Hybrid Common Control Channel Based MAC Protocol for Cognitive Radio Ad-Hoc Networks

Satish Anamalamudi and Minglu Jin

***Abstract*—Multi-channel hidden terminal due to imperfect CR node synchronization is one of the crucial problems in dynamic channel availability of Cognitive radio ad-hoc networks. Most state-of-the-art CR MAC protocols either use "In-band" or "Out-of-band" overlay based common control channel (CCC) design for network setup, CR co-ordination message exchange and CR node synchronization. With In-band CCC, neighbor discovery and network setup time will be very long especially whenever, available PU free spectrum channels are large in number. Moreover, multi-channel hidden terminal problem and node synchronization cannot be effectively resolved due to link based (sequence) and group based CCC design in opportunistic licensed spectrum bands. With out-of-band CCC, network setup with dedicated licensed or unlicensed channel is relatively fast compared with In-band technique. Subsequently, CR node synchronization problem will be reduced due to network-wide coordination (broadcast) without channel switching delay. But, out-of-band Common control channel is subject to saturation, intruder attacks and may have interference with other wireless services which will severely degrade the performance of CR networks. In this paper, hybrid CCC based MAC protocol is proposed to enhance the performance of the CR network with respect to CR node synchronization, multi-channel hidden terminal and network connectivity time. Experimental results show that the performance of proposed hybrid CCC based MAC protocol is out performed compared with existing In-band CCC-MAC protocols with higher PU free channels and saturated unlicensed out-of band CCC-MAC protocols.**

***Index Terms*—Cognitive radio, common control channel, synchronization, multi-channel MAC.**

I. Introduction

Enhanced radio technologies with a wide range of applications operating in different unlicensed spectrum bands result spectral congestion which leads to spectrum scarcity. National Telecommunications and Information Administration (NTIA) spectrum regulatory framework depict that most of the current allocated licensed frequency bands are solely for specific services (static) which shouldn't abrupt by unaccredited users. According to FCC [1], larger portion of the static licensed spectrum band is used sporadically and geographical variations in the usage of allocated spectrum with utilization ranging from 15% to 85% in the bands below 3GHz which shows that, usage of licensed spectrum mainly depends on location and specific wireless technologies.

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Hence, spectrum scarcity is mainly due to inadequate spectrum management polices rather than physical scarcity of its usage. One way to enhance the spectrum utilization is by allowing heterogeneous unlicensed radio services in the licensed spectrum band through dynamic spectrum access (DSA) and opportunistic routing. This brings up the concept of spectrum sharing which allows secondary users to share temporary licensed unused spectrum band (spectrum holes or white spaces) opportunistically without interrupting primary user's communication through Cognitive Radio Technology [2], [3]. With cognitive radio networks, a new approach of spectrum usage has been gaining significant interest to provide a solution for spectral crowding through the opportunistic usage of frequency bands that are not heavily occupied by legitimate users. Common control channel (CCC) plays a pivotal role in providing contention and collision free communication at MAC layer through CR node synchronization. With state-of-the art CCC based CR-MAC protocols, node synchronization cannot be fully accomplished which results multi-channel hidden terminal problem. This paper mainly focus on design of hybrid common control channel based MAC protocol for Cognitive radio ad-hoc networks to avoid multi-channel hidden terminal problem through CR node synchronization and co-ordination, robust to PU activity and reduced network setup time. The rest of the paper is organized as follows. Section II explains about related works with pros and cons of existing CR-MAC protocols. Section III discuss about proposed "hybrid common Control Channel based MAC protocol for Cognitive radio ad-hoc networks". Section IV describes about experimental results and Section V ends with conclusion and future work.

II. Related Works

In IEEE 802.11 multi-channel networks [4], one dedicated common channel is assumed to be available for entire network during control timeslot. Nodes which have data to transmit will contend and reserve the channel. Subsequently, data will be transmitted on selected unlicensed channels during data timeslot. Cognitive radio MAC protocol also operates similar to multi-channel wireless networks with the exception of unlicensed channel usage. Hence, it is difficult to select dedicated common control channel in CR networks. Hence, design of common control channel in the licensed PU free channel is more complex and utmost important for network setup, CR co-ordination message exchange and node synchronization to avoid multi-channel hidden terminal problem. There are many publications regarding common control channel design for Cognitive Radio MAC protocols.

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In [5], common control channel design is classified into two groups namely underlay and overlay. In underlay based approach, common control channel can design within the same channel used by PU through spread spectrum technique. But, there are lots of issues with this approach due to interference with simultaneous primary data transmission. Overlay approach is further divided into two sub-groups namely In-band (local) and Out-of-band (global) [5]. Most state-of-the-art MAC protocols either use In-band or out-of-band overlay based approach to design common control channel. [6]-[10] uses out-of-band technique for network setup and node co-ordination message exchange.

A. Out-of-Band Based CCC Design

In out-of-band, usually licensed or unlicensed predefined channel will be used as a common control channel to establish network setup, node coordination and synchronization. Hence, global connectivity is maintained during control message exchange which is relatively easy to establish and maintain network connectivity in heterogeneous licensed spectrum nature of CR networks. This in turn leads to less control signaling overhead which will enhance the performance of the CR MAC protocol. That's why, most of the existing CR-MAC protocols use unlicensed (2.4 GHz) common control channel for network setup, node synchronization and node co-ordination. But, unlicensed dedicated common control channel may be subject to interference with other communications like Bluetooth, sensor and IEEE 802.11 networks which will severely degrade the performance of CR networks [11]. Moreover, relay on single dedicated common control channel will be subject to security attacks like control channel jamming and Denial of service attacks (DoS) which may destroy the entire network with single point of failure [12]. Thus, designing common control channel through out-of-band technique has lot of issues with respect to security attacks, channel saturation and interference with other technologies.

B. In-Band Based CCC Design

In In-band CCC design, same spectrum band is allocated for both application data and control message exchange at different intervals of time i.e. common control channel is selected among the set of PU free licensed channels [5]. Currently, sequential and group based common control channel design is proposed for node co-ordination and synchronization to avoid multi-channel hidden terminal problem. In sequential based network setup, CR nodes have to first sense free channel list and scan each and every channel to find the common channel which takes long time for network connectivity[13]-[16]. Moreover, sequential CCC coverage is limited to transmitting and receiving nodes. Hence, each and every communicating node pair will have a different common control channel which is very crucial for neighbor discovery, co-ordination message exchange and synchronization. Moreover, In-band based CCC design is susceptible to PU activity i.e. CR node has to dynamically switch to another PU free channel whenever, primary user is active in current licensed incumbent channel. Thus, node synchronization is very complex because each and every CR node pair listens and communicates in different channel pair which leads to multi-channel hidden terminal problem which is shown in Fig. 1.

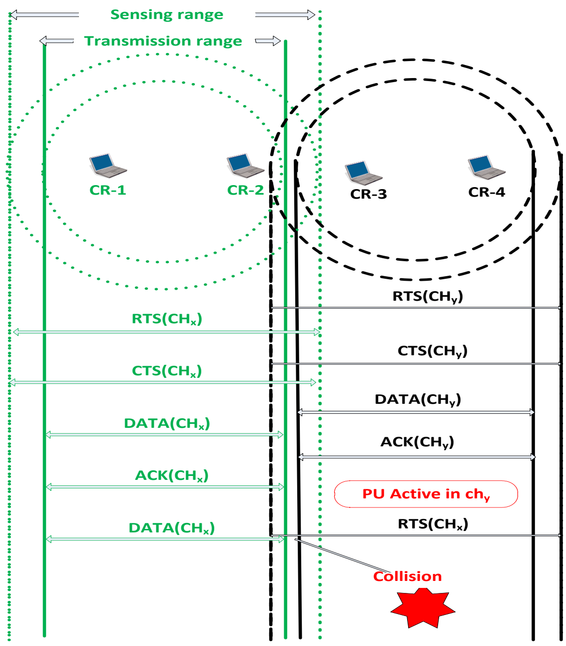

Fig. 1. Multi-channel hidden terminal problem in sequential CCC based MAC.

This in turn leads to high control signaling overhead which severely degrades the performance of MAC protocol. In group based CCC [17], [18], [19], [20], a common PU free channel for set of CR nodes (clusters) within a coverage area is selected as a control channel for control message exchange during beacon period (BP). But, group based CCC is operated on licensed incumbent channel which is susceptible to PU activity. That is CR nodes have to find another rendezvous channel and establish network connectivity from base which results high control overhead. This approach is non-resistant to RC jamming which is easy for intruders to target RC for single point of network failure. To overcome the drawbacks in existing solutions, this paper proposes a hybrid CCC based CR-MAC protocol which avoids multi-channel hidden terminal through the combination of both global and local CCC coverage. The main contribution of this work is fourfold; 1) reduced network connectivity time 2) robust solution for node synchronization and multi-channel hidden terminal 3) highly resistant to PU activity and 4) strong protection against jamming attacks.

III. Proposed Work

Hybrid CCC based CR-MAC works under half duplex radio i.e. each and every CR node either transmit or receive in the communication channel. In addition, terminals can carrier sense in one channel at a time.

A. System Model

In proposed System, Cognitive radio ad-hoc network is deployed within the primary network where SUs operate on PU free spectrum bands.

Let $k = \{1, 2, 3 \ldots\ldots K\}$ be the number of SU nodes.

Let $N^{[K]}$ be the total number of licensed channels at node 'K'.

Let V be the node-channel matrix of the whole CR network, i.e. $V = \left[V^{[1]} V^{[2]} V^{[3]} \ldots\ldots\ldots\ldots V^{[K]}\right]$

$$\text{where} \quad V^{[K]} = \begin{bmatrix} V^{[K]}_{[1,1]} & \cdots & V^{[K]}_{[1,N^{[1]}]} \\ \vdots & \ddots & \vdots \\ V^{[K]}_{[K,1]} & \cdots & V^{[K]}_{[K,N^{[K]}]} \end{bmatrix}$$

Here $V^{[K]}$ is the $K \times N^{[K]}$ matrix at K^{th}-node whose row represents SU nodes and column represent the channel number of SU nodes.

$V^{[K]}_{[i,j]} \rightarrow j^{th}$ channel of i^{th} node at K^{th} node location.

$V^{[K]}_{[i,j]}=0 \rightarrow j^{th}$ channel of i^{th} node is PU active.

$V^{[K]}_{[i,j]}=1 \rightarrow j^{th}$ channel of i^{th} node is PU free.

B. Network Setup and Neighbor Discovery

In traditional ad-hoc networks, node communicates to network through dedicated common control channel during network setup. With dynamic channel availability of CR networks, it is not possible to assign dedicated CCC for network setup, node synchronization and channel list exchange.

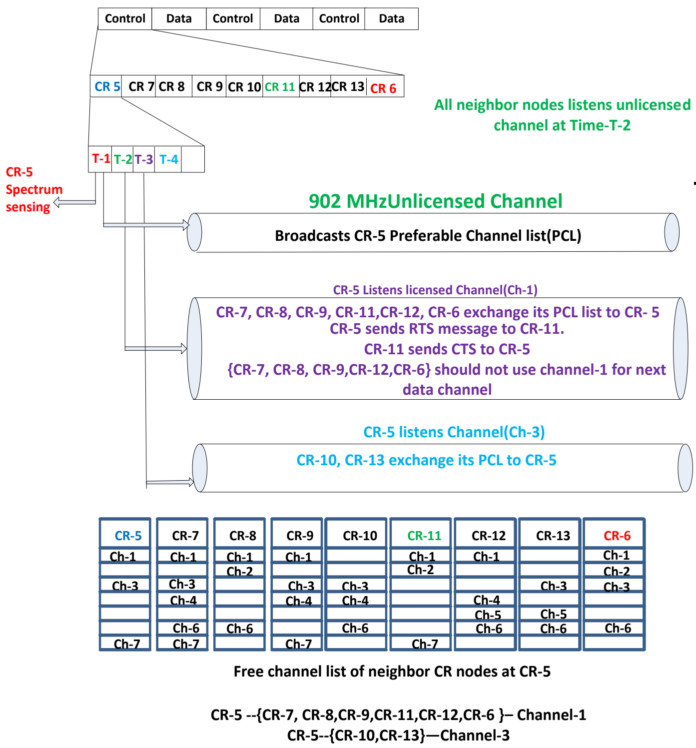

Fig. 2. Operation of hybrid CCC based MAC protocol.

In proposed work, communication timeslots are split into control and data time frames. Control slots are further divided into 'N' number of sub-frames where 'N' is equal to current number of communicating CR nodes. In 1st sub-frame, transmitter (CR5) sense its free channel list at time 'T1' and disseminate its preferable channel list (PCL) in 902 MHz unlicensed spectrum at 'T2'. Nodes other than transmitter listens 902 MHz unlicensed channel and receives transmitter's PCL at T2. Whenever, new node wants to join it has to sense PU free channel list, make PCL and listen 902 MHz channel during T2. During T3, CR5 listen its first preferable channel (ch1). Neighbors who have common preferable channel (ch1) with CR5 will exchange its PCL to CR5 (Fig. 2). Subsequently, CR5 listen its whole PCL for neighbor discovery.

Algorithm: 1: CR-MAC Neighbor discovery

```
K^th node spectrum sensing on N^[K] channels.
PU free channel list ← n^[K] ; where n^[K] ≤ N^[K]
    for (i=0; i< N^[K]; i++)
        if (i== PU_free) then
            V^[K]_[K,i] =1
        else V^[K]_[K,i] =0;
        end if
    end for
902 MHz ← Broadcast(Beacon + ⋃_{i=1}^{N^[K]} V^[K]_[K,i] )
⋃_{i=1}^{k-1} V^[i] ← Receive(Beacon + ⋃_{i=1}^{N^[K]} V^[K]_[K,i] )
    for(p=0; p<k; p++)
        for(j=0; j< N^[K]; j++)
            V^[p]_[K,j] ← V^[K]_[K,j]
        for end
    for end
```

Algorithm 1 briefly explains about the operation of neighbor discovery in proposed hybrid CCC based MAC protocol. In this paper, unlicensed 902 MHz is used only at Time 'T2' period. Licensed preferable common channel is used for subsequent control message to exchange PCL and neighbor discovery (T3-Fig. 2).

C. Virtual Carrier Sensing and CR Node Synchronization

Once transmitter receives the PCL from neighbor nodes during 'T3' it checks requests for data transmission from upper layers. Whenever, transmitter (CR5) has data to its neighbor, it broadcast RTS message in current licensed common control channel. Subsequent CTS message will be transmitted back from receiver whenever, it agree to transmit data in current common channel. Neighbors who have the same common control channel will update its network allocation vector so that current common control channel is allocated as a data slot for transmitter (CR5) and its neighbor (CR11). In subsequent time periods, Transmitter (CR5) will get whole network channel list information. This process will continue for next 'N-1' sub-frames and every node within the network will have complete network information with them. Virtual carrier sensing helps to reduce collisions due to multi-hidden terminal through node synchronization. Algorithm 2 shows the operation of virtual carrier sensing and node synchronization in proposed algorithm.

Algorithm: 2: Virtual carrier sensing(RTS/CTS) & CR node synchronization

for (i=0; $i< N^{[K]}$; i++)
  if($V^{[K]}_{[K,i]}$ ==1) **then**
    Kthnode ←Listens $V^{[K]}_{[K,i]}$ //PU$_{\text{free-channel}}$
    for(p=0; p<k; p++)
      for(j=0; $j< N^{[K]}$; j++)
        if($V^{[K]}_{[K,i]}$ && $V^{[p]}_{[p,j]}$ ==1) **then**
          $V^{[K]}_{[p,j]} \leftarrow V^{[p]}_{[p,j]}$
          if ('Node-K' User data = = True) **then**
            $V^{[K]}_{[p,j]}$ broadcast K$_{RTS}$→ $V^{[p]}_{[p,j]}$
            $V^{[K]}_{[p,j]}$ receive P$_{CTS}$ ← $V^{[p]}_{[p,j]}$
            $\bigcup_{i=1}^{k-1} V^{[i]} \leftarrow$ NAV $_{\text{Update}}$
          if end
        if end
      for end
    for end
  if end
for end

During data transmission period, every node has the information about which CR node is using which channel through RTS/CTS message that is shown in Algorithm.2. Common channel Scan Algorithm is proposed to collect information about nodes that are having same common channel. This helps to select backup or recovery channel during PU active in current CR transmission. After data transmission period, nodes in the control slot will be right shifted to get equal priority for all nodes to contend the next data slot.

D. Incumbent Protection

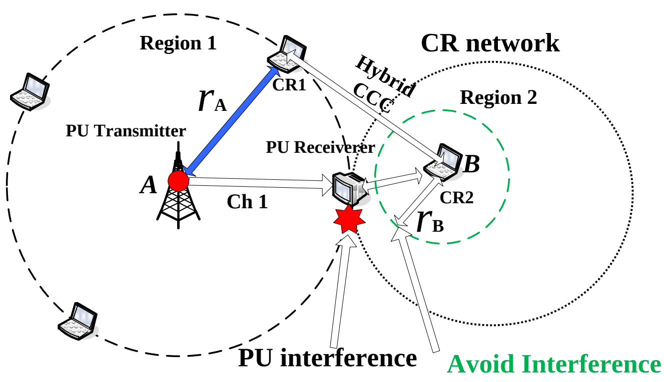

Fig. 3. Hidden terminal scenario in between PU and CR nodes.

In opportunistic spectrum Access, CR node data transmission is possible only when PU is inactive whereas, in spectrum sharing both PU and CR nodes can perform data transmission at the same time with a different input transmit powers until QoS of PU transmission is not degraded with CR interference. In both cases, PU receiver protection is crucial which mainly depends on control channel design. The scenario where PU receiver will have interference with CR is shown in Fig. 3. This paper presumes that at least one node (CR1) is aware of PU transmitter location, transmitting power and its transmitting range through spectrum sensing which exchange with CR2 during control slot via hybrid control channel. Subsequently, CR2 runs power control algorithm based on interference radius of region1 and control transmit power of CR data channels to protect interference with PU receivers.

The distance between A and CR1 is given by,

$$Distance = R \times arccos(C)$$

$$C = \begin{pmatrix} sin(LatA)sin(LatB) + \\ cos(LatA)cos(LatB)cos(LonA - LonB) \end{pmatrix}$$

$$AB = \begin{pmatrix} R \times \arccos[sin(LatA)sin(LatB) + \\ cos(LatA)cos(LatB)cos(LonA - LonB)] \end{pmatrix} \quad (1)$$

In general, location (latitude and longitude) of PU receiver and CR2 is available through GPS of any point. Therefore, we can use the distance formula to get the AB distance based on GPS techniques. 'r_A' and 'r_B' represents the radius of PU and CR transmission coverage area. The distance between "close but not overlap" in between PU and CR2 is given as

$$r_B \le AB - r_A \quad (2)$$

The equality form of (2) expression is given as

$$r_B = AB - r_A - \varepsilon \quad (3)$$

where $\varepsilon \ge 0$ is a power controller which can change the power range according to the application. Here, we give a theory unbound of r_B, when $\varepsilon = 0$

$$r_{B-upbound} = AB - r_A \quad (4)$$

From (3), one can obtain the non-interfering transmission range of CR2. Node can transmit as long as interference caused to the PU receiver is below the threshold level. Whenever, there is unavoidable CR interference with PU then it needs to vacate the current communication channel and communicate in another vacant channel. In most of the proposed protocols, CR needs to scan again in each and every channel to get connected during PU activity. This scenario has two problems- (1) Protocol control overhead will be increased, (2) TCP congestion window should start again from the first which will severely degrade the performance of CR MAC protocol. Our proposed work will abbreviate above two steps because each and every CR node has complete channel table information of the entire network and backup channel is selected during control time slots. Whenever, PU is active, secondary user will switch to backup channel and continue communication during current data slot. Whenever, CR doesn't have common backup channel during current data slot then it has to wait for next control slot and contend for channel to communicate.

Algorithm: 3: PU receiver protection

1: Spectrum sensing on $V_{[p,i]}^{[K]}$
2: **if**($V_{[p,i]}^{[K]}$ = =PU$_{\text{Active}}$) **then**
3: $V_{[p,i]}^{[K]}$=0; // Vacate PU channel
4: **for**(i=0;i< $N^{[K]}$; i++) //check for **another PU**
5: **if**($V_{[p,i]}^{[K]}$ && $V_{[K,i]}^{[P]}$ = =1) **then**
6: Spectrum sensing on $V_{[p,i]}^{[K]}$, $V_{[K,i]}^{[P]}$
6: **if**($V_{[p,i]}^{[K]}$ && $V_{[K,i]}^{[P]}$ ==PU$_{\text{free}}$&&SU$_{\text{free}}$) **then**
7: $V_{[p,i]}^{[K]}$ broadcast K$_{\text{RTS}}$→ $V_{[K,i]}^{[P]}$
8: $V_{[p,i]}^{[K]}$ receive P$_{\text{CTS}}$ ← $V_{[K,i]}^{[P]}$
9: $V_{[p,i]}^{[K]}$ ←Data/ACK→ $V_{[p,i]}^{[K]}$
10: **elseif**($V_{[p,i]}^{[K]}$ && $V_{[p,i]}^{[K]}$)!=(PU$_{\text{free}}$&&SU$_{\text{free}}$) &&(i< $N^{[K]}$))
11: **Go** to step : 4
12: **end if**
13: **end if**
14: **end for**
15: **end if**

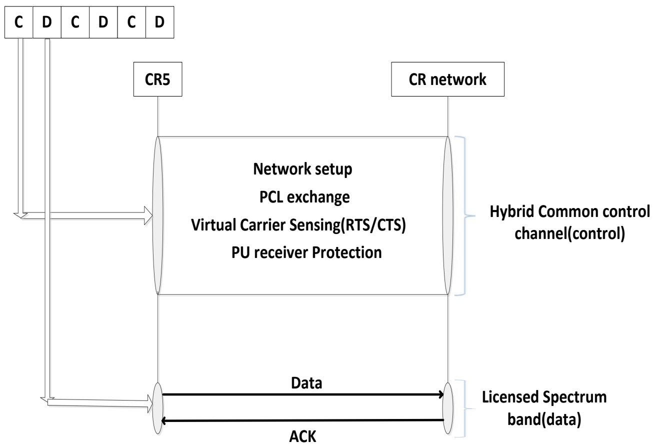

Fig. 4. Control and data slot scenario in CR-MAC protocol.

Algorithm 3 depicts the procedure to select new control channel during PU activity. With proposed method, control signal overhead will be minimized which results in enhanced network throughput. Moreover, proposed hybrid MAC protocol is highly resistant against intruder attacks because licensed common control channel is dynamically selected in every control slot. Figure.4 shows the control and data slot operation in proposed MAC protocol. Performance of CR-MAC is compared with aggregate network throughput and average network delay with respect to data rate per flow. Aggregate throughput network formulae are derived to know the upper threshold value of maximum throughput at different data rates (5).

$$Throughput_{\max} = \left(\frac{T_{Data}}{Delay}\right) = \left(\frac{T_{Data}}{T_{\mathrm{Prop}} + T_{PUfreeChannelTable} + T_{DCF}}\right)$$

$$Throughput_{\max} = \left(\frac{T_{Data}}{T_{DCF} + T_{PUfreeChannelTable}}\right)$$

$$T_{DCF} = \left\{\begin{matrix} T_{RTS} + T_{SIFS} + T_{CTS} + T_{SIFS} + \mathrm{T}_{DATA} + T_{SIFS} + \\ T_{ACK} + T_{DIFS} + T_{Backoff} \end{matrix}\right\}$$

$$T_{DCF} = \left\{\begin{matrix} T_{RTS} + T_{SIFS} + T_{CTS} + T_{SIFS} + \left(T_{PR} + T_{PHY} + \frac{8(L_{MAC} + MSDU)}{Datarate}\right) + T_{SIFS} \\ + \left(T_{PR} + T_{PHY} + \frac{8 * L_{\mathrm{ACK}}}{Datarate}\right)? + *T_{slotTime} + T_{SIFS} + \left[\frac{(CW_{min} * T_{slotTime})}{2}\right] \end{matrix}\right\}$$

$$T_{PUfreeChannelTable} = \left\{T_{PR} + T_{PHY} + \frac{8(n * L_{PUfreeChannelTable} + L_{senderIP} + L_{senderMAC})}{Datarate}\right\}$$

$$Throughput_{\max} = \left\{\frac{T_{Data}}{\left(\begin{matrix} T_{PR} + T_{PHY} + \frac{8(n * L_{PUfreeChannelTable} + L_{senderIP} + L_{senderMAC})}{Datarate} + T_{RTS} \\ + 4 * T_{SIFS} + T_{CTS} + 2 * (T_{PR} + T_{PHY} + T_{slotTime}) + \frac{8(L_{MAC} + MSDU + L_{\mathrm{ACK}})}{Datarate} \end{matrix}\right)}\right\}$$

$$\mathrm{C}W_{min} = 31, T_{slotTime} = 20\mu s, T_{DIFS} = 50\mu s, T_{SIFS} = 10\mu s$$
$$T_{SIFS} = 10\mu s, T_{PR} = 144\mu s, T_{PHY} = 48\mu s, L_{MAC} = 34 bytes, L_{DATA\_payload} = 0 - 2312 bytes.$$

$$L_{ACK} = L_{CTS} = 14 bytes, T_{CTS} = T_{PR} + T_{PHY} + \frac{8 * L_{\mathrm{CTS}}}{ACKrate}$$
$$T_{Backoff} = 310\mu s$$
$$L_{RTS} = 20 bytes, T_{RTS} = T_{PR} + T_{PH} + \frac{8L_{RTS}}{RTSrate}$$
$$L_{PUfreeChannelTable} = 12 bytes$$

$$Throughput_{\max} = \left\{\frac{T_{Data}}{\left(1872 + \frac{8(L_{MAC} + MSDU + L_{\mathrm{ACK}})}{Datarate}\right)}\right\} // PU = 5 channels$$

Maximum Theoretical Throughput with respect to data rate

$BandwidthTVWS(MHz)$	8	8	8	8	8	8	8	8
$PHYrate(Mbps)$	1	1	2	2	5.5	5.5	11	11
$Datasize(bytes)$	512	1024	512	1024	512	1024	512	1024
$ThroughputMax(Mbps)$	0.64	0.79	1.01	1.35	1.53	2.5	1.9	3.24

(5)

In proposed work, five and ten 8-MHz interleaved TV white space channels are selected from available 32 channels in 400 MHz spectrum band [21]. In order to reduce ARP (Address resolution protocol) broadcast overhead, proposed MAC includes IP address to its corresponding MAC address in its channel table. Maximum achievable throughput with respect to different data rate and packet size is shown in (5). This helps us to determine the upper threshold throughput that helps to reduce the collision rate. Moreover, from Shannon's channel capacity it is clear that SNR is directly related with data rate. Hence, increasing data rate needs higher input transmit power at sender nodes to achieve desired SNR at the destination. In CR networks, secondary transmission power shouldn't interfere with primary transmission which needs to use low transmission power at sender. Hence, 8 MHz with 2 Mbps data rate is selected for data and control transmission in the proposed work. Achievable throughput in practical networks might be lesser than theoretical throughput. This is due to increase in control signal overhead with respect to hidden terminals and PU activity.

IV. Experimental Results

Cognitive radio network simulator (NS-2.31) is used to implement and simulate proposed hybrid CCC based MAC protocol. This work is an enhancement of multi-channel MAC protocol at 400 MHz TVWS (8 MHz channel) with primary user implementation extension. Aggregate network throughput with respect to number of packets per second (or) data rate is used to check the performance of proposed MAC protocol in primary user network. Subsequently, average packet delay with respect to data rate is compared with unlicensed common control channel based MAC and licensed sequential based CCC MAC under PU active state. CR network is simulated with 10 primary users and 100 CR nodes in 5 PU channels. Number of flows in our scenario is considered as 50. Initially, we assume that each channel contains 2 primary and 20 secondary users. During simulation, CR nodes can move to inter channel signal range. In addition, during start of simulation we assume that CR nodes are out of coverage to PU users in every channel. Total simulation time is 50 seconds whose data transmission among CR nodes starts at 9seconds and primary user will be active at 15seconds with spectrum occupancy probability 0.2.

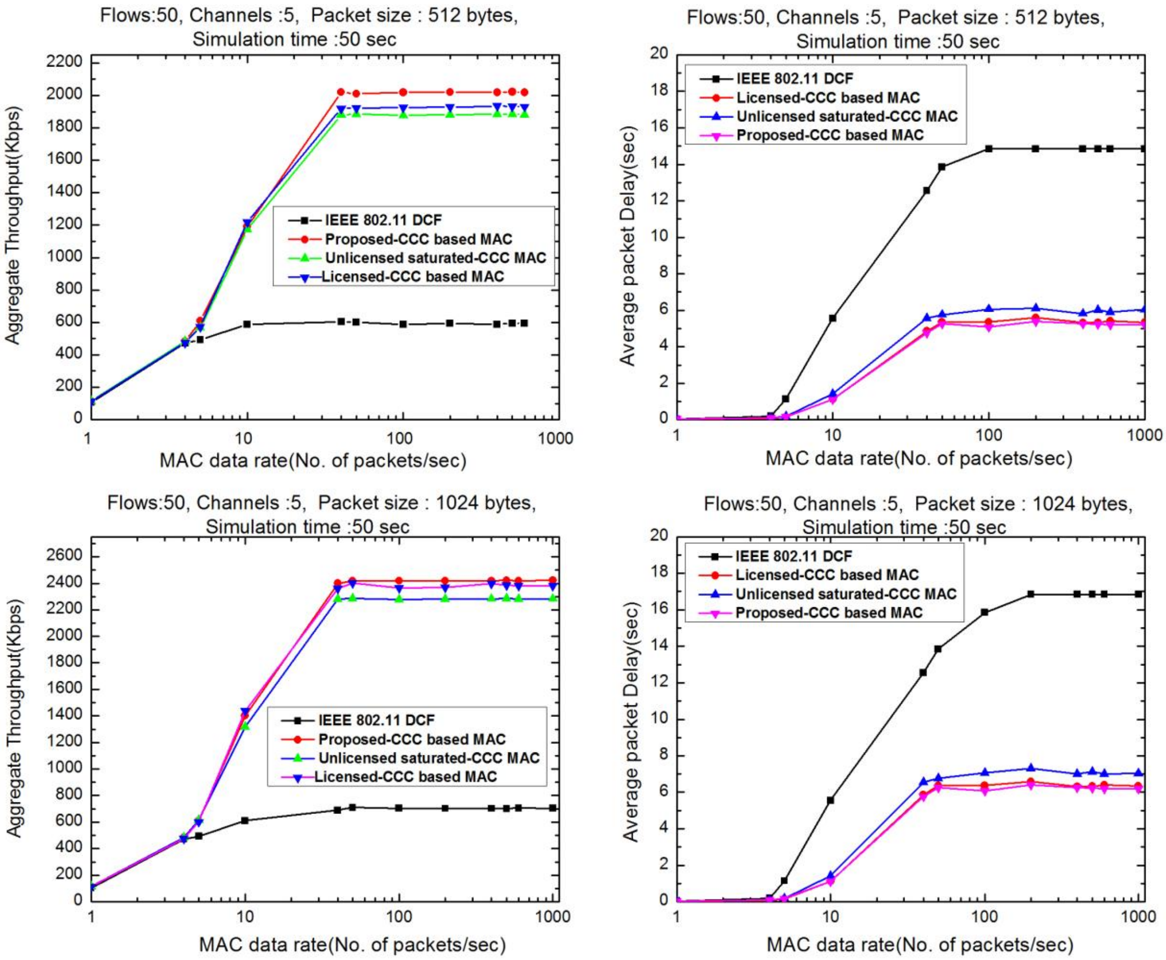

Fig. 5. Aggregate network throughput and average packet delay with respect to data rate in 5-channels.

Performance of Hybrid CCC based MAC is compared with aggregate network throughput with respect to data rate (No. of packets/sec) for different packet sizes and PU spectrum occupancy rate. Subsequently, average packet delay with respect to data rate is compared for heterogeneous packet size. In addition, proposed MAC is compared with existing licensed (In-band sequential) CR-MAC and Unlicensed (out-of-band) saturated CR-MAC protocols. Initially, PU spectrum occupancy rate at each channel is selected as 0.2 at 15th sec. Top left most graph of Figure.5 explains about aggregate network throughput with respect to data rate for 5 channels (8 MHz) with 512 byte CBR data. Since, IEEE 802.11 networks operate on single channel MAC protocol, aggregate network throughput is very less compared with multi-channel MAC protocols. For unlicensed saturated CCC MAC protocol, achieved aggregate network throughput is comparatively less compared with licensed and proposed CR MAC because of interference with other technologies like 802.11 networks, Bluetooth and sensor networks in 2.4 GHz control channel. In-band (Licensed) CCC MAC throughput is almost same as proposed CR MAC for 5 (8 MHz) TVWS spectrum band. This is because of time taken to scan and re-establish the path is less for fewer channels. Bottom left most graph of Figure.5 explains about aggregate network throughput with respect to data rate for 5 channels (8 MHz) with 1024 byte CBR data. Aggregate network throughput for 1024 bytes is higher than 512 bytes due to reduced protocol control overhead which can be theoretically compare with (5).

Top rightmost graph of Fig. 5 explains about average packet delay with respect to data rate for 512 byte CBR data in five 8 MHz TVWS. For single channel IEEE 802.11 networks, nodes have to contend and share single channel which has relatively higher delay compared with multi-channel MAC protocols. Average packet delay for licensed CCC and proposed CCC MAC is almost same whereas unlicensed saturated CCC based MAC has a relatively higher delay due to higher collision rate. Bottom right most graph of Fig. 5 shows average packet delay with respect to data rate for 1024 byte CBR data in five 8 MHz TVWS.

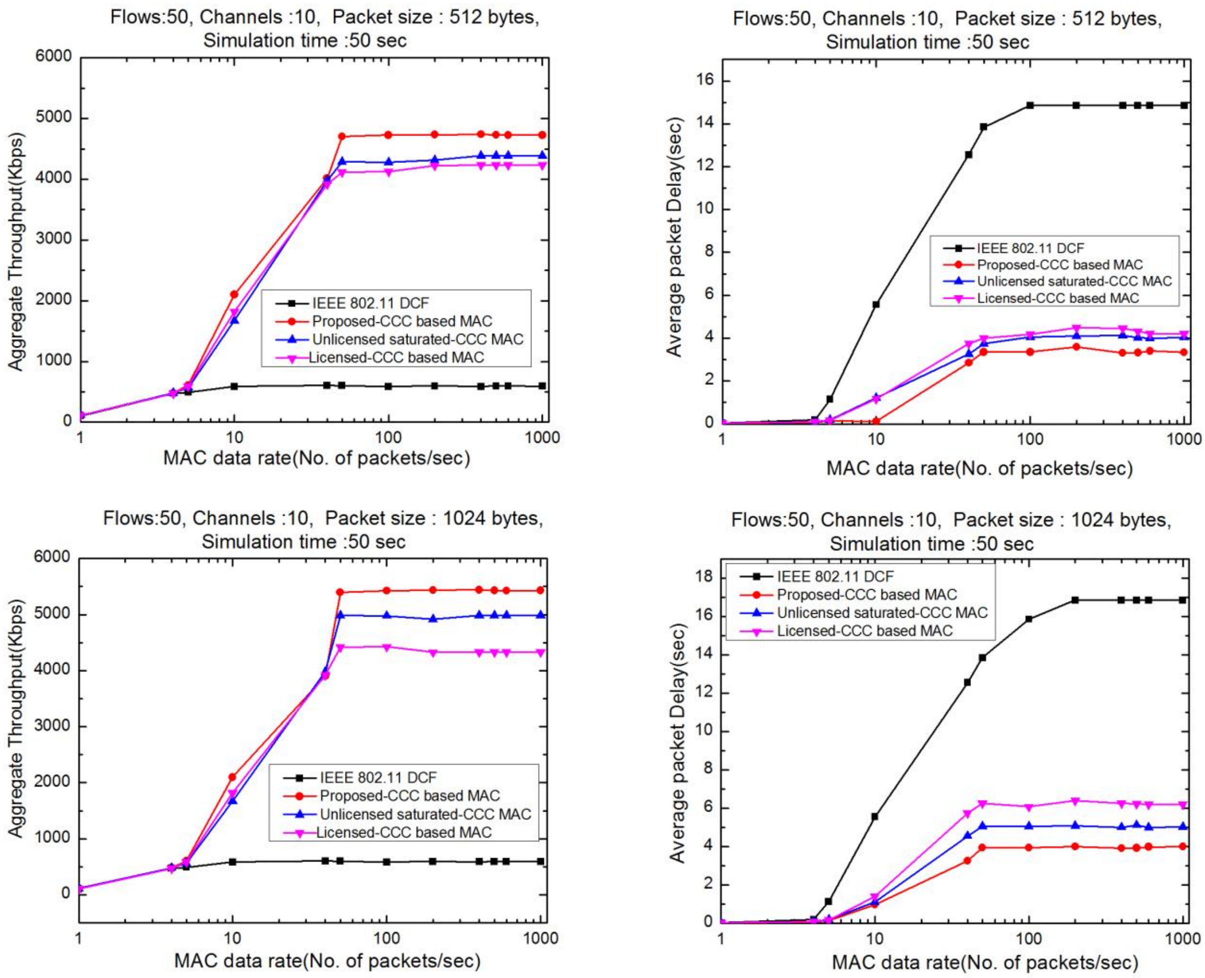

Fig. 6. Aggregate Network throughput and Average packet delay with respect to data rate in 10-channels.

In comparison with an average delay for 512 bytes, it is clear that 1024 bytes have comparatively higher packet delay due to longer byte data transmission. Hence, with 1024 byte data transmission aggregate network throughput increases whereas packet transmission and propagation delay also increases which results higher end-to-end delays. Top left most graph of Figure.6 shows the aggregate network throughput with respect to packet arrival rate (data rate) for ten 8-MHz channels in the TVWS spectrum band. Initially, 512 byte CBR data is generated at 9 sec. First flow starts at 9 sec whereas subsequent flows start after every 0.1 sec. Whenever, PU is active at all channels in 15th second, CR nodes try to find different channel from channel table and get connected for further communication. PU occupancy rate at 15th second is considered as 0.2 which explains PU coverage CR nodes to alleviate current channel or reduce input transmit power to avoid interference and collisions with PU communication. As the number of channels increases, aggregate network throughput will manifestly increase due to accumulated channel capacity from heterogeneous channels.

Hence, aggregate throughput in top left most graph of figure.6 is approximately double when compared with 5 PU channel throughput in top left most graph of figure.5. However, aggregate throughput for licensed (In-band) CCC based MAC is much less than proposed CR MAC. This is because when the number of channels is getting higher, time taken to find common control channel for channel table exchange, node synchronization and channel contention is high. Hence, signal overhead will be higher which results reduced aggregate network throughput that is clearly shown in top leftmost graph of figure.6. In general, unlicensed CCC based MAC protocol outperforms even proposed MAC when the unlicensed control channel is not saturated. But, it is more likely to have saturated because of heterogeneous data transmissions from different applications. Hence, saturated licensed CCC based MAC has lower aggregate throughput compared with proposed and licensed CCC based MAC. In bottom left most graph of Figure.6, aggregate network throughput is calculated for 1024 byte CBR data.

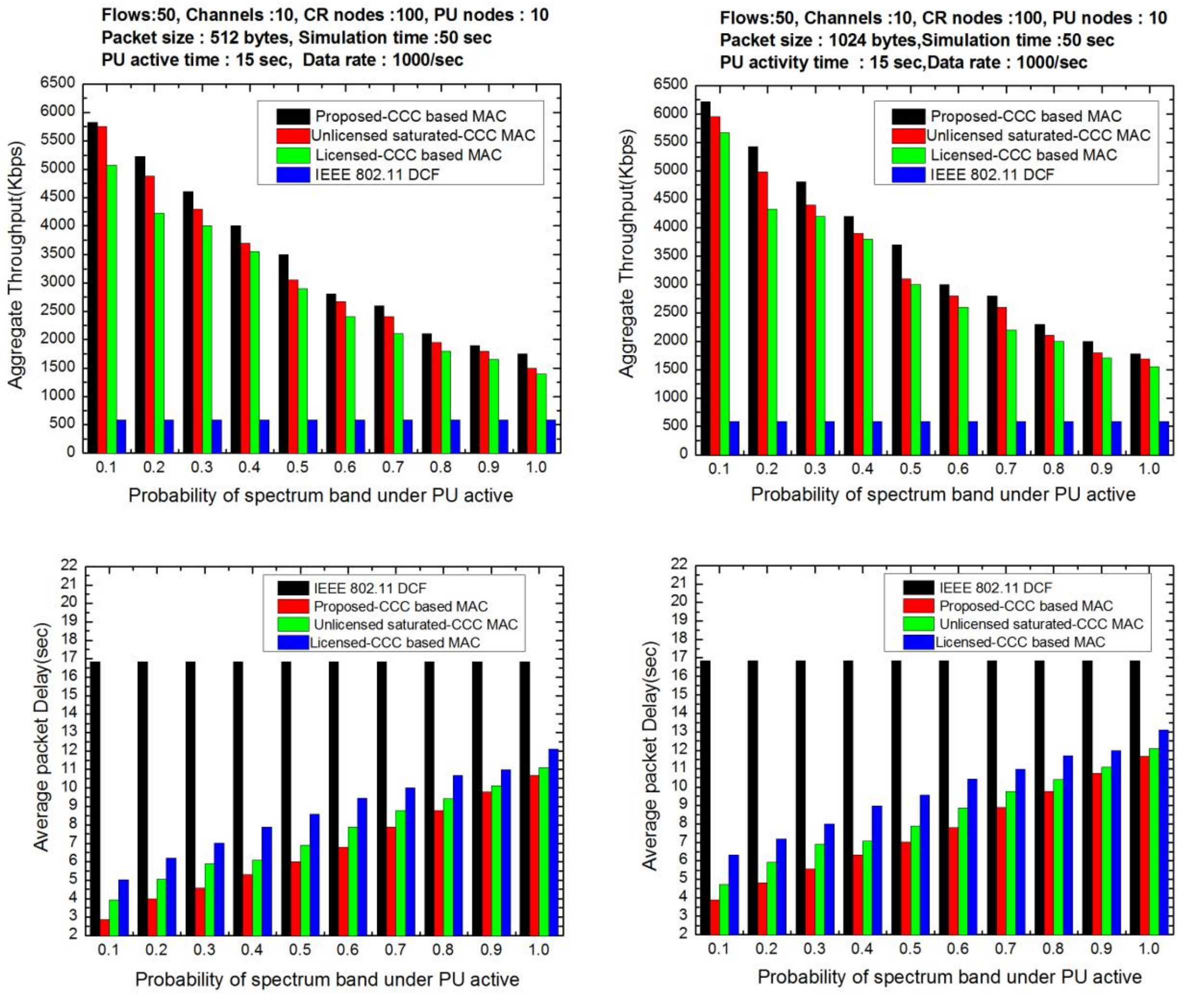

Fig. 7. Aggregate network throughput and average packet delay with respect to probability of PU spectrum occupancy rate.

This is illustrated to compare the aggregate throughput in between 512 and 1024 byte CBR data for 10 TVWS. Top left and rightmost graph of Figure.6 explains about average packet delay with respect to data rate for 512 and 1024 byte data. As the number of channels increase, network load will be shared among all channels which reduce average packet delay. But, packet drops due to dynamic PU active will results additional signal overhead which will often increases average packet delay. In addition, whenever packet size increases, time taken to reach from sender to receiver will also increases which results increased channel access time for other flows. That's why; average packet delay for 1024 bytes CBR data is higher than 512 byte CBR data transmission. Figure.7 shows how aggregate network throughput degrades and average packet delay increases when the PU spectrum occupancy increases from probability 0.1 to 1. In our scenario, spectrum occupancy rate corresponds to PU active region in its total coverage area. Initially, PU is active for probability 0.2 at 15 sec. Subsequently, its occupancy is increased to entire PU channel coverage area through dynamic PU active. Aggregate network throughput is very less whenever; PU occupancy rate is 1 due to frequent PU node active in its licensed spectrum band. With experimental results, it is clear that our proposed MAC contribution outperforms even in high dynamic PU activity compared with licensed CCC based MAC and unlicensed saturated CCC based MAC protocol.

V. Conclusion and Future Work

In order to enhance the performance of CR based MAC protocol, it is crucial to avoid collisions due to multi-channel hidden terminal (node synchronization), reduce network setup time (Control signal overhead), robust to PU activity and protection against intruders. Proposed hybrid CCC based MAC protocol provide solutions for above problems to enhance the performance of CR-MAC protocol. In proposed work, combination of 902 MHz and TVWS spectrum band (420 MHz) is used as a control channel for channel table exchange, node synchronization and dynamic PU activity. Theoretical upper bound for achievable throughput is calculated to compare the collision rate during simulation. From experimental results it is clear that the proposed methodology outperforms compared with licensed CCC based MAC and unlicensed saturated CCC based MAC protocol. In future, performance metrics of proposed IOB-CCC based MAC protocol is going to check with twenty and twenty-five 8-MHz channels and compare with sequential licensed based and dedicated-CCC based CR MAC protocol.

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REFERENCES

[1] D. Cabric, S. Mishra, D. Willkomm, R. Brodersen, and A. Wolisz. "A Cognitive Radio Approach for Usage of Virtual Unlicensed Spectrum," presented at 14th IST Mobile and Wireless Communications Summit, June, 2005.

[2] J. Mitola III, “Cognitive radio for flexible mobile multimedia communications,” presented at Sixth International Workshop on Mobile Multimedia Communications (MoMuC’99), San Diego, CA, 1999.

[3] Notice of Proposed Rule Making and Order, December 2003.

[4] S.-L. Wu, C.-Y. Lin, Y.-C. Tseng and J.-P. Sheu, “A New Multi-Channel MAC Protocol with On-Demand Channel Assignment for Multi-Hop Mobile Ad Hoc Networks,” presented at Int’l Symposium on Parallel Architectures, Algorithms and Networks (I-SPAN), 2000.

[5] B. F. Lo, “A survey of common control channel design in cognitive radio networks,” *Physical Communication*, vol. 4, issue 1, March 2011, PP. 26-39.

[6] B. Hamdaoui and K. G. Shin, “OS-MAC: an efficient MAC protocol for spectrum-agile wireless networks,” *IEEE Transactions on Mobile Computing*, vol. 7, no. 8, 2008, pp. 915–930.

[7] J. Jia, Q. Zhang, and X. Shen, “HC-MAC: a hardware constrained cognitive MAC for efficient spectrum management,” *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 1, 2008, pp. 106–117.

[8] H. Su and X. Zhang, “Opportunistic MAC protocols for cognitive radio based wireless networks,” in *Proc. 41st Annual Conference on Information Sciences and Systems*, 2007, pp. 363–368.

[9] D. Raychaudhuri and X. Jing, “A spectrum etiquette protocol for efficient coordination of radio devices in unlicensed bands, in: 14th IEEE Proceedings on Personal,” *Indoor and Mobile Radio Communications*, 2003, pp. 172–176.

[10] K. Chowdhury and I. Akyildiz, “OFDM based common control channel design for cognitive radio ad hoc networks,” *IEEE Transactions on Mobile Computing*, vol. 10, no 2, 2011, pp. 228–238.

[11] S. Anamalamudi and M. Jin, "Low rate common control channel based AODV routing protocol for cognitive radio ad-hoc networks," in *Proc. 2013 Fifth International Conference on Ubiquitous and Future Networks (ICUFN)*, pp. 625-630, 2-5 July, 2013, doi: 10.1109/ICUFN.2013.6614894.

[12] K. Bian and J. M. Park, “MAC-layer misbehaviors in multi-hop cognitive radio networks,” presented at the 2006 US-Korea Conference on Science, Technology and Entrepreneurship (UKC2006), 2006.

[13] Y. R. Kondareddy and P. Agrawal, “Synchronized MAC protocol for multihop cognitive radio networks,” presented at IEEE ICC 2008, 2008, pp. 3198–3202.

[14] C. Cormio and K. R. Chowdhury, “Common control channel design for cognitive radio wireless ad hoc networks using adaptive frequency hopping,” *Ad Hoc Networks*, vol. 8, 2010, pp. 430–438.

[15] X. Liu and Z. Ding, “Escape: a channel evacuation protocol for spectrum agile networks,” in *Proc. 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks*, 2007, pp. 292–302.

[16] B. F. Lo, I. F. Akyildiz, and A. M. Al-Dhelaan, “Efficient recovery control channel design in cognitive radio ad hoc networks,” *IEEE Transactions on Vehicular Technology*, vol. 59, no. 9, pp. 4513–4526, 2010.

[17] C. Cordeiro and K. Challapali, “C-MAC: a cognitive MAC protocol for multi-channel wireless networks,” in *Proc. IEEE DySPAN*, 2007, pp. 147–157.

[18] T. Chen, H. Zhang, G. M. Maggio, and I. Chlamtac, “CogMesh: a cluster based cognitive radio network,” in *Proc. IEEE DySPAN*, 2007, pp. 168–178.

[19] M.-R. Kim and S.-J. Yoo, “Distributed coordination protocol for common control channel selection in multichannel ad-hoc cognitive radio networks,” in *Proc. IEEE International Conference on Wireless and Mobile Computing, Networking and Communications*, 2009, pp. 227–232.

[20] L. Ma, C.-C. Shen, and B. Ryu, “Single-radio adaptive channel algorithm for spectrum agile wireless ad hoc networks,” in *Proc. IEEE DySPAN 2007*, pp. 547–558.

[21] M. Nekovee, "A survey of cognitive radio access to TV White Spaces," in *Proc. International Conference on Ultra Modern Telecommunications & Workshops*, p. 1, p. 8, pp. 12-14, Oct. 2009.

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