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# Hybrid Common Control Channel Based MAC Protocol with Proactive Handoff Scheme in Cognitive Radio Network

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## Abstract

The common control channel (CCC) design plays a pivotal role in achieving the desired quality of service in cognitive radio (CR) technology. Various schemes of CCC designs help CR network to obtain better performance. The reported work proposes a novel hybrid MAC protocol with a target channel selection scheme in proactive handoff. To implement hybridization, the protocol floats between unlicensed out-band and licensed in-band control channel design approaches. The compromised scheme of hybridization is used to achieve advantages of both in-band and out-band designs. The advantages like tight node synchronization, better throughput performance, less congestion in dedicated control channel are achieved while maintaining the decorum of CR technology. To perform hybridization, a primary user free channel list (PCL) is constructed at each CR node and shared with other nodes prior to data transfer. A rendezvous data channel selection has been done between transmitter and receiver nodes for data transfer. Further, the regular sharing of PCL works as a framework for best target channel selection in proactive handoff. The PCL statistics are used to calculate the primary user (PU) reappearance probability of channels at CR node. Prioritizing channels based on parameters like PU reappearance probability, bandwidth, and packet error rate helps CR nodes switch proactively to the best target channel. To observe the performance, a CR ad hoc network setup is created in NS-2. The performance of the proposed protocol is checked under variable traffic conditions and compared with different standard protocols and schemes like IEEE802.11 (out-band control channel design and reactive handoff) and proactive handoff. The proposed protocol outperforms the stated schemes in terms of average throughput and average delay at the cost of increased control overhead. As compared to the reactive handoff scheme, the required number of handoffs in the proposed protocol is reduced by an average of 19.03% for increasing packet generation rate and 32.09% for the increasing number of CR nodes in the scenario.

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# 1 Introduction

Modern days communication systems become more dependent over wireless technologies like Wi-Fi, cellular systems, Wi-Max, bluetooth etc. The prolific number of users in wireless technology are increasing day by day. So, the need of spectrum is also increasing day by day. To meet the demand of users the services are become licensed and user needs to purchase license from service providers to utilize spectrum. There are few applications, like industrial scientific and medical (ISM) are exempted from licensed use of spectrum. Free spectrum are provided for these applications by Federal Communication Commission (FCC) [1]. Similar to other wireless applications, ISM bands or other free applications become very crowded too and leads scarcity of spectrum to the needier users. Furthermore, the new applications suffers with unavailability of spectrum. One possible solution of the stated problem is dynamic spectrum allocation. Unlike traditional static allocations of spectrum where a fixed spectrum is allocated to licensed user, the dynamic allocation works more intelligently and opportunistic access is provided to users. The CR technology is working more prominently in the field of dynamic spectrum access [2]. In CR some intelligence is provided to users so it can sense the surrounding environment to make decisions for spectrum availability. First, the changes in the surrounding scenario is observed by CR user and then an intelligent decision of channel selection is made. The PU is the licensed user of spectrum. On the basis of unavailability of PU in licensed channel, the CR users are allowed to use licensed channels. The spectrum availability for secondary user (SU) is highly dynamic and PU dependent. Thus a CR network works as framework for dynamic spectrum access [3–5].

Further, tight node synchronization is necessary among CR users to establish a good communication link. In multi-channel scenario, the node synchronization can be achieved through a CCC design. Selection of a rendezvous channel for data transmission among CR users while maintaining high throughput is possible through delicate CCC design [6]. In CR-medium access control (CR-MAC) design the CCC plays a pivotal role for achieving better performance. A broad classification for all CR-MAC protocol is done in decentralize and centralize categories on the basis of presence of central entity to govern cognitive function. The decentralize category of CR-MAC seems more practical in mobile network topology. Based on the use of common channel, the CCC design in CR-MAC of ad-hoc network is categorized into in-band and out-band design [7]. The licensed in-band approach selects one channel as CCC from the available licensed data channels free from PU activity. High level of precision is needed in CCC selection to counter random PU re-appearance in the channel. Lack of synchronization among CR nodes is another limitation in in-band approach of CCC design of CR-MAC. The lack of synchronization increases the multi-channel hidden terminals and therefor affects the performance of the scenario. As soon as the hidden nodes in scenario increases the network suffers with heavy packet collision resulting in wastage of energy in the re-transmissions of packets [8]. On the other hand, in unlicensed out-band design, a dedicated unlicensed channel is used as control channel. The out-band approach has edge over in-band as availability of dedicated control channel is 24*7 but suffers with possibility of intruder attack, saturation and co-channel interference due to parallel technologies working in same CCC [9]. This has led to author's motivation to develop a hybrid CCC based MAC protocol. The proposed protocol is hybrid of out-band and in-band CCC design.

TV white space (TVWS) is recently approved for the use of CR applications by FCC [10]. The characteristics like good penetration and long transmission range makes TVWS

more desirable to use in CR applications [11]. In proposed work 902 MHz is used as unlicensed control channel among CR users. A list of PU free channels is constructed by every CR node. The list is known as PCL. The PCL is formed to share control information among CR nodes. The CR users in the close vicinity, become aware about network coordination through this control information. Once CR node coordination is achieved,the licensed in-band CCC is used for selecting a rendezvous data channel for data packet transmission. The switching from out-band to in-band CCC design helps scenario to achieve better performance in terms of throughput and delay. This is because of unavailability of parallel wireless technologies in control channel. The performance of delay parameter is also affected by coordination schemes used to achieve better synchronization among CR nodes. This effect of increased delay is compensated by less amount of collision due to hybrid CCC based CR-MAC protocol.

The second portion of the paper focuses on the use of PCL into proactive channel switching in handoff process. Regular sharing of PCL to the nearby CR nodes makes proactive handoff possible. The current status of primary channels is available at each CR node through PCL. The current status shows whether a primary channel is free from PU activity or not. The PCL available at each CR node is shared regularly to achieve the advantage of CR node synchronization. Whenever a PU re-appearance in licensed channel, the CR nodes have to switch their ongoing transmission into some other channel. This process is known as spectrum handoff. Traditionally the handoff is performed in "sense and react" manner [12, 13]. The re-appearance of PU is sensed first and then reacted in a way that the ongoing communication is held until some other PU free licensed channel is found to switch the communication. It is clear that, the "sense and react" approach suffers with extra delay. Due to dynamism in re-appearance of PU in CRN the situation become worse. Therefore the delay characteristic becomes very crucial to achieve better performance. Another issue with traditional handoff approach is that, when multiple channels are available for switching any channel is selected randomly without knowing the attributes of selected channel. The attributes/characteristics of channel like bandwidth, PER etc are ignored in traditional handoff. Therefore, sometimes a bad channel (poor in characteristics) is selected as next channel for switching in handover process.This increases the required number of handoffs in communication and delay in re-establishment of connection. The drawbacks of reactive approaches can be overcome by using proactive approach of handoff. In proactive handoff the channel for switching is predicted well before the need of channel switching. So multiple PU free licensed channels are available to CR nodes during ongoing transmission and if handoff is needed, the delay in handoff becomes very less as compare to reactive approach. In proposed proactive handoff algorithm, a channel having better past history and also good in attributes, is selected as next channel for switching. This reduces required number of handoffs of the scenario and the performance gets improved.

In presented paper the work has been done in two parts. The first part focuses on a hybrid CCC design based MAC protocol. The hybrid approach is used in CCC design to achieve better performance. An out-band CCC design is used for sharing of the control information through transmission of PCL in dedicated unlicensed channel of TVWS (902 MHz). Once, the neighbor CR nodes in close vicinity become aware of network setup in surrounding, the in-band approach is used for a rendezvous licensed channel selection. The empty spaces of licensed channels are used for sharing of control information through PCL. So hybrid CCC design based MAC protocol takes the advantage of 24*7 availability of dedicated out-band channel but also overcomes the issues of security and saturation by implementing in-band CCC design. The hybridization of CCC design provides higher level of security through partial use of out-band CCC design. Therefore, the common data

channel selection among CR nodes is made through in-band CCC design.The required CR node synchronization for in-band working is achieved through out-band CCC design. Better level of security and tight synchronization of nodes with less saturation in control channel helps to improve the performance of CCC design.

In second part of the research paper, a scheme of best target channel selection for proactive handoff is proposed. The proactive handoff approach is implemented by using the past statistics of channels. The stored PCL at each CR node provides the statistics. The novelty of the scheme lies in the selection of next switching channel. A channel with high bandwidth and having least probability of reappearance of PU with least PER is considered as best channel for switching and selected for handover. Thus, a best channel is selected to use as target channel in proactive handoff.

The organization of remaining paper is as follows. Section 2 gives state of the art in control channel design and handoff schemes. In Sect. 3, a suitable system model for hybrid MAC protocol is given. Section 4 gives detailed description of working of hybrid MAC protocol. Section 5, thoroughly focuses on target channel selection in proactive handoff scheme. In Sect. 6, a simulation setup is established along with detail description of simulation parameters. The simulated results are discussed and compared with other approaches in the same section. At last, the conclusion is given in Sect. 7. A list of acronyms and corresponding definitions is given in (Table 1).

## 2 Related Work

Average throughput and delay are the key parameters to decide the performance of the CR network. These parameters depend upon channel-path selection between end users. Selection of a collision free path is a pivotal need for CRN. The simultaneously active CR nodes and their non-interfering transmissions have a great impact on attainable throughput. The amount of average delay in the network is greatly affected by amount of collision in multi-hop communication scenario. Moreover, the multi-channel environment adds complexity in the scenario and affects the achievable performance. Existence of hidden terminals in the scenario is one of the main causes to degrade the performance. The unpredictability of hidden terminals due to muli-channel environment causes additional delay in the system performance. A better synchronization among CR nodes can reduce the effect of hidden terminals [4]. On the other hand, the extra control overhead is required to achieve better synchronization. So a data channel with less collision can be selected at the cost of increased control overhead. The CCC design is helpful in selecting collision free path and helps in improvement of performance. State-of-the-art MAC protocols of CCC design in CRN is broadly categorized into licensed in-band CCC design and unlicensed out-band CCC design [9]. In in-band design the data and control packets are shared through same licensed channels. To use a licensed channel as temporary control channel, a PCL is formed at each CR node. The in-band design is used with group based and sequential CCC design. The group based CCC design is mainly focuses on clustered networks. The application of group based CCC design in AHN scenario is very limited. The main drawback in the conventional approach of designing CCC is that each group has to find a cluster gateway to establish a communication link with other group [14]. In order to avoid it, the sequential design of CCC is used to find the rendezvous channel for each hop in frequency hopping scenario. The per hop coverage of CCC and delay in channel access are the main

**Table 1** List of acronyms and corresponding definitions

| Acronyms | Definition |
| --- | --- |
| CCC | Common control channel |
| QoS | Quality of service |
| CR | Cognitive radio |
| CRN | Cognitive radio network |
| PCL | Primary user ree channel list |
| CRAHN | Cognitive radio ad hoc network |
| PU | Primary user |
| PER | Packet error rate |
| NS-2 | Network simulator version-2 |
| SU | Secondary user |
| Wi-Fi | Wireless fidelity |
| Wi-Max | Worldwide interoperability for microwave access |
| ISM | Industrial scientific and medical |
| FCC | Federal communication commission |
| CR-MAC | CR-medium access control |
| TVWS | Television white space |
| DC | Data channel |
| DCrq | Data channel request |
| DCrp | Data channel response |
| RTS | Request to send |
| CTS | Clear to send |
| DATA | Data |
| ACK | Acknowledgment |
| CA | Channel advantage |
| IID | Independent and identically distribute |
| SBTP | State back transition probability |
| Thres | Local Threshold |

drawbacks of sequential CCC design [15]. The per hop CCC further increases the possibility of collision under the effect of multi-channel hidden terminals. The increased amount of collision needs re-transmission and causes energy drain in the network.

On the other hand the unlicensed out-band CCC design is framework of IEEE802.11 with multi-channel ad hoc network scenario. A dedicated unlicensed channel usually ISM-2.4 GHz band is used to exchange control messages. The licensed bands are used for data packet transmission. The performance of CR scenario is observed relatively better with dedicated out-band CCC design in comparison with in-band CCC design [7]. The global coverage of the control channel in out-band CCC design reduces the switching delays. It also avoids the possibility of interventions of PU in CCC. However with stated advantages, the dedicated out-band CCC design suffers from intruder attacks. Saturation and interference due to parallel working of other technology in ISM bands (like Blutooth, WiFi and WiMax etc)are again some major concern with dedicated CCC designs. Furthermore, the use of a dedicated channel in the scenario does not holds the decorum (opportunistic use of spectrum) of CR technology. Thus the out-band CCC design is not an alternative to the in-band CCC design [16, 17]. To overcome the stated limitations with in-band and out-band CCC design a hybrid approach is proposed in this research paper. To meet the decorum of

CR technology, it is necessary that the licensed in-band CCC design is preferred over out-band approach. Tight CR node synchronization is a basic need of in-band CCC design. To achieve tight synchronization, it is necessary to share control information prior to actual data transmission. It is achieved with the help of the exchange of PCL in dedicated control channel. A PCL is created at each CR node and contains a list of channel free from PU activity sensed at current instant. The PCL is shared regularly in control channel. Thus each node regularly updates status of the primary channels to create PCL. This has become motivation to develop a novel proactive handoff mechanism. The IEEE 802.11 with multi-channel CRAHN scenario works on traditional sense and react handoff mechanism. Whenever a PU appears in the licensed channel, the SU must have to stop ongoing transmission and start a search for new PU free channel. If it founds another PU free channel, the SU shifts its communication to that channel [12]. It is observed that the "sense and react" approach suffers from the problem of longer delay. The situation get worst with large number of primary channels. The delay in data channel selection and switching delay are two factors affecting the performance of the sense and react handoff scheme.

Furthermore, at the time of channel switching, if multiple channels are found PU free, the SU assumes all channels equally good. It is not realistic assumption because some channels are heavily utilized in comparison with others. The channels suffering with heavy utilization may cause disruption in the communication link. The PER for heavily utilized channels is also high [12]. These heavily utilized channels are observed bad for switching in handoff process. The bandwidth is also a crucial factor of deciding whether a channel is good or not. A channel having high bandwidth should be preferred. The selection of bad channels for switching can cause frequent disruptions or sometimes abrupt failure of communication link. Thus this sense and react approach performs poorly in both delay and throughput criteria of the scenario. The performance of handoff can be analyzed through latency parameter. The latency observed in reactive handoff is less than that in non-handoff schemes. The performance of reactive handoff is analyzed through modeling in [18] and results are measured in terms of latency of transmission and average channel utilization. To overcome the issues with this on-demand approach of channel switching, proactive handoff schemes are used. The target channel for switching is predicted well before the actual handoff required. The arrival of PU in the channels are formulated by using Poisson model in [19]. In proposed model, the target channel sequence for switching is predicted before handoff. As the sequence of target channels are predicted the probability of failure is observed to be less than traditional approaches and scheme outperforms the traditional schemes of random channel switching. The occurrence of handoff is dependent on traffic conditions of the primary channels. To obtain the probability of handoff, different traffic models are investigated in paper [20]. Authors simulated all these models to validate their results. The mobility of CR nodes is another factor affecting performance of CR scenario. In paper [21], a model is developed for analysis of intra-cell handoff in CR scenario with mobile CR nodes. The probabilistic modeling of CR scenarios is one of the most popular approach used by researchers [18, 22, 23]. Load balancing is key feature of papers [18, 22]. The load is distributed in different primary channels to achieve better performance [22]. The research in [18] is carried out on handoff in connection oriented networks. The effect of load balancing is verified through delay characteristic in the paper. The past statistics of primary channels is also used for proactive decision making in target channel switching. The prior history stored at each CR node is used for next switching channel selection [24]. The results in the paper show the effect of proactive switching in reduction of delay with less latency as compared to reactive switching. Research work in [25] is

done to investigate the effect of proactive handoff in reduction of interference between PU and CR users. Reduction in number of handoffs is the prime motive of authors of the paper. Some research has also been done by considering different coordination scheme. The CCC is not used in these schemes [25, 26]. Paper [26] focuses on handoff based on common hopping. The results shows better performance in terms of packet delivery ratio. In research paper [27] a protocol is designed to select a best target channel for switching. The target channel is selected based on minimum service time for CR user. The approach works for betterment of achievable throughput.

In the presented work a hybrid CCC based MAC protocol with proactive handoff scheme is proposed for CRN. Our work differentiates from prior proposals in the following aspects:

1. A more practical network coordination scheme is considered instead of using random data channel selection. The PCLs are shared before data packets transmission to realize channel rendezvous. The impact of network coordination scheme is investigated on the performance of the scenario.
2. A compromised approach of control channel design between in-band and out-band is implemented. The hybridization in control channel design is done to achieve advantages of tight node synchronization and less congestion in dedicated control channel while maintaining the decorum of CR technology.
3. A more viable approach is followed in target channel selection for proactive handoff. The prioritizing of channels has been done to get a target channel list. The channels are ranked on the basis of available bandwidth, PER and probability of being least occupied by PU. For a channel, the PCL statistics helps in calculating the probability of occupancy by PU.
4. Instead of considering a scenario with very few SUs and fix characteristics, a very diverse scenario is created. The CR nodes are free to roam in the dimensions with random velocity. PU arrival and departure in the channels is unknown to SUs. The bandwidth and PER distribution in channels is also random. A large number of SUs are considered in the scenario to contend for spectrum holes. Further, to observe the performance the number of SUs is varied.

As per the author's knowledge, the proposed work is the first attempt to use PCL to design hybrid MAC protocol for CRN. The sharing of PCL not only helps in hybridization of control channels but also used in calculation of probability of PU reappearance in the channel. The probability of PU reappearance along with channel bandwidth and PER are used for prioritize the target channels for proactive handoff scheme. Key contributions of proposed research work are as follows

1. A PCL is created at each CR node and shared prior to data packet. The availability of PU free channels at any node can be can be checked by seeing PCL matrix.
2. The PCL sharing further assists in development of hybrid MAC protocol. The hybridization is done for control channel designs between dedicated out-band and licensed in-band approaches. With hybrid MAC protocol, tight node synchronization is achieved while the chances of intruder attack and saturation in control channel are minimized.
3. The PCL sharing through hybrid MAC protocol then used in rendezvous data channel selection among the CR nodes. In this way, the selection of common data channel

reduces the effect of multi-channel hidden terminals in the scenario. The packet collision is reduced.

4. The PCL history of a CR node is used for target channel selection in proactive handoff scheme. The PCL statistics along with bandwidth and PER are used to rank the channel of highest weight. A best target channel is selected which is having least PU reappearance probability results in less delay and less number of required handoffs.

5. In simulation point of view, the control overhead, packet delivery ratio, average delay time, average throughput and number of required handoffs characteristics are observed with respect to increasing traffic (packet generation rate and number of CR nodes) in the scenario.

## 3 System Model

The CR network is set up in ad-hoc scenario [28]. The CR nodes are free to move randomly and no fix infrastructure is followed. The communication scenario between each pair of primary user transmitter and receiver is point to point. Each pair of primary transmitter and receiver has one primary channel to communicate. 902 MHz, an unlicensed channel of TVWS is taken as dedicated out-band CCC. The sharing of PCL through the dedicated unlicensed out-band CCC helps the CR nodes to select a common data channel to establish communication link among them. The regular sharing of PCL through licensed in-band channels facilitate proactive handoff in the CRN scenario. For the convenience of understanding it is assumed that each CR user has three interfaces named transmitter interface, receiver interface and control interface. These interfaces are used to tune channel for respective operations i.e; transmitter interface for transmission of data packets in licensed channel, receiver interface for reception of data packets from channel and control interface to share control information in control channel whether it is out-band design or in-band design.

Let CR scenario is set up with total $M$ CR nodes and total number of primary channels is $N$. Let these $N$ channels are denoted as $DC_1, DC_2, DC_3, DC_4 \dots DC_N$. As one PU pair can be randomly active in one primary channel, so there exists total $N$ pair of PUs. The PCL is formed at each CR user. It contains current status of the primary channel. The current status of a channel means, at current instant the channel is free from PU or not. At any time and at any CR node maximum $N$ channels can be observed PU free. The sharing of PCL before actual data transmission among CR users facilitate CR users to construct a matrix containing it's own PCL as well as PCL received from nearby CR nodes. The PCL matrix for $m$th CR node can be represented as $X^{[m]}$ and expressed as

$$X^{[m]} = \begin{bmatrix} X^{[m]}_{(1,1)} & \cdots & X^{[m]}_{(1,n)} \\ \vdots & \ddots & \vdots \\ X^{[m]}_{(m,1)} & \cdots & X^{[m]}_{(m,n)} \\ & \cdot & \end{bmatrix} \tag{1}$$

Here $m = 1, 2, 3, ..., M$ and the PCL matrix $X^{[m]}$ have $M$ rows and $N$ columns. The rows of the matrix represents CR nodes and the columns represent primary channels. An example of PCL matrix $X^{[3]}$ for $CR_3$ is shown in Fig. 1.

The individual element of matrix is represented as

$X^{[m]}_{(i,j)} \rightarrow j$th channel of $i$th node at $M$th CR node. $X^{[M]}_{(i,j)}$ can only have binary values.

|     | CR1 | CR2 | CR3 | CR5 | CR6 | CR8 | CR9 | CR14 | CR15 | CR17 |
|-----|-----|-----|-----|-----|-----|-----|-----|------|------|------|
| DC1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 |
| DC2 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 |
| DC3 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 |
| DC4 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 |
| DC5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |

**Fig. 1** Example of PCL matrix at node $CR_3$

$X_{(i,j)}^{[m]} = 0 \rightarrow j$th channel of $i$th CR node is free from PU, so a CR user can use the channel for communication.

$X_{(i,j)}^{[m]} = 1 \rightarrow j$th channel of $i$th node is PU occupied and channel can not be used by CR users.

If the PCL matrix of individual CR node is combined together, a composite matrix $X$ is formed and known as node channel matrix of the whole CR scenario. The node channel matrix $X$ can be represented as

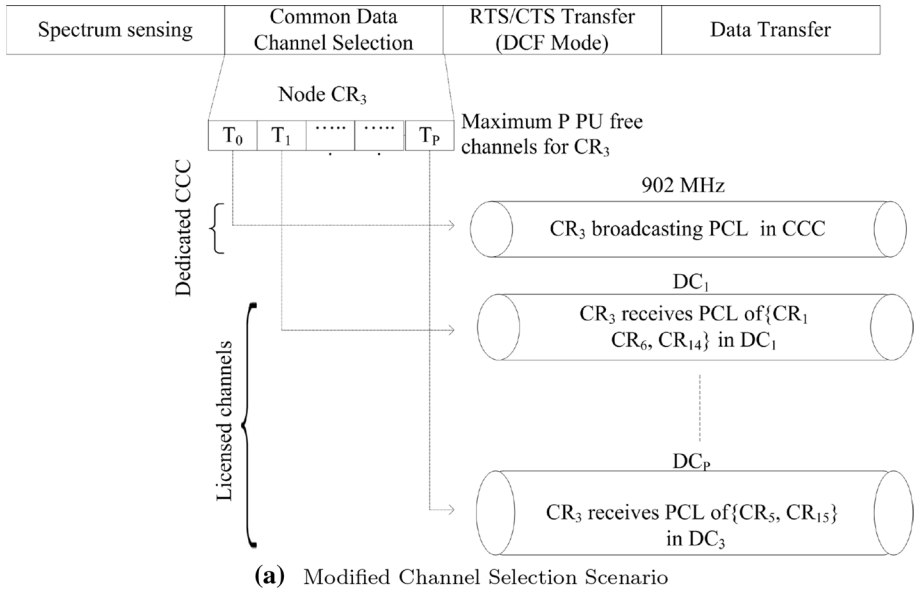$$X = [X^{[1]}, X^{[2]}..., X^{[M]}]. \tag{2}$$

The construction of Node Channel Matrix $X$ represents the network setup and topological information. It helps in achieving better CR node synchronization during the data packet transmission. Very tight node synchronization is needed to design in-band CCC. The situation become worst in multi-channel scenarios like CR. The tight synchronization among CR nodes reduces number of hidden terminals in the scenario. As the amount of collision is directly affected by number of hidden terminals thus the collision in scenario become less and the performance of scenario is improved.

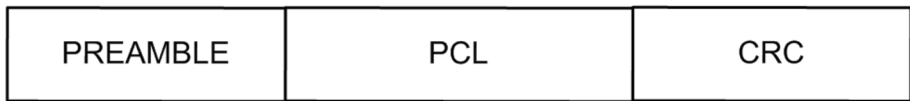## 4 Hybrid CCC Design Based MAC Protocol

A good way of sharing PCL is to use a separate beacon. Control beacons are small size packets shared by CR-MAC to transmit precise information. The beacons are used because they have small control overhead. Thus required information can be shared efficiently without implementing excessive congestion in control channel. The conventional format of PCL beacon is shown in Fig. 2b. The field denoted by PCL is variable in size and depends upon the number of licensed channels. To implement the hybrid MAC protocol, PCLs are shared in both dedicated out-band and licensed in-band control channel.

### 4.1 Hybridization of Control Channel

To perform hybridization between in-band and out-band control channel designs, the PCL beacon is used as control packet. Fig. 2a depicts the common data channel selection scheme between two CR nodes by using hybrid control channel design based MAC protocol. All $M$ CR nodes start with sensing of primary channels. A PCL is prepared at each
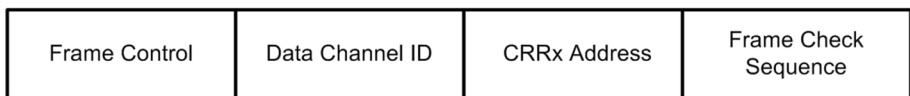
| Spectrum sensing | Common Data Channel Selection | RTS/CTS Transfer (DCF Mode) | Data Transfer |

**(a)** Modified Channel Selection Scenario

| PREAMBLE | PCL | CRC |

**(b)** PCL Beacon

| Frame Control | Data Channel ID | CRRx Address | CRTx Address | Frame Check Sequence |

**(c)** Packet Format of $DC_{rq}$

| Frame Control | Data Channel ID | CRRx Address | Frame Check Sequence |

**(d)** Packet Format of $DC_{rp}$

**Fig. 2** Common data channel selection by using hybrid MAC protocol

CR node. The sharing of PCL helps in common data channel selection. In common data channel selection section; the total time duration available at any node is subdivided into $P$ slots, where $P$ is the number of PU free channels. At any CR node, the maximum $N$ channels can be PU free; therefore $P \leq N$. The CR node which wants to initiate communication starts transmission in the first slot $T_0$. The slot $T_0$ is designated to transfer PCL in dedicated unlicensed channel. In subsequent time slots, the CR node tunes the PU free channels one by one to receive the PCL from other CR nodes, and constructs a PCL matrix as given in Eq. 2.

Let a CR node $CR_3$ has something to transmit to $CR_{15}$. It constructs a PCL through spectrum sensing. Once the PCL is formed at $CR_3$, it starts communication with the transmission of its PCL in a dedicated out-band control channel. It tunes the dedicated control

channel in $T_0$ time slot. The dedicated control channel is 902 MHz; which is an unlicensed band in TVWS. After receiving PCL of $CR_3$ the neighbor nodes become aware of PU free spectrum at $CR_3$. The neighbor nodes use licensed in band control channel to share their PCL with $CR_3$. To receive the PCL from neighbor nodes the $CR_3$ starts tuning its PU free channels in subsequent slots. Thus PCL is shared first in dedicated unlicensed out-band mode and then in licensed in-band mode. The in-band design of control channel is used for future control information sharing until a PU reappearance is observed in the channel. Thus, the sharing of control information has been done partially in dedicated unlicensed band and partially in licensed primary bands to achieve the stated advantages of hybrid design.

## 4.2 Modified Common Data Channel Selection Scheme

Once the hybridization of control channel has been done, the next step is to select a common data channel between nodes $CR_3$ and $CR_{15}$. The common data channel selection is necessary to implement DCF mode for data packets transmission. As node $CR_3$ gathers PCL from neighbor nodes, it forms a PCL matrix as given in Eq. 2. An example of PCL matrix for node $CR_3$ is depicted in Fig. 1. The PCLs of both $CR_3$ and $CR_{15}$ are compared and if any channel found vacant is selected as common data channel. In the comparison, if more than one channel is obtained vacant then a random selection is made among them. In the example, the data channel 3 ($DC_3$) is the PU free channel between $CR_3$ and $CR_{15}$. Thus ($DC_3$) can be designated for data packet transfer. To establish the connection with receiver node, a data channel request packet ($DC_{rq}$) is transmitted by $CR_3$ for confirmation from $CR_{15}$. In response of $DC_{rq}$, a data channel response ($DC_{rp}$) is sent back by $CR_{15}$. The format of $DC_{rq}$ and $DC_{rp}$ are shown in Fig. 2c, d respectively. Four way handshake mechanism (RTS/CTS/ DATA/ACK) of DCF mode comes into use for data transmission. The DATA packets are transferred only after the transmission of request to send (RTS) and clear to send (CTS) packets. After successful reception of data packets (DATA) the acknowledgement (ACK) packets are transferred by receiver node $CR_{15}$.

## 4.3 Proposed Algorithm of Hybrid MAC Protocol for Common Data Channel Selection

For total $m$ CR nodes and $n$ licensed data channels, the algorithm for proposed scheme is given in algorithm 1. The algorithm starts from the sensing of all $n$ licensed channels at every node. On the basis of PU absence/presence in the licensed channels a PCL is formed at every CR node. Further, the algorithm shows the implementation of hybrid MAC protocol. The PCL beacons are shared first in dedicated out band channel and then in licensed in band channels to implement the hybrid MAC protocol. Finally the common data channel selection is shown in algorithm 1.

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**Algorithm 1** Algorithm of proposed Hybrid MAC protocl for Common Data Channel Selection

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1: **for** $(m = 1; m \leq M; m + +)$ **do**
2:     *Let $k^{th}$ CR node Performs Senseing*
3:     *PCL formed for $k^{th}$ node as* $\Leftarrow X^k$
4:     **for** $(n = 1; n \leq N; n + +)$ **do**
5:         **if** $Channel j == PU_{free}$ **then**
6:             $X^{[k]}_{(k,j)} = 0$
7:         **else** $X^{[k]}_{(k,j)} = 1$
8:         **end if**
9:     **end for**
10: **end for**
11: $Broadcast \left( \bigcup_{j=1}^{N} X^{[k]}_{(k,j)} \right) \Rightarrow 902\ MHz$
12: **for** $(j = 1; j \leq P; j + +)$ **do**
13:     *PCL matrix X* $\Leftarrow Receive \left( \bigcup_{i=1}^{M} \bigcup_{j=1}^{N} X^{[k]}_{(i,j)} \right)$
14: **end for**
15: **if** $k = 3$ **then**                                      ▷ $CR_3$ is transmitter and $CR_{15}$ is receiver
16:     **for** $(j = 1; j \leq N; j + +)$ **do**
17:         **if** $X^{[3]}_{(3,j)} == X^{[15]}_{(15,j)} == 0$ **then**
18:             *Select j as common data channel*     ▷ $j = 3$, so $DC_3$ is the common channel
19:             *Send $DC_{rq} \Rightarrow$ in DC3*
20:             *Receive $DC_{rp} \Leftarrow$ in DC3*
21:             *Send RTS $\Rightarrow$ in DC3*
22:             *Receive CTS $\Leftarrow$ in DC3*
23:             *Send DATA $\Rightarrow$ in DC3*
24:         **end if**
25:     **end for**
26: **end if**

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# 5 Proactive Handoff Scheme

This section focuses on proactive handoff scheme based on a novel future channel selection mechanism in CR scenario. The novelty of reported scheme lies in the way of selection of future channel. The regular broadcast of PCL in dedicated out-band control channel helps the CR users to predict the target channel for switching. Sharing of PCL avails both current and past activities of PU to the surrounding CR nodes. The past statistics of channels make the handoff feasible in a way of target channel selection. The algorithm is developed in such a way that a channel having least PU reappearance probability will be selected as target channel while switching. Further, in the proposed approach, a channel advantage (CA) is calculated for every licensed channel. The channel advantage is a formula to calculate best future channel among all possible channels considering data rate (bandwidth) and PER. A channel is said to be best as future target channel if it satisfies three criteria

– It should have highest probability of being unoccupied by PU;
– The data rate should be high and
– The PER of the channel should be as low as possible.

It is assumed that each CR user has ample capacity to store PCL transmitted by neighbor CR nodes in the past. It is also considered that the PCLs are transmitted total k times in CCC. So each data channel can be divided into k slots of equal time length and indicated as $T_1$, $T_2$, $T_3$, ..., $T_k$ as shown in Fig. 3. Each slot has equal duration and completely independent with each other. The reappearance of PU in primary channel decides whether the slot will persist a value '1' (occupied by PU) or '0' (No PU activity observed). Thus time slots $T_1$, $T_2$, $T_3$, ..., $T_k$ can only have binary values indicating the presence or absence of PU in respective slots. It is then obvious to model the reported scenario as exponential ON/OFF model. In the model, the periods of ON and OFF time are independent and identically distribute (IID). Due to the IID of ON and OFF periods a continuous time Markov chain is formed. This Markov chain can be analyzed with renewal theory [12]. Let $\lambda_{\alpha_i}$ and $\lambda_{\beta_i}$ denote the inverse of ON and OFF periods respectively. Then the duration for which channel $i$ is observed ON will follows the exponential distributions as

$$f(\alpha_i) = \begin{cases} \lambda_{\alpha_i} e^{\alpha_i \lambda_{\alpha_i}} & if \ \alpha_i \geq 0 \\ 0 & otherwise \end{cases}.$$ (3)

In reported proactive handoff scheme, each CR node forms a PCL matrix. This matrix will provide the past channel statistics or handoff. The past channel observations are used to predict the next idle channel for switching in handoff process. The probability of $i$ th channel to be found idle during time interval $\Delta t$ can be derived using renewable theory as

$$P^i = \begin{cases} \dfrac{\lambda_{\alpha_i}}{\lambda_{\alpha_i} + \lambda_{\beta_i}} + \dfrac{\lambda_{\beta_i}}{\lambda_{\alpha_i} + \lambda_{\beta_i}} e^{-(\lambda_{\alpha_i} + \lambda_{\beta_i})\Delta t} & if \ s = 0 \\ \dfrac{\lambda_{\beta_i}}{\lambda_{\alpha_i} + \lambda_{\beta_i}} + \dfrac{\lambda_{\alpha_i}}{\lambda_{\alpha_i} + \lambda_{\beta_i}} e^{-(\lambda_{\alpha_i} + \lambda_{\beta_i})\Delta t} & if \ s = 1 \end{cases}.$$ (4)

At $\Delta t = T_p^i$, the probability $P^i$ is used to predict the possibility of $i$th channel occupied by a licensed user. A priority list of data channels $(DC_1, DC_2, DC_3, DC_4...DC_N)$ is prepared on the basis probability of being remain idle. This list is used for selecting the target channel for handoff. A channel with maximum successive PU vacant time slots possess rank one in the priority list. The probability of a channel being idle in successive slots is calculated through channels history available at CR nodes. The probability of being idle in consecutive time slots is calculated through formula k/state back transition probability (k/SBTP), where $k$= 1, 2, 3, …. Figure 4 represents the time-slot division for k/SBTP calculation in one channel. Same time-slot division is followed in all primary channels. The channel with highest k/SBTP is preferred over other channels for handoff.
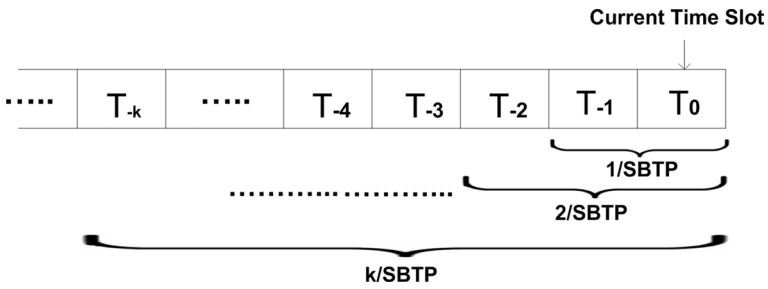
**Fig. 3** Exponential ON-OFF model of channel
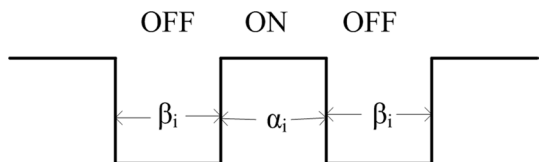
**Fig. 4** Time-slot division of channel to calculate k/SBTP

## 5.1 k/State Back Transition Probability (k/SBTP)

k/SBTP means that the a channel possesses idle k+1 consecutive time slots. To calculate k/SBTP, Eqs. 5–7 are used. For example, the 1/SBTP (k=1) for a channel gives the probability that two consecutive time slots (current and one previous) are PU vacant.

$$1/SBTP : Func_1(T_0, T_{-1}) = \begin{cases} 1 & if\ T_0, T_{-1}\ are\ idle \\ 0 & otherwise \end{cases} \tag{5}$$

$$1/SBTP : Func_2(T_0, T_{-1}, T_{-2}) = \begin{cases} 1 & if\ T_0, T_{-1}, T_{-2}\ are\ idle \\ 0 & otherwise \end{cases} \tag{6}$$

Similarly we can calculate $Func_3()\ ...Func_k()$. The equation for $Func_k()$ can be written as

$$k/SBTP : Func_k(T_0, T_{-1}, \dots, T_{-k}) = \begin{cases} 1 & if\ T_0, T_{-1}, \dots, T_{-k}\ are\ idle \\ 0 & otherwise \end{cases}. \tag{7}$$

The value of $k = 1, 2, 3, \dots$ represents the maximum consecutive PU free time slots of a channel. To get the sum of all $Func()$, function $Sum()$ is used as

$$Sum_k(T_0, T_{-1}, \dots, T_{-k}) = \sum_{i=1}^{p-1} Func_i(T_0, T_{-1} \dots, T_{-k}). \tag{8}$$

In above equation $i\ \epsilon\ p$. It is clear from the above equation that a channel with highest number of consecutive time slots, counted from current slot will achieve highest weight. The obtained weight is then used to calculate $k/SBTP$ as

$$P_k(T_0, T_{-1} \dots T_{-k}) = \frac{Sum_k(T_0, T_{-1} \dots, T_{-k})}{p-1}. \tag{9}$$

## 5.2 Channel Advantage

The proposed k/SBTP method of handoff has one major limitation. It is always possible that multiple channels can share rank one in priority list i.e. the highest k/SBTP of multiple channels can be equal. To overcome the limitation one possible solution is to chose one

random channel among all first ranked channels. A much better approach is used in the reported paper. To rank the channels the data rate and the PER parameters are also considered along with k/SBTP of the channels. It is assumed that each channel in the scenario has variable data rate and PER throughout the slots. A channel advantage is calculated for individual licensed channels to rank them. For *i*th channel, the CA in *k*th time slot is calculated as

$$CA_i^k = \frac{DR_i^k \cdot S_i^k}{PER_i^k}. \tag{10}$$

In above equation, for *k*th time slot of *i*th channel, the $CA_i^k$, $DR_i^k$, $S_i^k$ and $PER_i^k$ represents the channel advantage, data rate, total consecutive PU free slots and packet error rate respectively. Thus the equation includes PER and data rate with maximum number of unoccupied slots of a channel. The CA is calculated on each stage of k/SBTP and the channels are ranked according to their respective weights. Table 2 shows, how the reported ranking mechanism works.

## 5.3 Priority List

Figure 5 depicts the flow chart of proposed proactive handoff scheme. Whenever a node wants to perform handoff, it starts calculating 1/SBTP. In calculation of 1/SBTP, it is checked whether current and one prior time slot is PU vacant or not. The PCL stored in the form of Node Channel Matrix allows CR nodes to calculate 1/SBTP. Calculated 1/SBTPs for all channels are then compared with 'Thres' a local threshold level. The local threshold Thres has its initial value '0'. The channels are eligible for calculation of 2/SBTP, only if their 1/SBTP crosses the value of Thres. The CA for all eligible channels is calculated. The channels are ranked according to the values of their CA. The value of Thres is increased after each stage of SBTP calculation. Process continues until one best channel with highest channel advantage is obtained. The calculation of CA provides multiple advantages. First, the calculation of CA for individual channel avoid the possibility of getting multiple channels at rank one and it always gives the best target channel for proactive handoff. The second advantage is observed, when the number of licensed primary channels is very high. In that scenario the k/SBTP calculation may give multiple channels as best target channel. So the handoff may occur in a channel with poor data rate and high PER. Third advantage is that the proactive handoff, through ranking of channels is implementable for more realistic scenarios where the data rate and PER in channels are variable.

**Table 2** Example of channels ranking in proactive handoff (calculating CA for k = 7, p = 101 and Max(i) = 10)

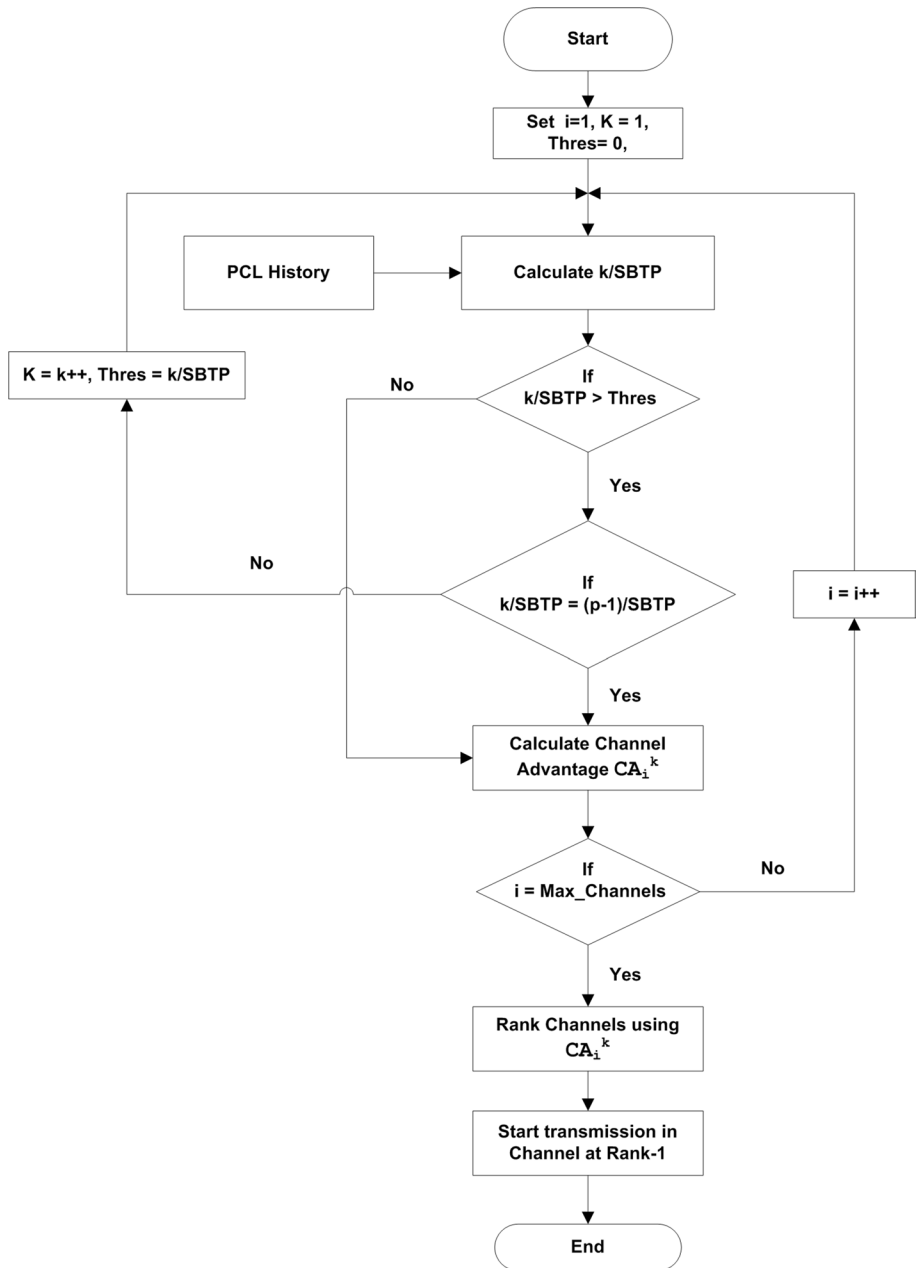| Sr. no. | Channel no. (i) | k/SBTP | Data rate | PER | CA | Channel rank |
|---------|-----------------|--------|-----------|-----|-----|--------------|
| 1. | 7 | 0.6 | 2.16 | 0.027 | 4711.11 | 1(DC9) |
| 2. | 9 | 0.7 | 4.35 | 0.049 | 6214.28 | 2(DC7) |
| 3. | 5 | 0.1 | 7.37 | 0.081 | 909.87 | 3(DC1) |
| 4. | 1 | 0.2 | 3.25 | 0.042 | 1547.61 | 4(DC5) |
| 5. | 2 | 0.1 | 5.69 | 0.063 | 903.17 | 5(DC2) |

**Fig. 5** Flow chart of proactive handoff scheme

## 6 Simulation Setup and Results

To observe the performance of CRN, the ad-hoc scenario is more generalized set up as compared to infrastructure based scenario. In order to perform simulation, an ad-hoc

environment is created in the Network Simulator (NS-2.31) [29]. It is assumed that the CR nodes have random movement in a dimension of $1000 * 1000\ m^2$. In scenario total 10 pair of PU (PU transmitter and PU receiver) are considered with total 10 licensed primary channels. So there is one licensed channel per PU pair. The data rate of primary channels is varied randomly in the range of 2–8 MHz. Likewise, PER of the channels is also variable in the range of 0.02–0.09. It means that 20–90 packets get corrupted out of 1000 transmitted packets. An unlicensed channel of TVWS 902 MHz is used as dedicated out-band control channel. To analyze the performance of scenario, the graphs of average throughput, average delay, packet delivery ratio, control overhead and number of handoffs are plotted against increasing amount of load in the network. The variation in load is achieved by increasing packet generation rate in a range of 10–1000 packets/s. The load in network is also varied by increasing the number of CR users from 30 to 100 CR users. Detail of other simulation parameters are mentioned in Table 3.

The obtained results are plotted in Fig. 6. In order to compare performance, first a scenario of IEEE802.11 is made compatible with CR. In CR compatible IEEE802.11 (notified as IEEE802.11), the conventional schemes of channels selection and handoff are followed. The conventional rendezvous data channel selection scheme is based on dedicated CCC. The modification in conventional channel selection scheme is made through sharing of PCL. Once, the PCL matrix is formed at CR node, the hybridization between dedicated unlicensed out-band and licensed in-band CCC design takes place. The results observed for the hybrid CCC design are denoted as hybrid control channel design in the graphs. However, the handoff strategy still remains reactive in the scenario. Further, the handoff strategy is modified. The proactive handoff algorithm is implemented. In graphs, the results for proactive handoff schemes are notified as Proactive Handoff Scheme. Finally, the results of Hybrid Control Channel Design and Proactive Handoff Scheme are jointly implemented and notified as proposed protocol in the graphs. For ease of understanding, the plotted graphs are parted in three sections. In first section the graph of control packet overhead, packet delivery ratio, average packet delay and average throughput of the network are plotted with respect to increasing packet generation rate as shown in Fig. 6a–d.

**Table 3** Simulation parameters to run CR scenario

| Sr. no. | Parameters | Values |
|---|---|---|
| 1. | Dimension of topology | $1000*1000\ (m^2)$ |
| 2. | No. of CR nodes (maximum) | 100 |
| 3. | No. of primary transmitters | 10 |
| 4. | No. of primary receivers | 10 |
| 5. | Total channels | 11 |
| 6. | Licensed channels | 10 (8 MHz bandwidth each) |
| 7. | Control channel | 1 |
| 8. | Primary user transmission range | 500 m |
| 9. | Transmission range for CR | 250 m |
| 10. | Maximum data rate | 1 Mbps |
| 11. | Interface queue length | 50 Packets |
| 12. | Maximum simulation time | 50 s |
| 13. | Packet size | 512 Bytes |
| 14. | Traffic type | CBR |

**(a)** Control Overhead



**(b)** Packet Delivery Ratio



**(c)** Average Delay



**(d)** Average Throughput



**(e)** Control Overhead



**(f)** Packet Delivery Ratio



**(g)** Average Delay



**(h)** Average Throughput



**(i)** Required Average Number of Handoffs



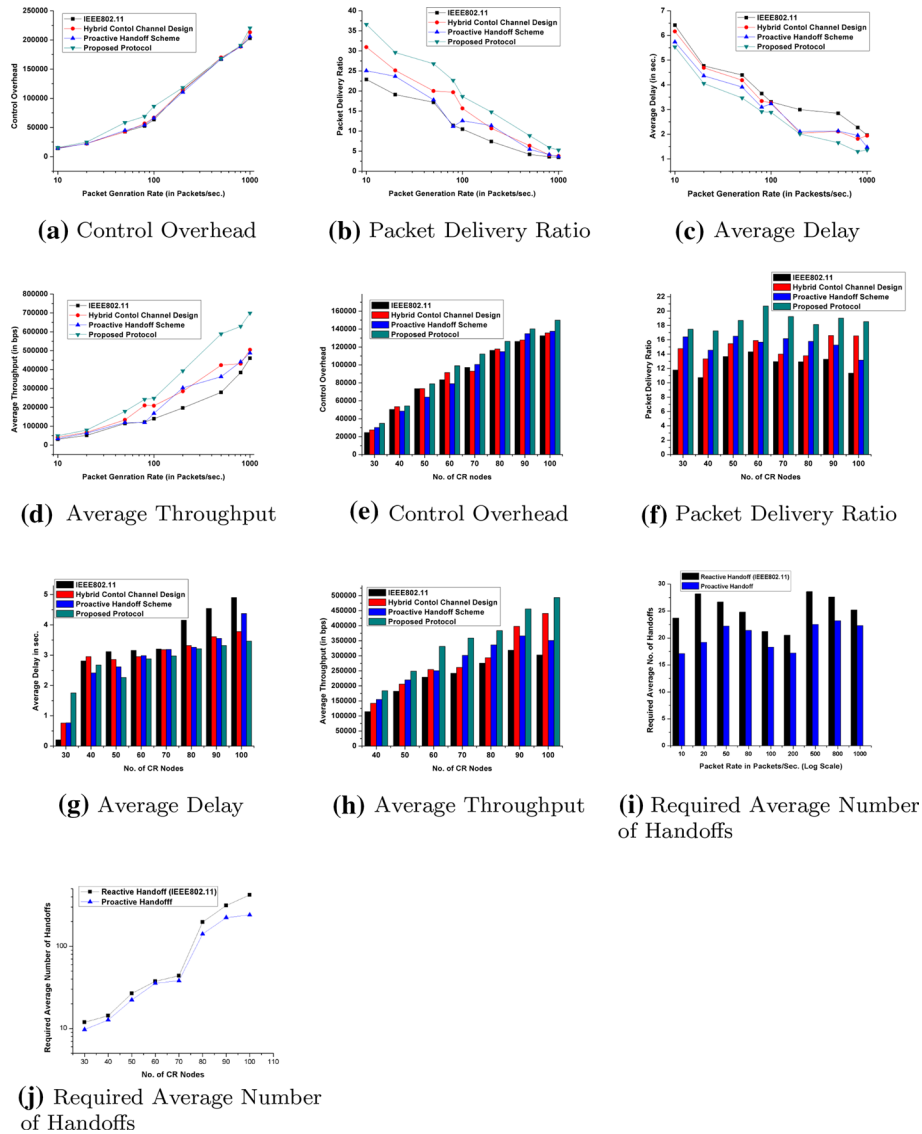**(j)** Required Average Number of Handoffs

**Fig. 6** The simulation results of control overhead, packet delivery ratio, average delay and average throughput are measured against increasing load. Results in **a**, **b**, **c** and **d** are observed with respect to increasing packet generation rate while **e**, **f**, **g** and **h** are observed against increasing number of CR nodes in the scenario. In graphs **i** and **j** the average required number of hadoffs are plotted against increasing traffic

As compared with IEEE 802.11, the graph shows a clear improvement in throughput and delay characteristics with hybrid CCC design at the cost of increased control overhead. The slight increment in control overhead is obvious as the PCL are shared among CR users in the close vicinity. Whenever, a CR user initiates communication, the sharing of PCL happens. The improvement in throughput and delay performance is observed as the multi-channel hidden terminals are negligible and the better synchronization is achieved among

CR users. Better synchronization helps in achieving collision free path selection among CR nodes. Lesser amount of collisions results in better throughput and delay characteristics. The amount of re-transmission of packets is reduced, thus very small end to end delay of the network is observed. Furthermore, the proposed hybrid CCC design is energy efficient technique because the amount of energy needed in re-transmission of packets is saved. The performance of proactive handoff is better in comparison with traditional reactive handoff strategies. In proactive handoff, the target channel for switching is available at CR node well before the actual handoff is needed. Best target channel is selected for handoff in the proposed scheme. In the approach, the selected channel has least PU re-appearance possibility. Therefore, very small number of handoffs are required to complete an ongoing communication. The next channel for switch or target channel is selected through the ranking of channels. To rank the channels, the PU reappearance probability along with data rate and PER are taken into consideration. Thus the chances of link failure and saturation are also very small. The amount of collision get reduced and the achievable throughput become high in the scenario. Furthermore, the number of channel switch are also get reduced because of small number of handoffs. This results in reduction of average delay in the network. Therefore, it can said that the average packet delay in the scenario is reduced because of the proactive handoff scheme. Finally, the hybrid CCC design along with proposed proactive handoff scheme is plotted. The result outperforms the results of both hybrid CCC design and proactive handoff scheme. The throughput and delay performances are improved with the proposed protocol. The control overhead become high, as PCL is needed to be share regularly to achieve hybridization in control channel design and proactive handoff. In second portion, the performance of scenario is tested against increasing number of CR nodes in Fig. 6e–h. The CR traffic increases congestion in the scenario. Again the performance of proposed protocol is observed better to both Hybrid Control Channel Design and Proactive Handofff Scheme. In third section of results a comparison of required number of handoffs is made between reactive handoff and proactive handoff strategies. As shown in graph 6i, j, the required number of handoffs in proactive approach is observed less than reactive approach of handoff.

## 7 Conclusion

In reported manuscript, the research work has been done in two sections. In first section a hybrid MAC protocol based on CCC design is implemented. The CR scenario uses dedicated out-band unlicensed control channel for setting up the communication link. In proposed hybrid MAC protocol, the out-band CCC design helps the CR user to know about the orientation of the scenario and helps to achieve better synchronization. Once a link has been established, the in-band licensed channels are used for control information sharing through PCL. The stored PCL of neighbor nodes helps in rendezvous data channel selection between two CR nodes for data packet transmission. In comparison to traditional IEEE802.11, the performance of throughput and delay is improved at the cost of increased control overhead. The hybrid CCC design approach helps to achieve better node synchronization to reduce the possibility of collision. In second portion of paper a proactive handoff scheme is proposed and implemented. The PCL history stored at each CR user makes it possible to predict future target channel for handoff. The target channel is selected in such a way that it has least reappearance probability of PU. Thus a best target channel is selected. Furthermore to overcome the problem of getting multiple channels as best channel in the

proposed approach of handoff, a channel advantage based on three parameters is calculated. Thus a channel having least probability of PU activity along with high bandwidth and low PER has been chosen as target channel for handoff. The approach reduces the average number of handoffs required in the scenario. This further improves throughput and delay performance of the scenario.

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