S_c + 1$)

When the UL of the cell 1 is the minimum: ($S_u + 1$, $S_d - 1$, S_c) or ($S_u + 1$, S_d, $S_c - 1$)

When the DL of the cell 2 is the minimum: ($S_u - 1$, $S_d + 1$, S_c) or (S_u, $S_d + 1$, $S_c - 1$)

When the UL of the cell 2 is the minimum: ($S_u + 1$, $S_d - 1$, S_c) or (S_u, $S_d - 1$, $S_c + 1$)

Step 5: If the objective function value is not increased for the consecutive T_{Rep} iterations, terminate the algorithm. Otherwise, go to Step 2.

4. Computational Results and Discussions

The performance of the proposed dynamic resource allocation algorithm is examined by generating three traffic load scenarios. In scenario 1, two cells have different UL/DL asymmetry. However, the total traffic load is fixed to 80 RUs in each cell. The traffic load of cell 1 is fixed to $T_1^u = T_1^d = 40$ RUs. Then, the traffic asymmetry of cell 2 is varied such that $0 \le T_2^d \le 80$. Thus, scenario 1 explains the situation where two cells have almost the same number of users but the traffic asymmetry varies in one cell. Scenario 2, which is the opposite situation of scenario 1, has the same UL/DL asymmetry in two cells with different amounts of traffic loads. In scenario 2, we have $T_1^u = 30$ and $T_1^d = 50$ RUs. The traffic load in cell 2 is varied from $T_2^d = 10 \sim 90$ RUs with the same UL/DL asymmetry as in the cell 1. Finally, scenario 3 represents downlink hot-spot region. By fixing $T_1^u = T_1^d = 40$ and $T_2^u = 20$, T_2^d is varied from 40 to 110 RUs.

Parameters used in this section are shown in Table 1. Typical values in cellular communication systems are selected for W, R, P_T, and γ. We set Q_T = 1.5 W because the maximum transmission power of a BS is typically 20 W and the maximum available RUs in a slot is 14 if other cell interference is ignored. $\delta = r / D = 0.7$ is selected so that the area of the inner region and the outer region becomes the same. To compare the performance of the proposed dynamic resource allocation algorithm, the MIP problems formulated in Section 2 are solved with the ILOG CPLEX optimization software [21], which is executed at 1 GHz CPU. Both the crossed slot and non-crossed slot allocation problems are solved with the traffic loads given in the three scenarios.

Tables 2, 3, and 4 illustrate the computational result of the proposed DRAA and the CPLEX. The solutions by the CPLEX for the crossed slot allocation (CSA) are the best solutions obtained by the CPLEX. Due to the exponential growth of the branches in the process of CPLEX, it fails to obtain the optimal solution for CSA. Thus, the running time of 10,000 seconds is chosen to insure a sufficient time enough to guarantee the near optimal solution. The optimal solutions by the CPLEX for the non-crossed slot allocation (NCSA) are also compared in the tables. In all scenarios, the CSA shows higher objective function value than the NCSA, which means that the use of crossed slot is desirable to handle the traffic asymmetry in the CDMA-TDD two-cell model. However, it is clear that the CSA by the CPLEX may not be applicable to the real system due to the large CPU times. The proposed DRAA on the other hand can solve the resource allocation problem in real time in any traffic scenarios.

Figure 6 shows the result of the scenario 1. The proposed DRAA well approximates the solution given by the CSA. It also outperforms the optimal solutions by NCSA in most cases. The residual capacity of three procedures increases as the UL load of cell 2 is increased. This is because the UL load in the two cells can be simultaneously satisfied as in Figure 4 by increasing the UL slots.

In Figure 7 for the scenario 2, all the three procedures show that the residual capacity decreases as the total traffic load increases. The performance of the proposed DRAA is not satisfactory in this scenario. It shows that the DRAA is not so helpful when two cells have the same traffic asymmetry.

The superiority of the proposed DRAA over the NCSA is illustrated in Figure 8. In the scenario 3 which represents the downlink hot-spot situation, as the DL traffic at the hot-spot increases the DRAA converges to the solution by the CSA. Moreover, the solution gap of the DRAA and the NCSA is increased as the DL traffic is increased.

In the above analysis, it is clear that the CPLEX based CSA shows the best performance due to the organized optimization by the branch and bound method. However, the running time of 10,000 seconds is not adequate for the resource allocation in the real field. Thus, the CSA is experimented by limiting the execution time. Figure 9 shows the performance of CSA when the running time is restricted to 1, 10, 100, and 10,000 seconds for the scenario 1. The figure shows that the CSA with 10 or100 seconds of running time well approximates the optimal solutions. However, the performance is unpredictable when the running time is less than 10 seconds. Thus, the use of CSA is desirable if the system allows the execution time of the resource allocation procedure to be approximately 10 seconds. However, the large execution time of the algorithm may not be applicable in the environment where real time update of the resource is required for the rapidly changing traffic load. Thus, the proposed DRAA will be advantageous over the CSA when a bearer service instantaneously requires very high data rate for either UL or DL. By rearranging resources to the UL and DL in each cell at the admission phase, the service blocking probability of the system can be reduced dramatically.

Finally, figure 10 shows the use of S_u, S_d, and S_c in the scenario 3. As shown in the figure, more slots are used as the crossed slot as the difference of UL/DL asymmetry between the two cells increases. It shows the effectiveness of the crossed slots in the proposed DRAA to tackle to the traffic asymmetry problem.

5. Conclusion

To cope with the future UL and DL traffic asymmetry problem, a dynamic resource allocation problem is examined based on the CDMA-TDD. The problem is formulated as a mixed integer programming problem which satisfies the traffic load and also maximizes the residual capacity for the unexpected bearer services.

A dynamic resource allocation algorithm (DRAA) is proposed by considering the maximum capacity of each type of time slot. The maximum capacity of a time slot used as either a crossed, UL, or DL slot is examined by analyzing the E_b / N_0 constraints in the CDMA-TDD. The procedure then maximizes the minimum residual capacity at each link in each cell by iteratively increasing or decreasing the number of time slots assigned to the crossed, UL, and DL slots.

Three scenarios of the traffic asymmetry patterns are employed to simulate various traffic situations. Computational results show that the proposed DRAA effectively solves the resource allocation problem when the two cells have different UL/DL asymmetries. Compared to the CPLEX, the DRAA is proved to provide real-time solution updates that reflect the dynamic change of the UL and DL traffic load in each cell.

Appendix: Linear conversion of the constraints (4) and (5) in Section 2

Note that equations (4) and (5) are nonlinear constraints in the formulation. The constraint (5) is converted into (9) ~ (12) and they can be expressed as the linear function of N_{ij} as follows.

$$\begin{cases} N_{1j} + \zeta N_{2j} \le \dfrac{W}{SR\gamma_u} + 1 \\ \zeta N_{1j} + N_{2j} \le \dfrac{W}{SR\gamma_u} + 1 \end{cases} \quad \text{if } u_{1j} = 1,\ u_{2j} = 1 \tag{24}$$

$$N_{1j} + N_{2j} \le \frac{W}{SR\gamma_d} + 1 \qquad \text{if } u_{1j} = 0,\ u_{2j} = 0 \tag{25}$$

$$\begin{cases} N_{1j} + \dfrac{\delta^n Q_T}{2^n P_T} N_{2j} \le \dfrac{W}{SR\gamma_u} + 1 \\ \dfrac{\bar{I} P_T}{Q_R} N_{1j} + N_{2j} \le \dfrac{W}{SR\gamma_d} + 1 \end{cases} \quad \text{if } u_{1j} = 1,\ u_{2j} = 0 \tag{26}$$

$$\begin{cases} \dfrac{\delta^n Q_T}{2^n P_T} N_{1j} + N_{2j} \le \dfrac{W}{SR\gamma_u} + 1 \\ N_{1j} + \dfrac{\bar{I} P_T}{Q_R} N_{2j} \le \dfrac{W}{SR\gamma_d} + 1 \end{cases} \quad \text{if } u_{1j} = 0,\ u_{2j} = 1 \tag{27}$$

where the normalized radius δ is defined as $\delta = r / D$. However, (24)~(27) are Either-Or constraints where only one choice can be made among the four constraints. They must be reformulated into the linear programming format where all specified constraints must hold [20]. To resolve the problem, we use the well known method which introduces a very large positive value *M* [20]. For example, constraint (24) is converted as follows by adding *M*.

$$N_{1j} + \zeta N_{2j} \le \frac{W}{SR\gamma_u} + 1 + (1 - u_{1j})M + (1 - u_{2j})M \tag{28}$$

$$\zeta N_{1j} + N_{2j} \le \frac{W}{SR\gamma_u} + 1 + (1 - u_{1j})M + (1 - u_{2j})M \tag{29}$$

The constraints (28) and (29) have the practical use only when $u_{1j} = u_{2j} = 1$, where the newly added terms including *M* are eliminated and the constraints are identical to the original constraints. Otherwise, they are satisfied automatically because *M* is much larger than the left-hand side of the inequalities.

Constraints (25) ~ (27) are also converted in the same way.

$$N_{1j} + N_{2j} \le \frac{W}{SR\gamma_d} + 1 + u_{1j}M + u_{2j}M \tag{30}$$

$$N_{1j} + \frac{\delta^n Q_T}{2^n P_T} N_{2j} \le \frac{W}{SR\gamma_u} + 1 + (1 - u_{1j})M + u_{2j}M \tag{31}$$

$$\frac{\bar{I}P_T}{Q_R} N_{1j} + N_{2j} \le \frac{W}{SR\gamma_d} + 1 + (1 - u_{1j})M + u_{2j}M \tag{32}$$

$$\frac{\delta^n Q_T}{2^n P_T} N_{1j} + N_{2j} \le \frac{W}{SR\gamma_u} + 1 + u_{1j}M + (1 - u_{2j})M \tag{33}$$

$$N_{1j} + \frac{\bar{I}P_T}{Q_R} N_{2j} \le \frac{W}{SR\gamma_d} + 1 + u_{1j}M + (1 - u_{2j})M \tag{34}$$

By replacing (5) with (28) ~ (34), the non-linear constraint (5) is converted into the linear form.

The linear conversion of (4) can also be done with the help of *M*. (4) is nonlinear because the product of two variables $u_{ij}N_{ij}$ exists. Let $Y_{ij} = u_{ij}N_{ij}$. Then, $Y_{ij} = \begin{cases} N_{ij} & \text{if } u_{ij} = 1 \\ 0 & \text{if } u_{ij} = 0 \end{cases}$, which means

$$\begin{cases} Y_{ij} \le N_{ij} \\ Y_{ij} \ge N_{ij} \end{cases} \quad \text{if } u_{ij} = 1 \tag{35}$$

$$\begin{cases} Y_{ij} \le 0 \\ Y_{ij} \ge 0 \end{cases} \quad \text{if } u_{ij} = 0 \tag{36}$$

In (35) and (36), $Y_{ij} \le N_{ij}$ and $Y_{ij} \ge 0$ should be satisfied regardless of the value of u_{ij}. Adopting *M* to (35) and (36), the rest constraints are expressed as follows.

$$Y_{ij} + M(1 - u_{ij}) \ge N_{ij} \tag{37}$$

$$Y_{ij} \le u_{ij}M \tag{38}$$

Thus, all constraints of the formulation for the resource allocation problem shown in Section 2 are expressed as linear inequalities.

References

[1] 3GPP Technical Specification 25.221, Physical Channels and Mapping of Transport Channels onto Physical Channels (TDD), http://www.3gpp.org.

[2] 3GPP Technical Specification 25.222, Multiplexing and Channel Coding (TDD), http://www.3gpp.org.

[3] 3GPP Technical Specification 25.223, Spreading and Modulation (TDD), http://www.3gpp.org.

[4] 3GPP Technical Specification 25.224, Physical Layer Procedures (TDD), http://www.3gpp.org.

[5] M. Haardt, A. Klein, R. Koehn, S. Oestreich, M. Purat, V. Sommer, and T. Ulrich, The TD-CDMA Based UTRA TDD Mode, IEEE Journal on Selected Areas in Communications, Vol. 18, No. 8, 2000.

[6] H. Holma and A. Toskala, WCDMA for UMTS, Wiley and Sons, 2000.

[7] 3GPP Technical Specification 25.922, Radio Resource Management Strategies, http://www.3gpp.org.

[8] O. Lehtinen and J. Kurjenniemi, UTRA TDD Dynamic Channel Allocation in Uplink with Slow Reallocation, IEEE VTC, Spring, 2003.

[9] V. Huang and W. Zhuang, Optimal Resource Management in Packet-Switching TDD CDMA Systems, IEEE Personal Communications, 2000.

[10] T. Kreingchaiyapruk and I. Forkel, Adaptive Switching Point Allocation in TD/CDMA Systems, IEEE VTC, Fall, 2002.

[11] G.. Zhang and E. Zeira, Fast Permutation Based Time Slot Allocation for 3G WCDMA TDD Systems, IEEE VTC, Spring, 2003.

[12] W. S. Jeon and D. G. Jeong, Comparison of Time Slot Allocation Strategies for CDMA/TDD Systems, IEEE Journal on Selected Areas in Communications, Vol. 18, No. 7, 2000.

[13] J. Lee,Y. Han, and D. Kwon, An Adaptive Time Slot Allocation Strategy for W-CDMA/TDD System, IEEE VTC, Spring, 2001.

[14] F. Nazzarri and R. F. Ormondroyd, An Effective Dynamic Slot Allocation Strategy Based on Zone Division in WCDMA/TDD Systems, IEEE VTC, Fall, 2002.

[15] H. Yomo and S. Hara, An Up-link/Down-link Asymmetric Slot Allocation Algorithm in CDMA/TDD-Based Wireless Multimedia Communications Systems, IEEE VTC, Fall, 2001.

[16] D. G. Jeong and W. S. Jeon, Time Slot Allocation in CDMA/TDD Systems for Mobile Multimedia

Services, IEEE Communication Letters, Vol. 4, No. 2, 2000.

[17] H. Haas and S. McLaughlin, A Dynamic Channel Assignment Algorithm for a Hybrid TDMA/CDMA-TDD Interface Using the Novel TS-Opposing Technique, IEEE Journal on Selected Areas in Communications, Vol. 19, No. 10, 2001.

[18] C. Mihailescu, X. Lagrange, Ph. Godlewski, and A. G. Acx, Dynamic Resource Allocation in Locally Centralized Cellular Systems, IEEE VTC, Spring, 1998.

[19] S. H. Wie and D. H. Cho, Time Slot Allocation Scheme based on a Region Division in CDMA/TDD Systems, IEEE VTC, Spring, 2001.

[20] F. S. Hillier and G. J. Lieberman, Introduction to Operations Research, Sixth Edition, McGraw-Hill, 1995.

[21] ILOG CPLEX 7.0, http://www.ilog.com.

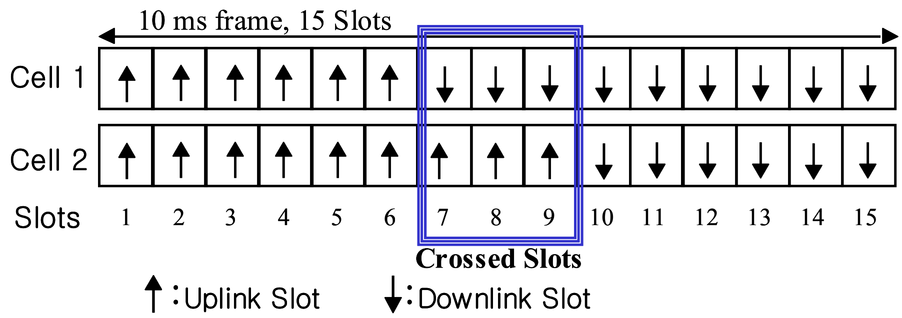

Figure 1. Crossed slots in TDD system

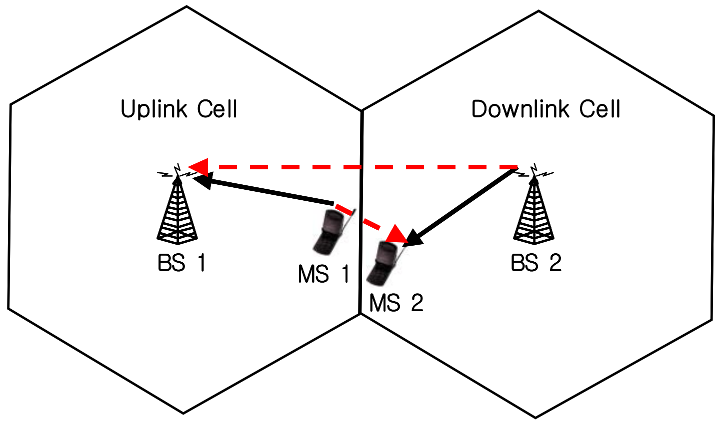

Figure 2. Interference problem in a crossed slot

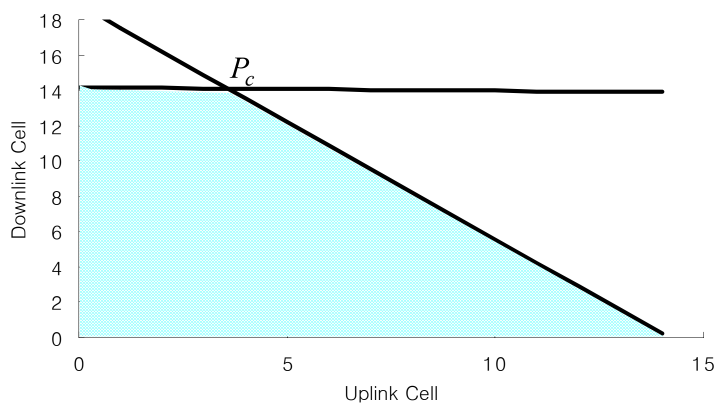

Figure 3. Capacity of a time slot: Crossed slot case

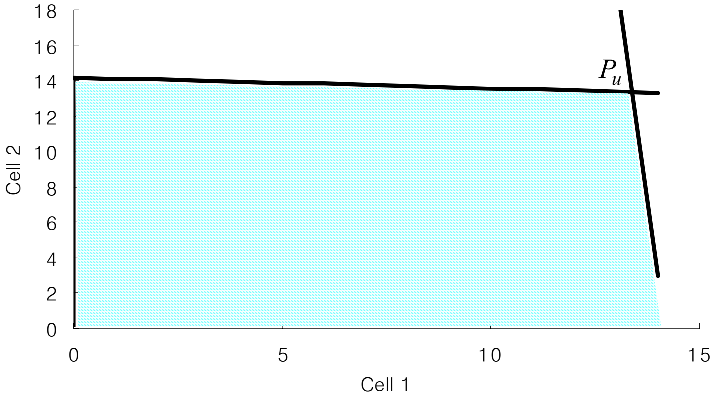

Figure 4. Capacity of a time slot: UL slot case

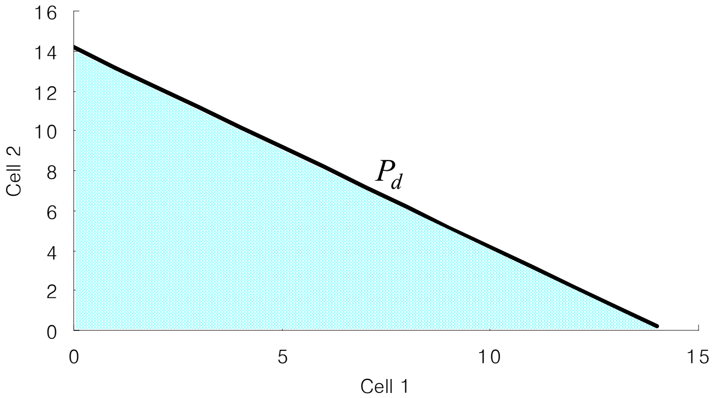

Figure 5. Capacity of a time slot: DL slot case

Table 1. Parameters used for E_b / N_0 analysis

Parameters	Values
W	5 MHz
R	8 Kbps
Q_T	1.5 W
P_T	$125 \times \delta^n$ mW
δ (r / D)	0.7
γ $(= \gamma_u = \gamma_d)$	5 dB

Table. 2 Computational result in Scenario 1

UL:DL load in cell 2	CSA		NCSA		DRAA	
	Objective value	CPU time (seconds)	Objective value	CPU time (seconds)	Objective value	CPU time (seconds)
0:80	0.468	10,000*	0.291	2.080	0.350	0.00002
10:70	0.550	10,000*	0.375	1.950	0.500	0.00003
20:60	0.650	10,000*	0.400	6.670	0.517	0.00004
30:50	0.740	10,000*	0.550	3.980	0.650	0.00003
40:40	0.775	10,000*	0.625	18.440	0.625	0.00002
50:30	0.840	10,000*	0.600	16.000	0.775	0.00003
60:20	0.825	10,000*	0.625	22.980	0.767	0.00001
70:10	0.825	10,000*	0.675	17.250	0.700	0.00004
80:0	0.825	10,000*	0.630	7.470	0.671	0.00001

*: Terminated by the time limit

Table. 3 Computational result in Scenario 2

UL:DL load in cell 2	CSA		NCSA		DRAA	
	Objective value	CPU time (seconds)	Objective value	CPU time (seconds)	Objective value	CPU time (seconds)
6:10	1.367	10,000*	1.300	27.020	1.170	0.00002
12:20	1.200	10,000*	1.000	7.350	1.000	0.00003
18:30	1.000	10,000*	0.767	9.550	0.733	0.00002
24:40	0.850	10,000*	0.700	2.340	0.680	0.00004
30:50	0.680	10,000*	0.540	2.740	0.520	0.00002
36:60	0.517	10,000*	0.400	0.660	0.400	0.00002
42:70	0.371	10,000*	0.262	5.150	0.238	0.00001
48:80	0.229	10,000*	0.104	11.260	0.083	0.00003
54:90	0.129	10,000*	0.000	5.140	0.000	0.00003

*: Terminated by the time limit

Table. 4 Computational result in Scenario 3

UL:DL load in cell 2	CSA		NCSA		DRAA	
	Objective value	CPU time (seconds)	Objective value	CPU time (seconds)	Objective value	CPU time (seconds)
20:40	0.850	10,000*	0.675	51.820	0.750	0.00001
20:50	0.750	10,000*	0.550	18.980	0.650	0.00002
20:60	0.650	10,000*	0.400	6.670	0.517	0.00004
20:70	0.525	10,000*	0.350	7.960	0.500	0.00005
20:80	0.450	10,000*	0.275	1.820	0.350	0.00003
20:90	0.375	10,000*	0.178	3.350	0.300	0.00003
20:100	0.300	10,000*	0.100	3.290	0.300	0.00003
20:110	0.236	10,000*	0.025	4.220	0.200	0.00004
20:120	0.175	10,000*	0.000	2.960	0.125	0.00003

*: Terminated by the time limit

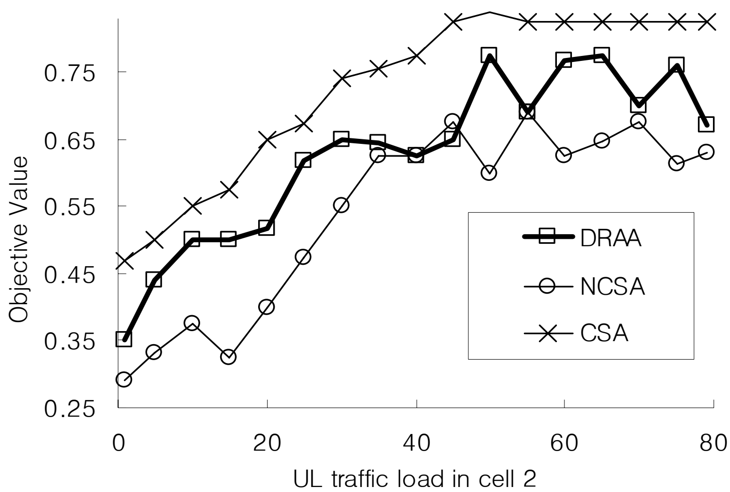

Figure 6. Result of Scenario 1

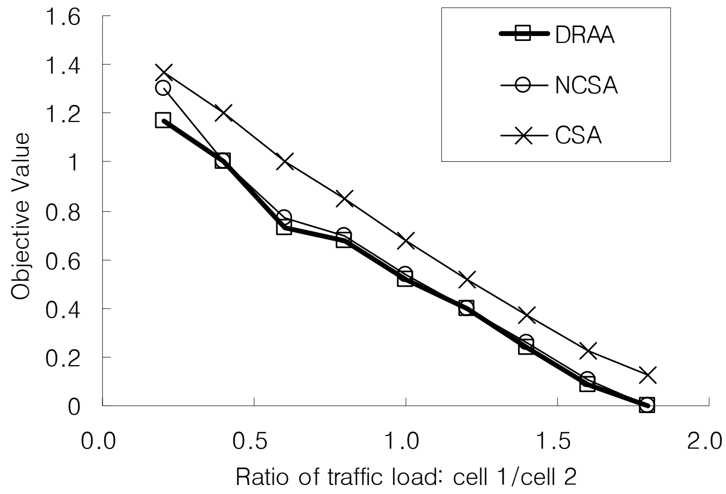

Figure 7. Result of Scenario 2

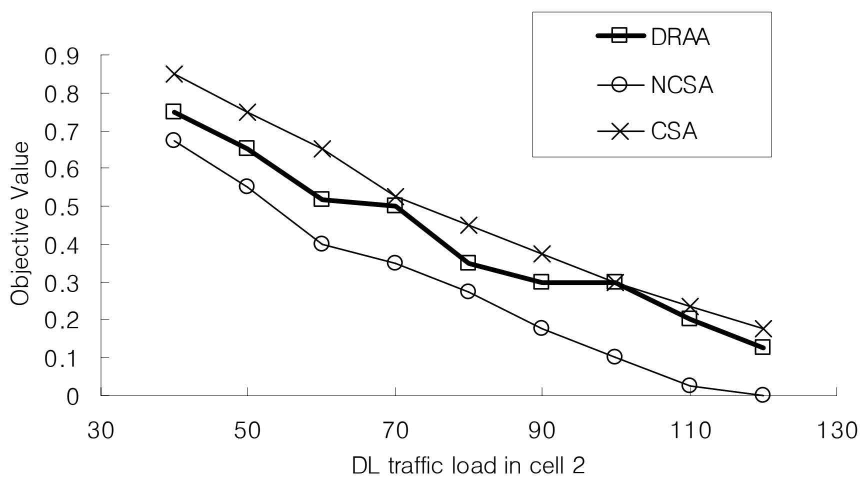

Figure 8. Result of Scenario 3

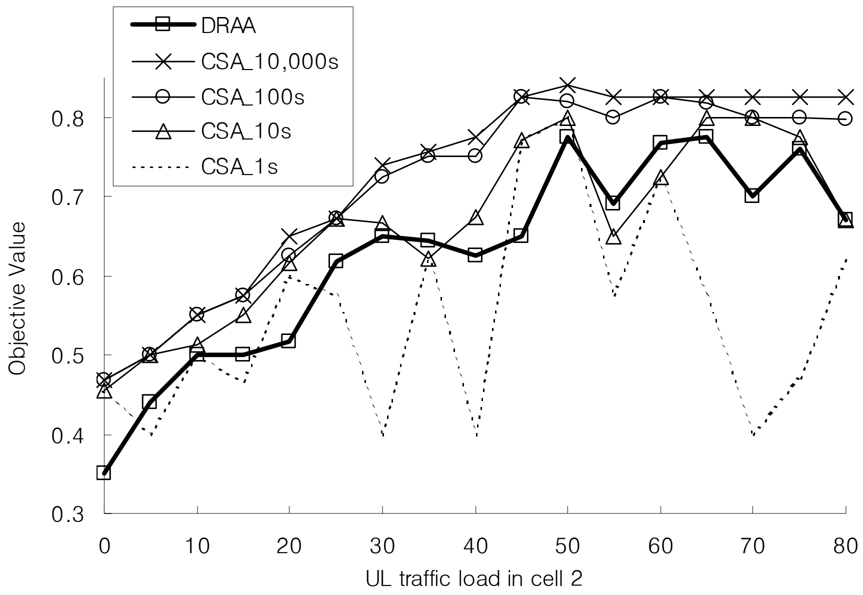

Figure 9. Performance of the CSA with regard to the time in Scenario 1

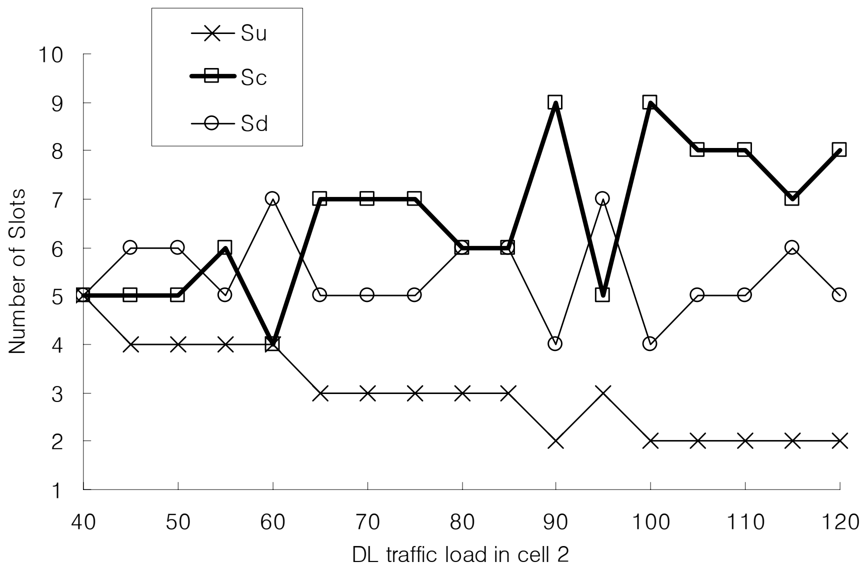

Figure 10. Number of S_u, S_c, and S_d in Scenario 3