Hybrid Overlay/Underlay Spectrum Access Based on Cooperative Prediction and Multi-objective Optimization of Power Budget in Cognitive Radio Network

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Abstract

One of the main issues of secondary users in cognitive radio networks is to increase transmission time and to decrease the number of switching during transmission. As spectrum sensing by conventional methods is time-consuming, in this paper we predict channel's idle and busy time using Kalman filter. When the channel is idle, secondary user start transmission in overlay mode, when the channel is predicted to be busy, it can adjust its transmission power and continue in underlay transmission mode, without switching to another channel. In this mode optimum power budget is obtained using multi-objective optimization with evolutionary algorithm. Through simulation we compare the performance of overlay, underlay and hybrid mode, and show that the hybrid method with prediction could provide better system utility.

Keywords: cognitive radio, evolutionary algorithm, hybrid overlay/underlay, multi-objective optimization, prediction

1. Introduction

The tremendous growth in radio transmission systems and fixed spectrum assignment policy have been led to the scarcity in frequency bands and inefficiency in the spectrum usage. Recently, cognitive radio (CR) has been introduced as a new communication paradigm to opportunistically exploit the existing frequency spectrum. In CR network primary users (PUs) are licensed users who are allowed to operate in a fixed spectrum band and secondary users (SUs) are unlicensed users who opportunistically operate on the unused frequency bands. Commonly, spectrum access is performed in overlay mode, in which SU starts transmission whenever the channel is idle, and switches to another unused frequency band when the a primary user appears on that channel. This switching process practically causes a time delay and decreases spectrum efficiency, therefore spectrum access in underlay mode have been suggested. In underlay spectrum access PU and SU could share one frequency band, as long as SU adjusts its transmission power such that minimizes the interference with PU, while maximizes the bit rate for both PU and SU. So in order to increase system utility, hybrid overlay/underlay spectrum access is proposed.

Ayman Sabbah and Mohamed Ibnkahla (2016) propose an optimization scheme for hybrid spectrum access and use both interweave and underlay spectrum access. Muhammad Usman and Insoo Koo (2014) develop the access strategy for hybrid underlay-overlay cognitive radios with energy harvesting, where SU obtains its required energy from the environment or PU’s signal. Prabhat Thakur et al (2016) introduce an improved hybrid spectrum access method that influences positively on throughput and data-loss rate. Hence, in this paper cooperative prediction via Kalman filter is used to determine idle and busy periods, also to increase the performance and maximize the capacity for both PU and SU, multi-objective optimization subject to interference reduction and maintaining the received power of secondary receiver higher than the outage power, is proposed, which has never been addressed in the literature.

The rest of this paper is organized as follows. In section 2 network configuration and cooperative system model is presented. In section 3 prediction method based on Kalman filter is introduced. Section 4 describes the overlay transmission and section 5 explains the underlay transmission. In section 6 the multi-objective optimization problem is analyzed. In section 6 the system utility is calculated. In section 7 we will have the results and simulations, and finally in section 8 we will conclude the paper.

2. NETWORK CONFIGURATION AND COOPERATIVE SYSTEM MODEL

We assume a multiple PU, multiple SU system, where SUs are responsible for spectrum sensing and prediction of idle and busy periods (Hamid Eltom et al, 2016). One central node called data center is considered for secondary network, which controls all the SUs. To improve prediction accuracy we divide SUs into different groups, each group is responsible to sense and predict one frequency band. One advantage of node clustering is to decrease the process load, because one SU doesn’t necessarily need to detect all the frequency bands, and will use the shared results of all other SUs in the network. Also sensing one frequency band with more than one node will result in the higher sensing accuracy. We assume node clustering by data center is made such that the highest accuracy results, i.e. there should be the minimum distance between SUs in one group and PU which is to be sensed, however each group should have at least one member.

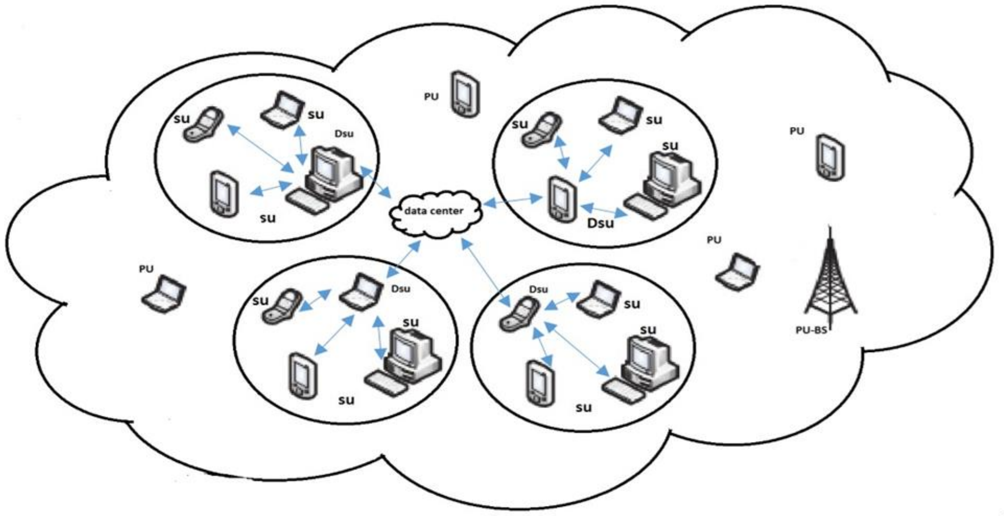


Figure 1. Network topology

Figure 1 shows the topology of this network. In each group one SU node is designated (DSU), other SUs send their prediction results to this node. Whenever a SU needs a channel, sends its request to the designated node, then this node sends this request to the data center, according to the request data center will assign a channel to the user. Data center will continually receive the prediction results for next moment from the designated node and update its table.

3. PREDICTION METHOD BASED ON KALMAN FILTER

3-1 channel observation

Each SU observes the energy of a channel to be able to predict the channel future state, therefore in a given duration the channel traffic and idle and busy periods are collected. If we represent the energy diagram by 0 and 1 model, raising edges are representative of PU's arrival to the channel and falling edges are indicative of PU's departure from the channel. The moments corresponding to these edges are stored and used for prediction. We assume arrival rate and departure rate of PU follow Poisson distribution. All we should do is to approximately predict the arrival moment of PU, that is the raising edge of energy diagram, and the departure moment of PU, that is falling edge, for $i+1$ (i: edge counter), using kalman filter. If the received energy is lower than decision threshold at the moment of receiving channel request by the group, they will calculate the idle period for that channel as below:

$$\hat{d}_{off} = \hat{t}_u(i+1) - t_d(i) - t_{req} \tag{1}$$

In which $\hat{t}_u$ is the corresponding moment of raising edge, t_d is the corresponding moment of falling edge and t_{req} is the moment of receiving channel request. If the channel energy is higher than decision threshold at the moment of at the moment of receiving channel request by the group, the busy period is calculated as:

$$\hat{d}_{on} = \hat{t}_d(i+1) - t_u(i) - t_{req} \tag{2}$$

Finally, SUs in each group send their results to the designated node, in this node all the results are averaged to obtain final values for idle and busy periods of each channel, this values are transmitted to the date center by designated node.

3-2 kalman filter definition

Kalman filter is a linear estimator which estimates system state using some noisy observations. To perform this algorithm only previous state and current observation are enough for prediction (Mostafa Mohammadkarimi et al, 2014). The system states to be predicted are the moments of raising and falling edges of energy diagram, $T(i)=[t_u(i+1),t_d(i+1)]$. $t_u(i)$ and $t_d(i)$ aren't generally observable and some observed date $x(i)=[x_u(i),x_d(i)]$ are used for prediction of those parameters. This model is represented by two equations: state equation and observation equation. State equation stands for relation between state of i th moment and state of $i+1$ th moment:

$$T(i+1)=F.T(i)+w \tag{3}$$

Where F is state transition matrix which maps $T(i)$ to $T(i+1)$. w is process noise, $w \sim N(0,Q)$. Observation equation explains relation between true data $T(i)$ and observed data $x(i)$:

$$x(i)=T(i)+v \tag{4}$$

v is observation noise, $v \sim N(0,Q)$. The initial state and noise vector are mutually independent. Let ε be the prediction error, we have:

$$\varepsilon = T(i+1)-\hat{T}(i+1) \tag{5}$$

$$P=\mathrm{cov}[\varepsilon] \tag{6}$$

The error covariance matrix is considered as estimation accuracy measure. $\hat{T}(i\,|\,i)$ is defined as state estimation at the moment i given observation up to i and i. The state prediction equations are as below:

$$\hat{T}(i+1\,|\,i)=FT(i\,|\,i) \tag{7}$$

$$P(i+1\,|\,i)=\mathrm{cov}[T(i+1)-\hat{T}(i+1\,|\,i)]=Fp(i\,|\,i)F^{T}+Q \tag{8}$$

The update equations are:

$$\tilde{z}(i)=x(i)-\hat{T}(i\,|\,i) \tag{9}$$

$$\Phi(i)=\mathrm{cov}[\tilde{z}(i)] \tag{10}$$

$\tilde{z}(i)$ is measurement residual and $\Phi(i)$ is its covariance. For optimal kalman gain we have:

$$k(i)=P(i+1\,|\,i)\Phi^{-1}(i) \tag{11}$$

$$\hat{T}(i+1\,|\,i+1)=\hat{T}(i+1\,|\,i)+k(i)\tilde{z}(i) \tag{12}$$

$$P(i+1\,|\,i+1)=(I-k(i))P(i+1\,|\,i) \tag{13}$$

The estimation of F is performed using yule-walker equations, F should be defined so as to minimize mean square error:

$$\theta = E[T(i+1) - \hat{T}(i+1)]^2 = E[T(i+1) - F.T(i) - w]^2 \tag{14}$$

Minimizing θ with respect to F leads to these linear equations:

$$\sum_{n=1}^{t} f_{1,n} R_T(n-1) = R_T(l) \qquad l = 1,2,\ldots,t \tag{15}$$

Where t is the system memory size and $R_T(l) = E[T(i)T(i+1)]$, we have:

$$F = \begin{bmatrix} f_{1,1} & f_{1,2} & \cdots & f_{1,t-1} & f_{1,t} \\ 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & 0 \\ 0 & 0 & \cdots & 1 & 0 \end{bmatrix} \tag{16}$$

4. OVERLAY TRANSMISSION METHOD

If allocated channel is free and there is no PU on that, SU could transmit with maximum power. We assume Rayleigh fading for channel, also we assume channel CSI is known at the transmitter and the receiver, so as channel coefficient and average SNR. Channel coefficients could be obtained easily via channel estimation methods, learning, feedback or estimation of received signal power (Yichen Wang et al, 2014). In this mode transmitted signal from secondary transmitter to the secondary receiver could be written as:

$$Y_{ST}^{SR} = \sqrt{g_0} S_{st} H_{st}^{sr} + z_{sr} \tag{17}$$

Where Y_{ST}^{SR} is received signal at the secondary receiver, g_0 is power budget in overlay mode, S_{st} is transmitted signal of secondary transmitter, H_{st}^{sr} is the channel coefficient between secondary transmitter and secondary receiver, z_{sr} is the noise at the secondary receiver assumed to be standard normal distributed. In this mode, transmitter uses its maximum transmission power. The instantaneous signal to noise power ratio at the secondary receiver is:

$$\gamma = \frac{|H_{st}^{sr}|^2 P_{st}}{P_Z} = \gamma_0 |H_{st}^{sr}|^2 \tag{18}$$

Where γ_0 is SNR for AWGN channel, γ is SNR for the channel, P_{st} is the average of transmitted signal power and P_Z is the noise power. The average of channel capacity in secondary link is then:

$$\bar{c}_{ov} = B\int_0^\infty \log_2(1+\gamma) f(\gamma) d\gamma \tag{19}$$

Where B is the channel bandwidth and $f(\gamma)$ is the probability distribution of SNR. If we write the channel response as $H_{st}^{sr} = H_{st,i}^{sr} + jH_{st,q}^{sr}$ and let the Inphase and Quadratic component, i.e.

$H_{st,i}^{sr}$ and $H_{st,q}^{sr}$ respectively, be normal distributed $N(\mu,\sigma_1^2)$, where for Rayleigh fading channel $\mu=0$, then $|H_{st}^{sr}|^2$ is exponentially distributed with rate parameter $\frac{1}{2\sigma_1^2}$, and it is shown that SNR is exponentially distributed too, with rate parameter $\frac{1}{2\gamma_0\sigma_1^2}$ (Andrea goldsmith, 2005).

5. UNDERLAY TRANSMISSION METHOD

In the underlay mode, PU and SU transmit at the same time. So to avoid interference to the PU, SU needs to decrease its transmission power. g_u is the coefficient of power decrease. Therefore at the secondary link, received signal at the secondary receiver is:

$$Y_{st}^{sr} = \sqrt{g_u P_{st}}\, H_{st}^{sr} S_{st} + \sqrt{P_u}\, H_{pt}^{sr} S_{pt} + z_{sr} \tag{20}$$

Where g_u is the power budget in underlay mode, P_u transmitted signal power of PU, H_{pt}^{sr} is the channel coefficient between primary transmitter and secondary receiver and S_{pt} is the transmitted signal of primary transmitter. At the primary link the received signal at the primary receiver is:

$$Y_{pt}^{pr} = \sqrt{P_u}\, H_{pt}^{pr} S_{pt} + \sqrt{g_u . P_{st}}\, H_{st}^{pr} S_{st} + z_{pr} \tag{21}$$

Where H_{pt}^{pr} is the channel coefficient between primary transmitter and primary receiver, H_{st}^{pr} is the channel coefficient between secondary transmitter and primary receiver and z_{pr} is the noise at the primary receiver. Thus for the SINR at the primary receiver and secondary receiver we have:

$$SINR_{pr} = \psi_{pr} = \frac{P_u \,|\, H_{pt}^{pr} \,|^2}{g_u \,|\, H_{st}^{pr} \,|^2 \, P_{st} + P_{zp}} \tag{22}$$

$$SINR_{sr} = \psi_{sr} = \frac{g_u \,|\, H_{st}^{sr} \,|^2 \, P_{st}}{P_u \,|\, H_{pt}^{sr} \,|^2 + P_{zs}} \tag{23}$$

P_{zp} and P_{zs} are the noise power at the primary and secondary receiver, respectively, the noise is assumed to be standard normal distributed. Average capacity at the secondary and primary links are:

$$\bar{c}_{un}^{s} = B\int_0^\infty \log_2(1+\psi_{sr})\, f(\psi_{sr})\, d\psi_{sr} \tag{24}$$

$$\bar{c}_{un}^{p} = B\int_0^\infty \log_2(1+\psi_{pr})\, f(\psi_{pr})\, d\psi_{pr} \tag{25}$$

Where $f(\psi_{sr})$ is the probability distribution of ψ_{sr} and $f(\psi_{pr})$ is the probability distribution of ψ_{pr}. After some calculation for the distribution of SINR at the secondary and primary links respectively, we have:

$$f(\psi_{pr}) = \frac{2 g_u P_{st} P_u \sigma_1^2 \sigma_2^2}{(\psi_{sr} P_u \sigma_2^2 + g_u P_{st} \sigma_1^2)^2} e^{\frac{P_{zs}}{2 P_u \sigma_2^2}} \tag{26}$$

$$f(\psi_{sr}) = \frac{2 g_u P_{st} P_u \sigma_3^2 \sigma_4^2}{(\psi_{sr} g_u P_{st} \sigma_4^2 + P_u \sigma_3^2)^2} e^{\frac{P_{zp}}{2 g_u P_{st} \sigma_4^2}} \tag{27}$$

Such that $| H_{pt}^{sr} |^2 \approx \exp(\frac{1}{2\sigma_2^2})$, $| H_{pt}^{pr} |^2 \approx \exp(\frac{1}{2\sigma_3^2})$ and $| H_{st}^{pr} |^2 \approx \exp(\frac{1}{2\sigma_4^2})$.

6. MULTI-OBJECTIVE OPTIMIZATION PROBLEM

As we could see, g_u shows trade-off, with increase in this value, we will have better SINR at the secondary link, while the interference at the primary link will be increased. Also, the smaller values of g_u will result in the lower interference at the primary link, but will decrease the SINR at the secondary receiver. In addition, we need to have maximum capacity at both the primary and secondary links, which will result in the multi-objective problem:

$$\begin{aligned} &\max(\bar{c}_{un}^{s}, \bar{c}_{un}^{s}) \\ &st: \quad 1) SINR_{SR} \geq th \ , 2) SINR_{PR} \geq th \ , 3) P_{SR} \geq P_{out} \ , 4) 0 < g_u \leq 1 \end{aligned} \tag{28}$$

Where th is the acceptable threshold for the SINR at the primary and secondary receivers in which reasonable communication is performed. P_{out} is equal to the outage power, that is, for the received power P_{SR} lower than outage power, receiving will be dropped. In order to solve this multi-objective problem we've used the Elitist non-dominated sorting genetic algorithm that is one of the evolutionary algorithms. In the next section we will study this algorithm.

6-1 Elitist non-dominated sorting genetic algorithm

Solving the multi-objective optimization is performed using NSGA II algorithm (Mehnuma Tabassum Omar et al, 2015). In this method a set of pareto optimal solutions is obtained. That is the set of all non-dominated solutions in the search space, such that neither of solutions could be preferred over another solution. While running this algorithm, search-up path is directed toward the pareto optimal solutions and during the algorithm optimal solution is preserved in the populations. The advantage of this method is that in every iteration some optimal solutions are found and is useful for discrete variables having more than one optimal solution. The proceeding of this algorithm is briefly as follow:

At the first step random population P_o of size N is created. To create offspring population Q_o of size N, the binary tournament selection, recombination and mutation are used. At the second step, offspring population Q_t is created using parent population P_t . These two populations are combined together to form R_t of size 2N. Then a non-dominated sorting is done to classify the whole population R_t , and multiple non-dominated fronts F_i are created. It allows the global non-dominated check among the two populations. At the third step, new population is filled by solutions of different non-dominated fronts. The filling starts with the best non-dominated front and continues with the solutions of second non-dominated front, and so on. Since the entire size of R_t is 2N, all of the fronts could not be accommodated in the new population of size N. All the fronts which don't enter the new population will easily be removed. When the last allowed front is considered, its solutions may be more than reminding capacity of new population. Instead of random elimination of some of the solutions from last front, we use the crowded tournament selection operator. It is more likely that a lot of solutions from non-dominated fronts are included in the new population. Finally from the new population P_{t+1},

The offspring population Q_{t+1} is created using crowded tournament selection, cross-over and mutation. The algorithm continuous until the entire population converges to a pareto optimal front.

6-1-1 crowded tournament selection operator

For the last front which is not included in the new population, crowding sorting is done using crowding distance metric. In this operator two solutions are compared and the winner of tournament is determined. Let each solution i has two characteristics:

1. A non-domination rank r_i in the population.

2. A crowding distance d_i in the population. The crowding distance d_i of solution i is measure of search space around i where there are no other solutions.

According to these two characteristics, we define the crowded tournament selection operator: the solution i wins solution j in the tournament, if any of the following condition are true:

1. If solution i has better rank, that is $r_i \prec r_j$,

2. In the case of equal rank, if solution i has better crowding distance from solution j, that is $r_i = r_j$ and $d_i \succ d_j$.

6-1-2 calculation of crowding-distance

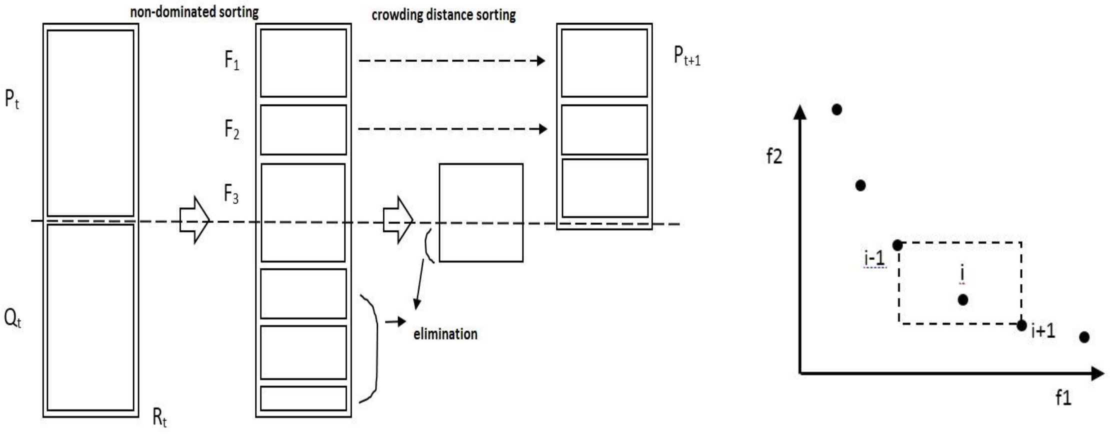
To get the density of solution around a given solution i, average distance of two solutions on either side of solution i along each objective is considered. This quantity serves as the estimation of obtained cuboid perimeter and is used to calculate to crowding-distance of each point in the fronts set F.

Step 1: put the number of solutions in F inside $l : l = | F |$. For each i in the set, first assign $d_i = 0$.

Step 2: for each solution in F calculate objective functions $f_m, m = 1,2$ and sort the set in worse order. Let the indices vector be I^m.

Step 3: in each $m = 1,2$, assign large distance $d_{I_1^m} = d_{I_l^m} = \infty$ to the boundary solutions, and for other solutions:

$$d_{I_j^m} = d_{I_j^m} + \frac{f_m^{(I_{j+1}^m)} - f_m^{(I_{j-1}^m)}}{f_m^{\max} - f_m^{\min}} \qquad (29)$$



(a) (b)

Figure 2: (a) NSGA II proceeding, (b) representation of crowding distance.

Index I_j means the solution index of j th member of sorted list. I_1 is the index of a solution from boundary set with the lowest objective function value and I_l is the index of a solution with the highest objective function value. The second term on the right side of equation represent the difference between objective function values for two consecutive solution on either side of solution I_j. In figure 2(a) the NSGA II proceeding and in 2(b) an example of crowding distance are represented.

7. UTILITY FUNCTION

We assume a system in which secondary nodes perform spectrum detection without prediction and work in a non-cooperation manner. For underlay transmission, according to IEEE 802.22 standard, SUs need to perform spectrum sensing every 2 seconds, which will decrease the channel useful time, and whenever a PU appears on that channel, they shod switch to another idle channel. We compute the utility for SUs in each time slot separately and then calculate their summation over the transmission duration. When system is only in underlay mode, SU switches to the new channel only if its required capacity isn't insured. In the hybrid mode, SU works in overlay mode if the channel is idle, and changes to underlay mode if channel is busy and whenever its required capacity isn't provided, switches to another idle channel. Thus we could gain an utility function for SU in overlay, underlay and hybrid modes (Saed Alrabaee and Anjali Agarwal, 2012):

$$U_{np} = \begin{cases} overlay : (\log_2(c_0) - t_s) \times N_t^0 - t_{sw} \times N_s \\ underlay : \log_2(c_u) \times N_t^u - t_{sw} \times N_s \\ hybrid : (\log_2(c_0) - t_s) \times N_t^0 + \log_2(c_u) \times N_t^u - t_{sw} \times N_s \end{cases} \tag{30}$$

Where t_s is the sensing time, N_t^0 is the total number of time slot in which transmission is performed in overlay mode, t_{sw} is the switching delay, N_s is the total number of switching at the entire transmission duration and N_t^u is the total number of time slot in which transmission is performed in underlay mode.

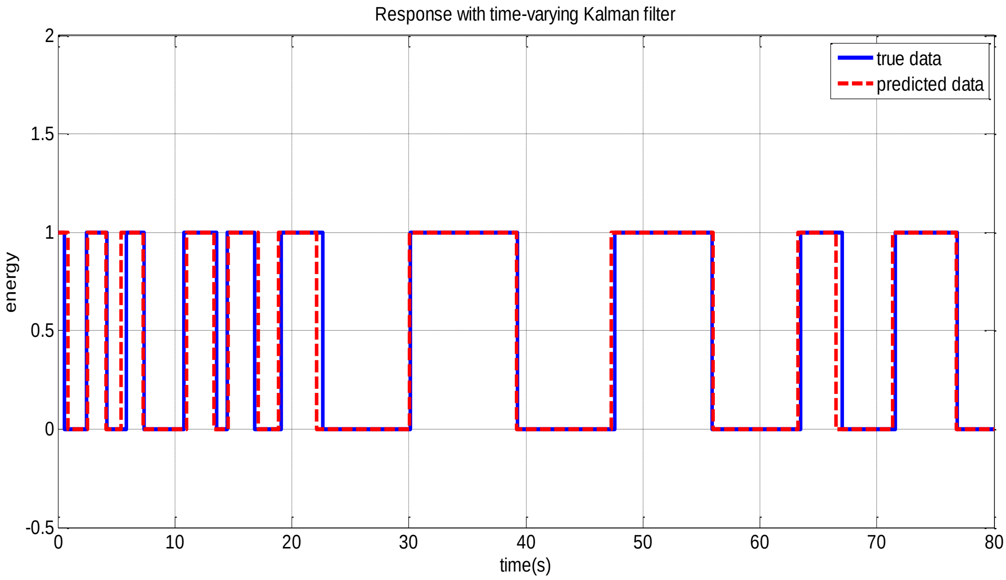
In the system in which SUs perform spectrum detection using prediction, there is no wasted time for sensing, in addition, prediction is done in cooperation manner, thus SU doesn't take any time for prediction. The only wasted time is the waiting delay from the moment of sending request until spectrum assignment to the user is done. So in the system with prediction and cooperation, sensing time will be removed from the above formulas:

$$U_p = \begin{cases} overlay: \log_2(c_0)_s \times N_t^0 - t_{sw} \times N_s \\ underlay: \log_2(c_u) \times N_t^u - t_{sw} \times N_s \\ hybrid: \log_2(c_0) \times N_t^0 + \log_2(c_u) \times N_t^u - t_{sw} \times N_s \end{cases} \tag{31}$$

8. RESULTS AND SIMULATIONS

8-1 kalman filter evaluation

To evaluate prediction accuracy using kalman filter, we compare the real data with the predicted data. An observation string of size 1000 is considered as the input for kalman filter and the future values for idle and busy period are predicted using this method. In figure 3(a) prediction result using 0 and 1 model is shown. The prediction accuracy in represented by mean square error diagram. In figure 3(b) the prediction error and the observation error is illustrated.



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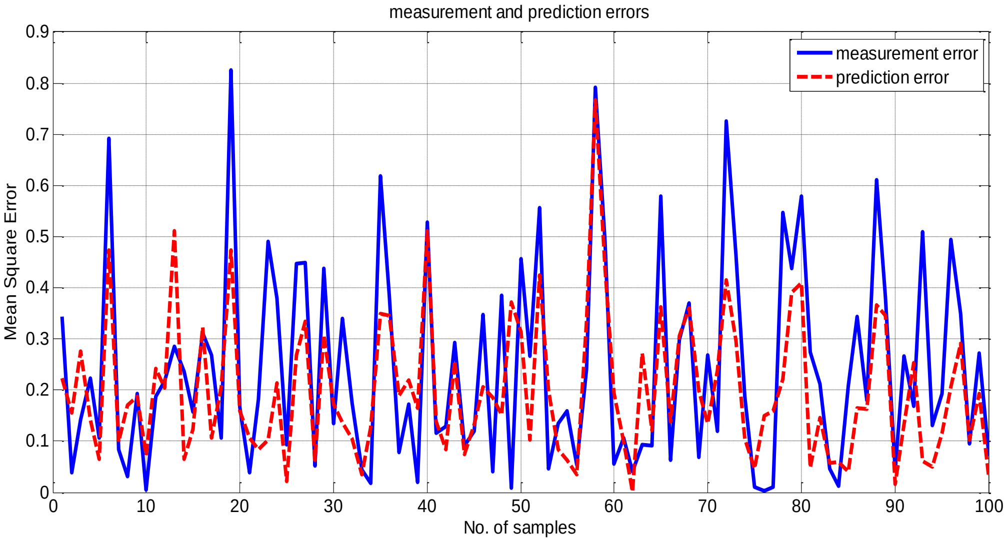
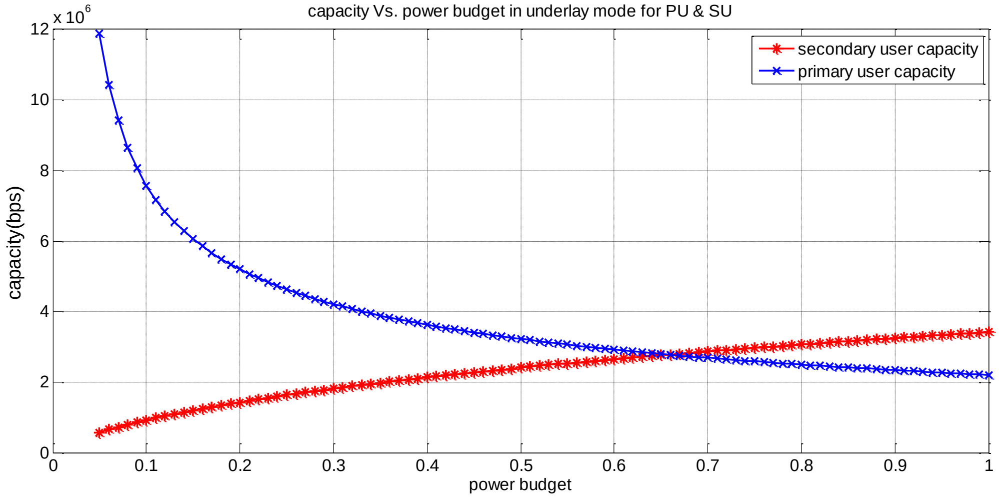


(b)

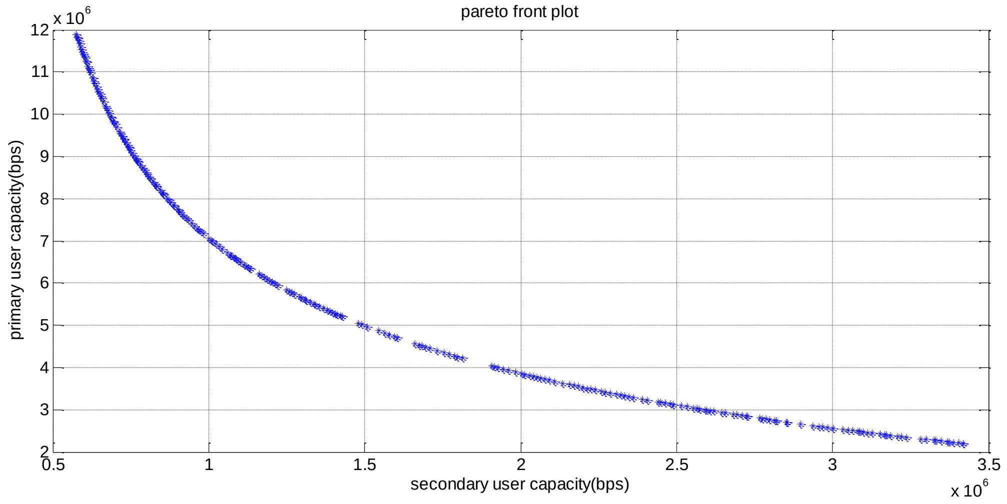
Figure 3: (a) prediction result and true data in 0 and 1 model, (b) prediction and observation mean square errors

8-2 multi-objective optimization evaluation

The goal of optimization is to maximize the obtained capacity of both PU and SU, when the SU transmit in the underlay mode at the common channel with PU. We showed that increasing power budget will increase capacity for secondary link, but causes more interference with PU and reduces the capacity of primary link. In figure 4(a) the capacity diagram for PU and SU with respect to power budget of SU and the trade-off between these two parameters have been shown. To obtain optimal solutions the NSGA II method has been used. This algorithm will lead some pareto optimal solutions. In figure 4(b) the diagram for pareto optimal front for two objective function, that is PU and SU capacities is represented. The total number of population is considered 250.



(a)



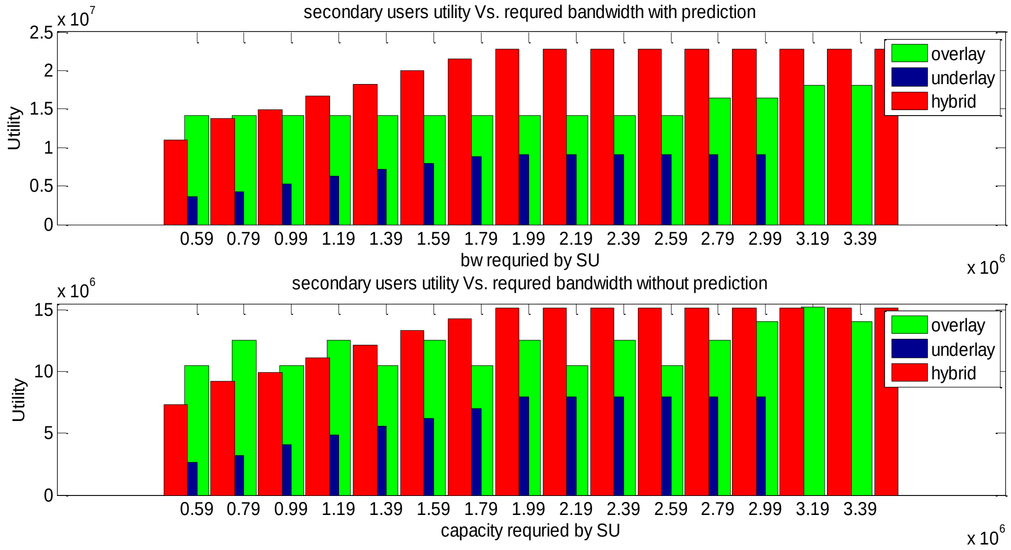
(b)

Figure 4: (a) capacity for PU and SU, (b) pareto optimal front results from multi-objective optimization

8-3 utility evaluation for hybrid overlay/underlay method

In section 7 the expression for SU's utility for two methods, with prediction and without prediction, each for three modes, overlay, underlay and hybrid, was computed. In figure 5(a) the plot of utility with respect to required capacity of SU, is shown for all of these cases. As could be seen in the hybrid mode, because of less required switching, the utility is better than two other cases. Also in underlay mode, because there is the probability that required capacity of user isn't provided, the utility in this case is lower than utility in the overlay mode.

The comparison of utility between two cases, with prediction and without prediction, shows the superiority of the method joint with prediction, because the sensing time is eliminated. Figure 5(b) shows the diagram for number of switching in three cases, overlay, underlay and hybrid, with respect to required capacity of SU. According to the diagram, we could see for the smaller of required capacity, the underlay method will have lower switching number than the overlay method, and hybrid method has the lowest switching number, because it can provide higher capacities for the users. However as one could see, with increase in the values of required capacity, SU in the underlay mode will need to switch more, because it may not be able to provide the required capacity. Also in this case, for the previous mentioned reasons, hybrid method will have the better performance from the perspective of number of switching.



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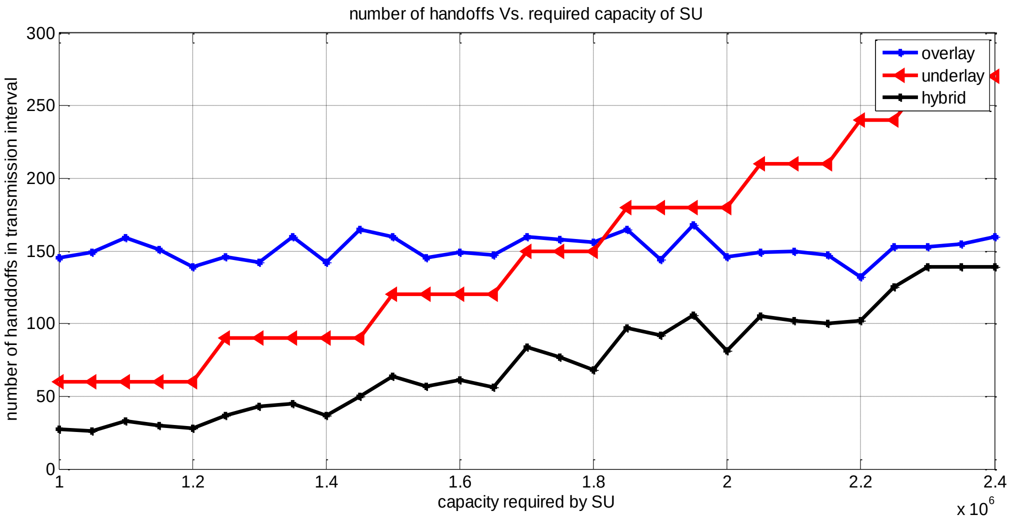

(b)

Figure 5: (a) the comparison of SU's utility with prediction (up), without prediction (down); (b) the comparison of number of switching

9. CONCLUSION

In this paper spectrum access using hybrid overlay/underlay method based on cooperative prediction and multi-objective optimization of power has been studied. The secondary users form cooperative groups to predict the future values for idle and busy periods of channel using kalman filter. In order to exploit optimal power budget in underlay transmission, multi-objective optimization via elitist non-dominated sorting genetic algorithm has been used, and optimum solutions for power budget which led to the maximum capacity for both PU and SU, have been obtained. In simulations, the evaluation of kalman filter based prediction and optimization problem have been performed. In addition, comparison among three cases, overlay, underlay and hybrid, has shown the superiority of hybrid method.

10. ACKNOWLEDEMENT

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