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A Database Assisted Quality of Service and Pricing based Spectrum Allocation Framework for TV White Spaces

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Abstract Analog to digital switchover of TV transmission has freed up a large amount of licensed spectrum. This spectrum is in the form of chunks, referred as TV White Spaces (TVWS). It is made compulsory by Federal Communications Commission (FCC) for unlicensed users to access TVWS through Access Points (APs), who have to query a FCC approved database e.g., WhiteNet, periodically to avail the free spectrum. It is important that for efficient utilization of available spectrum, APs must assign spectrum to end users based on their Quality of Service (QoS) requirements. Moreover, care must be taken in charging end users while meeting their QoS requirements, as different end users demand different pricing schemes i.e., fixed pricing and variable pricing. Considering these challenges, a pre-existing database architecture (WhiteNet) has been modified in this paper by adding new features in it. It is proposed to characterize end users' QoS requirements in the form of demand indices and provide admission control on the basis of pricing schemes. It is proved with our experimental results that our proposed scheme is a useful addition in FCC's TVWS database framework.

Keywords TV White Spaces · WhiteNet · Quality of Service · Database

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1 Introduction

Analog to digital transition of TV transmission has freed up a large spectrum which can be used by unlicensed users for different applications. This spectrum is in the form of chunks called TV White Spaces (TVWS). According to Federal Communications Commission (FCC), unlicensed users have to query a geo location database to access TVWS [1][2][3][4].

Recently, a lot of work has been done in different dimensions, mainly in architecture / functionality modeling of TVWS database and business modeling of the complete system. Some of the recently proposed architecture models include WhiteFi[7], Jello[8], WhiteNet[9] etc. WhiteFi is a limited coverage single Access Point (AP) network and Jello considers dynamic spectrum access on ad-hoc networks only[9]. As compared to WhiteFi and Jello, WhiteNet is an improved multi AP system and it works on modular basis[9]. Refering to WhiteNet, a lot of work has been done in different dimmensions. Some of these works are [1][2][3][4]. In [1], a hybrid pricing model is proposed. In this model, two types of pricing schemes are presented i.e. registration scheme and service plan scheme. In registration scheme, database operator reserves part of spectrum for end users, while in service plan scheme, end users are charged according to their queries. In [2], design framework for indoor multi AP white space network is presented. In this work, AP placement, spectrum allocation and AP association is optimized. In [3], a business model is presented in which revenue generation for spectrum database is considered. Moreover, joint pricing (static and dynamic) and admission control of spectrum is presented. In this work, only two types of end users i.e. light and heavy types are considered. Light users are those which use only one interval of time and heavy are those which use more than one interval. In addition to this, there is a limitation that only one user can access spectrum at one time. Moreover, it has not been explained that how fixed and variable prices are set. In [4], an oligopoly TV white space market has been investigated, where several secondary users compete to serve a group of end users. Two types of spectrum resources are considered i.e. dedicated and shared spectrum. Although a lot of work has been done indirectly towards the improvemenet of WhiteNet, but to the best of our knowledge no direct improvement has been proposed for it.

After carrying out a lot of study, we found that non of the proposed models have yet considered multiple types of applications associated with end users and their Quality of Service (QoS) requirements in much detail. Some examples of different applications associated with end users are E1/T1 (constant bit rate application), Voice over Inernet Protocol (VoIP), Video conferencing etc [10]. By QoS requirements we mean delay in transmission of data bits and throughput of the users. In addition to this, non of the models has considered the parallel provision of spectrum resources to end users. Although a lot of pricing models have been proposed (as discussed earlier), but non of the models have considered fixed and variable pricing services for end users associated with multiple types of applications. Moreover, non of the pricing model has considered prioritization of end users on the basis of their application type to increase spectrum utilization and revenue. Considering all these challenges, we present a framework and embed it in a pre-existing TVWS database architecture WhiteNet, in the form of two modules i.e. QoS Characterization DataBase (QDB) and Pricing DataBase (PDB).

The brief of our proposed work is mentioned below:

- A module (QDB) inside the WhiteNet, which characterizes the QoS requirements of the unlicensed end users in the form of demand indices and also provides admission control feature to stabilize requests of end users on the basis of pricing scheme they opt.
- A module (PDB) inside WhiteNet which deals with the pricing issues among geo-location database, APs and end users.
- Two different pricing schemes and associated admission control algorithms. One scheme is the fixed pricing scheme and the other one is the variable pricing scheme. Fixed pricing scheme is for the users who want to pay a fixed price at the cost of their QoS requirements' satisfaction, whereas variable pricing scheme is for the users who are conscious about their QoS requirements' satisfaction at the cost of price they pay. In our proposed model, an AP offers both types of pricing schemes and end users can choose any one of them.

The rest of the paper is organized such that section 2 will give brief on network scenario, section 3 will describe about the WhiteNet and it's pre-existing modules. Moreover, it will also briefly describe our proposed improvements in WhiteNet, section 4 will explain our proposed work in detail, section 5 will be about simulations and results and section 6 will be the conclusion.

2 Network Scenario

We consider a network scenario in which there is a geo-location database, multiple APs and end users, as shown in Fig. 1. Geo-location database has the information of available TV spectrum in its vicinity and it is connected to a central geo location database from where it purchases the available spectrum, for unlicensed users. Unlicensed APs get the information of available spectrum resources from geo-location database after each interval t. Unlicensed end users avail the spectrum resources through unlicensed APs. An unlicensed AP first registers the status of its location and transmission power to the geo-location database and then avails the available spectrum resources. Pricing is done at geo-location database end as well as APs' end. Such a system can be useful for many applications e.g., broadband internet [11] for rural areas, smart metering [12] and home area networks [9] etc.

3 WhiteNet and Proposed Improvements

WhiteNet consists of a B-SAFE algorithm and WhiteNet Local Database (WLD) [9]. B-SAFE is an algorithm to distribute spectrum among APs. The

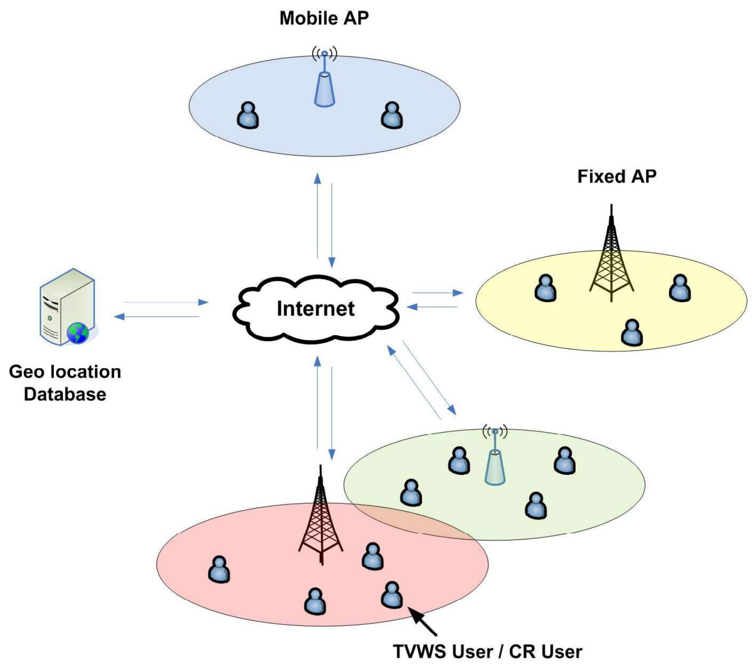

Fig. 1 Network Scenario

detail of B-SAFE is out of the scope of this paper and hence not been discussed. WLD consists of Vacant TV Channel DataBase (TDB), Local AP DataBase (ADB) and AP Contention DataBase (CDB). TDB stores the information of available TV channels in the vicinity of WLD, ADB stores the information of local APs i.e. interference relationship among APs, spectrum occupancy and location. CDB has the role to do contention among APs, if there is some competition among APs.

We propose to add two new modules in WLD, namely QDB and PDB. These modules are shown in Fig.2. QDB characterizes the requests of end users in the form of demand indices. We consider four different types of end users i.e. constant bit rate users, video conferencing users, VoIP users and best effort users. These users are categorized as type 1, type 2, type 3 and type 4 users respectively. Moreover, QDB provides admission control feature to APs by prioritizing the end users associated with them and stabilizing the end users' requests depending upon type of pricing scheme they opted.

PDB deals with the pricing issues among central geo-location database, WLD and APs and end users. Depending upon the amount of spectrum allocated to each AP, WLD calculates the revenue to be generated by APs. Moreover, it offers two types of pricing schemes to end users through APs i.e., fixed pricing scheme and variable pricing scheme. In fixed pricing scheme, the cost to be paid by an end user in each interval remains the same at the cost of its QoS requirements' satisfaction. While in variable pricing scheme,

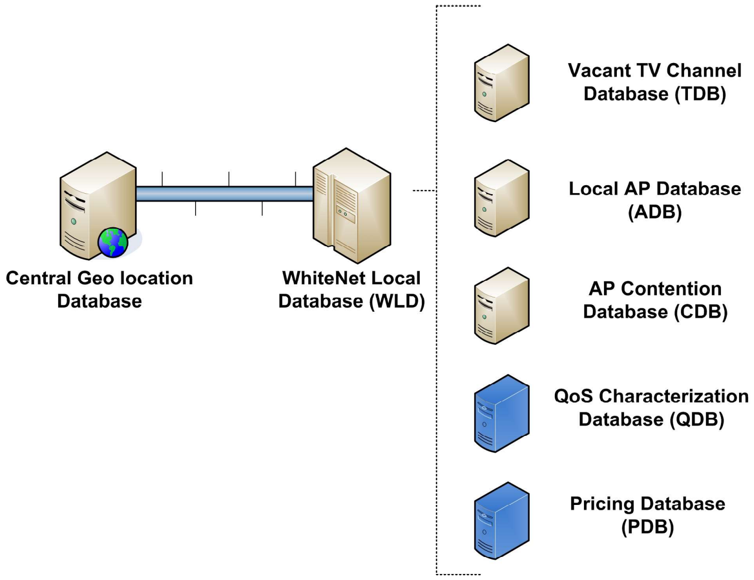

Fig. 2 WhiteNet with proposed improvements

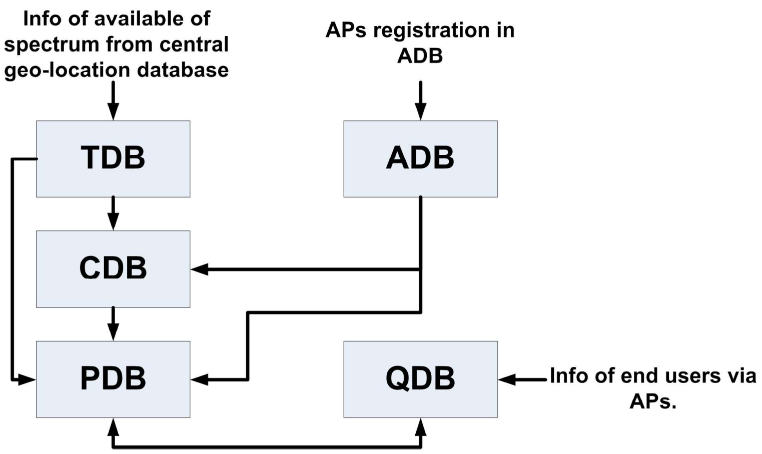

Fig. 3 Modified WhiteNet Framework

in each time interval, end user has to pay different price (if price of spectrum changes) whereas it's QoS requirements' satisfaction remains same. The proposed framework has been shown in Fig. 3.

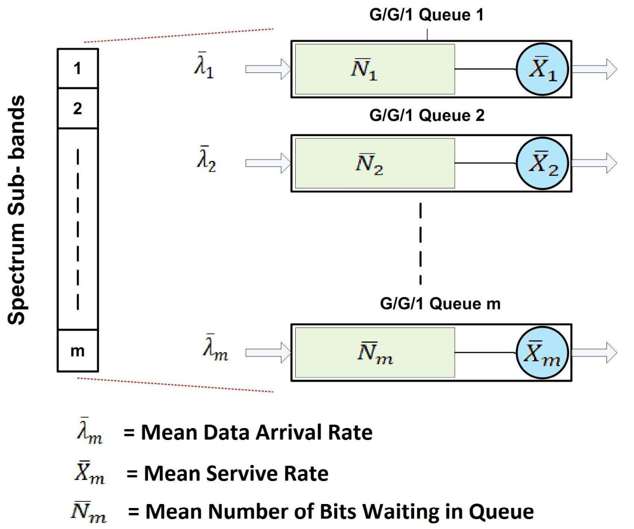

Fig. 4 Spectrum Sub Band Queuing Model

4 Proposed Improvements in WHITENET

4.1 QoS Characterization and Demand Map (DeM)

The available unlicensed spectrum is divided into l sub-bands. Each sub-band can be modeled as a G/G/1 queuing system [10], as shown in Fig. 4. In G/G/1 queuing system, arrival rate of users and the service rate of the server both are generally distributed. As mentioned earlier, we have considered four types of end unlicensed users. To characterize their QoS requirements i.e., delay and throughput, a Demand Map (DeM) is made. The mean arrival rate of data bits of i^{th} type of unlicensed user in m^{th} spectrum sub band is denoted by $\bar{\lambda}_{i,m}$. So, the spectrum utilization by i^{th} type of user in the m^{th} sub-band is denoted by

$$\rho_{i,m} = \frac{\bar{\lambda}_{i,m}}{\bar{X}_m}, \qquad \forall m \in [1, 2, ...l] \tag{1}$$

where $\bar{X}_m$ is the mean service rate of m^{th} spectrum band. Similarly, the average number of waiting bits of i^{th} type of user in a queue is $\bar{N}_{i,m}$ is given by

$$\bar{N}_{i,m} = \bar{\lambda}_{i,m} \times \bar{W}_{i,m}, \qquad \forall i \in [1, 2, 3, 4] \qquad \forall m \in [1, 2, ...l] \tag{2}$$

where $\bar{W}_{i,m}$ is the average waiting time for the bits of i^{th} type user, in m^{th}spectrum band.

We define the spectrum request, in terms of delay and throughput requirements, as product of $\bar{X}_m$ and $\rho_{i,m}$. This product is named as *Demand* ($D_{i,m}$)

of type i user for m^{th} sub band. Mathematically

$$D_{i,m} = \bar{N}_{i,m} \times \rho_{i,m}, \quad \forall i \in [1,2,3,4] \quad \forall m \in [1,2,...l] \quad (3)$$

$$D_{i,m} = (\bar{\lambda}_{i,m} \times \bar{W}_{i,m})(\frac{\bar{\lambda}_{i,m}}{\bar{X}_m}). \quad \forall i \in [1,2,3,4] \quad \forall m \in [1,2,...l] \quad (4)$$

Maximum request of unlicensed users can be considered by maximizing the spectrum utilization factor and the number of bits waiting in the queue. Let $\bar{N}_{i,m(max)} = \bar{L}_{i,m}$ and $\rho_{i,m(max)}= 1$. Thus

$$D_{i,m(max)} = \bar{L}_{i,m}. \quad \forall i \in [1,2,3,4] \quad \forall m \in [1,2,...l] \quad (5)$$

We define a *Demand Index* ($DI_{i,m}$) of unlicensed users of type i willing to use the spectrum sub band m as a ratio of $D_{i,m}$ and $D_{i,m(max)}$.

$$DI_{i,m} = \frac{D_{i,m}}{D_{i,m(max)}}, \quad \forall i \in [1,2,3,4] \quad \forall m \in [1,2,...l] \quad (6)$$

$$DI_{i,m} = \frac{\bar{\lambda}^2_{i,m}\bar{W}_{i,m}}{\bar{X}_m\bar{L}_{i,m}}. \quad \forall i \in [1,2,3,4] \quad \forall m \in [1,2,...l] \quad (7)$$

As $DI_{i,m}$ has both the factors, average waiting time $\bar{W}_{i,m}$ and average arrival rate $\bar{\lambda}_{i,m}$, so it covers both delay and throughput requirements of the unlicensed users of i^{th} type willing to use m^{th} sub band. For each sub band, demand indices of end unlicensed users are calculated. A *Demand Map* (DeM) contains demand indices of all end users in all sub bands.

The distribution of data arrival rate of different types of users is different. Type 1 users are the constant bit rate users and hence have deterministic behavior of data arrival rate. Type 2 users are the video conferencing users and have gamma distribution of data arrival rate [13]. Type 3 users are VoIP users and they have data arrival rate distribution according to Markov Modulated Poisson Process (MMPP) [14,16]. Type 4 users are best effort users and their data arrival rate follows poisson distribution [10]. Each type of user selects and sees the spectrum sub band queue according to its data arrival rate distribution type. So, the same G/G/1 queue behaves as following for four different queuing models:

- D/G/1 Queuing System - Type 1 users.
- Ga/G/1 Queuing System -Type 2 users.
- MMPP/G/1 Queuing System -Type 3 users.
- M/G/1 Queuing System -Type 4 users.

The average waiting time $\bar{W}_{1,m}$ of type 1 users is as follows[15]:

$$\bar{W}_{1,m} = \frac{\bar{\lambda}_{1,m}\sigma^2_{s(m)}}{2(1-\rho_{1,m})}, \qquad \forall m \in [1,2,...l] \tag{8}$$

where $\sigma_{s(m)}$ is the coefficient of variation of service time distribution. By substituting the value of average waiting time in (7) we get the demand index of type 1 users.

$$DI_{1,m} = \frac{\bar{\lambda}^3_{1,m}\sigma^2_{s(m)}}{2\bar{X}_m(1-\rho_{1,m})\bar{L}_{1,m}}. \qquad \forall m \in [1,2,...l] \tag{9}$$

The average waiting time $\bar{W}_{2,m}$ of type 2 users is as follows[10]:

$$\bar{W}_{2,m} = \frac{\bar{\lambda}_{2,m}(1+s\sigma^2_{s(m)}\bar{X}^2_m)}{2\alpha\bar{X}^2_m(1-\rho_{2,m})}, \qquad \forall m \in [1,2,...l] \tag{10}$$

where s is the shape parameter of Gamma Distribution. So, the demand index of type 2 user becomes

$$DI_{2,m} = \frac{\bar{\lambda}^3_{2,m}(1+s\sigma^2_{s(m)}\bar{X}^2_m)}{2\alpha\bar{X}^3_m(1-\rho_{2,m})\bar{L}_{2,m}}. \qquad \forall m \in [1,2,...l] \tag{11}$$

The average waiting time $\bar{W}_{3,m}$ of type 3 users data bits in the queue is given by[16]:

$$\bar{W}_{3,m} = \frac{\bar{\lambda}_{3,m}(1+\sigma^2_{s(m)}\bar{X}^2_m)}{2\bar{X}^2_m(1-\rho_{3,m})}, \qquad \forall m \in [1,2,...l] \tag{12}$$

So the demand index of type 3 users is as follows:

$$DI_{3,m} = \frac{\bar{\lambda}^3_{3,m}(1+\sigma^2_{s(m)}\bar{X}^2_m)}{2\bar{X}^2_m(1-\rho_{3,m})\bar{L}_{3,m}}. \qquad \forall m \in [1,2,...l] \tag{13}$$

Average waiting time $\bar{W}_{4,m}$ of type 4 users is given as [10]:

$$\bar{W}_{4,m} = \frac{\bar{\lambda}_{4,m}(1+\sigma^2_{s(m)}\bar{X}^2_m)}{2\bar{X}^2_m(1-\rho_{4,m})}. \qquad \forall m \in [1,2,...l] \tag{14}$$

So the demand index of type 3 users is as follows:

$$DI_{4,m} = \frac{\bar{\lambda}^3_{4,m}(1+\sigma^2_{s(m)}\bar{X}^2_m)}{2\bar{X}^2_m(1-\rho_{4,m})\bar{L}_{4,m}}. \qquad \forall m \in [1,2,...l] \tag{15}$$

In all l spectrum sub bands, demand indices of all four types of users are calculated and are used for pricing and spectrum allocation to end users.

4.2 Pricing between Central Geo-Location Database, WLD, APs and End Users.

WLD purchases spectrum from central geo location database for an interval of period t, at a price P, given by [1]

$$P = P_o B^{\gamma} \tag{16}$$

where P_o is the price per unit bandwidth and B is the amount of bandwidth purchased by WLD for interval t. The value of γ is directly proportional to the scarcity of available spectrum. The reservation cost P is a convex function on B. The cost to be paid by WLD increases exponentially as the demand for the spectrum increases linearly. WLD distributes the spectrum among APs using B-SAFE [9] algorithm and charges them the price to be paid, proportional to the amount of spectrum allocated to them. The utility of WLD during interval t can be abbreviated as U_{WLD}, which is the difference between the price paid by WLD to central geo-location database for interval t and the total revenue generated by the WLD from the APs connected to it, during the same interval. Mathematically,

$$U_{WLD} = \sum_{n=1}^{N} P_{AP(n)} - P(1+\alpha) \tag{17}$$

where $\sum_{n=1}^{N} P_{AP(n)}$ is the total revenue generated by WLD from N APs during interval t, $P_{AP(n)}$ is the price charged to n^{th} AP by WLD during interval t and α is the percentage of profit to be earned by WLD during interval t. The utility of WLD should be greater or at least equal to 0 i.e., $U_{WLD} \geq 0$.

As described earlier, each AP has to query the WLD after a time interval of period t. The utility of n^{th} AP during an interval t can be defined as,

$$U_{AP(n)} = \sum_{i=1}^{4} P_{i,n}\kappa_{i,n}C_n - P_{AP(n)}(1+\beta_n), \qquad \forall n \in [1, 2, ...N] \tag{18}$$

where β_n is the minimum percentage of profit to be earned by n^{th} AP. The term $\sum_{i=1}^{4} P_{i,n}\kappa_{i,n}C_n$ is the total revenue generated by n^{th} AP from all four types of users, during interval t. Here $P_{i,n}$ is the price per unit bandwidth, charged by n^{th} AP to type i user for interval t, $\kappa_{i,n}$ is the cumulative demand index of type i end users, for m sub bands. Mathematically,

$$\kappa_{i,n} = \sum_{m=1}^{l} DI_{i,m}, \qquad \forall i \in [1, 2, 3, 4] \tag{19}$$

and C_n is the capacity of n^{th} AP. Mathematically,

$$C_n = B_{AP(n)}(1 - SNR_{AP(n)}), \tag{20}$$

where $B_{AP(n)}$ is the spectrum allocated to n^{th} AP and $SNR_{AP(n)}$ is the signal to noise ratio of n^{th} AP.

4.3 Types of Pricing Schemes and Admission Control Mechanism

We propse two types of pricing schemes and admission control. One of them is fixed pricing scheme and the other one is variable pricing scheme. The difference between them is that in fixed pricing scheme, users are charged fixed prices according to their type in each interval of time at the cost of the QoS requirements' satisfaction, while in variable pricing scheme, end users are charged variable prices according to their type and QoS requirements. For simplicity, we propose the fixed and variable pricing admission control algorithms considering the scenario that the total spectrum demand of all four types of end users (before admission control) is greater than the available spectrum resources i.e. $\sum_{i=1}^{4} \kappa_{i,n}>1$ and the demand indices κ_1, κ_2, κ_3 and κ_4 are greater than 0.4, 0.3, 0.2 and 0.1 respectively. The admission control mechanism design for other different posible scenarios is left as future work.

4.3.1 Fixed Pricing Scheme and Admission Control

Fixed pricing scheme is for those end users which are interested in paying a fixed price at the cost of degradation of their QoS requirements. Prices are set during the first interval i.e. when users query the database to avail the spectrum. After the prices are set, whenever the price of the available spectrum ($P_{AP(n)}$) changes in next intervals, the demand indices / spectrum allocation (QoS requirements) of end users is adjusted to generate the required revenue. In the first interval, AP maintains maximum fairness in spectrum utilization among all four types of end users by allocating equal spectrum resources to them i.e. $\kappa_{1,n}$=$\kappa_{2,n}$=$\kappa_{3,n}$=$\kappa_{4,n}$=0.25. and calculates the prices to be paid by each type of end user using equation 21. Prices should be set such that $P_{1,n}>P_{2,n}>P_{3,n}>P_{4,n}$. The reason for setting prices this way is that type 1 users have the most deterministic data rate / constant data rate followed by type 2, type 3 and type 4 users and will ensure us maximum spectrum utilization and therefore revenue generation. For simplicity, we consider, $P_{1,n}=4P_{4,n}$, $P_{2,n}=3P_{4,n}$ and $P_{3,n}=2P_{4,n}$.

$$\sum_{i=1}^{4} P_{i,n}\kappa_{i,n}C_n = P_{AP(n)}(1+\beta_n). \qquad \forall n \in [1,2,...N] \tag{21}$$

In next intervals of time, when $P_{AP(n)}$ increases, AP increases the spectrum utilization of type 1 and type 2 users, and decreases spectrum utilization of type 3 and type 4 users to satisfy equation 21. The reason for increase in type 1 and type 2 users demand is obvious i.e. to generate more revenue due to their determinisntic behaviour / constant bit rate. The decrease in demands of type 3 and type 4 users is that we have to keep the total spectrum utilization index less than or equal to 1 i.e. $\sum_{i=1}^{4} \kappa_{i,n} \leq 1$. The upper bounds of type 1 and type 2 users are 0.4 and 0.3 respectively. Similarly, the lower bounds of type 3 and type 4 users are 0.2 and 0.1 respectively. AP keeps on adjusting the demand indices until the targeted required total revenue at β_n% profit is achieved. Now, when $P_{AP(n)}$ decreases, rather than enjoying the extra profit it can earns due to unfairness in spectrum allocation, it decreases the type 1 and type 2 users spectrum utilization and increases the type 3 and type 4 users spectrum utilization until targeted required revenue at β_n% is achieved. The maximum limit of adjustment is that $\kappa_{1,n}$=$\kappa_{2,n}$=$\kappa_{3,n}$=$\kappa_{4,n}$=0.25 i.e. total fairness. If $P_{AP(n)}$ further decreases, then AP will only maintain spectrum utilization of end users and will enjoy the excess profit. Similarly, when P_{AP} increases beyond the limit of maximum allowed unfairness i.e. $\kappa_{1,n}$=0.4, $\kappa_{2,n}$=0.3, $\kappa_{3,n}$=0.2 and $\kappa_{4,n}$= 0.1, AP will not adjust the demand indices further, rather it will have to bear the loss. AP implements the algorithm 1 to perform fixed pricing admission control.

Algorithm 1 Fixed Pricing Admission Control Algorithm

```
procedure FIXED PRICING ADMISSION CONTROL
    for each interval t ∈ T do
        if t = 1 then
            κ1= 0.25
            κ2= 0.25
            κ3= 0.25
            κ4= 0.25
            Calculate P1,P2,P3 and P4 using
                    Σ_{i=1}^{4} Pi κi C = PAP(1 + β),
                    P1 = 4P4,
                    P2 = 3P4,
                    and P3 = 2P4.
        else
            if Σ_{i=1}^{4} Pi κi C<PAP(1 + β) then
                while Σ_{i=1}^{4} Pi κi C<PAP(1 + β) do
                    κ1 = κ1 + 0.03.
                    κ2 = κ2 + 0.01.
                    κ3 = κ3 − 0.01.
                    κ4 = κ4 − 0.03.
                end while
            else if Σ_{i=1}^{4} Pi κi C>PAP(1 + β) then
                while Σ_{i=1}^{4} Pi κi C>PAP(1 + β) do
                    κ1 = κ1 − 0.03.
                    κ2 = κ2 − 0.01.
                    κ3 = κ3 + 0.01.
                    κ4 = κ4 + 0.03.
                end while
            else
                κ1 = κ1.
                κ2 = κ2.
                κ3 = κ3.
                κ4 = κ4.
            end if
        end if
    end for
end procedure
```

4.3.2 Variable Pricing Scheme and Admission Control

Variable pricing scheme is for those users which are conscious about their QoS requirements at the expense of the price they pay. At the start of first interval i.e. when users query for spectrum, AP performs admission control for all four types of users such that type 1 users get the highest percentage of spectrum i.e. maximum upto 40 % of available spectrum, type 2 gets maximum upto 30 %, type 3 upto 20% and type 1 upto 10%. In the first interval, when the demands of all four types of users is more than available spectrum resources, AP first of all trims the demand of type 4 users upto a maximum limit i.e. $\kappa_{1,n}$ =0.1. If the total demand is still more than the available spectrum resources, then AP trims the demand of type 3 users upto the maximum limit of 0.2. If still there is more demand, then AP reduces the demand of type 2 users maximum upto 0.3. Similary the maximum limit for type 1 users is 0.4. Once the demands of all four types of users are adjusted prices $P_{1,n}$, $P_{2,n}$, $P_{3,n}$ and $P_{4,n}$ are calculated using the equation 21, subject to the condition that $P_{1,n}>P_{2,n}>P_{3,n}>P_{4,n}$. In this scenario also, for simplicity we assume that $P_{1,n}=4P_{4,n}$, $P_{2,n}=3P_{4,n}$ and $P_{3,n}=2P_{4,n}$. Now afterwards, in each interval of time, if there is an increase in $P_{AP(n)}$, AP will increase the prices $P_{1,n}$, $P_{2,n}$, $P_{3,n}$ and $P_{4,n}$ without changing their spectrum allocation. Similarly, a decrease in $P_{AP(n)}$ will result a decrease in prices $P_{1,n}$, $P_{2,n}$, $P_{3,n}$ and $P_{4,n}$. AP implements algorithm 2 for variable pricing admission control.

5 Simulations and Results

For simulations, we implemented this framework in MATLAB. We assumed that α and β equal to 10%, total number of unlicensed end-users equal to 100 [10] with data arrival rates randomly distributed between 100 kbps to 1000 kbps [10]. For uniformity, we set $\bar{L}_{n,m}$ equal to 1000 bits [10], $\bar{X}_m$ equals to 1000 kbps [10] and service rate's distribution follows Gaussian Distribution [10]. The shape parameter s for Gaussian Distribution is set to be 3.066 [10], P_o is assumed to be 10 cost units per MHz and γ is varied between 1 to 4 [1]. The details of the results for fixed and variable pricing admission control algorithms implementation are discussed in following sub sections.

5.1 Fixed Pricing Admission Control

Figures 5 to 7 refer to results of fixed pricing admission control algorithm implementation. Fig. 5 shows the demand indices of all four types of users which are adjusted by the AP subject to changes in P_{AP} in different time intervals. It can be observed from the figure that, in first interval, AP has allocated equal spectrum resources to all four types of users i.e. demand indices equal to 0.25. At this stage there is maximum fairness in spectrum allocation to all four types of end users. As shown in Fig. 6, prices for all four types

Algorithm 2 Variable Pricing Admission Control Algorithm

procedure VARIABLE PRICING ADMISSION CONTROL
  for each interval $t \in T$ **do**
    if $t = 1$ **then**
      while $\sum_{i=1}^{4} \kappa_i > 1$, **do**
        if $\kappa_4 > 0.1$ **then**
          $\kappa_4 = \kappa_4 - 0.01$
        else if $\kappa_3 > 0.2$ **then**
          $\kappa_3 = \kappa_3 - 0.01$
        else if $\kappa_2 > 0.3$ **then**
          $\kappa_2 = \kappa_2 - 0.01$
        else if $\kappa_1 > 0.4$ **then**
          $\kappa_1 = \kappa_1 - 0.01$
        else
          $\kappa_1 = 0.4$
          $\kappa_2 = 0.3$
          $\kappa_3 = 0.2$
          $\kappa_4 = 0.1$
        end if
      end while
    else
      $\kappa_1 = \kappa_1$.
      $\kappa_2 = \kappa_2$.
      $\kappa_3 = \kappa_3$.
      $\kappa_4 = \kappa_4$.
    end if
    Calculate P_1,P_2,P_3 and P_4 using

$$\sum_{i=1}^{4} P_i \kappa_i C = P_{AP}(1+\beta),$$
$$P_1 = 4P_4,$$
$$P_2 = 3P_4,$$
$$\text{and } P_3 = 2P_4.$$

  end for
end procedure

of users (P_1, P_2, P_3 and P_4) are set at this stage. Refering to Fig. 7, as the P_{AP} increases in the next interval, so does the total required revenue by AP i.e. $\sum_{i=1}^{4} P_i \kappa_i C$. It can be observed that using algorithm 1, AP increased the spectrum allocation to type 1 and type 2 users and decreased the spectrum allocation to type 3 and type 4 users until required total revenue target is achieved. The reason for decrease for type 3 and type 4 is that we have to keep the total spectrum utilization index less than or equal to 1 i.e. $\sum_{i=1}^{4} \kappa_{i,n} \leq 1$. The required total revenue was achieved by adjusting the spectrum allocation to all four types of users, without changing the price they are being charged. Now the fairness factor has been reduced.

Again refering to Fig.5, in next intervals of time, as the P_{AP} decreased, the AP decreased the κ_1 and κ_2, and increased κ_3 and κ_4 until required total revenue (at β rate of profit) is achieved. Instead of earning the extra profit, AP increased the fairness among users. The maximum limit is the %100 fairness. As P_{AP} is further decreased than maximum fairness limit, then AP did not changed the demand indices, rather it earned the extra profit. This limit is shown by dotted line labeled 'Lower Limit' in Fig. 7. Similarly, if the increase in P_{AP} was beyond the limit of maximum allowed unfairness (κ_1=0.4, κ_2=0.3, κ_3=0.2 and κ_4=0.1), then AP had to bear the loss. This limit is shown by a dotted line labeled 'Upper Limit' in Fig. 7.

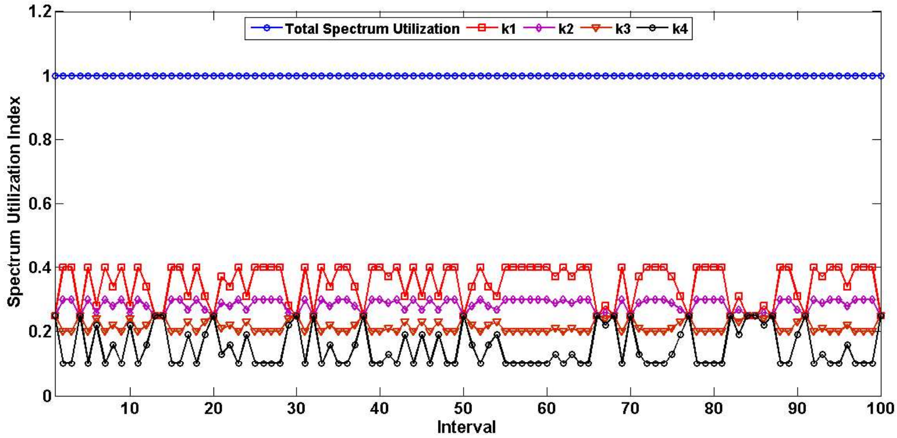

Fig. 5 Total spectrum utilization and demand indices for all four types of users (κ_1, κ_2, κ_3 and κ_4) (Fixed Pricing Admission Control)

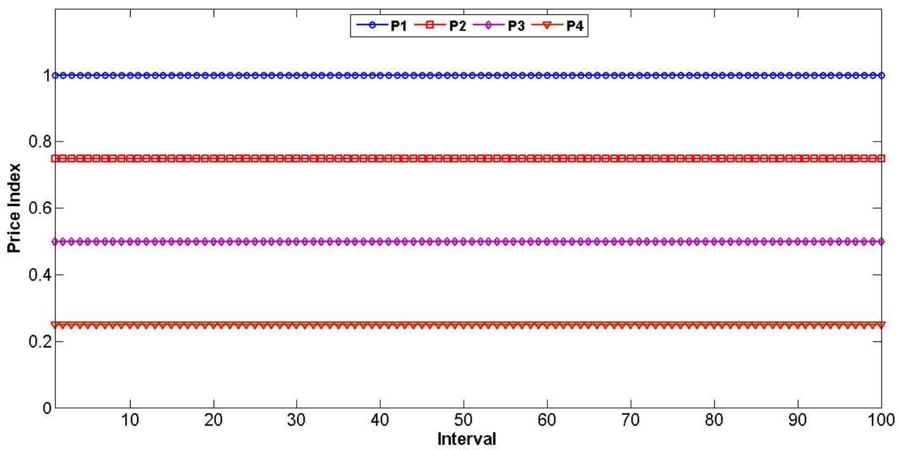

Fig. 6 Prices (P_1, P_2, P_3 and P_4) charged to all four types of users (Fixed Pricing Admission Control)

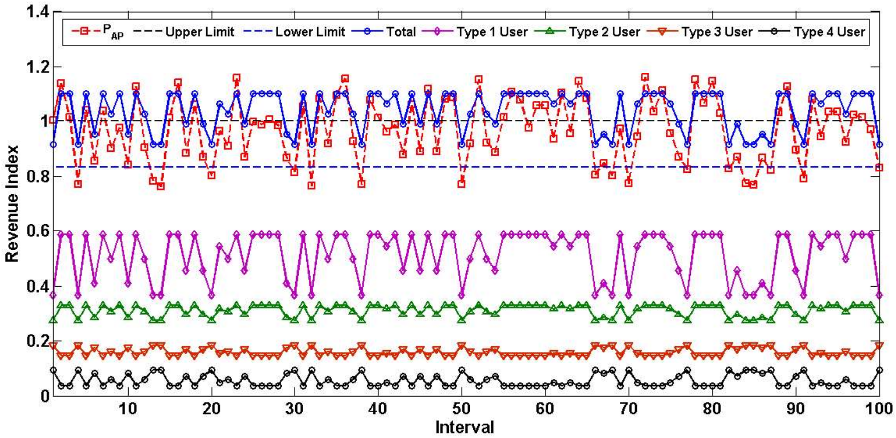

Fig. 7 Price paid by AP (P_{AP}), total revenue generated by AP and revenue generated by individual users. (Fixed Pricing Admission Control)

5.2 Variable Pricing Admission Control

Figures 8 to 10 refer to results of variable pricing admission control algorithm implementation. As it can be seen in Fig. 8, in first interval, AP did the admission control of end users such that $\sum_{i=1}^{4} \kappa_{i,n} \leq 1$. First of all, AP trimed the demand of type 4 users upto the maximum limit that κ_4=0.1, then AP trimed the demand of type 3 users upto the maximum limit that κ_3=0.2. Following this practice, as the demand was still more than supply, then AP trimed the demand of type 2 and type 1 users upto the maximum limit that κ_2=0.3 and κ_1=0.4 respectively. After the demand indices were adjusted, then AP calculated the prices P_1, P_2, P_3 and P_4 using algorithm 2. In next intervals, whenever the P_{AP} changed, AP did not changed the demand indices of the end users rather it calculated the prices P_1, P_2, P_3 and P_4 to achieve the required total spectrum target. The prices P_1, P_2, P_3 and P_4 paid by each end user (for 100 intervals) are shown in Fig. 9 and the revenue generation by individual users and the total revenue generated by the AP are shown in Fig.10.

6 Conclusion

In this work, a pre-existing TVWS database framework (WhiteNet) has been modified by adding two new modules in it i.e. PDB and QDB. PDB deals with pricing issues and QDB deals with QoS characterization and admission control issues. Moreover, two pricing schemes with admission control are presented. Simulation results show that the fixed pricing scheme is useful for the users who are conscious about the cost they pay and variable pricing scheme is useful for those users who are conscious about the QoS requirements' satisfaction. It has been observed that in case of fixed pricing scheme admission control, if the price of the available spectrum increases then the fairness related to

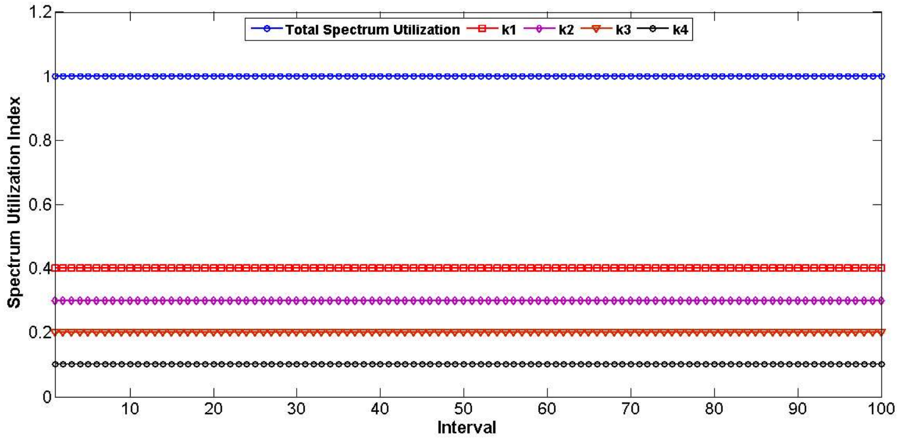

Fig. 8 Total spectrum utilization and demand indices for all four types of users (κ_1, κ_2, κ_3 and κ_4) (Variable Pricing Admission Control)

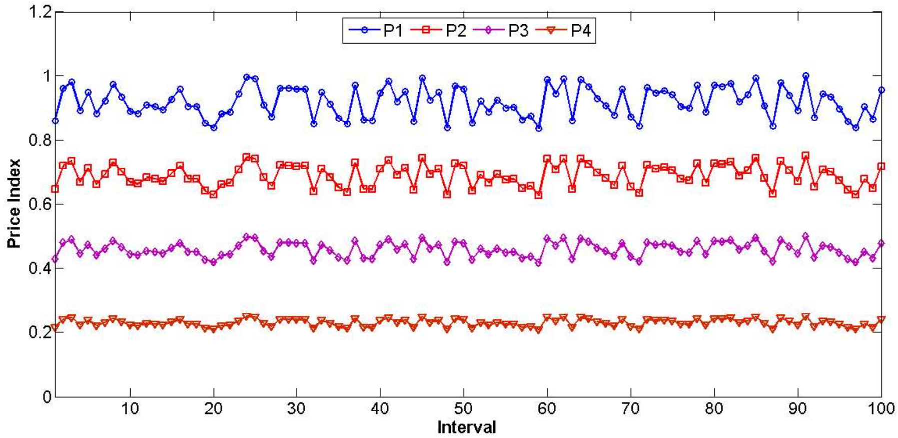

Fig. 9 Prices (P_1, P_2, P_3 and P_4) charged to all four types of users (Variable Pricing Admission Control)

spectrum allocation to end users decreases as the system tries to maximize the spectrum utilization of users which have most deterministic and constant data rate and vice versa. There is a certain limit for increase in price of available spectrum resources as beyond a certain limit, system cannot increase the spectrum allocation to end users and it has to bear the loss. Moreover, if the price of available spectrum resources decrease beyond a certain limit (maximum fairness among users) then system's profit start to increase, as maximum fairness has already been achieved. Overall, our proposed framework is a good improvement in FCC's TVWS database framework.

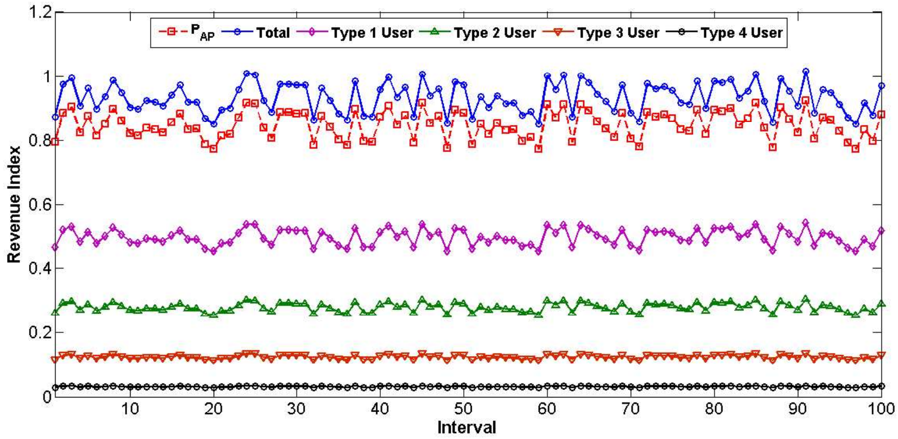

Fig. 10 Price paid by AP (P_{AP}), total revenue generated by AP and revenue generated by individual users. (Variable Pricing Admission Control)

References

1. Feng, X., Zhang, Q. & Zhang, J. (2014). Hybrid Pricing For TV White Space Database. *IEEE Transactions on Wireless Communications* 13 (5), 1-10.
2. Zhang, Jincheng, et al. WINET: Indoor white space network design. *IEEE Conference on Computer Communications (INFOCOM), Kowloon, 2015*,(IEEE, Hongkong, 2015).
3. Jiang, C., Duan, L. & Huang, J . (2016). Optimal Pricing and Admission Control for Heterogeneous Secondary Users. in *IEEE Transactions on Wireless Communications* PP (99), 1.
4. Luo, Y., Gao, L. & Huang, J. (2015). Price and inventory competition in oligopoly tv white space markets. *IEEE Journal on Selected Areas in Communications*, 33 (5): 1002-1013.
5. Gong, S. , Chen, X., Huang, J. & Wang, P. (2012) On-demand spectrum sharing by flexible time-slotted cognitive radio networks. *IEEE Conference on Global Communications, Anaheim, 2012*, (IEEE, California, 2012), 1205-1210.
6. Abdullah, M. & Mahmood, S. (2011). Priority Queuing Based Spectrum Sensing Methodology in Cognitive Radio Network. *MS thesis, Blekinge Institute of Technology.*
7. Bahl, P., Chandra, R., Moscibroda, T. et al.(2009). White Space Networking with Wi-Fi like Connectivity. *ACM SIGCOMM Computation Communications* 39 (4), 27-38.
8. Yang, L., Hou, W., Cao, L., Zhao, B. Y. & Zheng, H. (2010) Supporting Demanding Wireless Applications with Frequency-agile Radios. in *NSDI, 2010*, (NSDI, 2010), 65-80
9. Feng, X., Zhang, J. & Zhang, Q. (2011) Database-assisted multi-AP Network on TV White Spaces: System Architecture, Spectrum Allocation and AP Discovery. in *IEEE Symp. on DySPAN, Aachen, 2011*, (IEEE, Germany, 2011), 265-276.
10. Canberk, B., Akyildiz, I. & Oktug, S. (2010) A QoS-aware framework for available spectrum characterization and decision in cognitive radio networks. in *IEEE 21st Int. Symposium on Personal Indoor and Mobile Radio Communications, 2010, Istanbul*, (IEEE, Turkey, 2010), 1533-1538.
11. Feng, X., Zhang, Q. & Li, B.(2013) Enabling co-channel coexistence of 802.22 and 802.11af systems in TV White Spaces in *IEEE International Conference on Communications, Budapest, 2013*, (IEEE, Hungary, 2013), 6040-6044.
12. Nokovee, M. (2010) Cognitive Radio Access to TV White Spaces: Spectrum Opportunities, Commercial Applications and Remaining Technology Challenges in *DySPAN, Singapore, 2010*, (IEEE, Singapore, 2010), 1-10.
13. Heyman, D. (1997) The GBAR source model for VBR videoconferences. in *IEEE/ACM Transactions on Networking.* 5 (4), 554-560.

14. Castellanos-Lopez, S., Cruz-Perez, F., Rivero-Angeles, M. & Hernandez-Valdez, G. (2011) Joint Call and Packet Level Performance Analysis of CAC Strategies for VOIP Traffic in Wireless Networks. in *IEEE Global Telecommunications Conference, Houston, 2011*, (IEEE, USA, 2011), 1-6.
15. Kleinrock, L. (1976) *Queuing Systems: Computer Applications*. Wiley and Sons, Volume 2.
16. Heffes, H. & Lucantoni, D. (1986). A Markov Modulated Characterization of Packetized Voice and Data Traffic and Related Statistical Multiplexer Performance. in *IEEE Journal on Selected Areas in Communications* 4 (6), 856-868.