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Scheduling Algorithms for Dynamic Spectrum Sharing

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Abstract

The *secondary service* is able to access the spectrum allocated to *primary service* through spectrum sharing mechanisms. Cognitive radio technology which enables secondary users to share spectrum with primary users in an opportunistic manner can be implemented for this. Scheduling or resource allocation is a major factor for efficient utilization of any shared resource. Opportunistic scheduling policies which utilize time varying multipath fading channel are best to implement in wireless networks. In this paper, performance analyses of resource allocation algorithms for secondary users are presented, specifically, rate-based, delay-based and utility function based scheduling algorithms. Performance analyses of scheduling algorithms are made by theoretical and simulation analysis of fundamental mechanisms in wireless resource management, like throughput fairness, delay fairness. Effect of different channel fading conditions on scheduler performance is presented in detail, in particular, Rayleigh fading and Nakagami fading channels are considered. The simulations are done using the software MATLAB.

Keywords: Cognitive radio, Dynamic spectrum sharing, Radio resource allocation, Scheduling, Spectrum underutilization.

1. Introduction

Many distinct radio access technologies operate in various frequency bands; these technologies are implemented to provide services that are both common and disparate. A static or fixed spectrum allocation policy is implemented now, in which frequency bands are statically assigned to different wireless services. The results of survey done by Ofcom shows, there will be a significant increase in demand for these services over the next 10-15 years. At the same time use of voice calls which is the conventional application for the cellular services is reducing significantly. This change is due to rapid growth of data centric applications like use of 3G data cards, video streaming, online gaming and download applications. There are other data centric applications which are to be introduced in coming years and expected to increase the traffic much more in coming years [1].

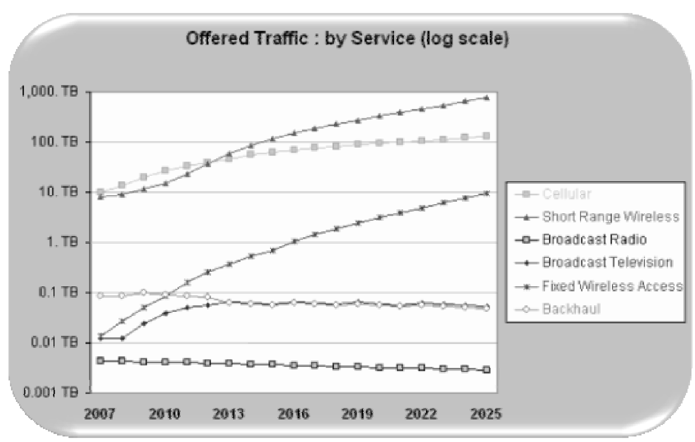

Figure 1: Total offered traffic (Terabytes) by service (log scale) over the coming years [1].

Figure 1 shows the expected network traffic of different wireless services over the next 10-15 years.

Spectrum regulators grant exclusive access to the spectrum for the primary services [2], [3]. Spectrum is idle when primary users are not transmitting, creating white spaces in the spectrum. This state considered as, underutilization of the allocated spectrum [4], [5], [7].

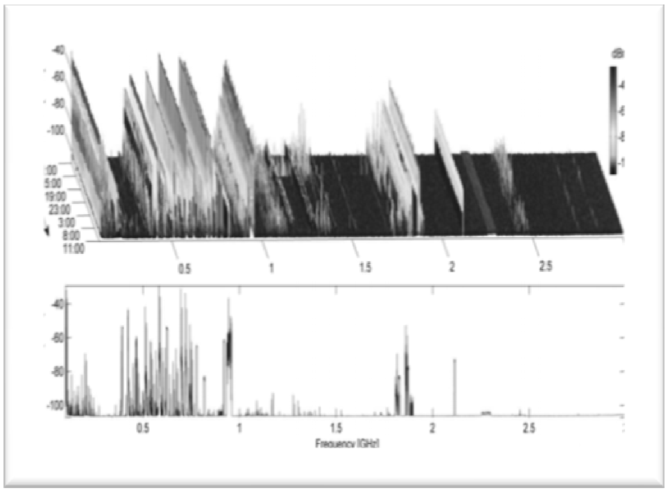

Figure 2: Usage measurement results of allocated spectrum [4].

Figure 2 shows the study result on radio spectrum utilization measurements carried out in Europe. Figure 1.3 shows the underutilized frequencies in spectrum where there is low primary user transmission. Survey results show that frequencies above 1 GHz are highly unused.

This low utilization of radio spectrum is a main reason for the idea of spectrum sharing and dynamic spectrum allocation policies (DSA) which allows efficient use of the spectrum by making use of these white spaces.

For dynamic setting like wireless networks scheduling is very much challenging. Because, channel capacity is time varying as a result of the multiple super imposed random effects such as mobility and multipath fading. The time varying nature of the wireless channel can be utilized for scheduling secondary users; this can provide comparable performance as static policies [11]. Scheduler follows channel-aware scheduling strategies, which enables secondary users for dynamically access available channel (wireless resources) based on channel state information (CSI).

This paper focuses on developing scheduler algorithms for dynamic resource allocation and exploring elementary parameters in resource management like capacity, fairness in throughput and delay of multiple user networks operating in different types of fading environments. Critical performance analyses of different scheduling policies are carried out to compare and find scheduling policies which provide better overall system performance. In addition, a study on radio resource allocation for spectrum sharing systems in the presence of channel sensing (estimation) error is conducted.

2. System Model

A cognitive radio network of *N* secondary users and *M* primary users is considered and all users are wishing to communicate using a common channel. A point to point wireless channel is considered with band width *B Hz* and this channel is considered to be flat fading WGN (White Gaussian Noise). As well, performance analysis of proposed schedulers is carried out in different channel fading conditions as such Rayleigh fading and Nakagami fading. These fading channel models will be discussed in channel model section.

Network consists of two services trying to access *B Hz* primary spectrum: *primary service* and *secondary service*. Spectrum is officially allocated to primary users. The secondary service shares the spectrum with primary service using a Dynamic Spectrum Access (DSA) approach [7]. Since, there is no direct communication between secondary and primary users; primary user is not alert about the secondary user activities. Thus, secondary user access strategy must satisfy the minimum interference level acceptable by the primary receiver.

In [9], [12] the impact of the interference threshold constraint on the achievable capacity of the secondary user and the power constraints that the secondary service need to maintain for effective transmission are discussed.

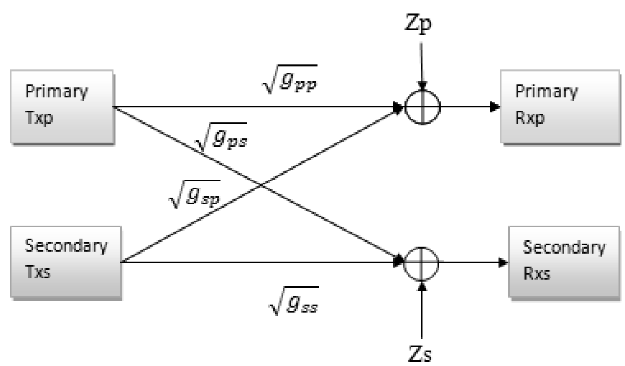

Figure 3: Spectrum sharing system [9]

Consider a spectrum sharing set-up with a primary and secondary transceiver denoted by *Txp / Rxp* and *Txs / Rxs,* respectively. Figure 3 shows the schematic diagram of the spectrum sharing system considered. Maximum transmit power of secondary transmitter *Txs* is assumed to be $\overline{P}_s$.

In each time slot t, $g_{ss}[t]$ and $g_{sp}[t]$ denote channel power gain from secondary transmitter to secondary receiver and primary receiver respectively. In addition, $g_{pp}[t]$ and $g_{ps}[t]$ represents channel power gains from primary transmitter to primary receiver and secondary receiver respectively. $Zp[t]$ and $Zs[t]$ are additive white Gaussian noise of at *Rxs* and *Rxp*, $\sigma_s^2$and σ_p^2 are respective variances of noise and σ_s^2=*NoB.*

2.1 *Scheduling System Architecture*

Secondary user network has *N* secondary user nodes. Also, a *full-buffer assumption* scenario is considered in this project work. The full-buffer assumption scenario is a simplified version of traffic transmitted by secondary user in a data session. In full-buffer assumption, the number of secondary users in the network at a time slot is considered constant and all secondary user buffers have unlimited amount of data to transmit.

Figure 4 shows architecture of the *N* secondary user scheduler over a shared channel with primary user. Each user has a buffer that can accommodate incoming packets. Scheduler in secondary user has channel state information which is necessary information for scheduling. As shown in figure 2.4, scheduler is responsible for selecting users from secondary network to have access to available channel. Scheduler must have channel side information corresponding to each secondary user in the network. In addition, scheduler also monitors channel access delay of each user. Scheduler selects a single secondary user from *N* users in network at each time slot *t*. Scheduler follows a specified algorithm to prioritize the secondary users channel access.

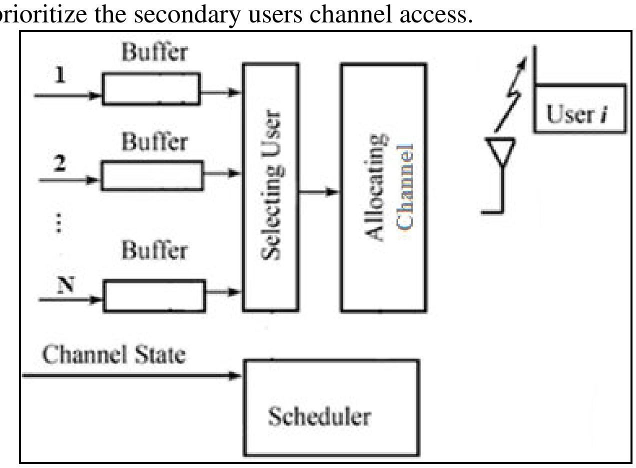

Figure 4: Scheduling system architecture [13]

2.2 *Channel Model*

Signal transmission through wireless communication channels are subjected to power loss. Three major power loss effects are attenuation that causes steady decrease in power, short-term fading (Rayleigh fading) and long-term fading (log-normal fading). Fading results in power fluctuations over time [14].

As mentioned above, fading results in power loss which fluctuates over time. This fading power loss fluctuation is characterized by channel power gain. Let g_{sp} and g_{ss} indicate instantaneous channel power gains from secondary transmitter to the primary and to secondary receiver respectively. The power channel gains $g_{ss}[t]$, $g_{sp}[t]$, $g_{pp}[t]$, $g_{sp}[t]$ between each node and other node in network are considered to be random independent and identically distributed (i.i.d) across time and follows a given distribution $p_{ss}(g_{ss})$, $p_{sp}(g_{sp})$, $p_{pp}(g_{pp})$, $p_{ps}(g_{ps})$. Furthermore, channel power gains are to be time varying, but fixed over the duration of time slot. Channel availability (perfect channel state information) is available at the scheduler, i.e., instantaneously prior to the transmission, scheduler has the knowledge of channel coefficients.

Since the constraint is imposed on parameter transmitter power, fairness of throughput and delay, scheduler should have a perfect knowledge of g_{sp} as well as g_{ss} (i.e. a two dimensional CSI).

Two channel fading models are considered and the average achievable secondary service capacity is calculated for each channel fading model for different spectrum scheduling scenarios. Two channel models considered are, Rayleigh fading channel and Nakagami fading channel.

2.3 *Fundamental Metrics of Scheduling*

Fundamental performance metrics for scheduling are *throughput* and *delay* (waiting time) of secondary users in network. An ideal scheduler must allocate channel to a secondary user by maintaining fairness in delay and maximizing secondary user achievable throughput. Delay is the time secondary user needs to wait to get access to channel. In spectrum overlay strategy, channel availability is determined by spectrum sensor (energy detector) continuously. Spectrum sensor provides information about channel state, i.e. whether channel is busy or not. If energy detected by spectrum sensors is below a threshold value, channel assumed to be free of primary service (idle channel) and channel is available to secondary service for transmission. This channel availability sensing based spectrum access is used in overlay strategy.

In underlay strategy, channel is used by secondary user most of the time by maintaining interference level at primary receiver below a specified threshold value. In [9], a detailed study on the secondary transmitter power control criterion that must be satisfied for the interference constraint at primary receiver for underlay spectrum sharing strategy is presented.

3. Scheduling Algorithms

Scheduler for secondary users must be able to assign wireless resources based on channel state information (CSI). Most important concept followed for scheduling is to select one secondary user with best channel state for transmission [15]. Since channel variations across secondary users are independent, opportunistic or channel aware scheduling can significantly improve performance of secondary user network. This characteristic is also named as *multiuser diversity*.

Major desired feature of wireless resource allocation must be the effective trade-off between spectral efficiency, fairness, and Quality of Service (QoS). Generally, scheduling in spectrum allocation is based on concave objective function to maximize a system parameter (in this case 'secondary user throughput') as well as to minimize delay (waiting time to get access to the channel) of secondary users. In this study three scheduler algorithms are analyzed. Scheduler algorithms monitor and compare these parameters and then prioritize secondary users to access available channel. Important parameters considered for scheduling are, a) achievable throughput of secondary user b) Secondary user delay c) probability of channel availability d) Secondary user maximum transmit power.

Achievable throughput of secondary user can be related to channel power gain available to each user.

Achievable throughput of secondary users under overlay strategy is calculated by Shannon's channel capacity equation for fading channel [9],

$$C_O(pi) = pi\, E_{gs}\, B \log(1 + \frac{g_{ss}P_s}{N_0 B}), \tag{1}$$

$$s.t\ E_g P_s \leq \overline{P_s} \tag{2}$$

For underlay strategy, channel capacity,

$$C_U(pi) = pi\, E_{gs}\, B \log(1 + \frac{g_{ss}P_s}{N_0 B + g_{ss}P_p}), \tag{3}$$

$$s.t\ E_g P_s \leq \overline{P_s} \tag{4}$$

$$E_g g_{sp} P_s \leq Q, \tag{5}$$

where, channel power gains,

$$g \triangleq \left(\underbrace{g_{ss}, g_{sp}}_{g_s}, \underbrace{g_{pp}, g_{ps}}_{g_p} \right),$$

Here, Q is the interference threshold value at primary user receiver.

E_x represents the expectation corresponding to the value x. P_S is the transmission power allocated to the secondary transmitter TX_S. Here P_S is only a function of g_{ss}. The effect of cross channel power gain g_{sp} is eliminated in overlay strategy. In overlay strategy the secondary transmitter, *Txs* transmits when there is no primary service activity in the channel. Therefore there is no interference to at the primary receiver, *Rxp* [8], [9].

In next sections, detailed information about scheduling algorithms analyzed is given. As mentioned earlier, three scheduling algorithms are discussed, *Rate-based Scheduling, Delay-based Scheduling and Utility-function based Scheduling.*

A scheduler decides which user in secondary network get access to available channel in every time slot. This channel allocation to secondary user is based on an algorithms designed and implemented on scheduler. As a case study, a number of simple scheduling algorithms are evaluated. In addition, a scheduler based on utility function designed to meet challenges like delay and fairness while making use of multiuser diversity is discussed in next section.

Consider a network where N secondary users share available transmission channel. Channel time is divided in to discrete time slots. Each secondary user has channel state information which is updated in every time slots. Transmission rate (achievable channel capacity) or achievable throughput of *i th* secondary user at time slot *t* is denoted as, $R_i(t)$ and delay denoted as, $D_i(t)$. Slot by slot scheduling is followed in all the scheduling algorithms proposed in this project work. At each time slot *t*, two vectors are defined,

a) Rate vector :

$$R_i(t) = [R_1(t), R_2(t), R_3(t), R_4(t) \ldots\ldots, R_N(t)], \tag{6}$$

b) Delay vector :

$$D_i(t) = [D_1(t), D_2(t), D_3(t), D_4(t) \ldots\ldots, D_N(t)], \tag{7}$$

4. Scheduler performance analysis

In this section, performance analysis with the help of MATLAB simulations and comparison of proposed scheduling algorithms is explained.

As mentioned earlier, two important performance analysis metrics of secondary user network is achievable capacity and the waiting time (delay) of users. Scheduling algorithms must be able to provide fairness in throughput and delay to secondary users. In simulations, average achievable capacity of secondary user network is calculated for different scheduler algorithms and in different channel fading models. In this project, Rayleigh and Nakagami channel fading models are considered. Furthermore, performance analysis with accurate and inaccurate spectrum sensing is also analyzed.

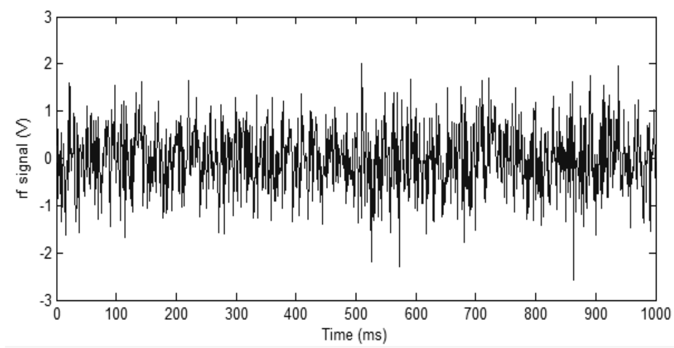

Figure 5: Rayleigh-faded rf signal fluctuation with time

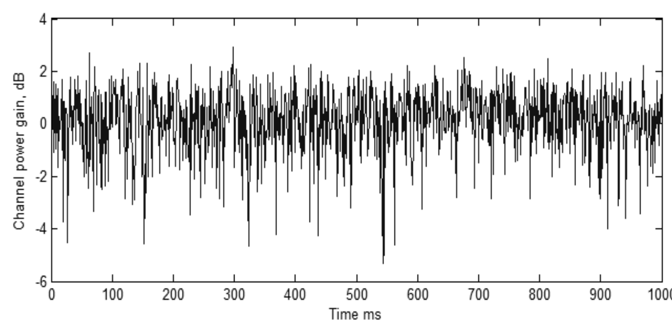

Figure 6: Rayleigh fading channel power gain (dB) variations. Variance $\sigma^2 = 1$

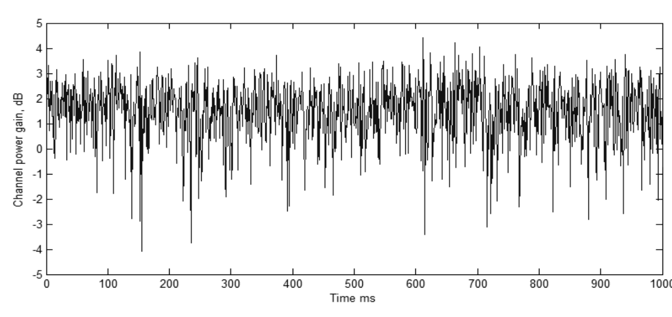

Figure 7: Rayleigh fading channel power gain (dB) variations. Variance $\sigma^2 = 2$

Figure 5 show plots of radio-frequency (rf) signal. It shows that the received signal power is random even in the absence of additive white Gaussian noise; this is due to the effect multipath fading [10]. Thus, multipath fading causes the random fluctuations in the received signal. In addition, it can be observed from Figure 6 and 9 that in a Rayleigh fading channel there is higher probability of channel power gain g_{ss} being in high gain as well as in deep fades when variance σ^2 becomes larger.
For simulation using MATLAB it is assumed that, channel is available with a probability P_i, accordingly primary user access the channel with probability P_b= 1- P_i. In addition, there is a threshold value for the channel availability probability P_{thr}.

Most of communication network application can be categorized in to two types: best-effort and delay-sensitive traffic [13]. But an ideal communication network should provide both of these properties to user. As mentioned earlier, in a secondary user network, there should be fairness in throughput and delay. Here we discuss effects of proposed scheduling policies on the achievable capacity, delay, fairness, transmitter power variations, probability of spectrum availability to secondary user in a multipath Rayleigh fading channel.

4.1 *Scenario1: Rate-based Scheduling*

This scenario can be considered as a best-effort transmission. Scheduler allocates available channel to secondary user having best channel condition or with highest achievable throughput. Scheduler algorithm is to allocate available channel to user with highest achievable throughput, so that the rate vector,

$$r(t) = \arg\max_{R(t)} R(t), \qquad (8)$$

Plot (Figure 8) of scenario 1: rate based scheduler shows that, throughput achieved with this scheduling is near to maximum achievable throughput. It is due to the opportunistic scheduling algorithm in which scheduler always selects the user with best channel conditions or selects the user with highest data rate.

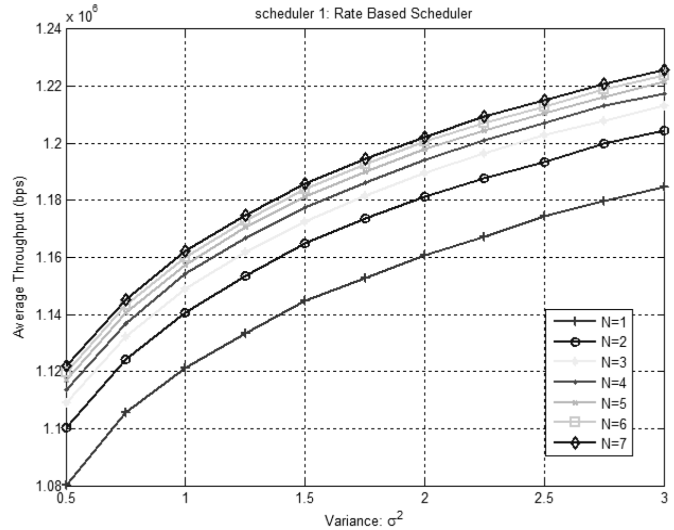

Figure 8: Scenario 1: Average throughput for scheduler scenario 1 *vs.* Rayleigh fading channel gain variance σ^2. Probability of spectrum availability p_i **= 0.4**.
N: number of secondary users in the network.

The result shows that, capacity grows with increasing variance of the Rayleigh fading channel gain, which implies better the channel conditions higher the achievable throughput. This growth in capacity with the increase in channel gain is mainly due to the fact that, when variance σ^2 becomes larger the probability of the getting higher level channel gain g_{ss} is high.

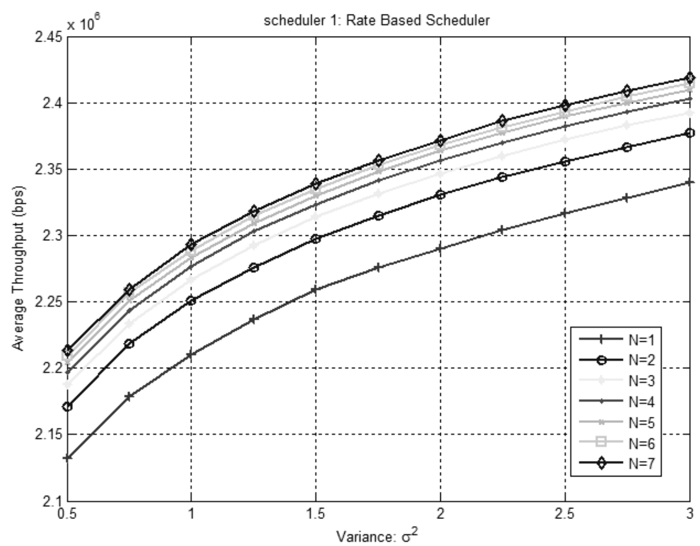

Figure 9: Scenario 1: Average throughput for scheduler scenario 1 *vs.* Rayleigh fading channel gain variance σ^2. Probability of spectrum availability p_i **= 0.8**.
N: number of secondary users in the network.

Figure 9 is the simulation result of same scheduling scenario but the secondary service having a higher probability of spectrum availability p_i. This simulation results clearly indicates that, there is a significant increase in average achievable capacity of the secondary service when channel availability probability is increased. Furthermore, it can be noticed from the Figure 8 and 12 that, when probability of channel availability increases from 0.4 to 0.8 (doubled) the achievable average capacity of the system is also doubled.

As we discussed earlier, this scheduler does not give any consideration to the waiting time of the secondary service. That is, some users in the secondary users having a bad channel condition (lower channel gain) may not get access to available channel. This leads to a condition that some users have to wait a long period of time i.e. until they get a good channel condition to get access to available channel. The simulation result verifies this condition.

User No.	1	2	3	4	5	6	7
Delay, D time units	15	54	30	21	6	2	25

TABLE I: Scenario 1: Delay Faced by Secondary Users

In Table I, D is the waiting time (time units) of seven secondary users considered. These values indicate that, secondary user no.2 has very high waiting time compared to other user in the network. Reason for this long waiting time for user no.2 may be due to lower channel gains available to that user. Therefore, proper consideration must be given for user waiting time (delay) in a scheduling algorithm to provide a fair service to all secondary users.

4.2 *Multiuser Diversity Gain for Opportunistic Scheduling*

In a Rayleigh fading environment, channel undergoes independent fading and is varying over time. The Therefore, in a communication network with a number of users it is more likely that there is a user with a good channel at any time. This is the basic principle of multi user diversity [17]. In a multi user secondary system, by serving the user with strongest channel we can maximize total throughput [17]. This can be verified from simulation results of scenario 1.

Channel variations are exploited by secondary user scheduler for spectrum sharing. This property is best utilized by secondary user scheduler to select high quality channel for transmission whenever channel is available. This method can also be considered as, opportunistic selection of users for transmission. According to [17], opportunistic selection of users for transmission can provide a multiuser diversity gain. Therefore, in a secondary user scheduler with opportunistic spectrum selection, capacity of secondary system grows as number of secondary users in the network increases.

Multiuser diversity gain in terms of capacity grows as $log_2(ln(Ns))$ for Rayleigh fading channel and N denotes the number of secondary users in the network [18].
This can be verified from the simulation results (Figure 8, 12 and 13),

In Figure 8, the average achievable capacity of secondary users for variance, σ^2 = 0.5 and N=1 is,

$Cavg$ = 1.08$Mbps$

and for, N=7,

$Cavg$ = 1.126$Mbps$.

Therefore, $\frac{1.08Mbps}{1.126Mbps}$ = 0.959 = $log_2(\ln(7))$.

4.3 *Scenario 2: Delay-based Scheduling*

Unlike best-effort transmission which is rate-based, this scenario can be considered as a delay sensitive transmission. Fairness in delay is necessary condition for assuring access to every secondary user in network. Scheduler allocates available channel to secondary user having highest waiting time (delay). This scheduler ensures service to every user in the network at the cost of reduced throughput of secondary system. This scheduler follows a First-In-First-Out algorithm. That is, at each time slot t scheduler assigns the available channel to the secondary user possessing highest delay or waiting time.
so that the rate vector,

$$r(t) = \arg\max_{D(t)} D(t), \quad (9)$$

This scheduling is suitable for delay sensitive traffic applications. The major disadvantage of this scheduler is that, probability of allocating a bad channel is high. This introduces a significant reduction of throughput. This scheduler provides a very low average achievable throughput to secondary system.

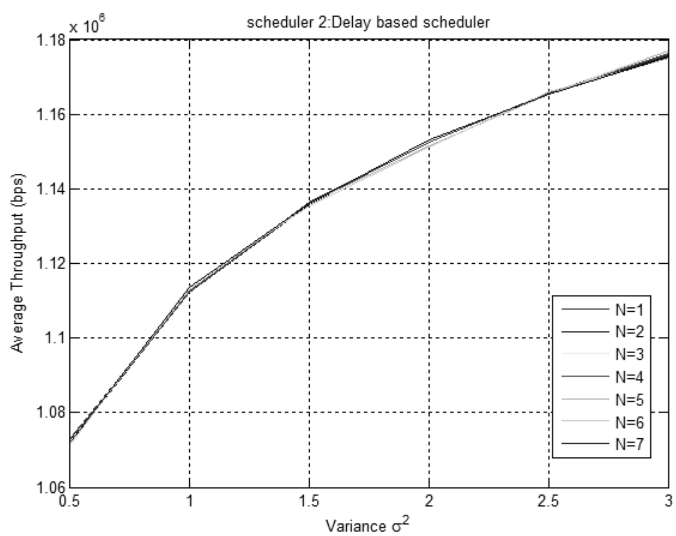

Figure 10: Scenario 2: Average throughput for scheduler scenario 2 *vs.* Rayleigh fading channel gain variance σ^2. Probability of spectrum availability p_i = **0.4**.
N: number of secondary users in the network.

Comparison of Figure 8 and Figure 10 showing the average achievable throughput of scenario 1: rate-based scheduler and scenario 2: delay based scheduler respectively, shows that average achievable throughput for delay-based scheduler is much lower for same channel conditions and probability of channel availability. The reason for this significant reduction in throughput for delay-based scenario is that, the scheduler always selects user with highest delay irrespective of its channel conditions.

In addition, multi-user diversity property by opportunistic spectrum access of secondary users is not possible in delay-based scheduling. This can be verified from Figure 10 and 15, that there is no significant increase in average throughput of secondary system with increase in number of secondary users in secondary network.

Furthermore, results of scenario 2 also shows that capacity grows when variance of Rayleigh fading channel gain is increased, which implies better the channel conditions higher the achievable throughput. This growth in capacity with increase in channel gain is mainly due to the fact that, when variance σ^2 becomes larger the probability of getting higher level of channel gain g_{ss} is high.

Since delay based scheduler always allocate available channel in a first in-first out manner, all the secondary users in network have equal chance to use available spectrum. Simulation result verifies this condition.

User No.	1	2	3	4	5	6	7
Delay, D time units	15	7	6	22	5	2	14

TABLE II: Scenario 2: Delay Faced by Secondary Users

In Table II, D is the waiting time (time units) of seven secondary users considered. Compared to the secondary user's delay for scheduler 1, delay values of scheduler 2 shows that the every secondary user in the network has opportunity to access regardless of channel conditions. That is no user in the network that has very high waiting time (delay) compared to performance of scheduler 1.

4.4 *Scenario 3: Utility function Based Fair Scheduling*

Utility functions are used to enumerate the advantage of certain resources. Utility functions give more importance to requirements of user applications, rather than system-centric quantities like throughput, power, outage-probability etc [16]. Scheduler algorithms that we discussed give priority to only one of the performance metrics of the secondary user such as, either throughput or fairness in delay. Since, most of the communication applications prefer a real-time traffic or data transfer with minimum waiting time, i.e. delay of the secondary must have considerable priority. Therefore a scheduler with channel allocation condition considering both delay and throughput and with a higher importance to delay of the secondary user is considered in this scheduling algorithm. Consequently, this scheduler is desirable to delay sensitive traffic and can achieve a better average achievable system throughput. Utility function also provides importance to average waiting times of secondary users.

This scheduler allocate available channel to secondary user having highest utility function at a time slot *t* where channel is available. This provides priority to secondary user having high delay and good channel conditions compared to other users. The utility function considered is,

$$U_i(t) = R_i(t)\exp\left(\frac{D_i(t) - \bar{D}}{\bar{D}}\right). \quad (10)$$

where, Average delay, $\bar{D} = \frac{1}{N}\sum_{i=1}^{N} D_i$, (11)

so that the corresponding rate vector,

$$r(t) = \arg\max_{U(t)} U(t). \quad (12)$$

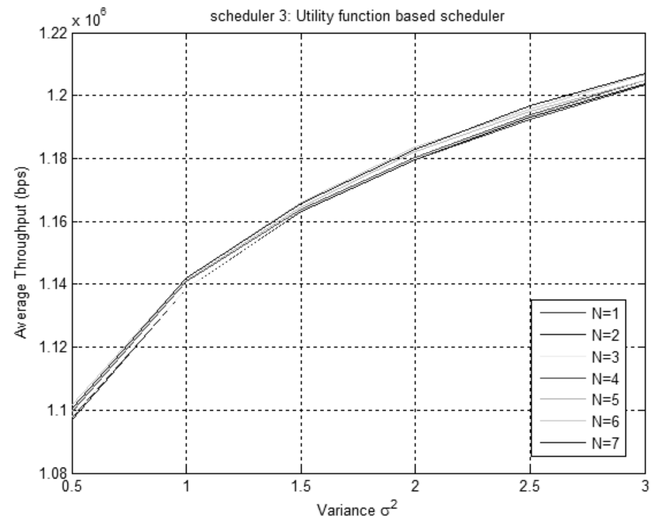

Figure 11: Scenario 3: Average throughput for scheduler scenario 3 *vs.* Rayleigh fading channel gain variance σ^2. Probability of spectrum availability, p_i = **0.4**.

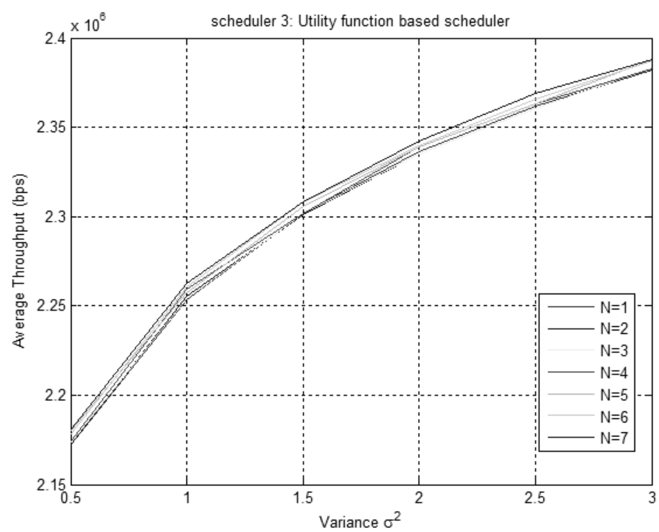

Figure 12: Scenario 3: Average throughput for scheduler scenario 3 *vs.* Rayleigh fading channel gain variance σ^2. Probability of spectrum availability, p_i = **0.8**.

In Figure 11, achievable throughput of scheduler 3 in different channel fading states is shown. It can be noted from graph that, average achievable capacity of the secondary users increases when variance σ^2 becomes larger. As we discussed earlier this is because there is higher probability of getting high channel gain g_{ss} when variance becomes larger. Furthermore, comparing Figure 11 and Figure 12, there is a significant increase in average achievable capacity when probability of spectrum availability p_i increases. The average capacity also increases when maximum transmit power level $\bar{P}_S$ of the secondary users are increased.

Delay (waiting time) faced by secondary users is much lower than rate-based scheduler and is analogous to delay based scheduler. Delay faced by users in a 7 secondary user network after 10000 time slots is,

User No.	1	2	3	4	5	6	7
Delay, D time units	7	11	4	3	12	19	9

TABLE III: Scenario 3: Delay Faced by Secondary Users

From Table III, delay faced by secondary users is much lower compared to rate-based scheduling and similar to delay faced by users in delay-based scheduling. In addition, there is no user in the network with exceptionally higher delay as in rate-based scheduling. This scheduler select a user having high delay, high achievable rate and with low average delay at each time slot where channel is available.

Multi-user diversity advantage of spectrum sharing system with multiple secondary users is more utilized by the utility-function based scheduler compared to the delay-based scheduler. However, rate of increase in diversity gain with number of secondary users in the network is much lower than rate based scheduling.

Conclusion

For, overlay spectrum sharing strategy we have analyzed the performance under accurate and inaccurate spectrum sensing conditions.

The analysis results indicate that, Rate-based scheduler provides maximum achievable throughput to secondary user network. Some users in secondary network have very high waiting time (delay) due to poor channel condition. This scheduling algorithm utilizes multi-user diversity property by the opportunistic bandwidth allocation. Delay-based scheduler guarantees spectrum access to every secondary user in the network, i.e. a first in-first out policy is adopted. Since it does not consider channel states of secondary users, achievable capacity is low as expected. Utility function based scheduler give priority to both the delay and throughput of secondary users. This scheduling algorithm provides much better throughput compared to delay-based scheduler. In addition, delay faced by secondary users are much lower compared to rate-based scheduler, i.e. no user in the secondary network suffer very high delay as in rate-based scheduler.

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