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Multi-Channel Opportunistic Spectrum Analytics and Adaptive Channel Assignment in Cognitive Radio Networks

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Abstract: Spectrum sensing and its efficient utilization are the main intriguing problems in Cognitive radio networks. Under-utilized spectrum creates opportunities to further investigate performance improvement through cognitive radio techniques. If the current spectrum is reclaimed by the primary user then the secondary user must vacate and switch to other available spectrum. Objective of secondary user is to maximize the probability of finding and utilizing an available channel while minimizing the investigation cost. The problem is proved to be NP-hard and a sufficient condition for a robust channel assignment need to be derived. In this study, we propose a "Multi-Channel Opportunistic Spectrum Analytics and Adaptive Channel Assignment (MC-OSACA)" technique, key objective of which is to maximize deliverable throughput through optimal spectrum sharing among cognitive users. The proposed approach strives to achieve a balance by minimizing interference to licensed users and maximizing the entire system performance providing opportunistic access to number of secondary users. It performs two major activities such as opportunistic spectrum sensing and adaptive channel assignment. First, spectrum analaytics using unbiased estimator is applied to find out an optimum list of idle channels. Second, these idle channel are fed to the next level estimator to predict the most appropriate channel for dynamic utilization in an adaptive environment for cognitive users. Moreover, we derive its performance bound on channel estimation and assignment through mathematical analysis. Prototype was developed to demonstrate the proof of concept and analyze the feasibility and practicality of using MC-OSACA technique in cognitive radio network. Simulation results show that our solution achieves better performance when compared to existing channel assignment approaches substantially satisfying the robustness constraints.

Key words: Cognitive radio networks, opportunistic spectrum sensing, channel estimation, adaptive channel assignment, channel bonding, channel notching, spectrum utilization

INTRODUCTION

Substantial growth in mobile data traffic during the last decade has indeed increased the need to opportunistically share the existing spectrum. As spectrum becomes scarce and crowded due to increasing demand for wireless services and application in wireless communication, it needs to be used efficiently. Cognitive Radio (CR) is a potential paradigm that tends to alleviate spectrum deficiency resulting from the policies of fixed spectrum allocation. Unlicensed spectrum utilization has become congested due to the large propagation of unlicensed wireless devices while on the other hand licensed spectrum is under-utilized. The Federal Communications Commission (FCC) found the utilization of the licensed spectrum is low most of the time and hence has approved unlicensed use of licensed spectrum through cognitive radio techniques (Selvakanmani and Sumathi, 2012). Thus, the technology of Cognitive Radio Networks (CRN) is proposed to solve the problem of spectrum scarcity and improve spectrum efficiency using CR techniques through dynamic configuration and adaptation of the operating spectrum. Secondary Users (SU) or unlicensed users are allowed to access spectrum owned by Primary User (PU) or licensed users using interweave, overlay or underlay approach.

In the interweave approach, SU detects the spectrum hole and the secondary signal is interweaved opportunistically through the gaps that arise in frequency and time. In overlay approach, the SU access spectrum

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when PU do not use it. Spectrum availability in overlay approach is identified by SU using spectrum sensing techniques (Jiang *et al*., 2009; Kim and Shin, 2008, 2012) and the SU uses the licensed spectrum concurrently with the PU. In underlay approach, SU can coexist with PU if the Interference Power Constraint (IPC) at the PU's receiver is not violent (i.e., tolerable limit should be below the aggregated interference at the primary). An unlicensed user must vacate spectrum when it is accessed by the licensed users in order to prevent interference with licensed user which limits the overall performance of the CRN. Several ongoing transmissions of the secondary users affect the activity region of licensed user as usually the licensed user appearance is larger than that of the unlicensed users. SU usually needs to employ mechanism to reliably detect the Pus particularly at low Signal-to-Noise Ratio (SNR). Moreover using CR techniques, unlicensed users have to spent considerable amount of time for spectrum sensing, neighbor discovery and channel switching in order to use another available spectrum. Additionally, whenever an unlicensed user performs channel switching, this in turn results in cascaded switching of multiple unlicensed users. It is NP-hard problem to predict when a primary user will appear in a given spectrum nor will a secondary user perform channel switching causing ripple effect for other SUs. Moreover, the problem becomes cumbersome in multi-hop cognitive radio networks where multiple links may be affected if multiple SUs operate on channels used by primary users. In such scenario when primary users occupies the spectrum, SUs through dynamic CR technique (Wang *et al*., 2011) should switch to other available channels without impacting coexisting SUs, causing network partition thus resulting in significant packet delay and packet drops degrading the Quality of Service for the SUs. Several CR techniques have been proposed in order to maximize spectral utilization and minimize harmful interference to the PUs by the SUs. Fundamental limits of spectrum sharing with interference constraints at the PU in fading environments were investigated by Ghasemi and Sousa (2007). Cooperative communication has been incorporated into cognitive radio by Jia *et al*. (2009) in order to improve the error performance of the SU link. An optimal channel-sensing strategy for a single-user case was derived by Chang and Li. Munagala proposed polynomial complexity algorithms to ensure that optimal sensing strategy is computationally prohibitive. An opportunistic channel sensing and access in cognitive radio networks was considered by Zhang *et al*. (2009), describing that when the sensing is imperfect an SU can access only limited number of channels at a time and by deriving logarithmic regret performance for different scenarios.

Number of research works focused on identifying the spectrum opportunities and dynamic spectrum access in CRNs where an SU continuously explores a set of selected channels until an unoccupied band is identified. Similarly, opportunistic communication with the interweave technique faces multiple challenges in dynamic spectrum access (Ding *et al*., 2010; Lai *et al*., 2014; Tumuluru *et al*., 2011) and sharing in a multiuser environment as detection of licensed users and coexistence of cognitive users across channels changes dynamically based on frequency and time.

In this study, we propose a "Multi-Channel Opportunistic Spectrum Analytics and Adaptive Channel Assignment (MC-OSACA)" mechanism that exclusively focus on the 'interweave' approach in cognitive radio. In this approach the secondary user or cognitive user intelligently detects occupancy in the different frequency bands by periodically monitoring the radio spectrum and then opportunistically utilizing them for effective communication with minimal or no interference to the active primary users. The proposed method performs two activities: opportunistic spectrum analytics and adaptive channel assignment. Using opportunistic spectrum analytics, secondary user explores for available channels (spectrum holes) based on unbiased estimation with minimum variance over time and frequency domain. SU stops probing when a set of idle channels are identified. Then through adaptive channel assignment process, SU predicts and updates the system state (i.e., SU performs channel bonding and channel notching) as per the change in environment and selects the best channel from the idle list for dynamic utilization. SU continues to explore (learn the current system state) against the list of detected channels for future utilization. Continuous analysis against the system's current state tends to reduce estimation cost in future while maintaining network connectivity when PU appears. The main objective of this proposed MC-OSACA approach is to maximize sum throughput in the system through opportunistic (Lai *et al*., 2011; Rashid *et al*., 2009; Yuan *et al*., 2010) utilization of optimal amount of spectrum, given the sensing and the tolerable interference limits. Prototype was developed using self written script in MATLAB to demonstrate the proof of concept and analyze the feasibility and practicality of using MC-OSACA technique in cognitive radio network. Simulation result shows the mean spectral utilization of the proposed scheme achieves fair end-to-end goodput across multiple-channels allocating distinct non-overlapping channels to each set of communicating radios increasing network connectivity and performance. Nevertheless, our solution outperforms existing channel assignment approaches substantially satisfying robust constraints.

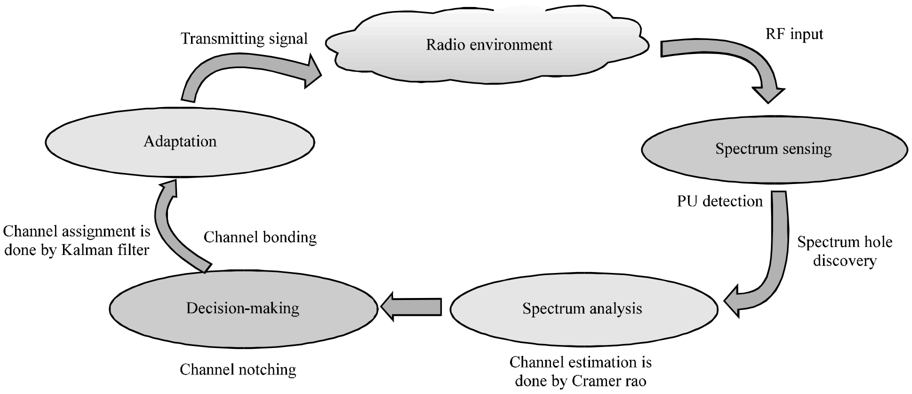


Fig. 1: Cognitive radio network operation using MC-OSACA mechanism

MATERIALS AND METHODS

System architecture and operations: In this system, we consider a cognitive radio networks with multiple Primary Users (PU) and Secondary Users (SU). We assume that the efficiency of spectrum usage can be maximized by the PU by sharing some portion of the bandwidth with SU. However, to guarantee its own performance (to provide a particular quality of service requirement), the PU should retain a given amount of bandwidth (the bandwidth requirement for PU may be time-varying). Let us assume that each PU updates Radio Environment Map (REM) regarding its channel (bandwidth/spectrum) availability. SU through sensing scheme probes REM to find list of available channels. Objective of SU is to maximize its end-to-endoutage probability by efficient spectrum utilization through most appropriate channels selection. To maximize its own throughput, the SU would explore to find the optimal PU for the channel that the SU achieves the highest spectral efficiency during transmission. Upon spectrum allocation, the SU transmits in the allocated spectrum to enhance the transmission performance. To meet the requirement of a specific application, Bit Error Rate (BER) must be maintained at a target level and through channel estimation; the CU can obtain the received Signal to Noise Ratio (SNR) of the channel. In summary for the secondary user, given the received SNR, target BER and assigned spectrum then the transmission rate (in bits per second) can be obtained. Each SU through channel estimation knows its spectral efficiency and its achievable goodput per unit of data transmission. SU's gain relates to the QoS in a real network. In other words, the higher the QoS required by the SU, the greater the gain will be. SU can use priority parameter representing different weights to different SU for spectrum utilization to achieve different QoS requirement. If priority = 1 for each SU, all SUs who use the spectrum offered by the PU will have same marginal goodput (transmission rate) which provides strict fairness among SUs (i.e., all SUs have equal rights to utilize the maximum bandwidth they desire). We assume that the communication system operates in a slotted fashion. Time slot is divided into channel analysis phase (time needed to analyze one channel) and channel assignment or transmission (time needed for data transmission) phase. If at least one of the analyzed channels is said to be unoccupied then SU can successfully transmit one packet. We consider a cognitive radio system with interference tolerance limits at the PU and SU and with sensing limits at the SU.

Cognitive radio network operation using MC-OSACA mechanism is represented in Fig. 1. We assume that the secondary users can access the radio frequency (traffic) statistics of the primary users that are logged into the Radio Environment Map (REM). Using the initial set of statistical information, MC-OSACA mechanism initiates channel analytics process. First, a reliable cooperative spectrum sensing detection mechanism is performed to analyze availability of unused bands that prevents harmful interference to the licensed users. During spectrum analytics process, the proposed scheme uses Cramer Rao bound for estimating and extracting a global decision using the shared local sensing results to discover the list of spectrum hole at a varying timeslot.

Cramer Rao bound is extremely useful to find a minimum variance for all possible values of parameters. The estimation process using the sensed parameters retrieved from channels, calculates variance for each parameter in order to identify channels with unused bands. Next, the set of identified channels with spectrum hole are further assessed on its quality. The quality of channel accessed by CU is measured by SNR ratio. A higher SNR value means that the signal strength is stronger in relation to the noise levels which allows higher

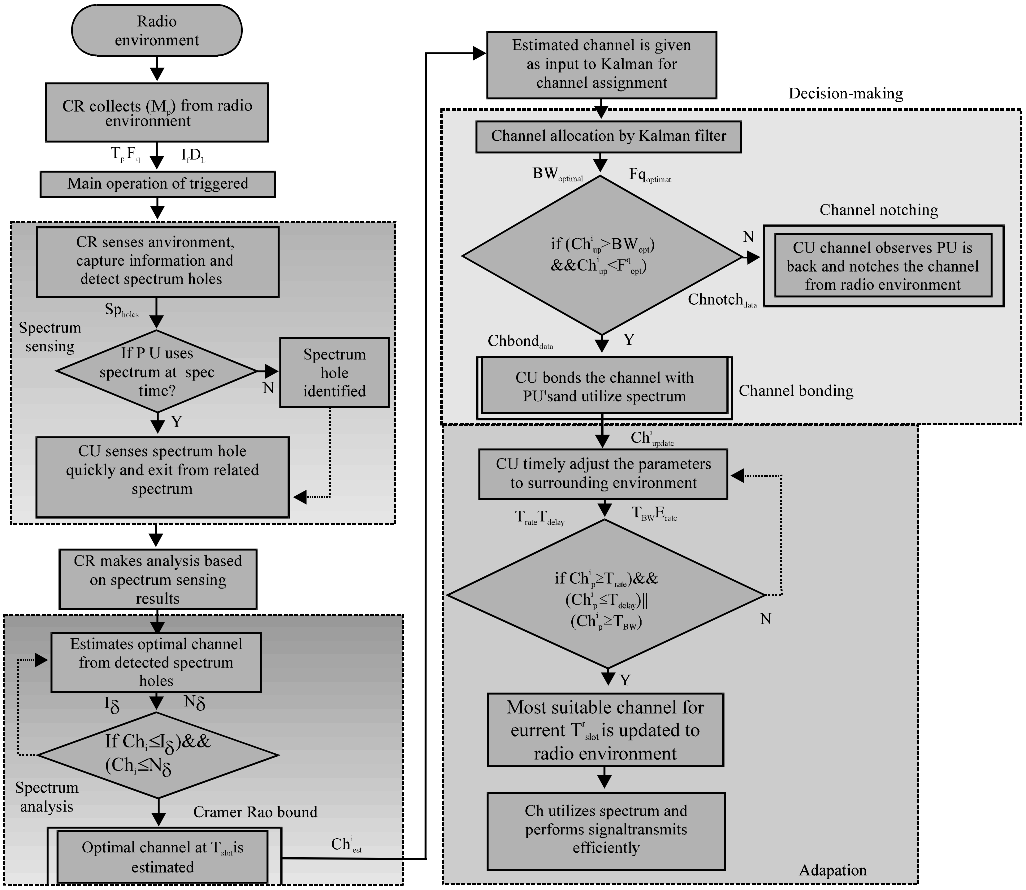


Fig. 2: Overall flow model using MC-OSACA approach in multiuser cognitive radio networks

data rates and fewer retransmissions all of which offers better throughput. Of course, the opposite is also true. A lower SNR allows SUs to operate at lower data rates which decreases throughput. Estimation and decision making using minimum variance factor strives to achieve high reliability over fading channels. Based on quality assessment, channels above the optimal SNR are considered for bonding while notching the others. Idle channels that are selected using channel analytics process is fed to the next stage for further estimation. During the adaptive channel assignment phase, the set of selected idle channels are given as the input to the Kalman Filter (next level estimator) for dynamic adjustments as per the change in radio environment and final assignment. The filter's algorithm is a two-step process, state of the system is predicted in the first step and the second step uses noisy measurements to refine the estimate of system state. The prior prediction of channels is combined with current observation of channels to refine the state estimate for further update.

The parameters taken for the update phase filtering process is re-validated against the dynamically varying parameters (include bandwidth, frequency in the radio environment). If the re-estimated observation on parameters matches with the current observation channel characteristics, then the channel is bonded and updated to radio environment otherwise the channel (low SNR causing channel error) is notched from assignment and current observation is updated to the radio environment. The CR should keep track of the change in radio environment as environment changes over time and space. By using adaptive channel estimation approach, the SU can dynamically adjust transmission rate based on channel quality. Overall flow model using MC-OSACA approach in multiuser Cognitive radio networks is shown in Fig. 2. The phases involved in MC-OSACA Model are:

- Opportunistic spectrum analytics phase
- Adaptive channel assignment phase

Opportunistic Spectrum Analytics (OSA) Phase: This phase starts with sensing of communication or operating parameters (Transmit power Tpower, Frequency F, Interference I and access availability avail) in the environment. CR using its cognitive capability selects proper communication parameters specific to environment (by allowing the system to interact with environment). Moreover, its reconfiguration capability allows the system to modify the communication parameters without changing any hardware.

Spectrum sensing: Spectrum hole or radio spectrum not in use for significant periods of time in certain areas is one the most important findings from the measurement reported. Lot of spectrum hole (a set of frequency bands at a particular time assigned to a PU but was not utilized by that PU) observed from the findings indicates under-utilization. While at the other hand, unlicensed spectra are heavily accessed and have high spectrum utilization by the SUs and are overcrowded. Proposed approach seeks to overcome the spectral shortage problem allowing SUs to communicate without interfering with theprimary users at certain time and space. During this phase, the main operation of CR nodes is to sense the environment periodically for channel identification (within their sensing range). Upon receiving channel availability information, it would respond to these infrastructures (REM) with a set of available channels and relevant information. As shown in Fig. 3 Area 1 represents communication range of 1 primary user within this region

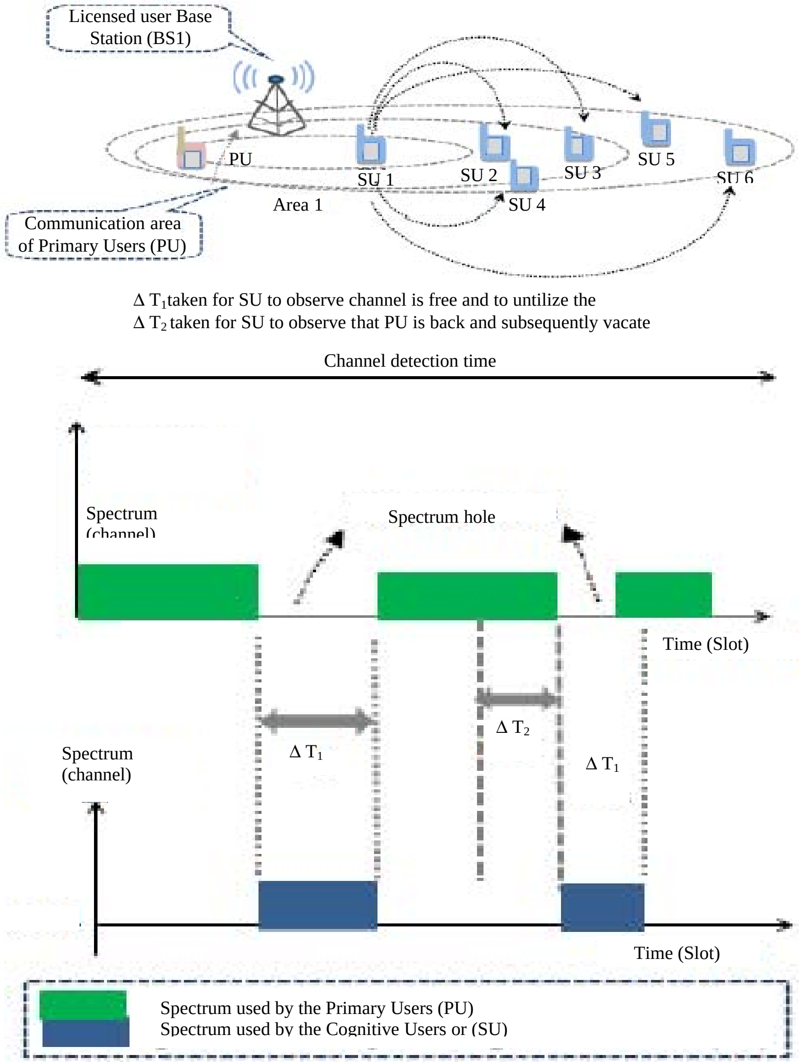


Fig. 3: Overall flow model using MC-OSACA approach in multiuser cognitive radio networks

the SUs build communication links with frequency while the PUs are not active. We assume that each secondary user can detect primary user within a region (radius) around it. Let us consider a certain channel which will be used by a primary user periodically. Each channel has only two possible states; idle (off) or busy (on). When a channel is in use (by a primary user), it is termed as busy; otherwise, it is termed as idle. Consider the channel is also open to ‘n’ secondary users and let the set of secondary users be $S = SU_{1\text{-}6}$. Objective of the proposed approach is to improve spectral efficiency among the secondary users by allowing opportunistic access to the channel when not in use. Let us assume that the data traffic arrive at each primary user in an independent and identically distributed fashion with arrival probability ‘p’. All secondary users consistently monitor the channel through sensing mechanism. When a secondary user has data to transmit, SU randomly selects one of the available channels for secondary communication. Let us consider, a scenario where delay intolerant data arrives at an arrival probability ‘p’ (same as the primary user) at the secondary user, then the transmission rate at both primary and secondary is set to be the same. In such scenario, the licensed (primary) user transmit their data successfully via the channel. While the unlicensed (secondary) user data can undergo the following; SU’s data transmission fails if there are no free channels available at that instant of time; SU’s data transmission is said to be lost if two of more SUs occupies the same idle channel for transmission (collision is caused). Loss in communication by the secondary user can be prevented by effective sensing, analysis and channel estimation mechanism. MC-OSACA technique focus on improving system performance by optimizing goodput (throughput) for each SU such that sum throughput of the overall system improves. Goodput refers to the total amount of data that is successfully delivered per unit time. Here the total amount of data ($T_{sum-data}$) indicates the sum goodput of PUs (G_{PU}) plus sum goodput of SUs (G_{SU}). In our approach, SU applies cooperative sensing method (cooperative sensing technique is effective especially when SUs suffers from serious fading or when the PUs sends signal with small power where SU hardly achieves accurate spectrum detection thus severely causing interference) to sense channels which are in IDLE state. When more than one channels are detected to be IDLE, the SU randomly chooses one of the channels for secondary communication where cooperation between the SU using cooperative sensing prevents two or more secondary users from choosing the same channel. Further using priority parameter, SUs are categorized depending on their QoS requirement. Among set of channels selected, SU with high priority selects the channel with maximum bandwidth for data transmission. Sensing is performed by SUs in uniform time intervals (the observation time for sensing primary user is assumed to be very small compared to the length of the time slot). Example if we consider the time slot for SU is 200 msec then SU performs data transmission for 180 msec. After finishing data transmission for 180 msec, it will perform spectrum sensing for 20 msec periodically. Algorithm 1 details the steps involved in the opportunistic spectrum analytics phase.

Algorithm 1; opportunistic spectrum analytics process:

```
Input: Cognitive Users (CU) dynamically senses operating parameters, analyses and decides using OSA process for effective spectrum utilization.
1. CU senses the operating parameters (e.g. Transmit power ($T_p$), Frequency ($F_q$), Interference $I_f$, Delay $D_L$) from
   radio environment
2. CU $Cu_i$ activates spectrum sensing process. Periodically sense the environment, captures dynamic operating information. Detects the spectrum holes
         /*Spectrum sensing*/
         Initialize $ch_{count} = 0$;
         for each $Cu_i$
             if $P_U$ is not utilizing spectrum at $T_{slot}$ then
             /*Spectrum Hole Detection*/
             $C_{uf}$ Senses $Sp_{hois}$ in the Ru and vacate spectrum;
                  Store $ch_{data}$; /*Store list of spectrum holes in the list separately and increment the counter*/$ch_{count} = ch_{count}+1$;
         end
   end /*for loop*/
3. Find the optimal bands among available for the CU. CR analyses sensed spectrum. Spectrum analysis is done to select an optimal channel from all detected spectrum holes based on QoS requirements of CU’s and interference threshold of PU’s.
   /*Spectrum Analysis*/
   Initialize $hole_{count} = 0$;
   for each spectrum holes at $T_{slot}$
             if (channel $Ch_i \leq$ interference threshold $I_s$) && ($Ch_i \leq$ noise threshold $N_{\varepsilon}$)) then
                channel ($Ch_f$ ) is selected as optimal channel;
            else
                channel occupied by $Cu_i$ moves to another spectrum hole;
                Store $hole_{data}$;/*Store list of derived spectrum holes in the list separately*/
                $hole_{count} = hole_{count}+1$;
        end
   end /*for loop*/
4. In the list of sensed channels of a CU, the most appropriate spectrum band is estimated by Cramer Lao algorithm. Therefore estimated channels $\{Ch^i_{est}\}$ are given as the input to the Kalman filter for further channel decision-making. Thus, an appropriate channel at particular timeslot is chosen. Refer Algorithm2 for the elaborated Cramer Rao and Algorithm 3 for Kalman Filter process
5. Retrieve the list of suitable channels ($Chbond_{data}$) for current transmission from Algorithm 2 and 3 [by applying Cramer Rao and Kalman Filter] and CUs communication parameters like (CUs transmission rate, acceptable error rate, maximum delay and transmission bandwidth) have to be timely adjusted based on spectrum sensing, spectrum analysis and assignment results.
     Initialize $suitable_{count} = 0$; /*Parameter adjustment-adaptation of parameter to the radio environment*/
     for each suitable channel at $Tr_{slot}$
       if (channel $Ch^i_p \leq T_{rate}$)&&($Ch^i_p \geq Error_{rate}$)||($Ch^i_p \leq T_{delay}$)&&(($Ch^i_p \leq T_{gw}$) then
```

```
        Most suitable channel for current transmission slot ($Tr_{slot}$ ) is
      selected;
      $suitable_{count} = suitable_{count}+1$;/*Store suitable channels separately and
      increment the counter*/
      end
   end /* for loop*/
6. The list of suitable channels for current $Tr_{slot}$ is updated to radio
   environment. Since the radio environment changes over time and space,
   the cognitive radio should keep track of the changes of the radio
   environment. So, repeat step (3) till step (6) for 'n' cognitive users.
   Output: List of suitable channels ($Ch^i_p$) for current $Tr_{slot}$
```

Let us consider, initially all primary channels will be in on or off state randomly distributed as shown in Fig. 4. The duration that the primary user passage shows on (Busy) and Off (Idle) are independently exponentially distributed. For channel n, the period of On, B_n, follows an exponential distribution with mean $1/\lambda B_n$. On the other hand, the period of Off, I_n, also follows an exponential distribution with mean $1/\lambda I_n$.

Calculating mean for busy channel B_n (On): Let X be a continuous variable, set of values the random variable can take R= [0, N], let:

$$\lambda B_n \in R$$

$$E(X) = \int_0^N x f X(x)\,dx$$

$$= \int_0^N x\left(\lambda B_n \exp(-\lambda B_n\right)dx$$

Exponential distribution S [0, ∞] is defined as $fX(x) = \int_0^\infty \lambda \exp(-\lambda x)$ if $x \in S$; $x \notin S$, X is exponential distribution with λ. Integrating by parts:

$$= \int_0^N \left[-x\exp(-\lambda I_n x)\right] + \int_0^N \exp(-\lambda I_n)\,dx$$

$$= (0-0) + \left[-\frac{1}{\lambda I_n}\exp(-\lambda I_n x)\right]_0^N$$

$$= 0 + \left(0 + \frac{1}{\lambda I_n}\right)$$

$$E(X) = \frac{1}{\lambda I_n}$$

Calculating mean for idle channel I_n (OFF): Let X be a continuous variable, set of values the random variable can take R= [0, N], let:

$$\lambda I_n \in R$$

$$E(X) = \int_0^N x f X(x)\,dx$$

$$= \int_0^N x\left(\lambda I_n \exp(-\lambda I_n\right)dx$$

Exponential distribution S [0, ∞] is defined as $fX(x) = \int_0^\infty \lambda \exp(-\lambda x)$ if $x \in S$; $x \notin S$, X is exponential distribution with λ. Integrating by parts:

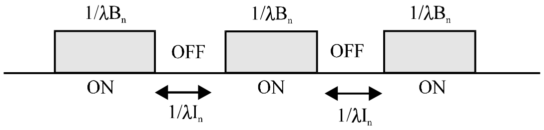


Fig. 4: ON/OFF decision on whether Primary User (PU) is present or not

$$= \int_0^N \left[-x\exp(-\lambda I_n x)\right] + \int_0^N \exp(-\lambda I_n)\,dx$$

$$= (0-0) + \left[-\frac{1}{\lambda I_n}\exp(-\lambda I_n x)\right]_0^N$$

$$= 0 + \left(0 + \frac{1}{\lambda I_n}\right)$$

$$E(X) = \frac{1}{\lambda I_n}$$

Channel estimation using Cramer Rao: The sensing of spectrum results is analyzed to estimate the spectrum standard of the sensed SUs such as $\{SuU_{1-6}\}$. Here one issue is how to measure the quality of spectrum accessed by a SU. This quality can be characterized by the Signal to Noise Ratio (SNR), the average correlation and the white spaces availability. Information on the available spectrum quality for a CR user can be inaccurate and noisy. The sensed channel results is analyzed and best channel is estimated by Cramer Rao algorithm. Application of Cramer Rao in MC-OSACA method is detailed in Algorithm 2.

Algorithm 2; Channel estimation using Cramer Rao:

```
Input: List of sensed channels of cognitive user ($Ch_i$) at particular $T_{slot}$ is
given as input to process
1. Consider set of sensed parameters {$T_p$, $F_q$, $I_f$, $D_L$} and list of sensed
   channels {$Ch_i$}at $T_{slot}$ where the CR makes an analysis to select an
   optimal channel from all detected spectrum holes based on interference
   threshold of PUs.
2. In the list of sensed channels of a CU, the most appropriate spectrum
   band is estimated by Cramer Lao algorithm. By applying Cramer Lao
   Bound (CRLB) to set of sensed channels
   for each parameter retrieved from (sensed channels)
         /*Find minimum variance for all possible value of parameter*/
         Collect frequency values for each CR's and calculate sum and store
         in a list;
         $Fq_{data}$ = sum ($Ch^i_f$);
         $Var_{mindata}$ = var ($Fq_{data}$);
         /*calculate Mean Square Error (MSE) of minimum variance*/
               if ($Var_{mindata}$ is large) then
               Performance of estimator is poor;
               else
                Performance of estimator is good and channels with ideal
                frequency are estimated;
                Store $Var_{data}$;/*Store the list of variance values in the list
                separately*/
                end
end /*for loop*/
```

The quality of spectrum accessed by cognitive user is characterized by Signal to Noise Ratio (SNR),

```
Repeat for estimated channels {$Ch^{i}_{est}$}
        /* SNR Computation for set of estimated channels*/
        $SNR_{dB} = P_{signal\,dB} - P_{noise\,dB}$
        /*define range boundary for Cognitive User (CU) based on SNR ratio*/
        if ($Cu^{i}_{signal} > snr_{g}$) then /* to check signal strength*/
            Higher data rate and better throughput;
        else if ($Cu^{f}_{signal} < snr_{g}$)
            Lower data rate and decrease in throughput;
            Store $SNR_{data}$;/*Store the list of SNR values in the list separately*/
        end
    Until estimated channels {$Ch^{i}_{est}$} are processed;
Output: Estimated channels {$Ch^{i}_{est}$}
```

Cramer Rao bound is extremely useful if we find a Minimum Variance-Unbiased Estimator (MVUE) which is an unbiased estimator that has lower variance than any other unbiased estimator for all possible values of parameters. The estimation process starts with the sensed parameters retrieved from Channels C_1-C_6. The set S (x_1, x_2, x_3,...x_N,) contains list of possible frequency values taken from the measured set of frequencies which stores the sum of individual frequency (x_1, x_2, x_3,...x_6) values for the cognitive radios as sume the frequency of C_1 = x_1Hz, C_2 = x_2Hz, C_3 = x_3Hz, C_4 = x_4Hz, C_5 = x_5Hz, C_6 = x_6Hz:

$$S\left(x_1,x_2,x_3,\ldots x_N\right)=\frac{\partial}{\partial\theta}\log p\left(x_1,x_2,x_3,\ldots x_6\right) \tag{1}$$

$$=\frac{\partial}{\partial\theta}\log\left(p\left(x_1\right)p\left(x_2\right)p\left(x_3\right)\cdots p\left(x_6\right)\right) \tag{2}$$

$$=\sum_{i=1}^{6}\frac{\partial}{\partial\theta}\log p\left(x_i:\theta\right) \tag{3}$$

$$=\sum_{i=1}^{6}S\left(X_i\right) \tag{4}$$

Equation 4 indicates (x_i = x_1, x_2...x_6) where $x_i$is the actual frequency value obtained as a deterministic parameter. The Mean Square Error (MSE) of an unbiased estimator, σ_2 (unbiased variance), of a probability distribution parameter, θ is lower bounded by the reciprocal of the fisher information, I (θ) formally:

$$\left(\sigma^2\right)\geq\frac{1}{I(\theta)} \tag{5}$$

Equation 5 implies that variance of any unbiased estimator σ^2 of is then bounded by reciprocal of fisher information I(θ). σ^2 is large, the performance of the estimator is poor, similarly σ^2 is small, the performance of the estimator is good and finally the channel with ideal frequency is estimated. By finding nearest variance value, the estimated channels {C_2, C_1, C_5, C_3} are given as the input to the Kalman filter for further channel access. Let us assume a scenario as shown in Table 1 and 2 consisting of sensed parameters retrieved from $C_1 \ldots C_6$ channels.

Table 1: Sensed parameters by SUs

ChannelS utilization	Sensed parameters Frequency (MHz)	Noise (dB)	Bandwidth (kHz)	Timeslot (t)
C1	6	90	7	3
C2	2	20	4	4
C3	4	80	6	5
C4	8	75	3	7
C5	12	90	8	6
C6	10	80	2	3

Table 2: SNR computed for each channel

	Sensed parameters				
Channels utilization	Frequency (MHz)	Noise (dB)	Bandwidth (kHz)	Timeslot (t)	SNR (dB)
C1	6	90	7	3	37
C2	2	20	4	4	31
C3	4	80	6	5	40
C4	8	75	3	7	25
C5	12	90	8	6	43
C6	10	80	2	3	15

Signal to noise ratio calculation: As noise of the RF environment is taken into account SNR is one among the best ways to judge the quality of signal. The signal to noise ratio is the ratio between the wanted signal and the unwanted background noise is given as:

$$SNR=\frac{P_{signal}}{P_{noise}} \tag{6}$$

The above Eq. 6 can be expressed in decibels and then the formula can be simplified as:

$$SNR_{dB}=P_{signaldB}\text{-}P_{noisedB} \tag{7}$$

SNR computation for estimated channels

SNR calculation for SU$_1$: For instance, the received signal strength of the CU_1 (or SU_1) is -53 dB denoted as V_n and has the noise level to -90 dB denoted as V_s, then SNR (S/N) is:

$$S/N=20\log_{10}\left(\frac{V_n}{V_S}\right)$$
$$=37\,dB$$

SNR calculation for SU$_2$: For instance, the received signal strength of the CU (or SU_2) is -51 dB denoted as V_n and has the noise level to -20 dB denoted as V_s, then SNR (S/N) is:

$$S/N = 20\log_{10}\left(\frac{V_n}{V_S}\right)$$
$$= 31\text{dB}$$

SNR calculation for SU_3: For instance, the received signal strength of the CU3 (or SU_3) is -40 dB denoted as V_n and has the noise level to -80 dB denoted as V_s, then SNR (S/N) is:

$$S/N = 20\log_{10}\left(\frac{V_n}{V_S}\right)$$
$$= 40\text{dB}$$

SNR calculation for SU_5: For instance, the received signal strength of the CU_5 (or SU_5) is -32 dB denoted as V_n and has the noise level to -75 dB denoted as V_s, then SNR (S/N) is:

$$S/N = 20\log_{10}\left(\frac{V_n}{V_S}\right)$$
$$= 43\text{dB}$$

SNR computation for non-estimated channels

SNR calculation for SU_4: For instance, the received signal[; strength of the CU_4 (or SU_4) is -65 dB denoted as V_n and has the noise level to -90 dB denoted as V_s then SNR (S/N) is:

$$S/N = 20\log_{10}\left(\frac{V_n}{V_S}\right)$$
$$= 25\text{dB}$$

SNR calculation for SU_6: For instance, the received signal strength of the CU_6 (or SU_6) is -65 dB denoted as V_n and has the noise level to -90 dB denoted as V_s, then SNR (S/N) is:

$$S/N = 20\log_{10}\left(\frac{V_n}{V_S}\right) = 15\text{dB}$$

This results in the signal being clearly readable. If the signal is much weaker and above the noise say 80 dB then $S/N = 20\log_{10}(V_n/V_s) = 15\text{dB}$ which is marginal situation. Table 2 displays the SNR computed for SUs using the sensed parameters.

Adaptive threshold setting: As each channel has different power levels a threshold will be set for each band, respectively. When received power signal is higher than the threshold (λ) a channel is considered to be occupied by the PUs and unavailable for use by CR as shown in Fig. 5.

The CRs can transmit only during the allocated transmission times and when the channel is available. Figure 6 shows the relationships between the time allowed for each estimated channels of CRs to use their spectrum Tt.

When signal transmission is performed, it's important to define the range boundary of a CR based on SNR ratio (is the signal level minus the noise level). For example, a signal level of -53 dBm measured for a control channel and typical noise level of -90 dBm yields a SNR of 37 dB which is a healthy value to estimate a channel C_1. An increase in RF interference increases the noise level, thus decreasing SNR. A higher SNR value indicates that the signal strength is stronger in relation to the noise levels,

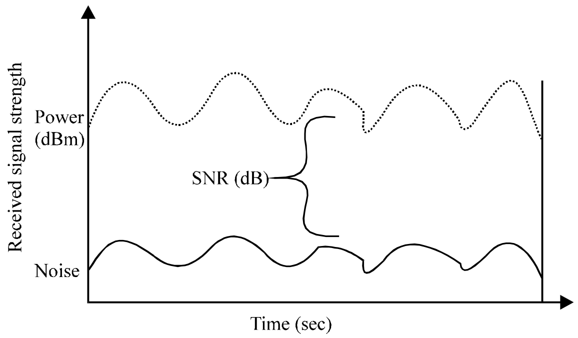


Fig. 5: Received signal strength estimation

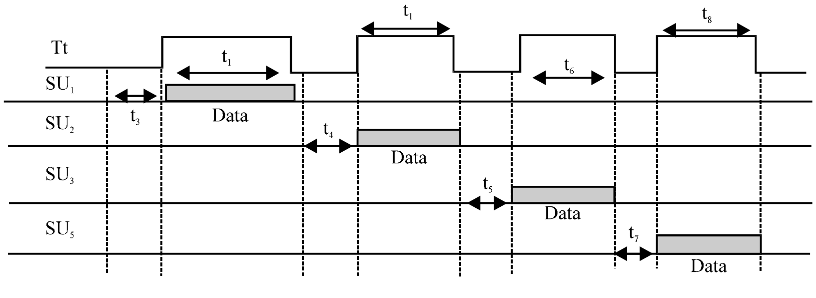


Fig. 6: Sharing of time slots among the estimated channels; t_1, t_2, t_6, t_8 is Primmary User (PUs) transmission time slot, t_3, t_4, t_5, t_7 is Secondary user (Sus) transmission time slot

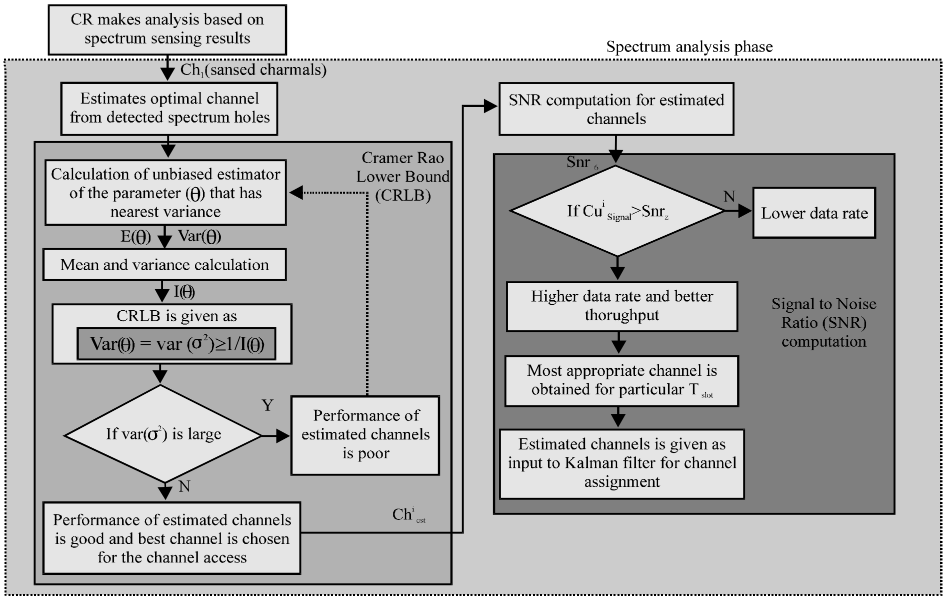


Fig. 7: Channel estimation using Cramer Rao lower bound

allowing higher data rates (offering better throughput) and fewer retransmissions while a lower SNR requires SU to operate at lower data rates, decreasing the throughput. SNR of 30 dB for example, may allow a CR (C_5) to communicate at 8GHz; whereas, a CR (C_6) SNR of 15 dB may only allow 2KHz. Therefore estimated channels $\{C_2, C_1, C_5, C_3\}$ are given as the input to the Kalman filter for further channel access. The flow model for estimating channel using Cramer Rao is shown in Fig. 7.

Adaptive Channel Assignment (ACA) phase: Spectrum band is said to be in busy or Idle state based on the sensing results. Dynamic allocation of spectrum (based on spectrum states sensed) is allocated to the SUs in service for efficient data communication. Practically, spectrum sensing errors such as, False Alarm (FA) where SU identifies a channel BUSY while that is actually Idle and Miss Detection (MD) where SU identifies a channel Idle (unoccupied) while a PU is transmitting on it are inevitable. These errors are Signal-to-Noise Ratio (SNR) and as well as sensing algorithm dependent. Problem caused due to FA and MD can be overcome through effective channel estimation and adaptive channel assignment mechanism. Objective of adaptive channel assignment process is to enable SU to intelligently detect occupancy in the different frequency bands by monitoring radio spectrum periodically and then opportunistically utilizing the spectrum bands for effective communication over the spectrum holes with minimal or no interference to the active primary users. The idle channels identified in OSA phase are fed to the next level estimator in ACA phase that infer parameters to predict and update system state, selecting the most appropriate channel for usage. Thus, the one selected from idle list is dynamically assigned in an adaptive environment for cognitive users. Adaptive channel assignment process is illustrated in detail in the following study.

ACA using Kalman filter: Kalman filter is an optimal estimator that infers parameters from indirect, inaccurate and uncertain observations. It is recursive in manner such that measurements can be processed as they arrive. For each instance, you can use previous output as input. Algorithm 3 describes the steps involved for channel assignment using Kalman filter is MC-OSACA approach.

Algorithm 3; Channel assignment by Kalman filter:

```
Input: Estimated channels $\{Ch^i_{est}\}$ are given as the input to the Kalman filter
1. The estimated channels$\{Ch^i_{est}\}$ are given as the input to the Kalman filter
   for further channel access. Applying Kalman Filter (KF) to set of
   estimated channels,
Initialize $Ch^i_f$ with measurement: noise $Ch^i_{n0}$
Repeat for each frequency $Ch^i_f$ of CU
/*calculate current estimation value of channel at each timeslot*/
    If noise is from channel $Ch_i$
        $x_k$ = Kalman Filter Prediction ($Ch^i_{no}$);
    else
            /*Calculate Kalman Gain*/
            $P_k$ = Kalman Filter Updation ($x_k$, $x_{k-1}$,);
            Current estimation of frequency of $Cu_i$;
            Store $Ch_{estdata}$; /*Store the current estimated
            frequency value in the list*/
    end
```

```
Until all frequencies $Ch^i_f$ of CUs are processed.
/*the parameters taken for the update phase filtering process is re-validated against the dynamically varying parameters include Bandwidth, Frequency in the radio environment.)
Repeat for current estimated channels $\{Ch^i_{update}\}$
            /*Channel Bonding*/
            if
($Ch^i_{update}$ >$BW_{optimal}$)&&($Ch^i_{update}$ <$Fq_{optimal}$) then
              Store the list of estimated channels (bonded) in the list
              $Chbond_{data}$ = bond ($Ch^i_{update}$);
            else
            /*Channel Notching*/
                            Store the list of estimated channels (notched) in
                            the list
            $Chnotch_{data}$ = notch ($Ch^i_{update}$);
       end
Until all current estimated channels $\{Ch^i_{update}\}$ are processed
2.  The list of appropriate channel ($Chbond_{data}$) at that timeslot for particular
    Cognitive user (CU) is chosen and given to parameter adjustment (Refer
    step 6 in algorithm 1).
Output: list of appropriate channel ($Chbond_{data}$) at that timeslot for particular
Cognitive user (CU) is chosen
```

Kalman filter's 2 step process: Kalman filter estimates the state of a system from measured data. The filter's algorithm is a 2 step process:

- Predict-predicts the state of the system
- Update-uses noisy measurements to refine the estimate of system state

Predict: The predict phase uses the state estimate from the previous cooperative sensing parameters $\{T_p, F_{q\ i}\}$ time step to produce an estimate of the state at the current time instant. This predicted state estimate of the channels $\{C_2, C_1, C_5, C_3\}$ is also known as the a priori state estimate:

$$x_{K-1} = x_{k-1} \tag{8}$$

$$P_{K-1} = P_{k-1} \tag{9}$$

Update: In the update phase, the current a priori prediction of channels is combined with current observation of channels $\{C_1, C_3\}$ to refine the state estimate. This improved estimate is termed the a posteriori state estimate:

$$K_K = \frac{P_K}{P_K + R} \tag{10}$$

$$x_K = x_K + K_K(z_K - x_K) \tag{11}$$

$$P_K = (I - K_K H) z_K \tag{12}$$

Kalman filter is given by the equation shown in Fig. 8. For example, by applying Kalman filter to the above estimated Channels $\{C_2, C_1, C_5, C_3\}$ by taking an

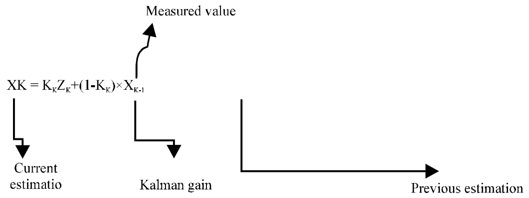


Fig. 8: Kalman Filter equation

Table 3: Dynamic values of CU1

Time slot (msec) (k)	Frequency (Hz) (z_K)
1	0.39
2	0.50
3	0.48
4	0.29
5	0.25
6	0.32

assumption of measurement noise (R) to be 0.1 V and solving one particular frequency value for cognitive user (C_1). Consider the following dynamic measuring parameters values for cognitive user (C_1) (Table 3).

Assuming the initial state k = 0 is the initial time values. Let's assume estimate of $x_0 = 0$ and $P_0 = 1$. Our aim is to calculate current estimation value x_K of C_1 channel for each time slot. Let's assume k = 1, $z_K = 0.39$ Hz, H = 1 since measurement value contains both state and noise $x_{K-1} = x_{1-1}$ 0; (since $P_0 = 1$) if, we chose $P_0 = 0$, indicates there is no noise in the environment. This assumption would lead all the consequent x_K to be zero. So, generally for appropriate estimation, we choose P_0 something other than zero. Applying "prediction" by k = 1 from Eq. 8, we get $x_{K-1} = x_{1-1}$ $x_0 = 0$; and from Eq. 9, we get $P_{K-1} = P_{1-1} = 0$; $P_0 = 1$ by applying "update".

Calculation of Kalman gain (K_K): From Eq. 10:

$$S = HP_K \times H^T + R$$

$$B = H \times HP_K$$

$$K_K = \left(\frac{S}{B}\right)$$

Substituting:

$$S = 1 + 0.1 = 1.1$$

$$B = 1$$

$$K_K = \left(\frac{S}{B}\right) = 1.1$$

Substituting K_K in Eq. 11:

$$x_K = x_K + K_K(z_K - x_L)$$

$$x_K = 0 + 1.1(0.390 - 0)$$

$$x_K = 0.355$$

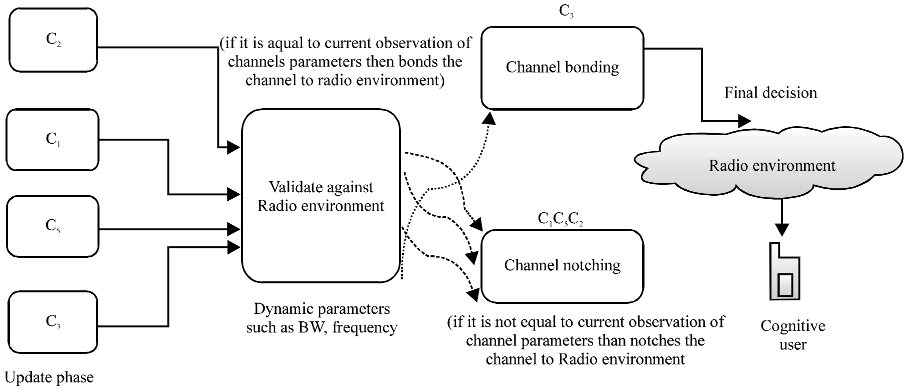


Fig. 9: Predict and update filter process for channel assignment

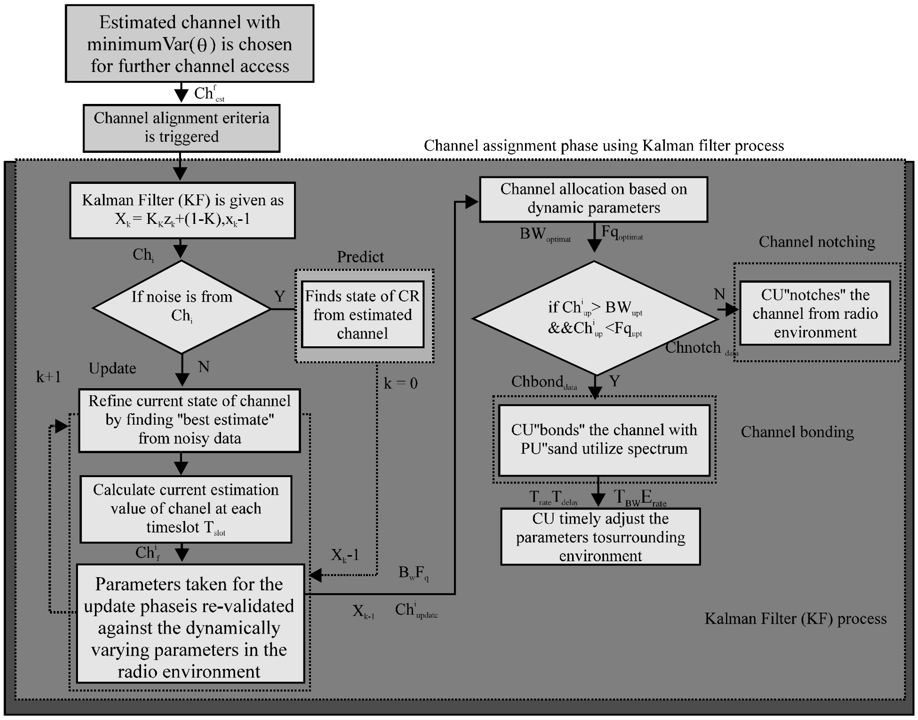


Fig. 10: Process flow for channel assignment using Kalman filter

Again substituting in Eq. 12:

$$P_K = \left(I\text{-}K_K H\right) z_K$$

$$P_K = \left(1\text{-}1.1\right)1$$

$$P_K = 0.091$$

Thus, the current estimation of frequency ($x_K = 0.355$ Hz) of one cognitive user 1 is calculated by applying the above procedure. The remaining cognitive user's frequency values indicate like (i.e., C_2 ($x_K = 0.424$ Hz, $C_5 = 0.442$ Hz, $C_3 = 0.4205$ Hz)). Once primary user appears, cognitive radio will switch to the channel which has optimal bandwidth to resume communication if idle channels exist; otherwise, cognitive radio will keep sensing the spectrum until the next idle channel appears (Fig. 9 and 10).

Bandwidth consideration for channel assignment: Decision making for channel switching takes channel bandwidth into consideration to achieve the best Quality of Service (QoS):

$$\text{Packet} = T^{n}_{\text{remain}} \times BW^{n}$$

$$T^{n}_{\text{remain}} = T^{n}_{\text{IDLE}} - \alpha\left(T_{\text{switch}} - T_{\text{sence}}\right)$$

$$\alpha = \begin{Bmatrix} 1, \text{if channel}\left(\text{Previous}\right) = \\ \text{Channel}\left(\text{Current}\right); 0, \text{else} \end{Bmatrix}$$

$$\text{Channel} = \text{argmax}\left(\text{Packet}\right)$$

where ‘Packet’ means the packet capacity of the channel which performs transmission once and is equal to the product of channel’s remaining idle time (T^{n}_{remain}) and channel’s bandwidth (BW^{n}). If it needs to do channel switch, channel idle time has to subtract switch and spectrum sensing time to calculate the channel remaining idle time. Finally, we will find the channel which has the maximum packet capacity to be our spectrum switch channel. From the predicted state estimate of the channels $\{C_2, C_1, C_5, C_3\}$ which is also known as the a priori state estimate by the above update phase, current priori prediction of channels is combined to refine the current observation of channels $\{C_1, C_3, C_2\}$. The parameters taken for the update phase filtering process is re-validated against the dynamically varying parameters include bandwidth, frequency in the radio environment of particular cognitive users). If the parameters matches with the current observation channel characteristics, Channel $\{C_3\}$ is bonded and to be timely adjusted based on the communication parameters to adaptively react to environmental change to the radio environment. If the parameters doesn’t matches with the current observation Channel $\{C_1\ C_5\ C_2, C_1\}$ characteristics, then the channel arises with channel allocation error and notches the Channel $\{C_1\ C_5\ C_2\}$ from the radio environment. Figure 9 depicts predict and update activity performed using Kalman filter during channel assignment and Fig. 10 depicts the flow model of adaptive channel assignment using Kalman filter.

RESULTS AND DISCUSSION

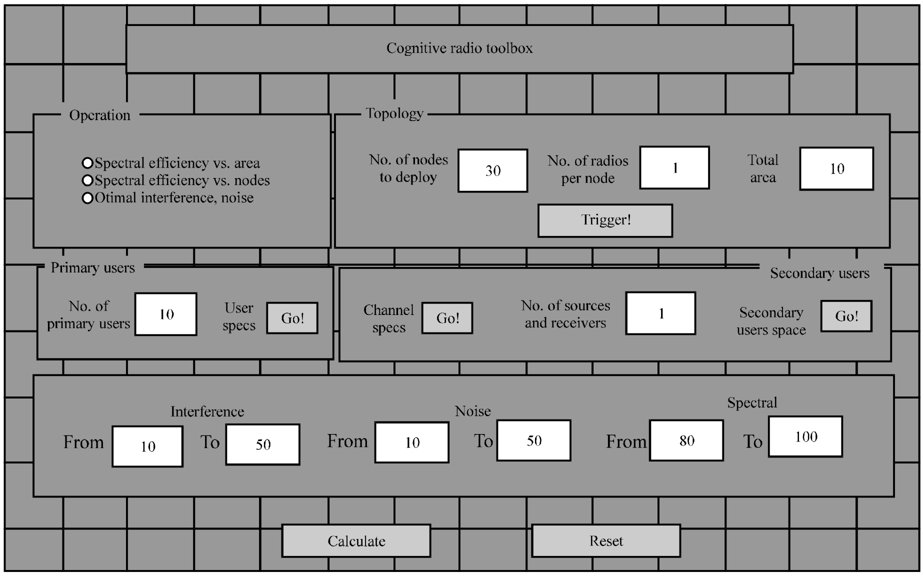
Simulation and experimental analysis: Performance of the proposed MC-OSACA approach is evaluated using a prototype developed in MATLAB. The Graphical User Interface (GUI) tool implemented for the proposed MC-OSACA cognitive radio network Model is shown in Fig. 11. The GUI Specifications consists of the following features.

Operation: This enables the user to select one of the three available modes of operating the interface.

Topology: This decides the topological arrangement of the given number of nodes over a particular area as decided by the mode of operation in combination with user input.

Primary users panel: This study allows the user to input information regarding the primary users and their channel requirements for transmission.

Cognitive radio panel: This study allows the cognitive user to place requests for channel assignment or to



No. of nodes to deploy: 30
No. of radios per node: 1
Total area: 10
No. of primary users: 10
User specs
Channel specs
No. of sources and receivers: 1
Secondary users space
Interference From 10 To 50
Noise From 10 To 50
Spectral From 80 To 100

Fig. 11: The graphical user interface toolbox for MC-OSACA CRN

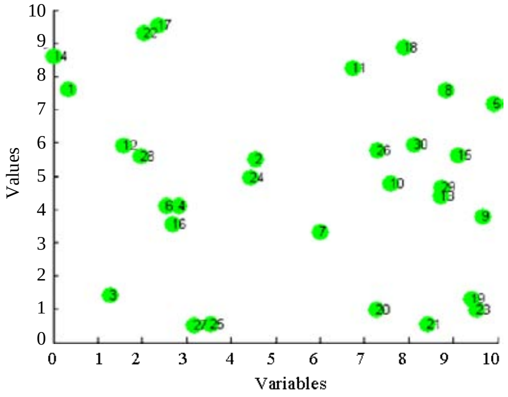
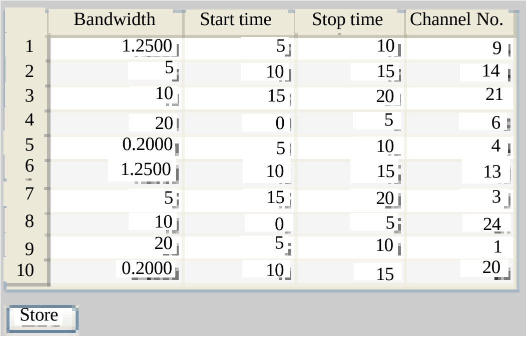
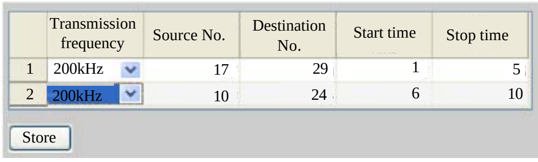


Fig. 12: Topology model of MC-OSACA



	Bandwidth	Start time	Stop time	Channel No.
1	1.2500	5	10	9
2	5	10	15	14
3	10	15	20	21
4	20	0	5	6
5	0.2000	5	10	4
6	1.2500	10	15	13
7	5	15	20	3
8	10	0	5	24
9	20	5	10	1
10	0.2000	10	15	20

Fig. 13: PU specifications



	Transmission frequency	Source No.	Destination No.	Start time	Stop time
1	200kHz	17	29	1	5
2	200kHz	10	24	6	10

Fig. 14: SU specifications

release a cognitive user as per the requirements. The set of 3 radio buttons in the operation module specify the type of operation for the toolbox.

Spectral efficiency vs. area: This allows the user to specify the number of nodes for the network while the area is set by default values.

Spectral efficiency vs. node: This allows the user to specify the area of node deployment for the network while the number of nodes is set by default values.

Optimal interference, noise: This allows the user to specify both, the number of nodes for the network as well as the area for node deployment.

Topology module contains two input fields and two push buttons that takes input on the number of SUs to be deployed and the region over which the nodes are to be deployed. The 'Trigger' button generates a plot of the specified number of nodes deployed over the specified area as shown in Fig. 12.

The primary users module enables the input/edit of the primary user data including number of primary users, their bandwidth, start and stop time of transmission and the channel number over which they are transmitting as shown in Fig. 13.

Secondary users module takes input of the cognitive user, the number of channels theuser wishes to access and the minimum bandwidth requirements of each channel as shown in Fig. 14.

The specification button 'Go' generates a data table to input the specified number of nodes indicating the carrier frequency (in MHz) of transmission of each node allotted to each node. It takes the frequency of transmission, the time slots for transmission, the source and destination node pair details. The execution begins when the user hits the calculate button. Figure 15 illustrates various stages of the MC-OSACA executing process, starting from cooperative channel sensing, estimation and assignment of the most appropriate channels between source and destination for data communication. Figure 16 shows the effective spectrum utilization between PU and SUs using MC-OSACA approach.

The performance of the proposed system is analyzed to identify the effectiveness of spectrum utilization among the PUs and SUs in a multiuser CRN environment. Evaluation is done to detect the sum goodput, i.e., the total amount of data that is successfully delivered per unit time by the PU and SU. Let us consider the CR system for data communication with number of primary users N = 5. Let the secondary users (n) keep increasing ('n' varies from 1-20) based on time variance. The scenario for perfect Primary Radio Detection (PRD) is analyzed first. PRD at the SU and PU indicates that both users have zero interference tolerance, i.e., I = 0. SUs spectrum detection and assignment for a perfect sensing prevents collision among SUs and PUs. The sensing region (R_s) keeps varying thus, the number of SUs increases or decreases as increases or decreases. Assume both SU and PU transmit data at a rate whose probability $\rho = 0.5$ (bps/Hz). Figure 17 displays the sum goodput for increasing cognitive users.

From the results, we can observe that the goodput is maximum for perfect sensing (when $R_s = 2$) as channel estimation and utilization for sucessful data transmisison

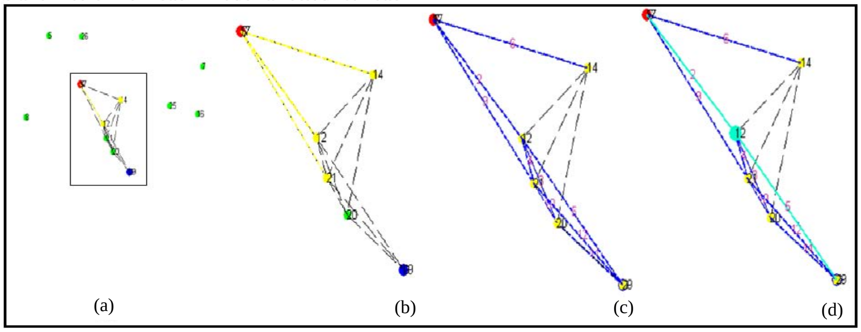


Fig. 15: a) SU senses all channels between source and destination; b) Cooperative sensing using MC-OSACA approach; c) SU identifies idle channels between source and destination and d) Using adaptive channel allocation, most optimal channel is selected between source and destination

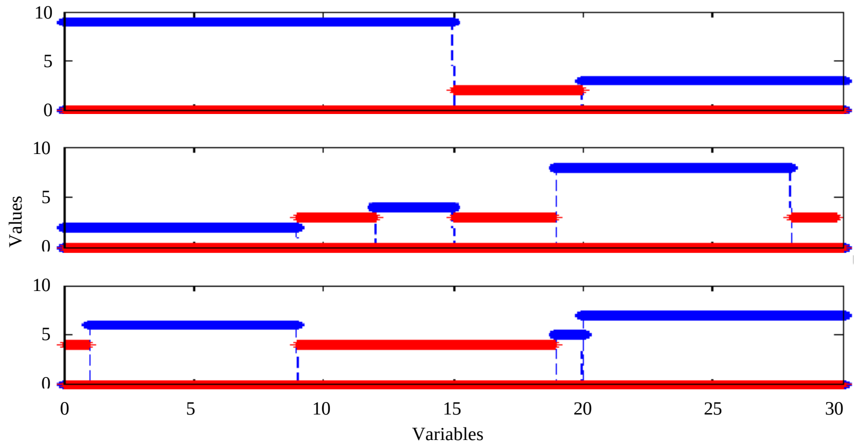


Fig. 16: Spectrum utilization of primary and cognitive user

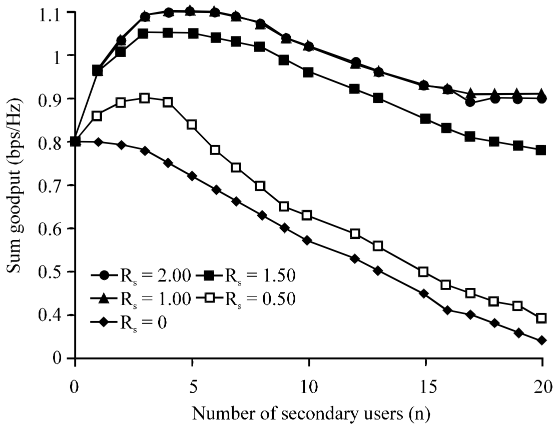


Fig. 17: Sum goodput vs number of secondary users for I = 0

using the proposed approach appripriatly detects PUs and the coexisting SUs in varied time slots. While for R_s = 0 where no sensing is done, goodput reduces causing data loss during transmission due to interference with the PU, i.e., even presence of single SU goes undetected causing interference to busy primary users. Results from the observations indicates that the proposed approach achieves higher goodput through perfect sensing, channel estimation and untilization in a multiuser CRN environment. Additionally from the observation it is identified with moderate sensing R_s = 1 (sensing takes place at both secondary transmitter and receiver), the sum goodput is almost near to perfect sensing as most of the PUs are deteced in such moderate sensing setup.

Figure 18 considers a scenario where the primary and secondary users have a interference tolerance I = 2 (radio interference environment). Observation from the Fig. 18 shows that the sum goodput is lower in interference constrained environment than that for zero interfernce tolerance, i.e., I = 0 setup. Here the optimal sensing region is around 0.65, providing more opportunities for the secondary users for spectrum utilization. This implies that secondary systems make use of the interference level of the primary links to transmit more ferociously. Moreover, from the observation, it’s found that many seconday

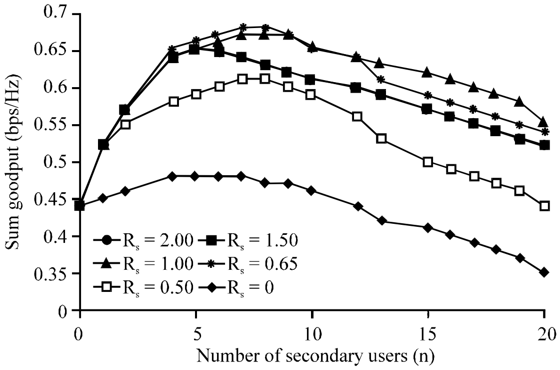


Fig. 18: Sum goodput vs. number of secondary users for I = 2

users are accomodated for the same sensing region. Thus, the effectiveness of MC-OSACA proves to be better in spectrum analytics and channel assignment resulting in successful data transmission improving the goodput in both setup (I = 0 and I>0). The combination of opportunistic spectrum sensing and adaptive channel assignment enhances successful data transmission in a multiuser CR network.

CONCLUSION

Cooperative spectrum sensing is one of the method for cognitive radio selection and realization. Our proposed work uses interveawe technique to scan the spectrum holes dynamically in the presence of multiple primary and secondary users. MC-OSACA creates a combined effort of opportunistic spectrum sensing and adaptive channel assignment. Deep spectrum analaytics using unbiased estimator in a minimum variance factor was conducted throughout our experiment to find out an optimum list of idle channels. These idle channel informations are fed to a second level estimator that infers parameters to predict and update system state. This helps to predict the channels from idle list and assign them dynamically in an adaptive environment for cognitive users. Our theoritical and mathematical analysis helped to conduct a system level simulated experiment to prove the effectiveness of MC-OSACA and its novelty features in spectrum analytics and channel assignment for multiple users. However, MC-OSACA can also be extended using some of the machine learning algorithms and advance classifications to quickly solve the prediction errors that may arise in a severly radio interference environment. Our further research would continue to emphasize on this area and postulate suitable learning algorithms and its impact.

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