Abstract—Time division duplex (TDD) systems and their crossed-slot interference problem in cellular environment have been attracting increasing interest. To mitigate the crossed-slot interference, we propose the RERegion-based Decentralized Time Slot Allocation (RED-TSA) strategy, and evaluate its call blocking probability, uplink SINR, and overall uplink throughput compared with those of previous TSA strategies. A statistical traffic model is adopted to simulations for a realistic modeling of dynamic call traffic. A major advantage of the proposed RED-TSA strategy is that it can be implemented autonomously in each cell without any coordination between cells. Furthermore, simulation results show that the improvement of uplink throughput in the RED-TSA strategy increases as the portion of data calls increases.

I. INTRODUCTION

In traditional wireless communication systems, frequency division duplex (FDD) has been employed since it is easy to implement and suitable for voice services. Recently, multimedia services are increasing with the widespread use of various wireless applications, such as web browsers, real-time video, and interactive games [1]. Multimedia services tend to cause asymmetric traffic between the uplink and downlink. In FDD systems, asymmetric traffic naturally results in unusable system bandwidth, while time division duplex (TDD) systems provide a pragmatic means for reducing the wasted bandwidth by simply reallocating uplink and downlink slots according to traffic conditions. Thus, TDD has been adopted to some wireless communication standards recently, such as W-CDMA and IEEE 802.16e standards.

Time slot allocation strategies in TDD systems have been studied since they may dominate the overall performance of TDD systems in cellular environments. For example, each cell may greedily consider its own traffic condition and allocate time slots according to uplink and downlink requirements. However, it is known that the approach results in two kinds of additional intercell interference scenarios [2]. The intercell interference occurs in crossed-slots, which are defined as time slots in which the directions of transmissions in neighboring cells are opposed, and is referred to as crossed-slot interference. As illustrated in Fig. I (a), suppose that Cell 1 operates in downlink period and Cell 2 operates in uplink period. Hereafter, B and M denote base station (BS) and mobile station (MS), respectively. Then, the downlink signal emitted from BS1 causes interference to the uplink signal from MS2 to BS2, and at the same time, the uplink signal emitted from MS2 causes interference to the downlink signal from BS1 to MS1. The former is called BS-to-BS crossed-slot interference and the latter is called MS-to-MS crossed-slot interference. While MS-to-MS crossed-slot interference causes minimal degradation in downlink, BS-to-BS crossed-slot interference can severely decrease signal power to interference plus noise power ratio (SINR) performance in uplink, especially when the MS2 is located near the edge of Cell 2. The reason is that the transmit power of BS is normally orders of stronger than that of MS and the propagation environment between BSs is less lossy and less fluctuating due to large antenna height [4]. Thus, we focus on the mitigation of the BS-to-BS crossed-slot interference in uplink.

There have been some works on time slot allocation in TDD systems since the possibility that the proper time slot allocation could mitigate the crossed-slot interference was demonstrated in [3]. One approach is based on the use of sector antennas. The scheme in [4], [5] avoids strong crossed-slot interference by coordinating the directions of sector antennas in each cell. In [6], a virtual cell concept has been presented in a tri-sector cellular system. Three sectors, each belonging to one of three adjacent cells, form a virtual cell, and time slot allocation is performed in each virtual cell rather than over the entire network. Another approach is based on the use of the location information of MSs [7], [8]. Crossed-slot interference is mitigated by properly scheduling the transmissions of MSs near the cell edge according to the transmission status of neighboring cells. The aforementioned works, however, require centralized controls between cells, which makes them unsuitable for employment in practical systems.

In this paper, we propose a new RERegion-based Based Decentralized Time Slot Allocation (RED-TSA) strategy. The proposed RED-TSA strategy also mitigates the crossed-slot interference problem based on the location information of MSs as in [7], [8]. However, RED-TSA strategy utilizes the location information of its own MSs and does not require coordination between cells. Time slot allocation is performed autonomously in each cell irrespective of the status of neighboring cells. Thus, the proposed RED-TSA strategy enables decentralized management of crossed-slot interference. We evaluate the proposed RED-TSA strategy through call blocking probability, uplink SINR, and overall uplink throughput.

II. SYSTEM MODEL

In this section, we model the received uplink signal at reference BS interfered by BS-to-BS crossed-slot interference. We assume a hexagonal cellular structure and omni-directional antennas are adopted in both MSs and BSs. For simplicity of analysis, time division multiple access (TDMA) is assumed in the system model, and power control is not considered. The subscript n and k are used as the index for cell and time slot, respectively. At the reference BS, \( B_0 \), the received signal power in the \( k \)-th uplink time slot can be computed as

\[
S_k = p_M \times G(x,y) \times L(x,y),
\]

where \( p_M \), \( G(x,y) \), and \( L(x,y) \) represent the transmit power of the MS, propagation loss, and log-normal shadow fading between two stations, \( x \) and \( y \), respectively. Since different wireless propagation conditions are applied depending on the stations, propagation loss function \( G(x,y) \) and shadowing function \( L(x,y) \) are defined as

\[
G(x,y) = \begin{cases} 
0.5 & \text{(both BSs)} \\
-d_{xy}^{-\alpha_{BB}}, & \text{(one BS, one MS)}
\end{cases},
\]

\[
L(x,y) = \begin{cases} 
10^{-\xi_{BB}/10}, & \text{(both BSs)} \\
10^{-\xi_{BM}/10}, & \text{(one BS, one MS)}
\end{cases},
\]

where
then compared with each other. blocking probability, uplink SINR, and overall uplink throughput, based decentralized time slot allocation (RED-TSA) strategy. The have been proposed for decentralized TDD systems are reviewed. 

\[ \alpha \]

Then, through (1)-(5), SINR at reference BS in the \( k \)-th uplink time slot can be expressed as

\[
I_{n,k} = \begin{cases} 
\phi_{n,k} \times B_{\text{to}} \times G(B_{0}, M_{n,k}) \times L(B_{0}, M_{n,k}) + \psi_{n,k} \times B_{\text{to}} \times G(B_{0}, B_{n}) \times L(B_{0}, B_{n}), \\
0, \quad \text{(otherwise)}
\end{cases}
\]

where \( p_{B} \), \( \phi_{n,k} \) and \( \psi_{n,k} \) are the transmit power of the BS, uplink activity factor, and downlink activity factor, respectively, and defined as

\[
\phi_{n,k} = \begin{cases} 
1, \quad \text{(if the \( k \)-th time slot in the \( n \)-th cell is in uplink)} \\
0, \quad \text{(otherwise)}
\end{cases}
\]

\[
\psi_{n,k} = \begin{cases} 
1, \quad \text{(if the \( k \)-th time slot in the \( n \)-th cell is in downlink)} \\
0, \quad \text{(otherwise)}
\end{cases}
\]

Then, through (1)-(5), SINR at reference BS in the \( k \)-th uplink slot can be computed as

\[
\text{SINR}_{k} = \frac{S_{t}}{\sum_{i=1}^{K} n_{B}}.
\]

where \( n_{B} \) denotes noise power received at BS.

III. TIME SLOT ALLOCATION STRATEGIES FOR DECENTRALIZED TDD SYSTEMS

In this section, previous time slot allocation (TSA) strategies which have been proposed for decentralized TDD systems are reviewed. Then, we propose our scheme, which is referred to as region-based decentralized time slot allocation (RED-TSA) strategy. The performances of the TSA strategies are evaluated in terms of call blocking probability, uplink SINR, and overall uplink throughput, then compared with each other.

A. Greedy-TSA Strategy

Since time slot allocation information of neighboring cells is unknown in decentralized systems, the simplest approach in each cell is to greedily satisfy its own traffics. Thus, in this Greedy-TSA strategy, time slot allocation is performed according to the traffic condition of each cell, not considering the crossed-slot interference. When a new call arrives, uplink and downlink time slots are allocated depending on the types of the call. Uplink time slots are allocated from the head slot of a frame while downlink time slots are allocated from the tail slot of a frame so that crossed-slot interference can be avoided when cell loading is low. The only case when the new call is blocked is that there are not enough time slots left in a frame. Assuming the arrival of Class-\( l \) call in the \( n \)-th cell, the new call blocking event due to the shortage of available time slots, referred to as \( \Omega \), is defined as

\[
\Omega = \{ \sum_{i} C_{n,i}(\Delta^{(u)}_{i} + \Delta^{(d)}_{i}) > K \},
\]

where \( C_{n,i} \) and \( K \) are the number of Class-\( l \) calls under service in the \( n \)-th cell and the total number of time slots in a frame, respectively. \( \Delta^{(u)}_{i} \) and \( \Delta^{(d)}_{i} \) denote the numbers of required uplink and downlink resource units, i.e., time slots here, for a Class-\( l \) call. Then, the new call blocking probability for Class-\( l \) call in the \( n \)-th cell is

\[
\chi^{\text{Greedy}}_{n,i} = \Pr\{ \Omega \}.
\]

Denoting the portion of Class-\( i \) calls among newly arriving calls by \( \rho_{i} \), the expected new call blocking probability in the \( n \)-th cell can be calculated as

\[
\chi^{\text{Greedy}}_{n} = \sum_{i} \rho_{i} \chi^{\text{Greedy}}_{n,i}.
\]

On the other hand, even if the new call is not blocked, the time slots allocated to that call do not guarantee successful wireless transmission. Severe BS-to-BS crossed-slot interference decreases SINR at uplink crossed-slots as calculated in (6), which results in outages at the \( k \)-th time slots when SINR \( \chi^{\text{Greedy}}_{n} \). Note that outage slots do not contribute to throughput. Considering both the new call blocking and outage occurrence, we calculate the average uplink throughput as the overall performance measure of TSA strategies. The average uplink throughput in the reference cell can be calculate as

\[
R_{\text{avg}} = E\left[\sum_{l} (C_{0,l} - T_{0,l})r^{(u)}_{l}\right],
\]

where \( T_{0,l} \) denotes the number of Class-\( l \) calls where outage has occurred, i.e., SINR < \( \gamma \) among its allocated \( \Delta^{(u)}_{l} \) uplink time slots, and \( r^{(u)}_{l} \) denotes the uplink information rate of Class-\( l \) call, i.e., rate supported by \( \Delta^{(u)}_{l} \) resource units.

B. Fixed-TSA Strategy

In the Fixed-TSA strategy, a strong constraint is applied in time slot allocation so that the system may not be degraded by crossed-slot interference. All cells in a cellular network have a predefined value, which is the maximum number of uplink (or downlink) time slots in a frame. Denoting \( K_{F} \) as the maximum number of uplink time slots in a frame, i.e., the maximum number of downlink slots is \( K - K_{F} \), the new call blocking scenario in the Fixed-TSA strategy is depicted in Fig. 2 (a). As in the Greedy-TSA strategy, uplink time slots are allocated from the head slot and downlink time slots are allocated from the tail slot. A new arriving call will be blocked when there is no more available time slot left in a frame. Moreover, the call will also be blocked when either the required uplink time slots or downlink time slots exceed the maximum number of time slots, i.e., \( K_{F} \) in uplink and \( K - K_{F} \) in downlink. Thus, time slots in a frame remain underutilized in this case. The new call blocking probability...
for Class-\(i\) call in the \(n\)-th cell is
\[
\chi_{n,i}^{Fixed} = 1 - \Pr \left\{ \sum_{l} C_{n,l} \Delta_{l}^{(u)} + \Delta_{i}^{(u)} \leq K_F, \right. \\
\left. \sum_{l} C_{n,l} \Delta_{l}^{(d)} + \Delta_{i}^{(d)} \leq (K - K_F) \right\}
\]
and expected new call blocking probability in the \(n\)-th cell is
\[
\chi_{n}^{Fixed} = \sum_{i} p_{i} \chi_{n,i}^{Fixed}.
\]

The Fixed-TSA strategy is expected to show higher new call blocking probability than the Greedy-TSA strategy due to the additional constraint in resource allocation. On the other hand, SINR of the Fixed-TSA strategy in each time slot is expected to be higher than that of the Greedy-TSA strategy since the Fixed-TSA strategy intrinsically prevents time slots from being crossed-slots in neighboring cells, i.e., \(\psi_{n,k} = 0\) in (3). The overall performance of the Fixed-TSA strategy is calculated as in (10). It is difficult to determine which strategy outperforms the other between the Greedy-TSA and the Fixed-TSA strategy. The reason for this is that the overall performance, \(R_{aver}\), is dependent on parameters such as the asymmetry factor of each call class, the portion of each call class arriving calls, new call arriving rate, and user distribution in a cell. For example, in commercial WiBro systems (IEEE 802.16e Mobile WiMAX), the Fixed-TSA strategy is adopted for simple intercell interference management. In all synchronized cells, 27 OFDM symbols and 15 OFDM symbols are respectively dedicated to downlink and uplink among total 42 OFDM symbols in a frame.

C. RED-TSA Strategy

Based on discussions above, the Greedy-TSA strategy is advantageous in new call blocking performance while the Fixed-TSA strategy is advantageous in SINR performance. Therefore, we propose the RED-TSA strategy as a compromise. The main idea of the RED-TSA strategy is that a cell is partitioned into inner and outer regions and that only critical crossed-slot interferences experienced by the MSs in the outer region are precluded. Detailed procedures are illustrated in Fig. 2 (b). Predefined boundary now limits the maximum number of uplink time slots for the MSs in the outer region by \(K_F\). It also limits the maximum number of total downlink time slots by \(K - K_R\). Uplink of the MSs in the outer region are serviced from the first time slots to the \(K_F\)-th time slot. Any arriving call will be blocked when the number of uplink time slots of the MSs in the outer region exceeds \(K_F\), or when the number of total downlink time slots exceeds \(K - K_R\). Arriving calls of the MSs in the inner region will not be blocked unless the total number of time slots in a frame is short. Note that MS3 is not blocked in Fig. 2 (b), which makes the RED-TSA strategy flexible in resource allocation. Assuming that MSs are evenly distributed and that the probability of an arriving MS being located in the outer region as \(\pi\), the new call blocking probability for Class-\(i\) call in the \(n\)-th cell is
\[
\chi_{n,i}^{RED} = \pi \left[ 1 - \Pr \left\{ \sum_{l} C_{n,l}^{outer} \Delta_{l}^{(u)} + \Delta_{i}^{(u)} \leq K_R, \right. \right. \\
\left. \left. \sum_{l} C_{n,l} \Delta_{l}^{(d)} + \Delta_{i}^{(d)} \leq (K - K_R) \right\} \right] \\
+(1 - \pi) \left[ 1 - \Pr \left\{ \sum_{l} C_{n,l}^{outer} \Delta_{l}^{(d)} + \Delta_{i}^{(d)} \leq (K - K_R) \right\} \right]
\]
where \(C_{n,l}^{outer}\) is the number of Class-\(l\) calls under service in the outer region of the \(n\)-th cell, i.e., \(C_{n,l} = C_{n,l}^{outer} + C_{n,l}^{inner}\). Then, the expected new call blocking probability in the \(n\)-th cell is
\[
\chi_{n}^{RED} = \sum_{i} p_{i} \chi_{n,i}^{RED}.
\]

The proposed RED-TSA strategy changes the crossed-slot interference scenario in Fig. 1 (a) into the modified scenario in Fig. 1 (b). In crossed-slots, only the MSs in the inner region transmit uplink signal. Thus, the received uplink signal power in crossed-slots increases due to reduced pathloss. In the \(k\)-th uplink time slots, SINR can be calculated through (1)-(6) and the overall performance of the RED-TSA strategy can be calculated in (10). It is expected that the RED-TSA strategy allocates time slots more flexibly than the Fixed-TSA strategy and, at the same time, results in less outages than the Greedy-TSA strategy.

On the other hand, the overall performances of the Fixed-TSA and the RED-TSA strategies depend on the predefined boundaries, as determined by \(K_F\) and \(K_R\), respectively, and finding optimal placement for them requires complicated studies. Here, for a simple approach, we focus on the long-term observation of traffic asymmetry and select \(K_F\) and \(K_R\) values that will result in the minimum new call blocking probability. The placements of predefined boundaries are calculated as
\[
\begin{align*}
& \text{Predefined boundary in Fixed-TSA strategy} = \arg\min_{K_F} \chi_{n}^{Fixed} \\
& \text{Predefined boundary in RED-TSA strategy} = \arg\min_{K_R} \chi_{n}^{RED}.
\end{align*}
\]

IV. NUMERICAL RESULTS

We assume a hexagonal cellular structure with cell radius \(r = 1\text{km}\). Frequency reuse factor is chosen to be 7 and 18 interfering cells (two-tier) are considered. The total number of time slots in each TDD frame is \(K = 120\). The transmit powers of MS and BS are set to \(p_M = 23\text{dBm}\) and \(p_B = 40\text{dBm}\), respectively. Noise power at BS is assumed to be \(n_B = -107\text{dBm}\), and the minimum SINR requirement at receivers is considered as \(\gamma = 4\text{dB}\). MSs are assumed to be uniformly distributed in each cell and the radius of the inner region is set to \(r_I = 732\text{m}\), i.e., the area of the inner region is one half of a cell. Here, we consider two different propagation environments. For BS-BS links, the path loss exponent is taken to be \(\alpha_{BB} = 3\) and the log standard deviation for shadowing variable is taken to be \(\xi_{BB} = 3\text{dB}\), while path loss exponent and log standard deviations for shadowing variable are \(\alpha_{BM} = 3.5\) and \(\xi_{BM} = 8\text{dB}\), respectively, for BS-MS links.

Since MSs in each cell may request different service classes, the traffic asymmetry between uplink and downlink in each cell may vary.
TABLE I
STATISTICAL TRAFFIC MODEL

<table>
<thead>
<tr>
<th>Service</th>
<th>Class-I Call</th>
<th>Class-II Call</th>
</tr>
</thead>
<tbody>
<tr>
<td>Example</td>
<td>Voice</td>
<td>Medium Multimedia (Web browsing)</td>
</tr>
<tr>
<td>Link</td>
<td>Uplink 12.2kbps</td>
<td>Downlink 12.2kbps</td>
</tr>
<tr>
<td></td>
<td>Uplink 9.96kbps</td>
<td>Downlink 384kbps</td>
</tr>
<tr>
<td>Information Rate, $r$</td>
<td>1/1</td>
<td>0.026/1</td>
</tr>
<tr>
<td>Asymmetry Factor</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Required Resource Unit, $\Delta$</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Portion of New Call, $\rho$</td>
<td>85% (2005)</td>
<td>70% (2010)</td>
</tr>
<tr>
<td></td>
<td>15% (2005)</td>
<td>30% (2010)</td>
</tr>
<tr>
<td>Mean Call Duration, $\frac{1}{\mu}$</td>
<td>60 sec</td>
<td>14 sec</td>
</tr>
<tr>
<td>New Call Arrival Rate, $\lambda$</td>
<td>variable</td>
<td>variable</td>
</tr>
</tbody>
</table>

We adopt the statistical traffic model in [9], which takes two classes of calls into consideration. Each class of calls arrives and completes according to Poisson process with rates $\lambda$ and $\mu$, respectively. A new call is determined as either Class-I call or Class-II call with the portion of new call, $\rho$. While Class-I calls require symmetric bandwidth between uplink and downlink, Class-II call require asymmetric bandwidth, i.e., larger bandwidth in downlink. The service examples are voice call and web browsing, respectively. The parameter values are based on spectrum calculations for IMT-2000 systems [1] and listed in Table I. Note that the portion of data calls among new arriving calls is expected to gradually increase up to 30% in 2010. Simulations are conducted by the Monte Carlo evaluation of equations which are derived in Section III. Simulation platform is constructed with MATLAB tools and simulations are observed over $10^3$ seconds. By (15), the number of fixed time slots in the Fixed-TSA strategy is determined as $K_F = 44$ for the year 2005 and $K_F = 32$ for the year 2010. Similarly, the number of fixed time slots in the RED-TSA strategy is determined as $K_R = 28$ for the year 2005 and $K_R = 26$ for the year 2010.

Fig. 3 shows how new call blocking probability $\chi$ varies with new call arrival rate $\lambda$ according to different time slot allocation strategies and traffic environments. The Greedy-TSA strategy shows the lowest new call blocking probability among three TSA strategies since available time slots in a frame are freely allocated to either uplink or downlink. On the contrary, the Fixed-TSA strategy shows the highest new call blocking probability since both uplink and downlink are individually constrained into fixed numbers of time slots and an arriving call will be blocked when any shortage occurs either in uplink or downlink. The proposed RED-TSA strategy forces the fixed number of time slots only to the MSs in the outer region, and the results show minimal degradation in new call blocking probability when compared with the best case, i.e., the Greedy-TSA strategy. On the other hand, new call blocking probability increases when the portion of data calls, $\rho_2$, increases. The ratio of required uplink and downlink time slots fluctuates more dynamically due to frequent data calls, which results in higher chances of new call blocking.

Fig. 4 shows how SINRs at uplink time slots are distributed according to time slot allocation strategies. As expected, the Fixed-TSA strategy shows the best SINR performance since there exists no crossed-slot interference, whereas the Greedy-TSA strategy shows an outage probability of 3.2% due to strong BS-to-BS crossed-slot interference. The RED-TSA strategy mitigates crossed-slot interference and reduces the outage probability down to 1.5%. Note that the Greedy-TSA strategy rather outperforms the RED-TSA strategy in high SINR region. The reason is because the RED-TSA strategy services the MSs near BS in the crossed-slots. In other words, the RED-TSA strategy improves SINR in the low SINR region in return for SINR reduction in the high SINR region, which provides a desirable tradeoff here. The SINR performance of the Random-TSA strategy is also presented as the worst reference. Its call admission control is basically the same as the Greedy-TSA strategy. However, time slot allocations are not performed even sequentially from the head or tail slots of a frame, and therefore, cellular environment is not considered. Thus, many time slots may be exposed to strong BS-to-BS crossed-slot interference and the Random-TSA strategy shows poor SINR performance.

Fig. 5 shows how average uplink throughput $R_{ave}$ varies with new call arrival rates $\lambda$ according to different time slot allocation strategies and traffic environments. The proposed RED-TSA strategy provides the maximum uplink capacity among the four strategies. In the case of $\rho_2 = 15\%$, the RED-TSA strategy provides 3.0% and 35.6% more uplink capacity than the Greedy-TSA and Fixed-TSA strategies, respectively. The reason is that the Greedy-TSA and Fixed-TSA strategies outperform other strategies only in one performance measure, i.e., either new call blocking performance or SINR performance, while the proposed RED-TSA strategy scores well-balanced performance in both performance measures. This improvement is further enhanced when the portion of data calls $\rho_2$ increases. Uplink capacity in the RED-TSA strategy increases up to 4.9% and 84.7%, respectively, compared to the Greedy-TSA and Fixed-TSA when $\rho_2 = 30\%$.

V. CONCLUSIONS
In this paper, we have proposed the REgion-based Decentralized Time Slot Allocation (RED-TSA) strategy for decentralized TDD systems. The overall performance of the RED-TSA strategy is compared with those of conventional decentralized TSA strategies. Our results show that the RED-TSA strategy compromises both new call blocking performance and SINR performance, while offering 3.0% and 4.9% more uplink throughput than the Greedy-TSA strategy under traffic expectations in the year 2005 and 2010, respectively. This paper makes two major contributions. First, the proposed RED-TSA strategy can be implemented autonomously in each cell without any coordination between the cells and its computational complexity is low, which makes it particularly easy to apply to practical TDD systems. Second, in contrast to the fixed traffic models of previous works, a statistical call traffic model is adopted in simulations for
a realistic modeling of dynamic call traffic, which enables us to evaluate the compromising effect of the proposed RED-TSA strategy between new call blocking performance and SINR performance. As the portion of data calls increases, traffic asymmetry may vary more dynamically in each cell. Then, the capacity improvement of the RED-TSA strategy in uplink is expected to increase further.

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