Comparison of Decentralized Time Slot Allocation Strategies for Asymmetric Traffic in TDD Systems

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Abstract

Recently, wireless multimedia services have been growing because of the spread of various wireless applications. Hence, time division duplex (TDD) systems and their crossed-slot interference problems in a cellular environment have been attracting growing interests. Considering large signaling overhead between cells, decentralized time slot allocation (TSA) strategy is suitable for practical implementation. Thus, Fixed-TSA strategy which fixes the same ratio of uplink and downlink time slots in all cells is adopted in commercial WiBro systems (IEEE802.16e Mobile WiMax) to mitigate the crossed-slot interference. However, the Fixed-TSA strategy reduces the flexibility in time slot allocation due to a strong constraint set by a predefined boundary. Moreover, the mathematical derivation of the optimal value for the predefined boundary has not been presented yet. In this paper, we propose two decentralized TSA strategies. The first one is Enhanced Fixed-TSA strategy, which dynamically adapts the predefined boundary of the conventional Fixed-TSA strategy according to traffic conditions. The second one is REgion-based Decentralized Time Slot Allocation (RED-TSA) strategy, which utilizes partial location information of MSs to reduce crossed-slot interference. We fully analyze the proposed TSA strategies in terms of new call blocking probability, average bit error probability, and the overall system throughput. Numerical results show that the proposed RED-TSA strategy provides the highest system throughput by compromising both new call blocking performance and average bit error performance, whereas it requires

This paper was presented in part at the IEEE Consumer Communications and Networking Conference (CCNC), Las Vegas, USA, Jan. 2006. This work was supported by the Korea Science and Engineering Foundation (KOSEF) through the National Research Lab. (NRL) Program funded by the Ministry of Science and Technology (No. M10300000316-06J0000-31610).
additional location information and complicated computation. On the contrary, the proposed Enhanced Fixed-TSA strategy requires reasonable computational complexity while it provides almost the same system throughput with that of the proposed RED-TSA strategy. In a nutshell, the proposed Enhanced Fixed-TSA strategy is more appropriate for the practical systems. Moreover, it can be directly applied to the current commercial WiMax/WiBro systems with minimum changes.
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], [2]. Multimedia services tend to cause asymmetric traffic between the uplink and downlink. In FDD systems, asymmetric traffic naturally results in unused system bandwidth, while time division duplex (TDD) systems provide a pragmatic means for reducing the wasted bandwidth by simply reallocating uplink and downlink time slots according to traffic conditions. Thus, TDD has been adopted to some wireless communication standards recently, such as WCDMA-TDD, IEEE 802.16e, and WiBro standards [3]–[6].

Time slot allocation in TDD systems has been studied for a decade 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 its uplink and downlink requirements, which is referred to as Greedy-TSA strategy. However, it is known that this approach additionally results in two types of intercell interference scenarios [7], [8]. Time slots in which the directions of transmissions are opposed in neighboring cells are defined as crossed-slots and the intercell interference which occurs in the crossed-slots is referred to as crossed-slot interference. As illustrated in Fig. 1(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 $B^{(1)}$ causes interference to the uplink signal from $M^{(2)}_1$ to $B^{(2)}$, and at the same time, the uplink signal emitted from $M^{(2)}_1$ causes interference to the downlink signal from $B^{(1)}$ to $M^{(1)}_1$. The former is called BS-to-BS crossed-slot interference and the latter is called MS-to-MS crossed-slot interference. While the MS-to-MS crossed-slot interference causes minimal degradation in downlink, the BS-to-BS crossed-slot interference can severely decrease signal power to interference plus noise power ratio (SINR) in uplink, especially when the $M^{(2)}_1$ 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 [10].

There have been many works on time slot allocation strategy in TDD systems after the possibility has

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1The specific case that the MS-to-MS crossed-slot interference causes severe degradation arises when MSs in neighboring cells are closely collocated along the boundary of those cells. However, the probability of the case is very low. Furthermore, the transmit power of MSs is normally orders of weaker than that of BS.
demonstrated that the proper time slot allocation could mitigate the crossed-slot interference in [9]. One approach is based on the use of sector antennas. The schemes in [10], [11] avoid strong crossed-slot interference by coordinating the directions of sector antennas in each cell. In [12], 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 [13]–[15]. 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 resulting in large signaling overhead, which makes them unsuitable for practical systems.

In commercial WiBro systems (IEEE 802.16e Mobile WiMax) [6], Fixed-TSA strategy which fixes the same ratio of uplink and downlink time slots in all cells is adopted as a practical decentralized TSA scheme. However, the Fixed-TSA strategy reduces the flexibility in time slot allocation due to a strong constraint set by a predefined boundary. Moreover, decision of the predefined boundary requires complicated mathematical analysis. The optimal value for the predefined boundary has not been derived yet. In this paper, we propose two new decentralized TSA strategies. One is the evolution of the conventional Fixed-TSA strategy, which alleviates the drawback of the conventional Fixed-TSA strategy by dynamically optimizing the predefined boundary. It is referred to as Enhanced Fixed-TSA strategy. The other is a new REgion-based Decentralized Time Slot Allocation (RED-TSA) strategy. The RED-TSA strategy mitigates the crossed-slot interference based on the location information of MSs as in [13]–[15]. However, the 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. After we evaluate the proposed TSA strategies in terms of new call blocking performance, average bit error performance, and overall system throughput, we compare numerical results of them.

This paper makes three major contributions.

- **Cross-layer analysis:** To the best of our knowledge, this is the first paper which evaluates the performance of time slot allocation strategy by cross-layer analysis. A statistical Markov-chain traffic model is adopted and cross-layer analysis is performed in terms of new call blocking probability and average bit error probability. Previous works have either analyzed the SINR-level performance under specific fixed traffic values [12] or presented only simulation results without analysis when
statistical traffic model is considered [13]. To capture the dynamic behaviors of the TDD systems such as effective mitigation of crossed-slot interference and flexible allocation of time slot resources, cross-layer analysis including the statistical traffic model in indispensable in evaluating time slot allocation strategies.

- **Enhanced Fixed-TSA strategy:** In the conventional Fixed-TSA strategy, the optimal value of the predefined boundary is roughly estimated based on long-term system simulations. Moreover, the determined predefined boundary cannot be updated adaptively with traffic condition since the simulation-based adaptation requires huge computational complexity and processing time. Based on the cross-layer analysis, the optimal value of the predefined boundary is easily derived and updated according to the traffic condition. We propose this improved Fixed-TSA strategy based on mathematical derivation and refer it to as Enhanced Fixed-TSA strategy.

- **RED-TSA strategy:** A new REgion-based Decentralized Time Slot Allocation (RED-TSA) strategy is proposed. Based on only partial information (location information of MSs in the corresponding cell), each cell autonomously mitigates crossed-slot interference under the RED-TSA strategy. The proposed RED-TSA strategy provides the highest system throughput in compared to the conventional Greedy-TSA and Fixed-TSA strategies.

The remainder of this paper is organized as follows. Section II describes the signal model considering crossed-slot interference scenarios and traffic model for performance analysis. Section III reviews previous decentralized time slot allocation strategies and explains the proposed TSA strategies. The proposed TSA strategies are analyzed in terms of the new call blocking probability and average bit error probability in Section IV. The optimal value for the predefined boundary is computed in Section V. In Section VI, numerical results of all time slot allocation strategies are given and compared each other. Finally, conclusions are drawn in Section VII.

II. **SYSTEM MODEL**

In this section, we model the received downlink signal at MSs and uplink signal at BSs in the reference cell (the 0th cell), which are interfered by MS-to-MS crossed-slot interference and BS-to-BS crossed-slot interference, respectively. Then, we model the statistical traffic model based on queuing theory.

A. **Signal Model**

We assume a hexagonal cellular structure and omni-directional antennas are adopted in both MSs and BSs. We assume a single user transmission scenario such as time division multiple access (TDMA) for
simplicity of analysis. Thus, only intercell interference from neighboring cells exists. However, the type of interfering source switches between BS and MS depending on whether the corresponding cell operates in uplink or downlink. The superscript \((j)\) is used as the index for cell and \(J\) denotes the total number of cells in the network. The downlink signal received at the MS in the reference cell is given by

\[
y_D = h_{BM}^{(0)} \sqrt{L_{BM}^{(0)} x_B^{(0)}} + \sum_{j=1}^{J} \left\{ \phi_D^{(j)} h_{BM}^{(j)} \sqrt{L_{BM}^{(j)} x_B^{(j)}} + \psi_D^{(j)} h_{MM}^{(j)} \sqrt{L_{MM}^{(j)} x_M^{(j)}} \right\} + n_M, \tag{1}
\]

where \(h_{BM}^{(j)}\) and \(h_{MM}^{(j)}\) denote short term fading from the \(j\)th cell BS and \(j\)th cell MS, respectively, and are i.i.d. complex Gaussian random variable \(\sim \mathcal{CN}(0,1)\). \(L_{BM}^{(j)}\) and \(L_{MM}^{(j)}\) denote propagation pathloss and long term fading (shadowing) from the \(j\)th cell BS and \(j\)th cell MS, respectively. \(\phi_D^{(j)}\) and \(\psi_D^{(j)}\) are non-crossed and crossed factors of the \(j\)th cell defined as

\[
\phi_D^{(j)} = \begin{cases} 
1, & \text{when the transmission direction in the } j \text{th cell is the same} \\
0, & \text{otherwise}
\end{cases},
\]
\[
\psi_D^{(j)} = \begin{cases} 
1, & \text{when the transmission direction in the } j \text{th cell is opposite} \\
0, & \text{otherwise}
\end{cases}.
\tag{2}
\]

The transmitted signal from BS, \(x_B\), and the transmitted signal from MS, \(x_M\), are constrained with \(E[|x_B|^2] = P_B, E[|x_M|^2] = P_M\). \(n_M\) is the additive white Gaussian noise (AWGN) with variance \(E[|n_M|^2] = \sigma_{n,M}^2\) at MS. Since the number of interfering BSs (or MSs) is sufficiently large and they are independent of each other, the interference plus noise is assumed to be a complex Gaussian variable \(z_M\) with variance \(\sigma_{z_M}^2\) by the Central Limit Theorem [32], which is computed later in Section IV. Hence, (1) can be expressed as

\[
y_D = h_{BM}^{(0)} \sqrt{L_{BM}^{(0)} x_B^{(0)}} + z_M.
\]

Similarly, the uplink signal received at the reference BS is given by

\[
y_U = h_{MB}^{(0)} \sqrt{L_{MB}^{(0)} x_M^{(0)}} + \sum_{j=1}^{J} \left\{ \psi_U^{(j)} h_{BB}^{(j)} \sqrt{L_{BB}^{(j)} x_B^{(j)}} + \phi_U^{(j)} h_{MB}^{(j)} \sqrt{L_{MB}^{(j)} x_M^{(j)}} \right\} + n_B, \tag{3}
\]

where

\[
\phi_U^{(j)} = \begin{cases} 
1, & \text{when the transmission direction in the } j \text{th cell is the same} \\
0, & \text{otherwise}
\end{cases},
\]
\[
\psi_U^{(j)} = \begin{cases} 
1, & \text{when the transmission direction in the } j \text{th cell is opposite} \\
0, & \text{otherwise}
\end{cases}, \tag{4}
\]

and

\[
E[|n_B|^2] = \sigma_{n,B}^2. \tag{5}
\]

The uplink signal model is also simplified into

\[
y_U = h_{MB}^{(0)} \sqrt{L_{MB}^{(0)} x_M^{(0)}} + z_B\text{ with } E[|z_B|^2] = \sigma_{z_B}^2.
\]
B. Statistical Traffic Model

We assume that the cellular network is homogeneous; all cells in the network behave statistically the same with each other. According to the different service requirements of MSs, incoming calls are categorized into several call classes and the system is now modeled as a multidimensional birth-death process [16], [17]. Each class of calls arrives and completes according to Poisson process with rates $\lambda_k$ and $\mu_k$, respectively. With $K$ classes of calls existing, the resulting statistical traffic model is $K$-dimensional Markov chain with $M/M/m/m$ type of queue. The call state probability that the number of Class-$k$ calls is $c_k$ is given by the product form [18]

$$
\Pi(c_1, c_2, \cdots, c_K) = \frac{\rho_1^{c_1} \cdot \rho_2^{c_2} \cdots \rho_K^{c_K}}{\eta},
$$

where $\eta$ is a normalization constant, $\rho_k = \frac{\lambda_k}{\mu_k}$, and $S$ is the set of all possible call states.

As listed in [1], [2], several call classes are expected for the next generation communication system. Here, we consider two service examples ($K = 2$) for simplicity of analysis, which are voice call (Class-I) and data call (Class-II). Let $\Delta_{D,k}$ and $\Delta_{U,k}$ denote the required number of downlink and uplink time slots for Class-$k$ call. Note that Class-I calls require symmetric bandwidth between uplink and downlink ($\Delta_{D,1} = \Delta_{U,1}$), while Class-II calls require asymmetric bandwidth, i.e., much larger bandwidth in downlink ($\Delta_{D,2} > \Delta_{U,2}$).

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 two new TSA strategies, which are Enhanced Fixed-TSA strategy and REgion-based Decentralized time slot allocation (RED-TSA) strategy. We compare the TSA strategies in terms of three performance measures. The first one is the new call blocking probability which indicates the flexibility in time slot resource allocation under dynamically changing traffic. The second one is the average bit error probability which shows the interference mitigation capability in a multicell environment. The last one is the system throughput which depends both on the new call blocking probability and average bit error probability, which effectively describes the overall performances of TSA strategies.
A. Greedy-TSA Strategy

Since time slot allocation information of neighboring cells is unknown in decentralized systems, the simplest approach for each cell is to greedily satisfy its own traffics. It is referred to as Greedy-TSA strategy. 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, which is basically the same as the conventional time slot allocation in a single cell environment. 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. \(^2\) The only case when the new call is blocked is that there are not enough time slots left in a frame.

On the other hand, even if a call is scheduled to be served without being blocking, successful wireless transmission is not always guaranteed. Interference from neighboring cells, especially severe BS-to-BS crossed-slot interference, and noise at receiver decreases SINR, which results in outages. Note that outages reduce system throughput. Considering both the new call blocking and outage occurrence, it is expected that the Greedy-TSA efficiently supports dynamic traffic in low cell loading. However, the system may suffer from large outages in high cell loading since there are no means to mitigate the crossed-slot interference.

B. Fixed-TSA Strategy & Enhanced Fixed-TSA Strategy

To avoid severe performance degradation due to crossed-slot interference, a strong constraint can be introduced in time slot allocation as in commercial WiBro systems (IEEE 802.16e Mobile WiMAX) [6]. All cells in a cellular network have the same predefined value, which fixes the maximum number of uplink (or downlink) time slots in a frame. It is referred to as Fixed-TSA strategy. Denoting \(N_F\) as the maximum number of uplink time slots in a frame, i.e., the maximum number of downlink slots is \(N_T - N_F\), 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 values, i.e., \(N_F\) in uplink and \(N_T - N_F\) in downlink. For example, the new arriving call of mobile station \(M_3\) in Fig. 2(a) should be blocked in the Fixed-TSA

\(^2\)There is no difference when the uplink side and the downlink side are switched each other.
strategy. This is because the time slots left in uplink cannot be used in downlink even though there are enough time slots left. Thus, time slots in a frame remain underutilized in this case.

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. However, 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 among neighboring cells. Outages may occur less frequently in wireless transmission. Thus, it is difficult to determine which strategy between the Greedy-TSA and the Fixed-TSA strategy outperforms the other since the overall system performance is dependent both on call blocking performance and outage performance. Moreover, it also requires complicated studies to find the optimal value of $N_F$ which varies according to traffic conditions such as the portion of each call class in newly arriving calls and cell loading.

Commercial WiBro systems, as a conventional form of Fixed-TSA strategy, determine the numbers of uplink and downlink time slots based on long-term system simulations without mathematical derivations. To be specific, 27 OFDM symbols and 15 OFDM symbols are respectively dedicated to downlink and uplink among total 42 OFDM symbols in all synchronized frame [6]. Since this conventional Fixed-TSA strategy without mathematical derivations can only roughly estimate the optimal ratio of the uplink and downlink based on simulation results, the decision of the predefined boundary may be inaccurate. More importantly, the searched predefined boundary cannot be updated adaptively according to the traffic conditions in practical systems since the simulation-based adaptation requires huge complexity and processing time.

Here, we propose Enhanced Fixed-TSA strategy, which is an evolution of the conventional Fixed-TSA strategy. The Enhanced Fixed-TSA strategy computes the optimal value of the predefined boundary based on cross-layer analysis which will be discussed in the next section. Since the optimal value of the predefined boundary is determined by the mathematical derivation, it is adaptively updated according to traffic conditions.

C. RED-TSA Strategy

Based on discussions above, the Greedy-TSA strategy is advantageous in flexible time slot allocation, whereas the Fixed-TSA strategy is advantageous in crossed-slot interference mitigation. Therefore, we propose the RED-TSA strategy which compromises both the advantages. The main idea of the RED-TSA strategy is that a cell is partitioned into inner and outer regions and only critical crossed-slot interference experienced by the MSs in the outer region are precluded.
This cell partitioning concept is firstly introduced in [19] for frequency reuse partitioning. Many previous works studying reuse partitioning technique and dynamic channel allocation technique have been proposed for the efficient radio resource management [20]–[25]. In [26], we have applied the cell partitioning concept to asymmetric TDD systems where two types of crossed-slot interference are additionally introduced. We have proposed a new time slot allocation strategy combined with the cell partitioning technique to solve the crossed-slot interference problem. Meanwhile, time slot allocation and cell partitioning are also considered in [27] to mitigate the crossed-slot interference in TDD systems. However, the cell partitioning in [27] is basically equivalent to a traditional 3-sectorization with increased frequency reuse factor. Hence, time slot allocation and cell partitioning techniques are not jointly designed. Moreover, the paper proposes only a heuristic time slot allocation algorithm which lacks mathematical analysis. Here, we propose the RED-TSA strategy which combines the cell partitioning and time slot allocation based on mathematical analysis.

Detailed procedures of the proposed RED-TSA strategy 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 $N_R$. It also limits the maximum number of total downlink time slots by $N_T - N_R$. Uplink of the MSs in the outer region are serviced from the first time slot to the $N_R$-th time slot; when a new call is coming in the outer region, the uplink time slots of the existing MSs in the inner region are moved toward the center of the frame. Any arriving call will be blocked when the number of uplink time slots of the MSs in the outer region exceeds $N_R$, or when the number of total downlink time slots exceeds $N_T - N_R$. 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 $M_3^{(j)}$ is not blocked in Fig. 2(b), which shows the RED-TSA strategy more flexible in resource allocation than the Fixed-TSA strategy.

The 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. The received uplink signal power in crossed-slots remains high due to reduced pathloss. Thus, it is expected that the RED-TSA strategy allocates time slots more flexibly than the Fixed-TSA strategy while it results in less outages than the Greedy-TSA strategy. As in the Fixed-TSA strategy, the overall performance of the RED-TSA strategy depends on the predefined boundary, $N_R$, and finding an optimal placement for it requires complicated mathematical analysis which is described in the next section.
IV. PERFORMANCE ANALYSIS

In this section, we first derive call state probability and new call blocking probability of the Greedy-TSA, (Enhanced) Fixed-TSA, and RED-TSA strategies based on the Markov-chain traffic model in Section II-B. Then, we calculate crossed-slot interference from the call state probability of each cell. Finally, the average bit error probability is computed under composite Rayleigh-Lognormal fading environment.

A. New Call Blocking Probability

1) Greedy-TSA: From (6), the call state probability in the Greedy-TSA strategy is given as

\[ \Pi_G(c_1, c_2) = \frac{\rho_1^{c_1}}{c_1!} \cdot \frac{\rho_2^{c_2}}{c_2!}, \]

\[ \eta_G = \sum_{(c_1,c_2) \in S_G} \frac{\rho_1^{c_1}}{c_1!} \cdot \frac{\rho_2^{c_2}}{c_2!}, \]

\[ \rho_1 = \frac{\alpha_1 \lambda}{\mu_1}, \quad \rho_2 = \frac{\alpha_2 \lambda}{\mu_2}, \]

where \( S_G \) is the set of all possible call states defined as \((c_1, c_2)\). A new call is determined as either Class-I call or Class-II call with the portions among new arriving calls, \( \alpha_1 \) and \( \alpha_2 \). In the Greedy-TSA strategy, \( S_G \) is truncated with

\[ c_1, c_2 \geq 0, \]

\[ c_1(\Delta_{D,1} + \Delta_{U,1}) + c_2(\Delta_{D,2} + \Delta_{U,2}) \leq N_T. \]

(8)

Fig. 3(a) illustrates two-dimensional Markov chain with \( N_T = 12, \Delta_{D,1} = \Delta_{U,1} = 1, \Delta_{D,2} = 3, \) and \( \Delta_{U,2} = 1 \). The number of all possible call states is \( |S_G| = 16 \). We define \( B_{G,1} \) and \( B_{G,2} \) as the sets of call states where new arriving Class-I call and Class-II call are blocked, respectively. The new call blocking probability of the Greedy-TSA is computed as

\[ \chi_G = \sum_{(c_1,c_2) \in B_{G,1}} \alpha_1 \Pi_G(c_1, c_2) + \sum_{(c_1,c_2) \in B_{G,2}} \alpha_2 \Pi_G(c_1, c_2). \]

(9)

2) Fixed-TSA: Similarly, the call state probability in the Fixed-TSA strategy is expressed as

\[ \Pi_F(c_1, c_2) = \frac{\rho_1^{c_1}}{c_1!} \cdot \frac{\rho_2^{c_2}}{c_2!}, \]

\[ \eta_F = \sum_{(c_1,c_2) \in S_G} \frac{\rho_1^{c_1}}{c_1!} \cdot \frac{\rho_2^{c_2}}{c_2!}, \]

\[ \rho_1 = \frac{\alpha_1 \lambda}{\mu_1}, \quad \rho_2 = \frac{\alpha_2 \lambda}{\mu_2}. \]

(10)
with truncation conditions for $S_F$

\[ c_1, c_2 \geq 0, \]
\[ c_1 \Delta_{U,1} + c_2 \Delta_{U,2} \leq N_F, \]
\[ c_1 \Delta_{D,1} + c_2 \Delta_{D,2} \leq N_T - N_F. \]  \hfill (11)

Fig. 3(b) illustrates two-dimensional Markov chain for the Fixed-TSA strategy when $N_F = 6$. Note that the Fixed-TSA strategy imposes stronger constraints on time slot allocation than the Greedy-TSA strategy. With similar definition to $B_F,1$ and $B_F,2$, the new call blocking probability of the Fixed-TSA strategy is calculated as

\[ \chi_F = \sum_{(c_1,c_2)\in B_F,1} \alpha_1 \Pi_F(c_1, c_2) + \sum_{(c_1,c_2)\in B_F,2} \alpha_2 \Pi_F(c_1, c_2). \]  \hfill (12)

The new call blocking probability is a function of the predefined boundary, $N_F$.

3) RED-TSA: The Markov chain model for the RED-TSA strategy requires additional two dimensions to express the possible call states since calls are categorized into calls from inner region and calls from outer region. A call state in the RED-TSA strategy is defined as $(c_{1,1}, c_{1,2}, c_{2,1}, c_{2,2})$, where $c_{1,1}, c_{1,2}, c_{2,1},$ and $c_{2,2}$ respectively denote the number of Class-I call in the inner region, the number of Class-I call in the outer region, the number of Class-II call in the inner region, and the number of Class-II call in the outer region. Hence, 4-Dimensional Markov chain model for the RED-TSA strategy is expressed as

\[ \Pi_R(c_{1,1}, c_{1,2}, c_{2,1}, c_{2,2}) = \frac{\rho_{1,1}^{c_{1,1}} \rho_{1,2}^{c_{1,2}} \rho_{2,1}^{c_{2,1}} \rho_{2,2}^{c_{2,2}}}{\eta_R}, \]

\[ \eta_R = \sum_{(c_{1,1}, c_{1,2}, c_{2,1}, c_{2,2})\in S_R} \frac{\rho_{1,1}^{c_{1,1}} \rho_{1,2}^{c_{1,2}} \rho_{2,1}^{c_{2,1}} \rho_{2,2}^{c_{2,2}}}{\eta_R}, \]

where $\beta_1$ and $\beta_2$ respectively denote the portions of new arriving calls from inner region and outer region.

The truncation conditions for $S_R$ are now

\[ c_{1,1}, c_{1,2}, c_{2,1}, c_{2,2} \geq 0, \]
\[ c_{1,2} \Delta_{U,1} + c_{2,2} \Delta_{U,2} \leq N_R, \]
\[ (c_{1,1} + c_{1,2}) \Delta_{D,1} + (c_{2,1} + c_{2,2}) \Delta_{D,2} \leq N_T - N_R \]
\[ (c_{1,1} + c_{1,2}) \Delta_{D,1} + (c_{2,1} + c_{2,2}) \Delta_{D,2} \leq N_T - N_R. \]  \hfill (14)
We define $B_{R,1.1}, B_{R,1.2}, B_{R,2.1}, B_{R,2.2}$ as the subsets of call states where new arriving Class-I call (inner region), Class-I call (outer region), Class-II call (inner region), and Class-II call (outer region) are blocked, respectively. Then, the new call blocking probability of the RED-TSA strategy is calculated as

$$\chi_{R} = \sum_{\vartheta \in B_{R,1.1}} \alpha_1 \beta_1 \Pi_R(\vartheta) + \sum_{\vartheta \in B_{R,1.2}} \alpha_1 \beta_2 \Pi_R(\vartheta) + \sum_{\vartheta \in B_{R,2.1}} \alpha_2 \beta_1 \Pi_R(\vartheta) + \sum_{\vartheta \in B_{R,2.2}} \alpha_2 \beta_2 \Pi_R(\vartheta), \quad (15)$$

where $\vartheta$ denotes the call state $(c_{1.1}, c_{1.2}, c_{2.1}, c_{2.2})$ defined in the RED-TSA strategy and $\{B_{R,1.1} \cup B_{R,1.2} \cup B_{R,2.1} \cup B_{R,2.2}\} \subset S_R$.

B. Crossed-Slot Interference

The strength of intercell interference experienced by the receiver in the reference cell depends on whether the interfering sources are BSs or MSs and it is a function of the current call states of the neighboring cells. As in [32], the average power of the interference and noise at the MS in the reference cell $\sigma^2_{z_M}$ is calculated as

$$\sigma^2_{z_M} = E\left[\sum_{j=1}^{\infty} \left\{ \phi_D^j h_{BM}^j \sqrt{L_{BM}^j x_B^j} + \psi_D^j h_{MM}^j \sqrt{L_{MM}^j x_M^j} \right\}^2 \right] + \sigma^2_{n,M}$$

$$\quad = \sum_{j=1}^{\infty} E\left[|\phi_D^j|^2\right] E\left[|h_{BM}^j|^2\right] E\left[|L_{BM}^j x_B^j|^2\right] + \sum_{j=1}^{\infty} E\left[|\psi_D^j|^2\right] E\left[|h_{MM}^j|^2\right] E\left[|L_{MM}^j x_M^j|^2\right] + \sigma^2_{n,M}$$

$$\quad = Pr\{\phi_D = 1|\Theta\} \sum_{j=1}^{\infty} E\left[|L_{BM}^j x_B^j|^2\right] + Pr\{\psi_D = 1|\Theta\} \sum_{j=1}^{\infty} E\left[|L_{MM}^j x_M^j|^2\right] + \sigma^2_{n,M}, \quad (16)$$

where $\Theta$ denotes the current call state of the reference cell, i.e., $(c_1^{(0)}, c_2^{(0)})$ for the Greedy-TSA and Fixed-TSA strategies and $(c_1^{(0)}, c_1^{(0)}, c_2^{(0)}, c_2^{(0)})$ for the RED-TSA strategy. The average power of the interference and noise at the BS in the reference cell $\sigma^2_{z_B}$ is calculated as

$$\sigma^2_{z_B} = E\left[\sum_{j=1}^{\infty} \left\{ \psi_U^j h_{BB}^j \sqrt{L_{BB}^j x_B^j} + \phi_U^j h_{MB}^j \sqrt{L_{MB}^j x_M^j} \right\}^2 \right] + \sigma^2_{n,B}$$

$$\quad = \sum_{j=1}^{\infty} E\left[|\psi_U^j|^2\right] E\left[|h_{BB}^j|^2\right] E\left[|L_{BB}^j x_B^j|^2\right] + \sum_{j=1}^{\infty} E\left[|\phi_U^j|^2\right] E\left[|h_{MB}^j|^2\right] E\left[|L_{MB}^j x_M^j|^2\right] + \sigma^2_{n,B}$$

$$\quad = Pr\{\psi_U = 1|\Theta\} \sum_{j=1}^{\infty} E\left[|L_{BB}^j x_B^j|^2\right] + Pr\{\phi_U = 1|\Theta\} \sum_{j=1}^{\infty} E\left[|L_{MB}^j x_M^j|^2\right] + \sigma^2_{n,B}, \quad (17)$$

where the cell index $j$ can be omitted with respect to $\phi_D, \phi_U, \psi_D$, and $\psi_U$ since the cellular network is assumed to be homogeneous.

We assume the followings for simplicity of analysis.

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• Interference source in the \(j\)th neighboring cell is assumed to be located in the center of the cell. Hence, the distance between the receiver in the reference cell and the interference source is \(d_{l,m} \approx \sqrt{3}rl\), where \(l\) denote the index of the tier to which the \(j\)th cell belongs. The \(l\)th tier consists of \(6l\) cells in a hexagonal cellular structure.

• Compared to the large cellular area where interference sources are spread, the area of the reference cell is relatively small. Thus, the average received interference is assumed to be the same at all positions in the reference cell.

Based on the assumptions above,

\[
\sum_{j=1}^{\infty} E \left[ \left| L_{j}^{(i)}(x_B^{(j)})^2 \right| \right] \approx \sum_{l=1}^{6l} \sum_{m=1}^{6l} P_B(d_{l,m})^{-4} = \sum_{l=1}^{6l} \sum_{m=1}^{6l} P_B(\sqrt{3}rl)^{-4} = \sum_{l=1}^{\infty} \frac{2P_B}{3r^4} \cdot \frac{1}{l^4} = \frac{2\zeta(3)P_B}{3r^4},
\]

where \(\zeta(\cdot)\) denotes a Riemann zeta function. Similarly,

\[
\sum_{j=1}^{\infty} E \left[ \left| L_{j}^{(i)}(x_M^{(j)})^2 \right| \right] \approx \frac{2\zeta(3)P_M}{3r^4},
\]

\[
\sum_{j=1}^{\infty} E \left[ \left| L_{j}^{(i)}(x_M^{(j)})^2 \right| \right] \approx \frac{2\zeta(3)P_M}{3r^4}.
\]

Note that smaller pathloss exponent 3 instead of 4 is considered in the BS-to-BS crossed-slot interference case as

\[
\sum_{j=1}^{\infty} E \left[ \left| L_{j}^{(i)}(x_B^{(j)})^2 \right| \right] \approx \sum_{l=1}^{6l} \sum_{m=1}^{6l} P_B(d_{l,m})^{-3} = \frac{2\sqrt{3}\pi^2 P_B}{18r^3}.
\]

1) Greedy-TSA: Given the call states of the reference cell and the \(j\)th cell, the probability that the \(j\)th cell also operates in downlink during the downlink period of the reference cell is \(\min \left\{ 1, \begin{array}{c} \text{number of DL slots in the} \text{ jth cell} \\ \text{number of DL slots in the 6th cell} \end{array} \right\} \). Thus, non-crossed probability in downlink can be computed as

\[
Pr\{\phi_D = 1|\Theta\} = \sum_{(c_1^{(j)},c_2^{(j)}) \in S_0} \Pi_G^{(j)}(c_1^{(j)},c_2^{(j)}) \min \left\{ 1, \frac{c_1^{(j)} \Delta D_1 + c_2^{(j)} \Delta D_2}{c_1^{(0)} \Delta D_1 + c_2^{(0)} \Delta D_2} \right\}.
\]

On the contrary, the probability that the \(j\)th cell also operates in uplink during the downlink period of the reference cell is \(\max \left\{ 0, \begin{array}{c} \text{number of crossed slots between two cells} \\ \text{number of DL slots in the 6th cell} \end{array} \right\} \). Thus, crossed probability in downlink can be computed as

\[
Pr\{\psi_D = 1|\Theta\} = \sum_{(c_1^{(j)},c_2^{(j)}) \in S_0} \Pi_G^{(j)}(c_1^{(j)},c_2^{(j)}) \max \left\{ 0, \frac{c_1^{(0)} \Delta D_1 + c_2^{(0)} \Delta D_2 + c_1^{(j)} \Delta U_1 + c_2^{(j)} \Delta U_2 - N_T}{c_1^{(0)} \Delta D_1 + c_2^{(0)} \Delta D_2} \right\}.
\]

Similarly, the non-crossed and crossed probabilities in uplink can be computed as

\[
Pr\{\phi_U = 1|\Theta\} = \sum_{(c_1^{(j)},c_2^{(j)}) \in S_0} \Pi_G^{(j)}(c_1^{(j)},c_2^{(j)}) \min \left\{ 1, \frac{c_1^{(j)} \Delta U_1 + c_2^{(j)} \Delta U_2}{c_1^{(0)} \Delta U_1 + c_2^{(0)} \Delta U_2} \right\}.
\]

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Pr\{\psi_U = 1|\Theta\} = \sum_{(c_1^{(j)}, c_2^{(j)}) \in S_G} \Pi_G^{(j)}(c_1^{(j)}, c_2^{(j)}) \max \left\{ 0, \frac{c_1^{(0)} \Delta_{U,1} + c_2^{(0)} \Delta_{U,2} + c_1^{(j)} \Delta_{D,1} + c_2^{(j)} \Delta_{D,2} - N_T}{c_1^{(0)} \Delta_{U,1} + c_2^{(0)} \Delta_{U,2}} \right\}.

Finally, we can compute the average interference and noise power at MS (downlink) using (18), (19), (22), (23) in (16), and the average interference and noise power at BS (uplink) using (20), (21), (24), (25) in (17) under the Greedy-TSA strategy.

2) Fixed-TSA: By nature, crossed-slots are avoided in the Fixed-TSA strategy. The crossed and non-crossed probabilities reduce to

Pr\{\phi_D = 1|\Theta\} = \sum_{(c_1^{(j)}, c_2^{(j)}) \in S_F} \Pi_F^{(j)}(c_1^{(j)}, c_2^{(j)}) \min \left\{ 1, \frac{c_1^{(j)} \Delta_{D,1} + c_2^{(j)} \Delta_{D,2}}{c_1^{(0)} \Delta_{D,1} + c_2^{(0)} \Delta_{D,2}} \right\},

Pr\{\psi_D = 1|\Theta\} = 0,

Pr\{\phi_U = 1|\Theta\} = \sum_{(c_1^{(j)}, c_2^{(j)}) \in S_F} \Pi_F^{(j)}(c_1^{(j)}, c_2^{(j)}) \min \left\{ 1, \frac{c_1^{(j)} \Delta_{U,1} + c_2^{(j)} \Delta_{U,2}}{c_1^{(0)} \Delta_{U,1} + c_2^{(0)} \Delta_{U,2}} \right\},

Pr\{\psi_U = 1|\Theta\} = 0.

The average interference and noise power at MS and BS under the Fixed-TSA strategy are computed using (18), (19), (26), (27) in (16) and (20), (21), (28), (29) in (17).

3) RED-TSA: Under the RED-TSA strategy, the computations of the non-crossed and crossed probabilities in downlink are basically the same as the Greedy-TSA strategy

Pr\{\phi_D = 1|\Theta\} = \sum_{\vartheta \in S_R} \Pi_R^{(j)}(\vartheta) \min \left\{ 1, \frac{(c_1^{(0)} + c_1^{(j)}) \Delta_{D,1} + (c_2^{(0)} + c_2^{(j)}) \Delta_{D,2}}{(c_1^{(0)} + c_1^{(j)}) \Delta_{D,1} + (c_2^{(0)} + c_2^{(j)}) \Delta_{D,2}} \right\},

Pr\{\psi_D = 1|\Theta\} = \sum_{\vartheta \in S_R} \Pi_R^{(j)}(\vartheta) \times

\max \left\{ 0, \frac{(c_1^{(0)} + c_1^{(0)} \Delta_{D,1} + (c_2^{(0)} + c_2^{(0)} \Delta_{D,2} + (c_1^{(j)} + c_1^{(j)}) \Delta_{U,1} + (c_2^{(j)} + c_2^{(j)}) \Delta_{U,2} - N_T}{(c_1^{(0)} + c_1^{(0)} \Delta_{D,1} + (c_2^{(0)} + c_2^{(0)} \Delta_{D,2}}} \right\},

where \vartheta denotes the call state \((c_1^{(j)}, c_1^{(j)}, c_2^{(j)}, c_2^{(j)}))\) defined in the RED-TSA strategy.

However, in uplink, the computations of the non-crossed and crossed probabilities depend on the region each call belongs to. While the uplink of the MSs in the outer region experiences no crossed-slot interference, the uplink of the MSs in the inner region experiences crossed-slot interference. Thus, the non-crossed and crossed probabilities in uplink of the MSs in the outer region are

Pr\{\phi_U = 1|\Theta\} = \sum_{\vartheta \in S_R} \Pi_R^{(j)}(\vartheta) \min \left\{ 1, \frac{(c_1^{(0)} + c_1^{(j)}) \Delta_{U,1} + (c_2^{(0)} + c_2^{(j)}) \Delta_{U,2}}{c_1^{(0)} \Delta_{U,1} + c_2^{(0)} \Delta_{U,2}} \right\},

Pr\{\psi_U = 1|\Theta\} = 0.
The non-crossed and crossed probabilities in uplink of the MSs in the inner region are

\[
Pr\{\phi_U = 1|\Theta\} = \sum_{\vartheta \in S_R} \Pi_R^{(j)}(\vartheta) \max \left\{ 0, \min \left\{ 1, \frac{k + v - a}{e} \right\} \right\},
\]

(34)

\[
Pr\{\psi_U = 1|\Theta\} = \sum_{\vartheta \in S_R} \Pi_R^{(j)}(\vartheta) \min \left\{ 1, \max \left\{ 0, \frac{a + e + w - N_T}{e} \right\} \right\},
\]

(35)

where

\[
a = c_{1,2}(0)\Delta_{U,1} + c_{2,2}(0)\Delta_{U,2},
\]

\[
e = c_{1,1}(0)\Delta_{U,1} + c_{2,1}(0)\Delta_{U,2},
\]

\[
k = c_{1,2}(j)\Delta_{U,1} + c_{2,2}(j)\Delta_{U,2},
\]

\[
v = c_{1,1}(j)\Delta_{U,1} + c_{2,1}(j)\Delta_{U,2},
\]

\[
w = (c_{1,1}(j) + c_{1,2}(j))\Delta_{D,1} + (c_{2,1}(j) + c_{2,2}(j))\Delta_{D,2}.
\]

Now, we complete the computations of the average interference and noise power for the downlink using (18), (19), (30), (31) in (16), the average interference and noise power for the uplink of the MSs in the outer region using (20), (21), (32), (33) in (17), and the average interference and noise power for the uplink of the MSs in the inner region using (20), (21), (34), (35) in (17) under the RED-TSA strategy.

C. Average Bit Error Probability

In our fading channel model, both multipath fading and shadowing are considered. Thus, the overall distribution of SINR becomes a composite Rayleigh-Lognormal distribution and the probability density function (PDF) of the SINR, \(\Gamma\), is given by [28]

\[
f_{\Gamma}(\gamma) = \int_0^{\infty} \frac{1}{s} e^{-\frac{s}{\xi}} \frac{\xi}{\sqrt{2\pi} \sigma s} \exp \left\{ -\frac{(10\log_{10} s - \bar{\gamma})^2}{2\sigma^2} \right\} ds,
\]

(37)

where \(\xi = \frac{10}{\ln 10} = 4.3429\), and \(\bar{\gamma}\) (dB) and \(\sigma\) (dB) are the mean SINR and the standard deviation of shadowing, respectively. Since the PDF in (37) cannot be reduced to any closed-form expression [29], we use the Gauss-Hermite quadrature integration to calculate error probability [30]. As derived in [31], the average bit error probability (BPSK considered) with given \(\bar{\gamma}\) is computed as

\[
P_e = \frac{1}{2\sqrt{\pi}} \sum_{p=1}^{N_H} w_{H,p} \left[ 1 - \sqrt{\frac{10^{(x_{H,p} \sqrt{2\sigma + \bar{\gamma}})/10}}{1 + 10^{(x_{H,p} \sqrt{2\sigma + \bar{\gamma}})/10}}} \right],
\]

(38)

where \(x_{H,p}\) is the \(p\)th zero of the \(N_H\)th-order Hermite polynomial, \(w_{H,p}\) is the \(p\)th weight factor tabulated in Table 25.10 of [30], mean SINR for downlink is calculated as

\[
\bar{\gamma} = 10 \log_{10} \left( \frac{P_B d^{-4}}{\sigma_{zm}^2} \right),
\]

(39)
and mean SINR for uplink is calculated as
\[ \bar{\gamma} = 10 \log_{10} \left( \frac{P_M d^{-4}}{\sigma_{z_B}^2} \right). \] (40)

Since \( \sigma_{z_M}^2 \) and \( \sigma_{z_B}^2 \) are functions of call states \( \vartheta \), the resulting \( \bar{\gamma} \) is also a function of call states. The overall average bit error probability is computed by weighted sum using (38), (39), (40) and the call state probability of each TSA strategy (7), (10), (13) as
\[
P_b = \sum_{\Theta \in S} P_c \cdot \Pi(\Theta). \tag{41}
\]

V. OPTIMAL PREDEFINED BOUNDARY

We first calculate the outage probability, \( P_t \), and derive the system throughput, \( T \). The optimal predefined boundary is defined as one which maximizes the system throughput. \(^3\)

A. Enhanced Fixed-TSA strategy

Denoting tolerable uncoded bit error probability as \( P_{b,th} \), we define \( d_t \) as the maximum distance from the cell center which satisfies \( \Pr\{P_b \leq P_{b,th}\} \). The outage probability of the downlink and uplink are respectively given as
\[
P_{t,F,D} = \Pr\{P_{b,F,D} > P_{b,th}\} = 1 - \Pr\{P_{b,F,D} \leq P_{b,th}\} = 1 - \left( \frac{d_{t,F,D}}{\tau} \right)^2, \tag{42}
\]
\[
P_{t,F,U} = \Pr\{P_{b,F,U} > P_{b,th}\} = 1 - \Pr\{P_{b,F,U} \leq P_{b,th}\} = 1 - \left( \frac{d_{t,F,U}}{\tau} \right)^2. \tag{43}
\]

Then, the system throughput in the Fixed-TSA strategy is computed as
\[
T_F = \text{downlink throughput} + \text{uplink throughput} = \\
\sum_{(c_1^{(0)}, c_2^{(0)}) \in S_F} \Pi_F^{(0)}(c_1^{(0)}, c_2^{(0)}) \left\{ c_1^{(0)} (1 - P_{t,F,D}) \Delta_{D,1} + c_2^{(0)} (1 - P_{t,F,D}) \Delta_{D,2} \right\} + \\
\sum_{(c_1^{(0)}, c_2^{(0)}) \in S_F} \Pi_F^{(0)}(c_1^{(0)}, c_2^{(0)}) \left\{ c_1^{(0)} (1 - P_{t,F,U}) \Delta_{U,1} + c_2^{(0)} (1 - P_{t,F,U}) \Delta_{U,2} \right\} + \\
\sum_{(c_1^{(0)}, c_2^{(0)}) \in S_F} \tau \Pi_F^{(0)}(c_1^{(0)}, c_2^{(0)}) \left\{ (1 - P_{t,F,D}) (c_1^{(0)} \Delta_{D,1} + c_2^{(0)} \Delta_{D,2}) + \\
(1 - P_{t,F,U}) (c_1^{(0)} \Delta_{U,1} + c_2^{(0)} \Delta_{U,2}) \right\}. \tag{44}
\]

\(^3\)The system throughput is normalized with the value, \( \tau \), which is defined as the transmission rate per unit time slot.
The optimal value of the predefined boundary which maximizes the system throughput in the Fixed-TSA strategy is computed as

\[ N_{F,opt} = \arg \max_{N_F} T_F. \] (45)

Thus, in contrast to the conventional Fixed-TSA strategy where the value for the predefined boundary is searched based on long-term simulation results, the enhanced Fixed-TSA strategy adaptively updates the predefined boundary by (45) according to the traffic condition.

B. RED-TSA strategy

The same mathematical technique used for the derivation of the optimal predefined boundary in the Enhanced Fixed-TSA strategy can also be applied to the RED-TSA strategy. Since the computations of the average bit error probability vary depending on which regions each MS belongs to, outage probabilities are computed separately. The downlink outage probability is given by

\[ P_{t,R,D} = \Pr\{P_{b,R,D} > P_{b,th}\} = 1 - \Pr\{P_{b,R,D} \leq P_{b,th}\} = 1 - \left(\frac{d_{t,R,D}}{r}\right)^2. \] (46)

The uplink outage probabilities of the MSs in the inner region and the MSs in the outer region are respectively

\[ P_{t,R,U,I} = \Pr\{P_{b,R,U,I} > P_{b,th}\} = 1 - \Pr\{P_{b,R,U,I} \leq P_{b,th}\} = 1 - \left(\frac{d_{t,R,U,I}}{r}\right)^2, \] (47)

\[ P_{t,R,U,O} = \Pr\{P_{b,R,U,O} > P_{b,th}\} = 1 - \Pr\{P_{b,R,U,O} \leq P_{b,th}\} = 1 - \frac{d_{t,R,U,O}^2 - r_R^2}{r^2 - r_R^2}, \] (48)

where \(r_R\) is the radius of the inner region. The system throughput in the RED-TSA strategy is computed as

\[ T_R = \text{downlink throughput} + \text{uplink throughput (inner region)} + \text{uplink throughput (outer region)} \]

\[ = \sum_{\vartheta \in S_R} \tau \Pi_{R}^{(0)}(\vartheta) \left\{ (c_{1,1}^{(0)} + c_{1,2}^{(0)})(1 - P_{t,R,D})\Delta_{D,1}\tau + (c_{2,1}^{(0)} + c_{2,2}^{(0)})(1 - P_{t,R,D})\Delta_{D,2}\tau \right\} \]

\[ + \sum_{\vartheta \in S_R} \Pi_{R}^{(0)}(\vartheta) \left\{ c_{1,1}^{(0)}(1 - P_{t,R,U,I})\Delta_{U,1}\tau + c_{2,1}^{(0)}(1 - P_{t,R,U,I})\Delta_{U,2}\tau \right\} \]

\[ + \sum_{\vartheta \in S_R} \Pi_{R}^{(0)}(\vartheta) \left\{ c_{1,2}^{(0)}(1 - P_{t,R,U,O})\Delta_{U,1}\tau + c_{2,2}^{(0)}(1 - P_{t,R,U,O})\Delta_{U,2}\tau \right\} \]

\[ = \sum_{\vartheta \in S_R} \tau \Pi_{R}^{(0)}(\vartheta) \left\{ (1 - P_{t,R,D})\left\{ (c_{1,1}^{(0)} + c_{1,2}^{(0)})\Delta_{D,1} + (c_{2,1}^{(0)} + c_{2,2}^{(0)})\Delta_{D,2} \right\} \right. \]

\[ + \left. (1 - P_{t,R,U,I})\left\{ c_{1,1}^{(0)}\Delta_{U,1} + c_{2,1}^{(0)}\Delta_{U,2} \right\} + (1 - P_{t,R,U,O})\left\{ c_{1,2}^{(0)}\Delta_{U,1} + c_{2,2}^{(0)}\Delta_{U,2} \right\} \right\}, \] (49)
where $\vartheta$ denotes the call state $(c_{1,1}^{(0)}, c_{1,2}^{(0)}, c_{2,1}^{(0)}, c_{2,2}^{(0)})$ defined in the RED-TSA strategy and $\tau$ is a transmission rate per unit time slot. Finally, the optimal value of the predefined boundary which maximizes the system throughput in the RED-TSA strategy is computed as

$$N_{R, opt} = \arg \max_{N_R} T_R.$$  

(50)

The predefined boundary in the proposed RED-TSA strategy is adaptively updated by (50) according to the traffic condition.

On the other hand, the radius of the inner region $r_R$ is also a parameter which affects the system throughput. For example, when the inner region is too large, even MSs in the inner region may suffer from strong crossed-slot interference since they may be located close to cell edge. Then, the performance gain from efficient crossed-slot interference mitigation decreases. When the inner region is too small, most MSs belong to the outer region and their uplink signal can be protected from crossed-slot interference by adjusting $N_R$. This, however, reduces the performance gain from flexible time slot allocation; increased $N_R$ lessens time slot resources for downlink. Hence, both $N_R$ and $r_R$ should be jointly optimized to maximize the system throughput. In this case, combinatorial optimization is required, which results in huge complexity. Here, we fix the radius of the inner region $r_R$ as one half of cell radius $r$, i.e., $r_R = \frac{1}{2}r$ for reasonable computational overhead. Although the maximization of the system throughput is not guaranteed, the numerical results show that the RED-TSA strategy outperforms the other strategies with the fixed $r_R$ value.

VI. NUMERICAL RESULTS

We assume a hexagonal cellular structure with cell radius $r = 1,000$ m. The total number of time slots in each TDD frame is $N_T = 12$. The transmission power of MSs and BSs is set to $P_M = 23$ dBm and $P_B = 40$ dBm, respectively. The antenna gain at BS is set to 17 dBi. Noise powers at BS and MS are assumed to be $\sigma^2_{n,B} = -100$ dBm and $\sigma^2_{n,M} = -90$ dBm. The processing gain of 10 dB is considered at receivers and the tolerable uncoded average bit error probability is assumed to be $P_{b,th} = 4\%$. MSs are uniformly distributed in each cell and the radius of the inner region in the RED-TSA strategy is set to $r_R = 500$ m. Here, we consider two different propagation environments [10]. For BS-BS links, the path loss exponent is taken to be 3 and the log standard deviation for shadowing variable is taken to be 8 dB, while path loss exponent and log standard deviations for shadowing variable are 4 and 8 dB, respectively, for BS-MS and MS-MS links. The portion of data calls among new arriving calls is expected to be $\alpha_2 = 15\%$ in the year 2005 and gradually increase up to $\alpha_2 = 30\%$ in the year 2010 [2].

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To validate the performance analysis, we compare the analytical results and simulation results for a simple case, i.e., Greedy-TSA strategy. The analytical results in Section IV are drawn using numerical tool, MATHEMATICA. For simulation results, MATLAB tool is used to observe the cellular network for 1,000,000 seconds ($\approx 278$ hours). In Fig. 4, new call blocking probabilities from analysis and simulation are plotted. The gap between analytical and simulation results is minimal. Since the observation time is finite, the initial period before the system reaches steady-state makes the simulated new call blocking probability slightly lower than that of analysis. On the other hand, Fig. 5 compares the analytical and simulation results of average bit error probability in uplink and downlink. There exists a gap between the analytic and simulation results. The reasons are as follows. Firstly, only two tiers of neighboring cells, i.e., 18 cells, are considered in the simulation for reasonable computational complexity. Secondly, the assumptions made for simplicity of analysis such as Gaussian approximation of interference and the simplified positions of interference sources cause the gap. Nevertheless, the analytic results closely agree with simulation results, which verifies that the analysis in Section IV is reasonable. Hence, the following results are obtained through the analysis.

Fig. 6 shows how new call blocking probability, $\chi$, varies with new call arrival rate, $\lambda$, according to the different time slot allocation strategies. Fig. 6 (a) and (b) respectively present the new call blocking probabilities of voice calls and data calls. 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 Enhanced Fixed-TSA strategy shows the highest new call blocking probability since both uplink and downlink are individually constrained into the fixed numbers of time slots and any arriving call will be blocked when shortage occurs either in uplink or downlink. The RED-TSA strategy forces the maximum number of time slots only to the uplink of 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, Class-II calls shows higher new call blocking probability than that of Class-I calls since data calls require more number of time slots. The performance gap between TSA strategies also increases due to dynamic traffic asymmetry.

Fig. 7 shows how average bit error probability in downlink and uplink, $P_b$, vary with the distance between MS and BS, $d$. In downlink, the differences between the average bit error performances of the Greedy-TSA, Fixed-TSA, and RED-TSA strategies are negligible since the performance degradation due to MS-to-MS crossed-slot interference in the Greedy-TSA and RED-TSA strategies is minimal. On the contrary, the average bit error performances in uplink differ notably as expected. The Fixed-TSA strategy shows the best average bit error performances since no crossed-slot interference exists in this case.
Greedy-TSA and RED-TSA strategies suffer from severe BS-to-BS crossed-slot interference resulting in large outage. However, note that only the uplink signal of the MSs in the inner region is degraded by the BS-to-BS crossed-slot interference in the RED-TSA strategy while the whole uplink signal of all MSs are degraded in the Greedy-TSA strategy. Thus, the RED-TSA strategy notably improves overall average bit error performance under crossed-slot interference.

Fig. 8 shows how the normalized system throughput, $T$, varies with the predefined boundary. The normalized system throughputs in the Enhanced Fixed-TSA and RED-TSA strategies, $T_F$ and $T_R$, are concave functions of the predefined boundaries, $N_F$ and $N_R$, respectively. The optimal values for the predefined boundaries which maximize the normalized system throughputs of the Enhanced Fixed-TSA and RED-TSA strategies are $N_F = 6$ and $N_R = 5$ in this case. However, the values vary according to the traffic conditions such as the portion of data calls and cell loading. Fig. 9 shows how the optimal values of the predefined boundaries, $N_F$ and $N_R$, vary with to the portion of Class-II calls (data calls) among new arriving calls, $\alpha_2$. As the portion of Class-II calls increases, the optimal $N_F$ and $N_R$ decrease to allocate more time slots to downlink. As an extreme case, if there exist only data calls, i.e., $\alpha_2 = 100\%$, the optimal $N_F$ converges to the point that the uplink and downlink ratio equals to the traffic asymmetry of the data call ($\Delta_{U,2} : \Delta_{D,2} = 1 : 3$).

Fig. 10 shows how the normalized system throughput, $T$, in each time slot allocation strategy varies with new call arriving rates, $\lambda$. In the conventional Fixed-TSA strategy, the ratio of downlink and uplink time slots are fixed to 2 : 1 as in commercial WiBro systems. The proposed RED-TSA strategy provides the highest normalized system throughput in all range of call arriving rate. When new call arriving rate is $\lambda = 0.08$ and the portion of data calls is $\alpha_2 = 30\%$ (year 2010), the RED-TSA strategy provides 61.5% and 16.9% gain over the Greedy-TSA and conventional Fixed-TSA strategies, respectively. The reason is that each Greedy-TSA and conventional Fixed-TSA strategy outperforms the other only in one performance measure, i.e., either in new call blocking performance or average bit error performance, while the RED-TSA strategy scores well-balanced performance in both performance measures. On the other hand, the proposed Enhanced Fixed-TSA strategy based on the mathematical derivation of (45) exactly adapts the predefined boundary according to the traffic condition and provides 12.6% gain over the conventional Fixed-TSA strategy in normalized system throughput. Note that the performance gap between the RED-TSA strategy and Enhanced Fixed-TSA strategy is kept small. Moreover, the Enhanced Fixed-TSA does not require additional information and large amount of computations while it provides almost the same system throughput with that of the RED-TSA strategy.
VII. CONCLUSIONS

In this paper, we have reviewed the time slot allocation (TSA) strategies for decentralized TDD systems and proposed two new TSA strategies, which are Enhanced Fixed-TSA strategy and REgion-based Decentralized Time Slot Allocation (RED-TSA) strategy. The new call blocking probability, average bit error probability, and overall system throughput of the TSA strategies are derived through cross-layer analysis and the optimal value for the predefined boundary is computed. Our results show that the proposed RED-TSA strategy provides the highest normalized system throughput by compromising both new call blocking performance and average bit error performance. The RED-TSA strategy offers 61.5% and 16.9% gain in normalized system throughput over the Greedy-TSA strategy and conventional Fixed-TSA strategy respectively ($\lambda = 0.08$ and $\alpha_2 = 30\%$). The proposed Enhanced Fixed-TSA strategy alleviates the drawback of the conventional Fixed-TSA strategy by dynamically updating the predefined boundary based on the mathematical derivation. The Enhanced-TSA strategy provides 12.6% improvement compared to the conventional Fixed-TSA strategy.

In a nutshell, among the proposed TSA strategies, the RED-TSA strategy slightly outperforms the Enhanced Fixed-TSA strategy in terms of normalized system throughput. However, there remain two practical issues as follows. Firstly, additional location information of MSs is required in the RED-TSA strategy even though the relating MSs is confined only within the corresponding cell. Secondly, to extract the optimal performance of the RED-TSA strategy, the radius of the inner region, $r_R$, also need to be jointly optimized, which requires combinatorial optimization with high computational complexity. On the contrary, the Enhanced Fixed-TSA strategy is notably practical since it can be simply implemented with reasonable computational complexity and without any additional information. Moreover, the Enhanced Fixed-TSA strategy can be directly applied to the current commercial WiMax/WiBro systems with only minimum changes.
REFERENCES


Fig. 1. Crossed-slot interference scenarios in TDD systems.
Fig. 2. New call blocking scenarios according to the time slot allocation strategies in TDD systems.
Fig. 3. Two-dimensional Markov chain with $N_T = 12$, $N_F = 6$, $\Delta_{D,1} = \Delta_{U,1} = 1$, $\Delta_{D,2} = 3$, and $\Delta_{U,2} = 1$. The call state is defined as $(c_1, c_2)$, where $c_1$ and $c_2$ are the numbers of Class-I and Class-II calls in the cell, respectively.
Fig. 4. Comparisons between the analytical results and simulation results of Greedy-TSA strategy: new call blocking probability $\chi$, where $\alpha_1 = 70\%$ and $\alpha_2 = 30\%$.

(a) Class-I calls: voice calls

(b) Class-II calls: data calls
Fig. 5. Comparisons between the analytical results and simulation results of Greedy-TSA strategy: average bit error probability $P_b$, where $\alpha_1 = 70\%$ and $\alpha_2 = 30\%$. 
Fig. 6. New call blocking probability versus new call arriving rate, where $\alpha_1 = 70\%$, $\alpha_2 = 30\%$, $\beta_1 = 0.25$, and $\beta_2 = 0.75$. 
Fig. 7. Average bit error probability versus distance from BS, where $\lambda = 0.08$, $\alpha_1 = 70\%$, $\alpha_2 = 30\%$, $\beta_1 = 0.25$, $\beta_2 = 0.75$, $N_F = 6$, and $N_R = 5$. 
Fig. 8. Normalized system throughput of the Fixed-TSA and RED-TSA strategies versus the predefined boundaries, \( N_F \) and \( N_R \), where \( \lambda = 0.08 \), \( \alpha_1 = 70\% \), \( \alpha_2 = 30\% \), \( \beta_1 = 0.25 \), \( \beta_2 = 0.75 \), and \( \tau \) is a transmission rate per unit time slot.
Fig. 9. Optimal predefined boundary versus the portion of data call, where $\lambda = 0.08$, $\beta_1 = 0.25$, and $\beta_2 = 0.75$. 
Fig. 10. Normalized system throughput versus new call arriving rate, where $\alpha_1 = 70\%$, $\alpha_2 = 30\%$, $\beta_1 = 0.25$, $\beta_2 = 0.75$, and $\tau$ is a transmission rate per unit time slot.