A Quality of Service aware Spectrum Decision for Cognitive Radio Networks

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***Abstract*—Cognitive radio networks have been proposed to solve the problems in wireless networks caused by the limited available spectrum and spectrum inefficiency. However, they impose unique challenges because of the high fluctuation in the available spectrum as well as diverse quality of service requirements of various applications. In this paper, a method for spectrum decision is introduced to determine a set of spectrum bands by considering the channel dynamics in the cognitive radio network as well as the application requirements. First, a novel spectrum capacity model is defined that considers unique features in cognitive radio networks. Based on this capacity model, a minimum variance-based spectrum decision is developed for real-time applications, which minimizes the capacity variance of the decided spectrum bands subject to the capacity constraints. For best effort applications, a maximum capacity-based spectrum decision is proposed where spectrum bands are decided to maximize the total network capacity. Simulation results show the performance of cognitive radio network for real time applications and best-effort applications.**

***Index Terms* - Cognitive radio networks, spectrum decision, spectrum characterization, real-time application, best-effort application, minimum variance-based spectrum decision, maximum capacity-based spectrum decision.**

I. INTRODUCTION

Today's Wireless networks are assigned by Government agencies to license holders on long term basis. Due to an increase in Spectrum demand, there has been a shortage in particular bands. On the other hand, a large portion of spectrum is still underutilized [5]. Hence, dynamic communication techniques have been proposed to solve spectrum inefficiency problems [12].

The key dynamic spectrum access technique is Cognitive Radio (CR) networking, which utilizes intelligent spectrum aware devices to use the licensed spectrum bands for transmission [13]. CR networks, however, impose unique challenges because of high fluctuation in the available spectrum bands as well as diverse quality-of-service (QoS) requirements of various applications.

To tackle these challenges, different functionalities are required in CR networks:

Spectrum sensing: A CR user should monitor the available spectrum bands for unused portions [1], [6].

Spectrum decision: A CR user should be allocated a band based on the QoS requirements.

Spectrum sharing: CR network access should be coordinated to prevent multiple users colliding in spectrum [3], [9].

Spectrum mobility: If the specific portion of the spectrum is required by the Primary user (PU), the CR user should move to other part of the spectrum.

In this paper, a method for Spectrum Decision is introduced to determine the spectrum bands by considering application requirements as well as dynamic nature of spectrum bands. First, each spectrum is characterised on the basis of PU activity and spectrum sensing operations. Based on this, spectrum decision for minimum variance in case of real time applications is considered. Then for best- effort applications, spectrum decision is proposed to maximize network capacity.

II. SPECTRUM CHARACTERIZATION

To understand the spectrum band properly, PU activity [14] and a CR capacity model is described.

Primary User activity

PU activity is the usage statistics of primary networks in each spectrum. The PU activity can be modelled as exponentially distributed inter arrivals [11]. PU activity in spectrum i is defined as two state birth death process with death rate a_i and birth rate b_i [2], [7].

Cognitive Radio Capacity Model

Each spectrum band i has a different bandwidth B_i. If the transmission power is considered identical within the spectrum, the normalized channel capacity $c_i(k)$ of spectrum band i can be expressed as $c_i(k) = r_i(k)/B_i$, where $r_i(k)$ is the capacity of user k.

However, in CR networks, each spectrum i cannot provide its original capacity $c_i(k)$. CR users cannot have a reliable spectrum permanently and need to move from one spectrum to another according to PU activity.

Also, CR users are not allowed to transmit during sensing operations, leading to periodic transmissions with sensing efficiency η_i [7].

These unique features in CR networks, show significant influence on the spectrum capacity $c_i(k)$. Hence, CR capacity $c_i^{CR}(k)$ is defined as the expected normalized capacity of user k in spectrum i as:

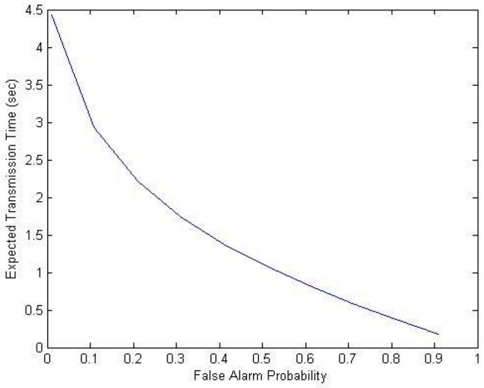

Fig. 1. Expected Transmission time in imperfect sensing

$$c_i^{CR}(k) = \frac{T_i^{off}}{T_i^{off} + \tau} . \eta_i . c_i(k), \tag{1}$$

where τ represents the spectrum switching delay, and T_i^{off} is the expected transmission time without switching in spectrum i. Since CR users face to the spectrum switching after the idle period, the first term in the equation represents the transmission efficiency when CR users occupy spectrum i.

If we consider perfect sensing, i.e., both false alarm and detection error probabilities are zero, T_i^{off} is obtained as $1/\beta_i$, which is the average idle period based on the ON-OFF model [2], [7]. But, in the case of imperfect sensing, we should account for the influence of sensing capability. Let Δt be a sensing period. Then, the average number of sensing slots in the idle period n_s is $[1/\beta_i/\Delta t]$. From this the expected transmission time can be obtained as:

$$T_i^{off} = \Delta t . \sum_{k=1}^{n_s - 1} k . (1 - P_i^f)^k . P_i^f + \frac{1}{\beta_i} . (1 - P_i^f)^{n_s}, \tag{2}$$

where P_i^f represents a false alarm probability of spectrum i at each sensing slot. Here, T_i^f can be expressed as the sum of the expected duration until when the false alarm is first detected in each slot. As P_i^f increases, T_i^f decreases, resulting in decrease in CR capacity, which is described in Fig. 1. Here, due to cooperative sensing technique, where the detection error probability converges to zero as the number of users increases [8]. Thus, the detection error probability can be ignored in estimating CR capacity.

III. SPECTRUM DECISION FOR REAL TIME APPLICATIONS

Real time applications require a reliable channel to support a sustainable rate R_S during session time. But in the CR networks, CR users need to stop transmission temporarily, which prevents the real time applications from maintaining its sustainable rate, leading to delay and jitter. When compared with conventional wireless networks, the additional delay factors uniquely introduced by CR networks can directly lead to data losses. For this reason, the data loss rate is used to evaluate the service quality of real time applications.

The CR network determines the bandwidth of the selected spectrum bands to meet the constraints on both sustainable $R_S(k)$ and target data loss rate P_{loss}^{TH}. When bandwidth $w_i(k)$ is allocated to the selected spectrum i for user k, the expected total capacity can be obtained as follows:

$$E[R_T(k)] = \sum_{i \in S} c_i^{CR}(k) . w_i(k), \tag{3}$$

where S is the set of selected spectrum bands. To satisfy the service requirement on the sustainable rate, $E[R_T(k)]$ should be equal to $R_S(k)$.

The variance of the total capacity leads to data loss and is, therefore, proportional to the data loss rate. Hence, we can use the following variance for resource allocation obtained by using Eq. 3, instead of data loss rate.

$$Var[R_T(k)] = \sum_{i \in S} \frac{T_i^{off} \eta_i . \left(T_i^{off} + \tau - T_i^{off} \eta_i\right)}{\left(T_i^{off} + \tau\right)^2} c_i(k)^2 . w_i(k)^2, \tag{4}$$

Based on the capacity variance obtained above, the CR network determines optimal bandwidth of the selected bands to minimize thevariance of the total capacity as follows:

$$Minimize: Var[R_T(k)], \tag{5}$$

$$subject\ to: \sum_{1=1}^{M} c_i^{CR}(k).w_i(k) = R_S(k), \tag{6}$$

$$w_i(k) < W_i \ (\forall i \in S). \tag{7}$$

Equations represent the constraints on the sustainable rateand the available bandwidth respectively.

IV. SPECTRUM DECISION FOR BEST-EFFORT APPLICATIONS

If the resource allocation is optimal, the spectrum decision to maximize the network capacity can be simplified as the following selection problem to choose spectrum bands so that decision gain can be maximized.

$$Maximize: \sum_{i \in A} (G - L)x_i, \tag{8}$$

$$subject\ to: \sum_{i \in A} x_i = N, \tag{9}$$

where G is the expected capacity gain when new user k with CR capacity $c_i^{CR}(k)$ joins spectrum i with available bandwidth W_i and L is the expected capacity loss of other users in that spectrum band. A is the set of currently available spectrum bands and N is the number of transceivers of a CR user. x_i represents the spectrum selection parameter. The decision gain can be defined as the sum of the difference between capacity gain and capacity loss caused by the addition of new user.

The capacity of each user competing for the same spectrum can be approximated as $C_i^{CR}(k).W_i/n_i$ where n_i represents the number of users currently residing in spectrum i. Based on this capacity, the decision gain can be derived as follows:

$$G - L = \frac{C_i^{CR}(k).W_i}{n_i + 1} - \sum_{j \in E_i} \left(\frac{1}{n_i} - \frac{1}{n_i + 1}\right).C_i^{CR}(j).W_i, \tag{10}$$

where E_i is the set of CR users currently residing in the spectrum band i. The first term represents the capacity gain of new user k and second term describes the total capacity loss of other CR users in spectrum i.

V. PERFORMANCE EVALUATION

Simulation Setup

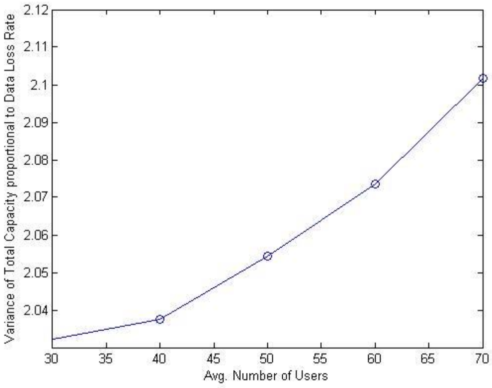

Fig. 2a Data loss Rate versus number of users

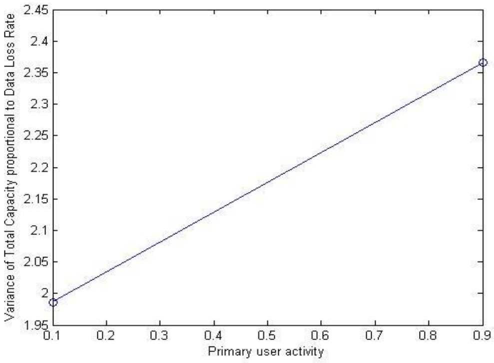

Fig. 2b Data loss rate versus PU activities

The CR network is assumed to operate in 4 licensed spectrum bands consisting of VHF/UHF TV, GSM, WCDMA and TETRA. The bandwidth of these bands are 6 MHz (TV), 200 kHz (GSM), 5 MHz (WCDMA) and 25 kHz (TETRA). The PU activities of each spectrum band i, a_i and b_i , are randomly selected over [0,1].

Sensing efficiency η_i and false alarm probability P_i^f are set to 0.9 and 0.99, respectively. These sensing capabilities are assumed to be identical over all spectrum bands. User-based and the band-based quality degradations use the same strategies as primary user and CR user appearances, respectively. Thus, these are not considered in the simulations.

The real-time application is assumed to support five different bitrates: 64, 128, 256, 512 kbps and 1.2 Mbps.

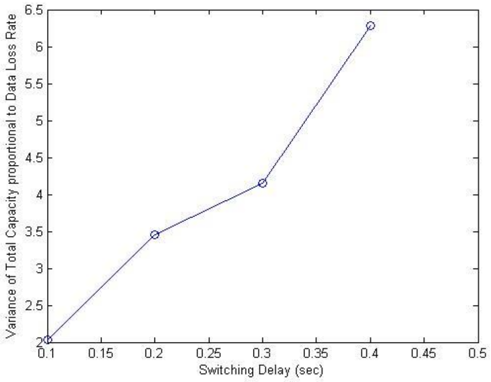

Fig. 2c Data loss rate versus switching delay

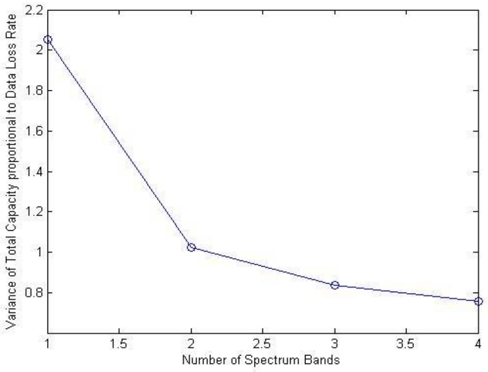

Fig. 2d Data loss rate versus spectrum bands count

Real Time Applications

First, a scenario with only real-time users is considered. Figure 2a shows how the average number of users influences the data loss rate. Here, three spectrum bands and 0.1 sec for the switching delay is assumed. For this simulation, CR user traffic from 10 to 80 is considered on average. When a small number of users are transmitting, the result shows low data loss rate. However, as the number of users increases, there is an increase in the data loss rate.

In Fig. 2b, the performance of the spectrum decision under two PU activity scenarios is investigated—low, high. Low PU activity is obtained at $b_i = 0.1$ and high PU activity is obtained at 0.9. The average number of users, the number of spectrum bands, and switching delay are set to 50, 3, and 0.1 sec, respectively. The Data loss rate increases with PU activity since a higher b_i introduces more frequent switching, leading to a significant performance degradation.

The relationship between the data loss rate and the switching delay is also shown in Fig. 2c. Here, 50 users and three spectrum bands are assumed. A longer switching delay results in a higher data loss rate.

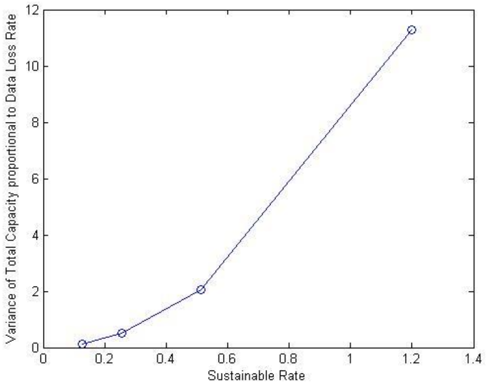

Fig. 2e Data loss rate versus sustainable rate

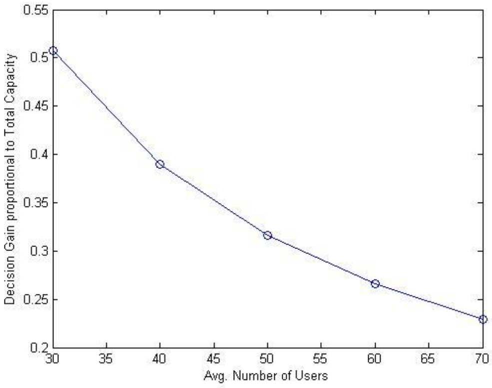

Fig. 3a Total network capacity versus number of users

The transmission with multiple transceivers can mitigate the effect of capacity fluctuations as well as prevent a temporary disconnection of communication channels. This phenomena is observed in Fig. 2d. Here, we assume 0.1 sec for the switching delay and 50 real-time users. An interesting point is that more spectrum bands do not always lead to good performance in the data loss rate. As the number of spectrum bands increases, the total amount of PU activities over multiple spectrum bands increases, which may cause an adverse effect on the data loss rate.

Also, Fig. 2e shows that the data loss rate increases when we increase the Sustainable Rate for the applications. Most of the data are lost when it is delivered at higher Sustainable Rate.

Best Effort Applications

In this simulation, it is observed how the number of users, PU activity, switching delay, and number of spectrum bands influence the total network capacity.

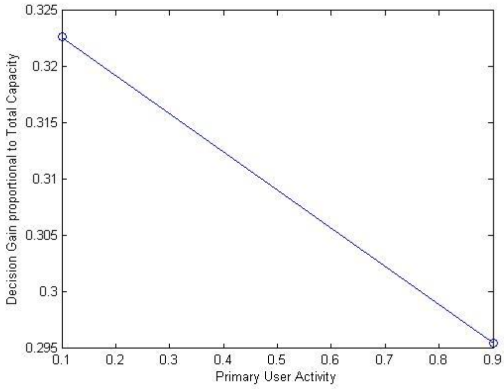

Fig. 3b Total network capacity versus primary user activities

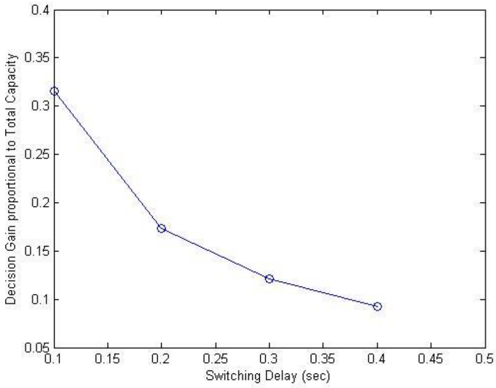

Fig. 3c Total network capacity versus switching delay

Figure 3a indicates the relationship between the number of users and total network capacity. With an increase in number of users, Total Capacity starts to decrease as there are more number of users competing for the spectrum band. In Fig. 3b, it is shown how PU activities influence the performance of the total capacity. When b_i is low, due to less frequent switching delay, total capacity is more. Figure 3c shows the simulation results on the total network capacity when 50 best-effort users with three spectrum bands are assumed. Here, it is observed that an increase in switching delay causes an adverse influence on network capacity. Also, Fig.3d shows how Total Capacity increases with an increase in number of Spectrum Bands.

VI. CONCLUSION

This Paper addresses the problem of the spectrum decision in CR networks. A method for spectrum decision is introduced to determine a set of spectrum bands by considering the dynamic nature of the spectrum bands as well as application requirements. First, a novel spectrum capacity model is proposed that considers unique features in CR networks. Based on this capacity model, a minimum variance-based spectrum decision is developed for real-time applications, which determines the spectrum bands to minimize the capacity variance. For the best effort applications, a maximum capacity-based spectrum decision is proposed where spectrum bands are decided to maximize the total network capacity. Simulation results shows the performance of Cognitive radio networks in case of real time applications and best-effort applications.

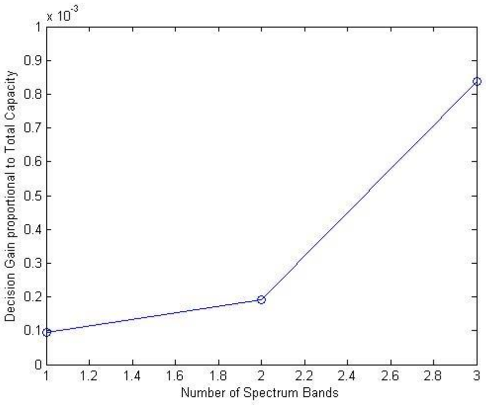

Fig. 3d Total network capacity versus number of spectrum bands

Future wireless networking will be characterized by the increased presence of devices seamlessly embedded in the environment. These devices will constitute a cognitive and self-optimizing entity that senses, responds and adapts to the presence of people, objects, and to varying environmental characteristics. This new feature is enabled by extending current CR concept beyond spectrum management. The future research covers the evolution into intelligent and self-optimizing CR networks from the perspective of each communication entity: network, service and user.

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