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Research Article

Fractional Frequency Reuse for Hierarchical Resource Allocation in Mobile WiMAX Networks

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We propose a frequency planning based on zone switching diversity scheme for multicell OFDMA mobile WiMAX networks. In our approach, we focus on the use of Fractional Frequency Reuse (FFR) for guaranteeing the quality of service for the different service flows in the system. We investigate an architecture that coordinates the allocation of resources in terms of slots (the basic allocation unit in time and frequency domain in an OFDMA frame) between the Radio Resource Controller (RRC) and the Radio Resource Agent (RRA) which resides in the Base Station (BS). The proposed algorithm attempts to capture three types of diversity, namely, mutual interference diversity, traffic diversity, and selective fading channel diversity. As a consequence, the proposed algorithm for slot allocation makes a trade-off between maximizing overall throughput of the system while guaranteeing the Quality of Service (QoS) requirements for a mixture of real-time and non-real-time service flows under different diversity configurations. Our algorithm is evaluated under various cell configurations and traffic models. The results reveal important insights on the trade-off between cell interference suppression and QoS assurance.

1. Introduction

One of the major concerns in mobile WiMAX (based on IEEE 802.16e standard) networks is the optimization of radio resource utilization, which can be enhanced by the frequency reuse when multicells scenarios are deployed. This is due to the use of Orthogonal Frequency Division Multiplex (OFDMA) for the inherent robustness to time dispersion of the radio channel [1].

Mobile WiMAX supports Orthogonal Frequency Division Multiple Access (OFDMA) communication system where frequency reuse of one is used, that is, all cells/sectors operate on the same frequency channel to maximize spectral efficiency. However, due to heavy cochannel interference (CCI) in frequency reuse one deployment, MSs at the cell edge may suffer degradation in connection quality. With mobile WiMAX, MSs operate on subchannels, which only occupy a small fraction of the whole channel bandwidth; the cell edge interference problem can be easily addressed by appropriately configuring subchannel usage without resorting to traditional frequency planning [2].

Resource allocation in multicell OFDMA networks has been developed in several works using Fractional Frequency Reuse (FFR). However, only few contributions have explicitly taken into account the nature of application being either real-time or non real-time. For example, authors in [3–6] proposed dynamic resource allocation scheme for guarantying QoS requirements while maximizing the whole throughput of the system. However, both schemes work only for non real-time application References [7–9] introduced the Radio Network Controller (RNC) to control a cluster of Base Station (BSs) in the multicell OFDMA system and to allocate resources in a distributed way however, these schemes allocate resources in the RNC without taking into account the reallocation scheme at each BS for coordinating resource according to the FFR. Authors in [10, 11] proposed a local resource allocation the BSs in a random way without taking into consideration the RNC. Thus the BS has not a global view about the adjacent cells in the system, leading to inefficient resource allocation.

In this paper, we propose a radio resource allocation scheme for multicell OFDMA downlink mobile WiMAX systems. Our scheme consists firstly of a hierarchical architecture based on message exchanges between Radio Resource Agent (RRA) at the Base Stations (BS) and Radio Resource Controller (RRC) which controls a cluster of BSs. The RRC coordinates the Intercell Interference (ICI) considering the types of service flows (SFs) and their Quality of Service (QoS) requirements at superframe level, whereas BSs allocate slots in each cell at frame level in a fair way using slot reallocation strategy between MSs at inner cell and outer ring cell.

The rest of paper is organized as follows. In Section 2, Subchannalizestion and Zone Switching Diversity in Mobile WiMAX are introduced. Section 3 describes the system model. Section 4 presents our hierarchical approach for resource allocation. Sections 5 and 6 present our simulation results and conclude the paper.

2. Zone Switching Diversity Overview in Mobile WiMAX

The mobile WiMAX physical layer is based on OFDMA which divides the very high rate data stream into multiple parallel low rate data streams. Each smaller data stream is then mapped to individual data subcarrier and modulated using some Phase Shift Keying Quadrature Amplitude Modulation (QPSK, 16-QAM, and 64-QAM) [2].

However, the available subcarriers may be divided into several groups of subcarriers called subchannels. Subchannels may be constituted using either contiguous subcarriers or subcarriers pseudorandomly distributed across the frequency spectrum. Subchannels formed using distributed subcarriers provide more frequency diversity [12]. This permutation can be represented by Partial Usage of Subcarriers (PUSC) and Full Usage of Subcarriers (FUSC) modes. The subchannelization scheme based on contiguous subcarriers in mobile WiMAX is called Band Adaptive Modulation and Coding (AMC). Although frequency diversity is lost, band AMC allows system designers to exploit multiuser diversity, allocating subchannels to users based on their frequency response [1].

In mobile WiMAX, the flexible subchannel reuse is facilitated by subchannel segmentation and permutation zone. A segment is a subdivision of the available OFDMA subchannels (one segment may include all subchannels). One segment is used for deploying a single instance of Medium Access Control (MAC). Permutation Zone is a number of contiguous OFDMA symbols in Downlink DL or Uplink UL that use the same permutation. The DL or UL subframe may contain more than one permutation zone as shown in Figure 1.

The subchannel reuse pattern can be configured so that MSs close to the base station, that is, in the inner cell operate on the zone with all subchannels available. While for the outer ring MSs, each cell or sector operates on the zone with a fraction of all subchannels available. In Figure 3, F1, F2, and F3 represent different sets of subchannels in the same frequency channel. With this configuration, the full load frequency reuse one is maintained for inner cell MSs to maximize spectral efficiency and fractional frequency reuse is implemented for outer ring MSs to assure edge-MS connection quality and throughput. The sub-channel reuse planning can be dynamically optimized across sectors or cells based on network load and interference conditions on a frame-by-frame basis. A scheme for subchannel reuse planning is not specified by the IEEE 802.16e standard and will be the subject of this paper.

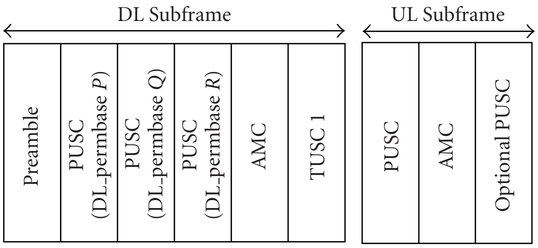

Figure 1: Multizone switching diversity frame structure.

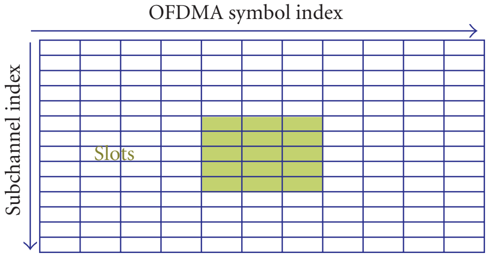

Figure 2: OFDMA based Slot frame.

3. Proposed Design for Mobile WiMAX Network Architecture

Even though the WiMAX Forum specified an architecture for resource allocation for mobile WiMAX systems [13], functions related to resource allocation using fractional frequency reuse (FRR) are not described in such architecture. Therefore, in this section we propose new functionalities to be added to this architecture in order to enable a hierarchical approach for managing resources using the concept of FFR.

3.1. Radio Resource Allocation Model. Our proposed mobile WiMAX architecture is compliant with the proposal in [1] as it decomposes resource allocation model into two functional entities: the Radio Resource Agent (RRA) and the Radio Resource Controller (RRC) as it is shown in Figure 4. The RRA resides in each cell at the BS to collect and maintain radio resource indicators, (such as Received Signal Strength Indication (RSSI), burst profiles, etc.), from all the MSs attached to the BS. The RRC is responsible for collecting the radio resource indicators from the various RRAs attached to it and then maintaining "regional" radio resource database. Resources are represented by slots—the basic units of resource allocation in time (symbol) and frequency (subchannel) domain in mobile WiMAX OFDMA frame (see Figure 3). Accordingly, we evoke the following

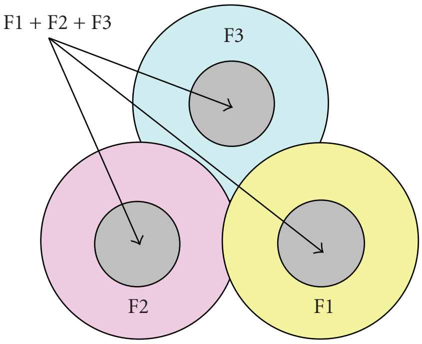

Figure 3: Fractional frequency reuse.

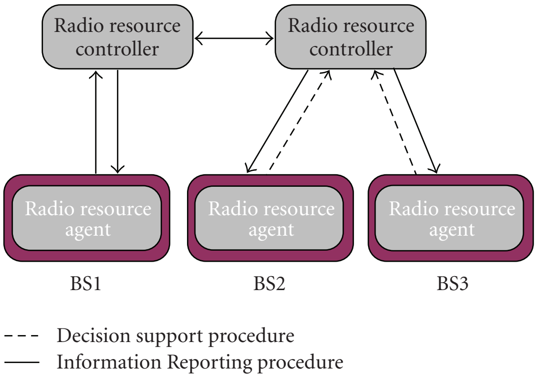

Figure 4: Radio resource allocation model.

assumptions in this architecture. (1) Neighboring cells may reuse the same slot; (2) each slot can only be assigned to one MS within a given cell, that is, there is no intracell interference.

We propose hierarchical approach for resource allocation for this architecture, and we add new information elements concerning SF types, their QoS requirements in terms of data rate, their channel qualities, and so forth. These information elements are collected by the RRA from all MSs which are in the inner cell or in the outer ring cell and then feedback to the RRC. The RRC utilizes such information to calculate the soft reuse factor in each cell. Then it sends its decision to the RRA of each cell, such decision includes the specific set of slots assigned to the MSs in the outer ring and in the inner cell. Upon receiving the decision, the RRA at the BS will make the actual pairing between slots and MSs based on their actual traffic load and employ a policy for load distributing among the MSs when it is necessary. Thus, depending on our architecture, information exchanged between RRA and RRC can be either *information reporting procedures* which is used for delivery of BS radio resource indicators from the RRA to the RRC or *decision-support procedures* from RRC to RRA which is used for communicating decision that may be used by the BS for resource allocation.

3.2. Link Model. We consider the downlink of mobile WiMAX system which consists of L BSs and $M = \sum_{l=1}^{L} M_l$ users, where M_l denotes the number of MSs that are connected to the BS-l. Let the indicator $\rho_{m,n}$ take the value 1 whenever a slot n is assigned to MS m and zero otherwise and let $P_{l,n}$ denote the transmission power employed by BS-l on slot n. Using these notations, the slot and power assignments are captured by the matrices $\mathbf{Y}_{M\times N} = [\rho_{m,n}]$ and $\mathbf{P}_{M,N} = [P_{m,n}]$ that determine the long term signal-to-interface-and-noise ratio values experienced by MS m on slot n as follows:

$$\vartheta_{i,n}(\mathbf{Y},\mathbf{P}) = \frac{P_{l(i),n}\cdot G_{i,l(i)}}{\sigma^2 + \sum_{l\neq l(i)}\sum_{m\in M} y_{m,n}\cdot P_{l,n}\cdot G_{i,l}}. \tag{1}$$

We model the instantaneous achievable rate at slot n for MS m as

$$R_{m,n} = \Delta B \Delta T \log_2\left(1+\vartheta_{m,n}(\mathbf{Y},\mathbf{P})\right)\left[\frac{\text{bits}}{\text{sec}}\right]. \tag{2}$$

Assume that F is the time duration of an OFDMA frame, then the mth MS achievable data rate (bps) for one frame is

$$U_m = \frac{1}{F}\sum_{m=1}^{M}\sum_{n=1}^{N} R_{m,n}. \tag{3}$$

Thus the total number of bits carried over slot n in the multicell system is:

$$T_n(\mathbf{Y},\mathbf{P}) = \sum_{i=1}^{M}\rho_{i,n}U_{i,n}. \tag{4}$$

3.3. Problem Formulation. As it is stated earlier, resource allocation takes place in two levels, namely, at the RRC and RRA at the BSs. In the first level, the RRC controls a cluster of BSs and makes slot assignment decision in a superframe time scale. The scope of the RRC is to handle interference among MSs at the outer ring cell in the overlapped cells and thus exploit the interference avoidance gain. We assume a one-to-one connection between an MS and an SF, hence the RRC is using information of different SFs for the different MSs in the system in order to calculate the soft reuse factor. Since Mobile WiMAX supports a variety of services with diverse quality requirements, including the real-time service with fixed bit rate (UGS), real-time service with variable bit rates and a bounded delay (rtPS), the non-real-time service with variable bit rates but insensitive delay (nrtPS), and the best effort service(BE). Thus, the RRC must be able to maximize the total system throughput subject to guarantee the constant traffic rate of unsolicited grant service, mean rate of real-time polling service and extended real-time polling service, and zero packet loss of non real-time polling service and best effort service. Thus, the optimization problem to be solved at the RRC is

$$\max \sum_{n=1}^{N} T_n \tag{5}$$

subject to

$$\begin{gathered} U_m \geq \text{ugs\_max\_rate} \quad \forall \text{SF} \in \text{UGS}, \\ \text{min\_rate} \leq U_m \leq \text{max\_rate} \quad \forall \text{SF} \in \{\text{ertPS}, \text{rtPS}, \text{nrtPS}\}, \\ \text{If } \rho_{m,n} = 1, \quad \text{then } \rho_{m',n} = 0 \quad \forall m \neq m'. \end{gathered} \tag{6}$$

However, the problem is rather different in the BS as it distributes the load among the MSs at the inner and outer ring cell in a fair way. Upon receiving the decision allocation from the RRC, each BS checks (i) the satisfaction level for all SFs in terms of data rate in each cell and (ii) minimize their degree of dissatisfaction by performing policy of slot reallocation. Thus the problem at the base station for the different types of SFs can be formulated as

$$\min \sum_{m=1}^{M} \left| \frac{U_m - \text{ugs\_max\_rate}}{\text{ugs\_max\_rate}} \right|^2 \quad \forall \text{SF} \in \{\text{UGS}\} \tag{7}$$

subject to

$$\text{ugs\_max\_rate} > 0,$$

$$\min \sum_{m=1}^{M} \left| \frac{U_m - \text{min\_rate}}{\text{min\_rate}} \right|^2 \quad \forall \text{SF} \in \{\text{ertPS}, \text{rtPS}, \text{nrtPS}\} \tag{8}$$

subject to

$$\text{min\_rate} > 0. \tag{9}$$

4. Hierarchical Resource Allocation Approach—HRAA

We propose in this section a Hierarchical Resource Allocation Approach (HRAA) at both the RRC and the BS. The cooperation between both the RRC and the BSs is necessary since each BS has to provide information to its associated RRC. Message exchanges between RRC and BS enable RRC to decide how to allocate resources among all the BSs in the system.

4.1. Resource Allocation at RRC. The first step for resource allocation at the RRC is achieved through calculating the number of slots for each BS in the system. This depends mainly on the information provided by the RRA at BS to the RRC, which includes information about the types of SFs, their data rates, and their channel qualities provided by the Channel Quality Indicator (CQI) message from the MSs. Upon receiving information, the RRC decides the number of slots for each BS through the following equation:

$$n = \left\lceil \frac{U_i}{(1/|M_t|)\sum_{j\in M_t} U_j} \, \frac{\bar{\mu}_i}{(1/|M_t|)\sum_{j\in M_t} \bar{\mu}_j} \right\rceil, \tag{10}$$

where $\bar{\mu}_i$ is the average traffic rate for connection i. In essence, this allocation exploits multiuser diversity by allocating more slots to the SFs with better channels. For instance, let us assume that the average traffic rate of all connection is the same, then the factor $U_i/(1/|M_t|)\sum_{j\in M_t} U_j$ is equal to one. A connection with relatively good channel conditions, that is, its $\bar{\mu}_i(t) > \sum_{j\in M_t} \bar{\mu}_j(t)/|M_t|$, will initially allocate two or more slots. On the other hand, a MS with relatively bad channel conditions will initially allocate only one slot. The role of weighting factor $U_i/(1/|M_t|)\sum_{j\in M_t} U_j$ is to weight the allocation proportional to SF's average rate.

The next step to be achieved by the RNC is slot assignment among MSs at the inner and outer ring cell. The RNC performs the assignment first for the MSs in the outer ring then the MSs in the inner cell. Each MS has one SF, that is, there is one-to-one mapping between an MS and its SF through a connection. Since UGS has strict QoS constraints, therefore, we prioritize it over all other types by allocating first the best slots to it. We proceed in slot allocation as follows.

(1) Calculate the achievable data rate U_m for the given slots as in (2) for all SFs in the system according to their CQIs.

(2) Calculate the number of slots for each SF as in (10).

(3) Allocate the best slots to all UGS SFs in the system one by one until the maximum sustained traffic rate is achieved for all of them, then set $\rho_{m,n}$ to 1.

(4) Allocate the residual slots with $\rho_{m,n} = 0$ to the remaining SFs prioritizing the real-time SFs (rtPS and ertPS) over the others. First allocate the best slots to rtPS and ertPS until their maximum sustained traffic rates are achieved. Then, allocate the slots to nrtPS up to their maximum sustained traffic rate. The algorithm of resource allocation is described in Algorithm 1.

4.2. Resource Allocation at the BS. At this level of resource allocation, each BS receives its assignment information concerning slot offset for each MS in the inner and outer ring cell. Accordingly, each BS will do the following steps to assure fairness and a good level of satisfaction for each SF in terms of data rate (see Algorithm 2).

(1) Check the level of satisfaction for each MS in terms of number of slots.

(2) Initiate the set of the dissatisfied MSs associated with rtPS, ertPS, and nrtPS in both inner and outer ring cell. The dissatisfaction of these MSs is due to the insufficient resource (slots) as the allocation for rtPS, ertPS, and nrtPS is done with the maximum data rate for the outer ring MSs.

(3) Reallocate the slots to guarantee the minimum reserved traffic for all dissatisfied SFs. This is done by searching the slots already allocated to the satisfied MSs and reallocating them to the dissatisfied ones starting by rtPS and ertPS SFs. If this reallocation does not lead to a violation of minimum reserved data rate for the satisfied MSs, then the reallocation will continue until all the SFs are satisfied.

5. Numerical Results

In this section, we present simulation results to illustrate the performance of our proposed algorithms. We use certified system parameters proposed by WiMAX Forum in order to simulate realistic environment and wireless communication system in Mobile WiMAX [13].

```
Input: SNR
Calculate each active MS's achievable data rate using(2)
Calculate the slot number for each SFs as in(10)
for every SF $\in$ {UGS} do
    First allocate slots $n$ to best MS $m$ with UGS SF
    Set $\rho_{m,n} = 1$
end for
for every SF $\in$ {rtPS, nrtPS and ertPS} do
    Allocate the residual slots at the maximum rate to the remaining SFs prioritizing rtPS
    and ertPS over nrtPS
    Set $\rho_m[k,t] = 1$
end for
Send slot assignment information to all BSs in the system
```

Algorithm 1: Resource allocation at RNC.

```
(1) Check the level of satisfaction of each MS
(2) Initiate the satisfied MS set $M := \{m \mid \Delta_m \geq 0\}$, and the dissatisfied MS set
    $\overline{M} := \{m \mid \Delta_m < 0\}$, where $\Delta_m = U_m - R_m$
(3) Choose the most satisfied MS $m$ such that $m = \arg\max_{j \in M} \Delta_j$, then update set $M$
(4) Find the worst slot among the slots that are originally allocated to $m$, that is,
    $(k^*, t^*) = \arg\min_{k \in K, t \in T} R_m[k,t]$
(5) if this reallocation does not make MS $m$ dissatisfied then
(6)     Allocate this slot, that is, $(k^*, t^*)$ to the dissatisfied MS $\overline{m}$ in $\overline{M}$ which can achieve the best
        throughput in that slot
(7) end if
(8) Continue (2) until MS $m$ becomes dissatisfied or MS $\overline{m}$ gets satisfied
```

Algorithm 2: Resource allocation at BS.

5.1. Simulation Environment. We used OPNET simulator for evaluating the performance of the proposed algorithms. We assume an OFDMA mobile WiMAX system with 7-sector sites. MSs are uniformly distributed in the area of the cells. Further simulation parameters are depicted in Table 1.

5.2. Simulation Results. Performance is measured first in terms of cell throughput, which is the total throughput divided by the number of cells in the system. Moreover, we consider three different allocation strategies which are then compared. The first one is uncoordinated in the sense that there is no RRC and the resource allocation is based on local information, we refer to this method as "Random" as slots are allocated randomly among MSs. The second scheme is a coordinated allocation where the RRC algorithm is executed every superframe but once each BS receives the slots assignments from the RRC then it follows these recommendations and no slot reallocation takes place which is referred as to "RRC+BS". Finally, the third scheme considers both RRC and BS for load distributing among MSs, this is referred to as "RRC+LD".

Figure 5 depicts the 50th percentile of the average cell throughput as a function of the bandwidth occupancy per cell. High bandwidth occupancy levels correspond to high loaded system and big overlapping areas of the used bandwidth among cells. In addition, when the bandwidth occupancy is 100% then the system is reuse-1 since every BS uses the whole bandwidth. In principle, the average cell throughput increases as we increase the bandwidth occupancy per cell. This is true since the more the slots that

Table 1: Simulation Parameters.

Simulation Parameters	Values
Channel bandwidth	5 MHz
Carrier Frequency	2.5 GHz
FFT size	512
Subcarrier frequency spacing	10.94 kHz
Number of null/guard band subcarriers	92
Number of pilot subcarriers	60
Number of used data subcarriers	360
Subchannel number	15
DL/UL frame ratio	28/25
OFDM symbol duration Number	102.9 μs
Data OFDM symbols in 5 ms	48
Modulation	QPSK, 16-QAM, 64-QAM
MS velocity	45 kmph
Number of MSs	20
UGS maximum traffic rate	64 Kbps
rtPS traffic rate	5 Kbps–384 Kbps
nrtPS traffic rate	0.01 Mbps–100 Mbps
Channel model	6-tap Rayleigh Fading

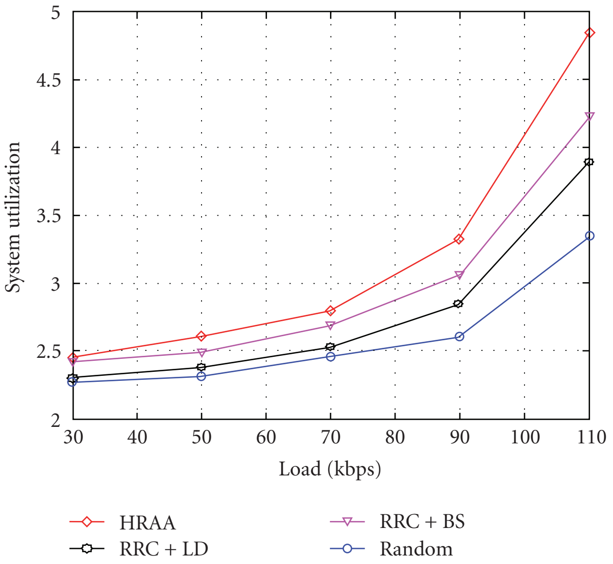

FIGURE 5: The 50th percentile of the average cell throughput for different load.

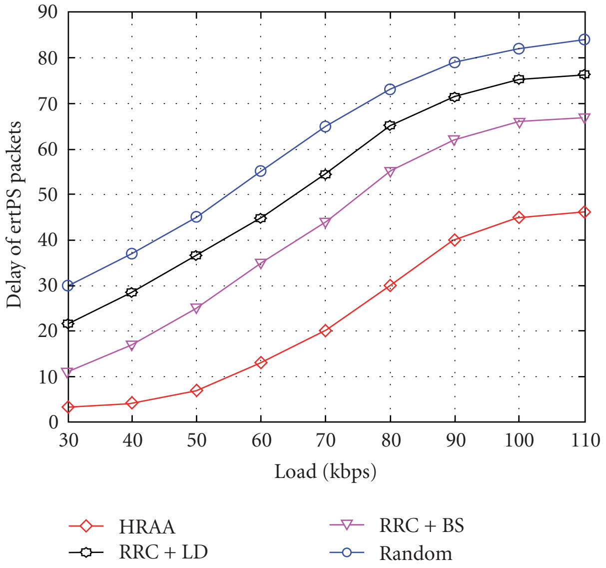

FIGURE 7: Delay comparison of ertPS SFs in outer ring cell versus load.

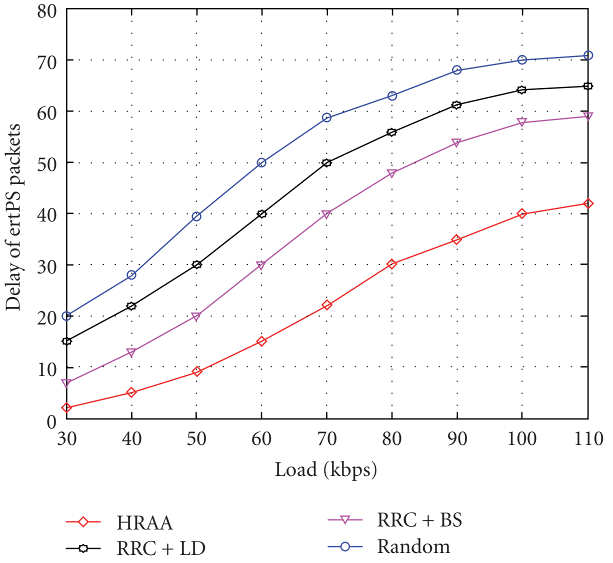

FIGURE 6: Delay comparison of ertPS SFs in inner cell versus load.

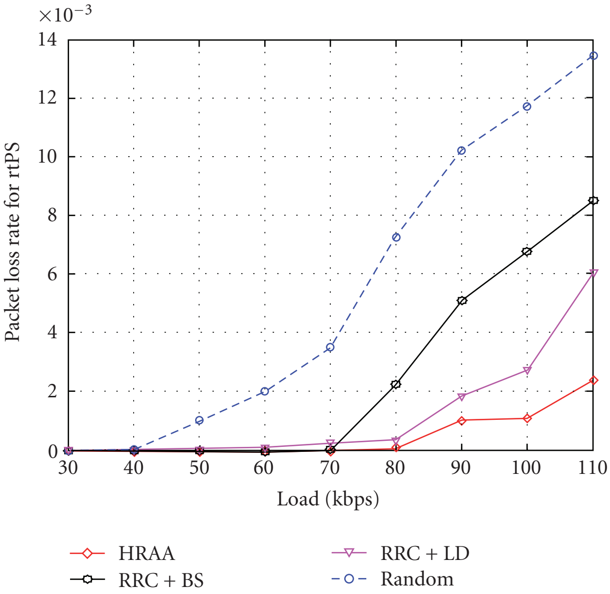

FIGURE 8: PLR comparison of rtPS SFs in inner cell versus load.

each BS uses the bigger is the average cell throughput. In other words, as we increase the load per cell, the average cell throughput increases but when with a lower rate due to the increase of interference and number of collisions. Accordingly, our approach achieves higher throughput due to the hierarchical and reallocation using.

The second parameter of performance that we measured is the delay of packet for ertPS. Note that we do not include UGS in the simulation since its QoS requirements are already guaranteed by our scheme. Figures 6 and 7 illustrate delay comparison for the different algorithms for inner and outer ring cell MSs. HRRA performs better in terms of delay than other schemes since it assigns the highest priority for the ertPS SFs even when the load of the cell increases, there is no violation of the delay. The approach RRC+BS performs better in terms of delay but it is higher than our approach since there is no calculation for the number of slots. Consequently, this will lead to the dissatisfaction for ertPS SFs in terms of slots as there is no reallocation method for the slots compared to our approach. The approach BS+LD has higher layer since it treats equally all the types of SFs. Finally, the worst delay performance is achieved by the random method, since there is no BS for coordinating slot allocation, slots are assigned randomly among MSs regardless their

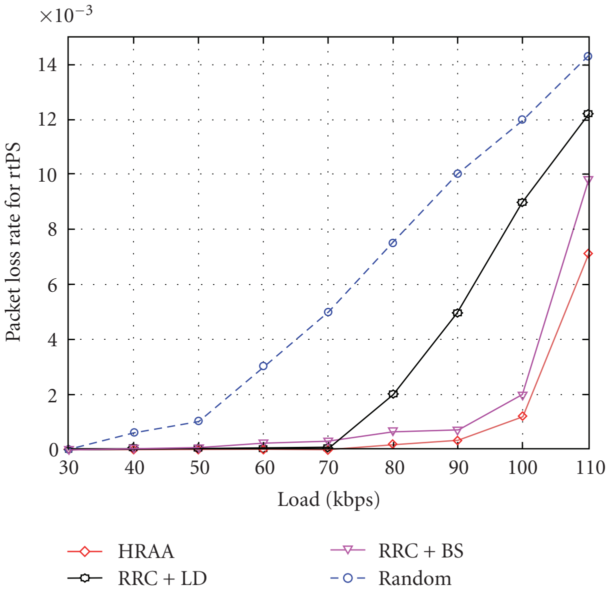

Figure 9: PLR comparison of rtPS SFs in outer ring cell versus load.

types. From both figures, we notice that the delay is slightly higher for outer ring cell MSs than for inner cell due to the use of FFR; however due to the reallocation scheme no violation is occurred for outer ring cell MSs having ertPS SFs.

Finally, we investigate the Packet Loss Rate (PLR) for rtPS SFs for both inner and outer ring cell MSs. Figures 8 and 9 depict PLR versus different loads. The PLR values for Random method are increasing awfully with the increase of load. The PLR for the RRC+LD method is higher than our method, this is because the RRC+LD tries to perform the equality of slot allocation for all types of SFs which is not a good solution specially when having different types of SFs in the cell. However, the PLR for HRAA increases slightly. This is due to the allocation policy for rtPS SFs as HRRA does not take into account only their delay but also their minimum data rate. Even when the load increases, the HRAA tries to guarantee the minimum data rate for rtPS SFs which will not lead to high packet loss due to the exceeded delay.

6. Conclusion

In this paper, we proposed a slot allocation scheme for multicell OFDMA mobile WiMAX system using zone switching diversity method. Based on our scheme we proposed an architecture in which resources are allocated in a hierarchical way. By using fractional frequency reuse in our scheme, QoS requirements for the different SFs in the inner and outer ring cell are guaranteed. Our scheme does not only coordinate the inner-cell interference but also utilizes opportunistic scheduling to increase the overall throughput of the system while guaranteeing QoS needs in terms of delay for ertPS SFs and packet loss rate for rtPS SFs. In our future work we will include MIMO technology in our scheme of resource allocation.

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