Cognitive Radio Based Bandwidth Allocation Scheme for WiMAX Networks

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***Abstract*— In WiMAX networks managing the uplink access is an important issue as it deals not only with the available bandwidth but also with the QoS requirements of different traffic classes. This paper proposes a new scheme for bandwidth allocation in WiMAX systems, named WiMAX Dual Cognitive Radio Scheme (WDCRS). The proposed scheme uses cognitive radio in order to attain high bandwidth utilization and to increase the total throughput. For performance analysis, an analytical model is developed, and the effect of applying cognitive radio on different service classes is studied and the bandwidth utilization for each service class is analyzed. The results show that the proposed scheme provides higher bandwidth utilization and lower blocking probability in comparison to several existing schemes.**

***Index Terms*— cognitive radio, bandwidth allocation, quality of service, IEEE 802.16, WiMAX**

I. Introduction

As a broadband wireless technology, the Worldwide Interoperability for Microwave Access (WiMAX) offers cost effective and quickly deployable alternative to cable and DSL networks [1-5]. It provides high bandwidth and various levels of quality of services (QoS) for different classes of traffic [6,7]. Based on the IEEE 802.16 standard, WiMAX supports fixed and mobile data access. The IEEE 802.16-2004 standard [8] provides fixed wireless broadband access, while the IEEE 802.16e standard [9] provides both fixed and mobile wireless broadband access. The IEEE 802.16e standard considers five classes of service [9,10]: Unsolicited Grant Service (UGS), Real-Time Polling Service (rtPS), Extended Real-time Polling Service (ertPS), Non-Real Time Polling Service (nrtPS), and Best Effort (BE). The UGS supports real-time traffic that periodically generates packets of fixed length, for example Voice over IP without silence suppression. The rtPS supports real-time traffic that periodically generates packets of variable length, for example MPEG video. The ertPS benefits from both UGS and rtPS. An example of ertPS traffic is Voice over IP with silence suppression. The nrtPS supports non-real-time traffic that generates packets of variable length and tolerant to delay, for example FTP. The BE service supports traffic that does not require throughput or delay guarantees, for example HTTP.

In WiMAX networks, managing the uplink access is necessary as users share the bandwidth to transmit their data. In this paper, a new bandwidth allocation scheme is proposed to attain high bandwidth utilization and to increase the total throughput. In the proposed scheme, the concept of cognitive radio [11-15] is applied to different service classes of a WiMAX uplink in order to enhance the bandwidth utilization while maintaining the QoS requirements of other classes. Cognitive radio allows secondary (or unlicensed) users to use the channel (or spectrum) allocated to primary (or licensed) users when they are not fully using it. In the proposed scheme, the nrtPS and BE service classes behave as secondary users so they can use channels that are unused by the other service classes (i.e.; the primary users). For performance analysis, an analytical model is developed and the blocking probability is derived.

Recently, a number of bandwidth allocations schemes for WiMAX have been presented. A priority-based scheduling algorithm [16] was introduced where different priorities are assigned to different classes of service. In this algorithm, UGS is allocated fixed bandwidth, and rtPS, nrtPS and BE have high, medium and low priorities, respectively. Connections of equivalent priority are served one packet from each connection in a round robin manner. A user-based bandwidth allocation scheme [17] was proposed, in which the users are categorized into three priority levels: high, regular, and low. High-priority users are allocated bandwidth first, followed by regular users, followed by low-priority users in a round robin manner. In [18], two approaches for bandwidth allocation were introduced: complete partitioning and complete sharing. In complete partitioning, UGS is allocated a fixed partition of the total bandwidth while rtPS, nrtPS, and BE are allocated the remaining bandwidth. In complete sharing, when UGS is allocated more bandwidth than required, the available bandwidth is allocated for rtPS and nrtPS. The BE service is allocated whatever bandwidth left after bandwidth is allocated to UGS, rtPS, and nrtPS. A bandwidth allocation scheme

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using complete partitioning [19] was proposed, where each partition is reserved to a specific type of connection characterized by its service class. Nearly-optimal values for partition sizes were obtained using analytical model. The BE service class was not considered in this scheme. In [20], two bandwidth management schemes were proposed: the WiMAX Complete Partitioning Scheme (WCPS) and the WiMAX Partial Sharing Scheme (WPSS). In WCPS, fixed partitions of the total bandwidth are allocated to all service classes, while in WPSS the bandwidth is shared between lower-priority classes (BE/nrtPS) and higher-priority classes (ertPS/rtPS). However, the higher-priority class can prevent the lower-priority class from using that bandwidth.

In previous work [21], we proposed a bandwidth management scheme, called WiMAX Dynamic Channel Allocation Scheme (WDCAS), in which the partial sharing concept in [20] and the cognitive radio for dynamic channel allocation [22-25] are used. In WDCAS, the BE service class is treated as a secondary user so it can use channels that are unused by the other service classes. Unlike our previous work [21], this work does not use partial sharing and it treats both the BE and nrtPS service classes as secondary users in cognitive radio networks.

The rest of the paper is organized as follows. Section 2 reviews the bandwidth management schemes WCPS, WPSS, and WDCAS. Section 3 provides a mathematical model and a detailed description of the WDCRS proposed scheme. Performance evaluation and simulation results are presented in Section 4. The paper is concluded in Section 5.

II. Bandwidth Management Schemes

In this section, the bandwidth management schemes, WCPS, WPSS, and WDCAS are reviewed.

A. WCPS

In WCPS, fixed, non-interacting partitions of the total bandwidth are allocated to the service classes UGS, rtPS, ertPS, nrtPS and BE, which makes each class independent of the other classes.

B. WPSS

In WPSS, UGS has an independent fixed partition, followed by partitions for the rtPS and nrtPS classes, followed by partitions for the ertPS and BE classes. WPSS uses the partial sharing concept, where partitions for high-priority classes can be used by low-priority classes. However, new arrivals of the higher-priority class can prevent the lower-priority class from using that partition. Accordingly, if rtPS/ertPS has some of its own channels idle then nrtPS/BE can use them. However, new rtPS/ertPS traffic will make nrtPS/BE release some or all of these channels.

C. WDCAS

WDCAS applies the partial sharing concept used in WPSS. At the beginning of each transmission period, each of the four higher-priority classes (i.e.; UGS, rtPS, ertPS, and nrtPS) is given a fixed number of channels. UGS is allocated channels that are not shared with other classes. The rtPS class is allocated less number of channels than that of UGS and, using partial sharing, is allowed to demand a share of the channels allocated to nrtPS. The ertPS class is allocated a number of channels less than that of rtPS, not shared with other classes. nrtPS is allocated the remaining channels which are shared with the rtPS class. WDCAS treats the BE class as a secondary user in cognitive radio networks. The BE service class does not get a predefined share of the channels; instead it uses whatever channels left after each higher-priority class (i.e.; UGS, rtPS, ertPS, and nrtPS) reserves the required channels.

III. Proposed Scheme

As seen in Section II, the WPSS and WDCAS apply the concept of fixed sharing to specific service classes, which means that some classes, without sharing, may not benefit from the idle channels unused by other classes.

In this section, a new bandwidth allocation scheme, called WiMAX Dual Cognitive Radio Scheme (WDCRS), is proposed. It considers the nrtPS and BE service classes as secondary users in cognitive radio networks so they can use channels that are unused by the other service classes. A preliminary version of this work appeared in [26], where we first introduced the idea of cognitive radio users. This version includes a detailed and extensive analysis, and has a comprehensive evaluation part. A system description and mathematical model of the proposed scheme are presented in the following sections.

A. System Description

In WDCRS, the lower-priority classes, BE and nrtPS, do not get a predefined share of the channels; instead they are treated as cognitive radio users, where the nrtPS class has priority to access the network first and search for available channels. By utilizing the BE and nrtPS class resources, each of the higher-priority classes will be allocated more channels and hence increasing the total throughput without affecting the QoS requirements. At the beginning of each transmission period, each of the higher-priority classes (i.e.; UGS, rtPS, and ertPS) is given a fixed number of channels, and each one uses its available resources to deal with the upcoming jobs. The BE and nrtPS classes take whatever resources left after all the jobs are set to be served. Note that the BE and nrtPS jobs can wait till the next transmission period since both the BE and nrtPS services are designed to support traffic that does not require any delay guarantee.

To illustrate channel allocation in WDCRS, assume that N channels are available at the beginning of a transmission period. The service classes will be allocated the channels as follows:

1. The UGS class is allocated n_1 channels. n_1 will be the largest allocation among the other classes (i.e.; rtPS and ertPS).
2. The rtPS class is allocated n_2 channels, where $n_2 < n_1$.

3. The ertPS class is allocated n_3 channels that are left after assigning channels to the UGS and rtPS classes (i.e.; $n_3 = N - (n_1 + n_2)$).
4. The nrtPS and BE classes are treated as cognitive radio users, where the nrtPS class has priority to access the network first and search for available channels. Both classes can reserve limited number of channels, n_4 and n_5, respectively, so that the total throughput is not affected.

B. Mathematical Model

Since each of the higher-priority classes (UGS, rtPS, and ertPS) in WDCRS has a fixed channel allocation pattern, the three classes can be studied separately. For the two lower-priority classes (BE and nrtPS), they are treated as two separate cognitive radio users given that the nrtPS class has priority to scan the resources first. To get the maximum utilization of the bandwidth, the choice of how to divide the total bandwidth among the service classes is to be an optimization problem. A mathematical model can be established for the optimization problem to be solved that is the optimum allocation of bandwidth that increases the throughput and reduces the blocking probability.

The three higher-priority classes (UGS, rtPS, and ertPS) have similar behaviors. In the following, we denote UGS, rtPS, and ertPS as class1, class 2, and class 3, respectively.

1. For UGS, rtPS and ertPS, the packets generated are Poisson processes and have the following probability of generation:

$$P\,(c_i\,;\lambda_i) = \frac{\lambda_i\,.\,e^{-\lambda_i}}{c_i!} \tag{1}$$

where
$P(c_i\,;\lambda_i)$: The probability of generation of c_i jobs in the ith class ($i = 1,2,3$).
c_i: The number of jobs in the ith class.
λ_i: The mean arrival rate for the ith class.

The blocking probability, which occurs when the total number of jobs exceeds the available number of channels, can be defined as:

$$P_{b_i} = Prob\,\{c_i > n_i\} \tag{2}$$

where
P_{b_i}: The blocking probability of ith class jobs.
n_i: The available number of channels assigned for ith class.

The average blocking probability is given by:

$$P_{b_i,av} = \sum_{c_i = n_i+1}^{\infty} \frac{\lambda_i\,.\,e^{-\lambda_i}}{c_i!} \tag{3}$$

Whereas, the average number of transmitted packets is given by:

$$P_{t_i,av} = \lambda_i - \sum_{c_i = n_i+1}^{\infty} [c_i - n_i]\frac{\lambda_i\,.\,e^{-\lambda_i}}{c_i!} \tag{4}$$

2. For nrtPS, the probability of packet generation is given by:

$$P\,(c_4\,;\lambda_4) = \frac{\lambda_4\,.\,e^{-\lambda_4}}{c_4!} \tag{5}$$

where
$P(c_4\,;\lambda_4)$: The probability of generation of c_4 jobs in the nrtPS class.
c_4: The number of jobs in the nrtPS class.
λ_4: The mean arrival rate for the nrtPS class packets.

Since no channels are assigned to this class, the probability that c_4 jobs will pass to the network is:

$$P_{pass}(c_4) = Prob\,\{c_4 < (N - (c_1 + c_2 + c_3))\}$$
$$= \sum_{c_1=0}^{n_1}\sum_{c_2=0}^{n_2}\sum_{c_3=0}^{n_3} \frac{\lambda_1\,.\,e^{-\lambda_1}}{c_1!}.\frac{\lambda_2\,.\,e^{-\lambda_2}}{c_2!}.\frac{\lambda_3\,.\,e^{-\lambda_3}}{c_3!} \tag{6}$$

under the condition $c_4 < (N - (c_1 + c_2 + c_3))$.

The blocking probability is defined as:

$$P_{b_4}(c_4) = 1 - P_{pass}(c_4) \tag{7}$$

The average blocking probability is given by:

$$P_{b_4,av} = \sum_{c_4=0}^{n_4} \frac{\lambda_4\,.\,e^{-\lambda_4}}{c_4!}.\left[1 - P_{pass}(c_4)\right] \tag{8}$$

where n_4 is the maximum allowed transmitted packets of the nrtPS class to be served. The average number of transmitted packets in the nrtPS class is:

$$P_{t_4,av} = \lambda_4\,.\left[1 - P_{b_4,av}\right]$$
$$= \lambda_4.\left[1 - \sum_{c_4=0}^{n_4} \frac{\lambda_4\,.\,e^{-\lambda_4}}{c_4!}.\left[1 - P_{pass}(c_4)\right]\right] \tag{9}$$

3. For BE, the probability of packet generation is given by:

$$P\,(c_5\,;\lambda_5) = \frac{\lambda_5\,.\,e^{-\lambda_5}}{c_5!} \tag{10}$$

where
$P(c_5\,;\lambda_5)$: The probability of generation of c_5 jobs in the BE class.
c_5: The number of jobs in the BE class.
λ_5: The mean arrival rate for the BE class packets.

The probability that c_5 jobs will pass to the network is:

$$P_{pass}(c_5) = prob\,\{c_5 < (N - (c_1 + c_2 + c_3 + c_4))\} = \sum_{c_1=0}^{n_1}\sum_{c_2=0}^{n_2}\sum_{c_3=0}^{n_3}\sum_{c_4=0}^{n_4}\left(\frac{\lambda_1 . e^{-\lambda_1}}{c_1!} . \frac{\lambda_2 . e^{-\lambda_2}}{c_2!} . \frac{\lambda_3 . e^{-\lambda_3}}{c_3!} . P_{pass}(c_4)\right) \quad (11)$$

under the condition $c_5 < (N - (c_1 + c_2 + c_3 + c_4))$.

The blocking probability is given by:

$$P_{b_5}(c_5) = 1 - P_{pass}(c_5) \quad (12)$$

The average blocking probability is:

$$P_{b_5,av} = \sum_{c_5=0}^{n_5} \frac{\lambda_5 . e^{-\lambda_5}}{c_5!} . [1 - P_{pass}(c_5)] \quad (13)$$

where n_5 is the maximum allowed transmitted packets of the BE class to be served.

The average number of transmitted packets in the BE class is:

$$P_{t_5,av} = \lambda_5 . [1 - P_{b_5,av}] = \lambda_5 . \left[1 - \sum_{c_5=0}^{n_5} \frac{\lambda_5 . e^{-\lambda_5}}{c_5!} . [1 - P_{pass}(c_5)]\right] \quad (14)$$

The average number of generated packets for the five service classes at any time is:

$$N_g = \sum_{i=1}^{5} \lambda_i \quad (15)$$

The average number of transmitted packets at a unit time is:

$$N_t = \sum_{i=1}^{5} \lambda_i [1 - P_{b_i}(c_i)] \quad (16)$$

The bandwidth utilization is defined as:

$$U = \frac{N_t}{N_g} * 100\% \quad (17)$$

For the best utilization, we should maximize the following constrain:

$$U = MAX \left[\frac{\sum_{i=1}^{5} \lambda_i [1 - P_{b_i}(c_i)]}{\sum_{i=1}^{5} \lambda_i}\right] \quad (18)$$

IV. Performance Evaluation

This section presents a performance evaluation of the WDCRS proposed scheme. In particular, we compare WDCRS with the bandwidth management schemes WCPS, WPSS, and WDCAS in terms of the bandwidth utilization and blocking probability. In addition, the effect of applying cognitive radio on the service classes is studied and the bandwidth utilization for each service class is analyzed. In the simulation environment, a constant upload data rate of 1Mbps is assumed, and it supports 100 channels. Poisson distribution was used for data generation and a packet size of 1024 bytes was assumed.

Fig. 1 shows the bandwidth utilization of the UGS class with WCPS, WPSS, WDCAS, and WDCRS. It is shown that WDCRS has a better performance since the total number of channels allocated for UGS in WDCRS is greater than that in the other schemes. This allows more packets of this class to pass to the network, which lowers the blocking probability and increases throughput. All four schemes reach saturation after arrival rate of 8 packets per second.

For rtPS, Fig. 2 shows that WDCRS has a better utilization compared with the other schemes. Note that the total number of channels allocated for rtPS in WDCRS is greater than that in the other schemes. The rtPS class in WDCRS reaches saturation after arrival rate of 8 packets per second.

For ertPS, Fig. 3 shows that WDCRS reaches the maximum utilization of the bandwidth and saturates very fast, and then it tends to lower its performance significantly, since both the nrtPS and BE classes start to search for channels first in the ertPS partitions and get whatever they could before they move to other partitions. The randomness in the WDCRS curve is due to the random process of generation in the nrtPS and BE packets.

For the nrtPS class, Fig. 4 shows that WDCRS has better bandwidth utilization than WPSS, since no partial sharing is applied. However, it has less utilization compared to WCPS which has fixed channel allocation for the nrtPS class. Note that the behavior of the nrtPS class in WDCAS is similar to that of the ertPS class in WDCRS (Fig. 3).

In Fig. 5, WDCRS and WDCAS have similar behavior for the BE class, and they tend to keep a slower slope till reaching saturation since the possibility of gaining channels in these schemes is higher and could lead to better performance. Note that WDCRS and WDCAS reach saturation at arrival rate of 4 packets per second, while WCPS and WPSS reach saturation at rate of 2 packets per second.

The overall bandwidth utilization of all schemes is shown in Fig. 6. It is shown that WDCRS has the highest utilization compared with the other schemes. It reaches saturation at arrival rate of 14 packets per second.

The blocking probability of all schemes is shown in Fig. 7. It is shown that WDCRS provides the lowest blocking probability compared with the other schemes. Moreover, it has a very low blocking probability, benefiting from using cognitive radio to deal with different traffic scenarios.

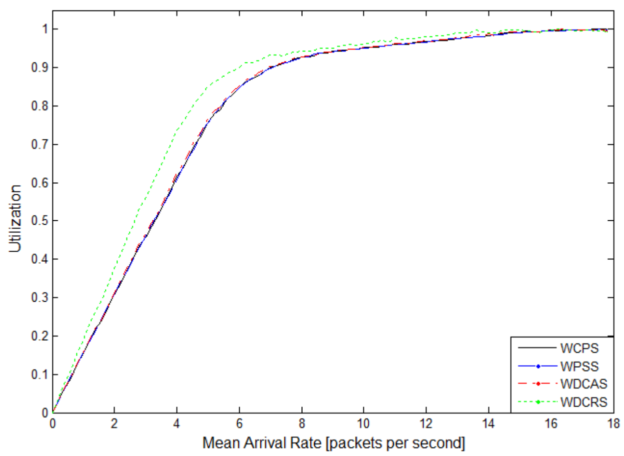

Figure 1. UGS Class Utilization.

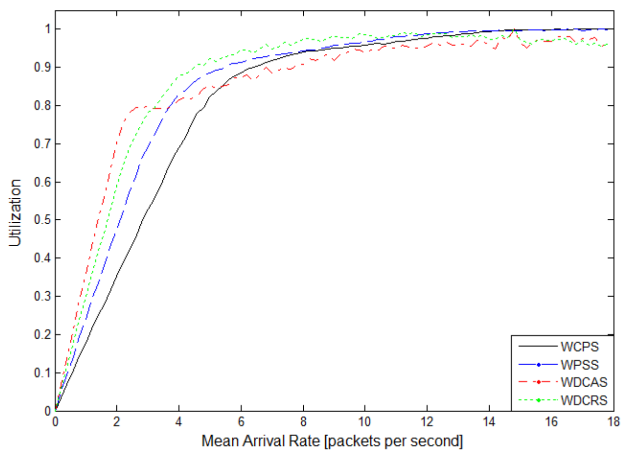

Figure 2. rtPS Class Utilization.

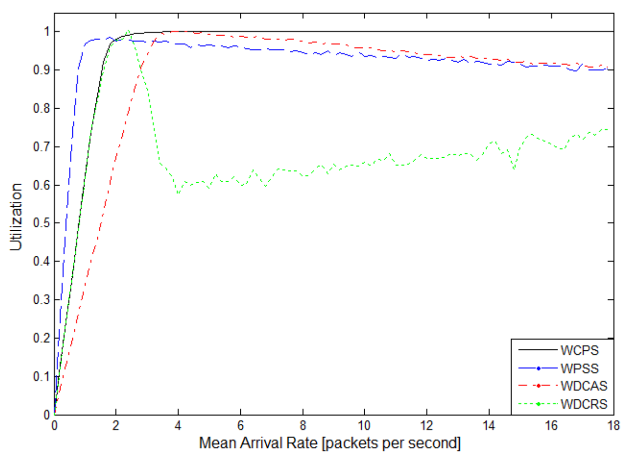

Figure 3. ertPS Class Utilization.

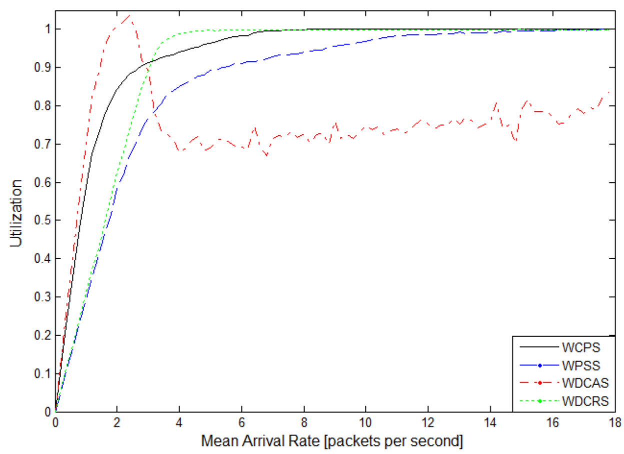

Figure 4. nrtPS Class Utilization.

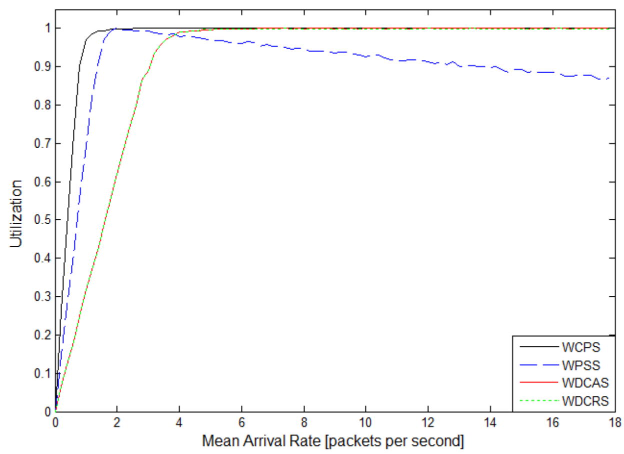

Figure 5. BE Class Utilization.

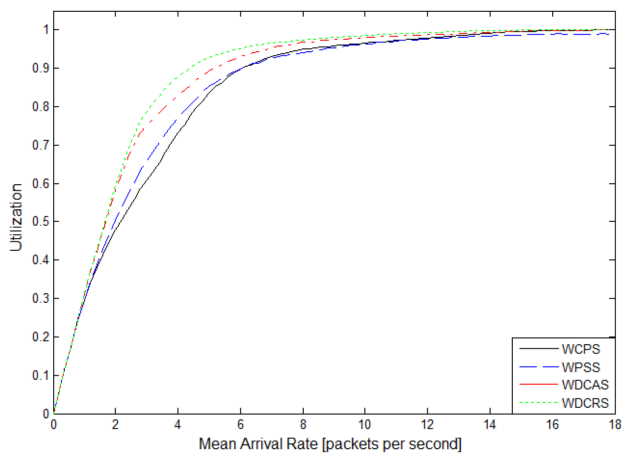

Figure 6. Overall Utilization.

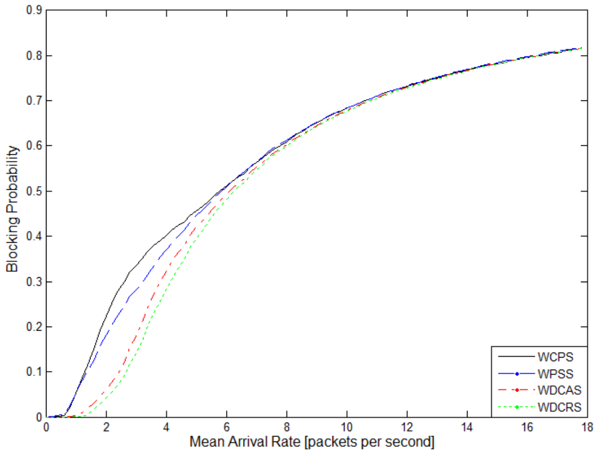

Figure 7. Blocking Probability.

V. Conclusion

In this paper a new scheme for bandwidth allocation in WiMAX systems is introduced. The proposed scheme attains high bandwidth utilization and increases the total throughput. It applies the concept of cognitive radio to lower-priority classes in order to enhance the bandwidth utilization while maintaining the QoS requirements of higher-priority classes. For performance analysis, an analytical model is developed, and the effect of applying the cognitive radio concept on different service classes is studied and the bandwidth utilization for each service class is analyzed. The proposed scheme is evaluated and compared with several schemes for similar traffic scenarios. The results show that the new scheme can provide higher bandwidth utilization and lower blocking probability in comparison to existing schemes.

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