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Master's Degree Thesis

A MAC Protocol for Concurrent Channel Access in Cognitive Radio ad Hoc Networks

Graduate School of Chosun University

Department of Computer Engineering

Sunil Kumar Timalsina

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무선인지 애드혹 네트워크에서의 병행 채널 접근을 위한

MAC 프로토콜

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Advisor: Prof. Moh, Sangman, PhD

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티말시나 수닐 쿠마르의 석사학위논문을

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Table of Contents

List of Tables

List of Figures

Acronyms

CA-MAC	Concurrent Access MAC
CCC	Common Control Channel
CCL	Common Channel List
CR	Cognitive Radio
CRAHN	Cognitive Radio ad hoc Network
CRN	Cognitive Radio Networks
CSMA/CA	Carrier Sense Multiple access with Collision Avoidance
D-CCC	Dedicated CCC
FCC	Federal Communications Commission
IEEE	Institute of Electrical and Electronics Engineers
MAC	Medium Access Control
N-CCC	Non CCC
NCM	Node Channel Matrix
ND-CCC	Non Dedicated CCC
ns-2	network simulator -2
PU	Primary User
SCL	Sorted Channel List
SU	Secondary User

한 글 요 약

무선인지 애드혹 네트워크에서의 병행 채널 접근을 위한 MAC 프로토콜

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무선 인지 애드혹 네트워크(CRAHN)는 무선 스펙트럼 자원의 효과적 이용을 추구하면서 애드혹 모드로 동작하는 자율적 장치들로 구성된다. 무선 인지 네트워크에서 비면허 사용자는 면허 사용자에게 간섭을 일으키지 않으면서 면허 스펙트럼 대역을 감지하고 기회가 있을 때마다 면허 대역을 접근한다. 이는 스펙트럼 접근을 위한 MAC 계층 설계에 중대한 주의를 요한다. 특히, 중앙 조정장치가 없는 애드혹 네트워크에서는 MAC 계층이 비면허 사용자의 면허 대역 접근에서 중요한 역할을 수행한다. 최근 이와 같은 목적으로 MAC 프로토콜 설계에 관한 수많은 연구가 발표되고 있다. 그러나, 대부분은 많은 한계와 가정으로 제한을 받고 있다. 본 연구에서는 CRAHN에서의 MAC 프로토콜을 분석하고 CA-MAC (Concurrent Access MAC)이라 불리는 MAC 프로토콜을 제안한다.

첫째, 공통 제어 채널(CCC) 요구사항에 따라 MAC 프로토콜을 분류하고 종류별로 주요 구현내용을 검토한다. 그리고 나서, 고유 특성과 성능 측면에서 프로토콜을 정성적으로

비교한다. 보통 무선 인지 장치는 다수의 사용 가능한 채널을 탐색한다. 일반적으로 전체 또는 일부 채널은 CRAHN 노드에게 공통 채널이 아니다. 그와 같은 운용 환경은 모든 네트워크 장치에게 공통 채널이 없는 경우에 CCC를 설정하는데 있어 문제를 야기한다.

둘째, CCC를 요구하지 않는 채널 환경에서 동작하는 CA-MAC이라 명명된 MAC 프로토콜을 제안한다. 제안한 프로토콜에서는 공통 채널이 하나만 있는 경우에도 한 쌍의 장치가 상호간 통신할 수 있다. 따라서, 채널 포화와 DoS 공격 같은 CCC 연관 문제가 아울러 해소된다. CA-MAC은 통신 장치들 사이에서 채널 접근을 분산시키고 네트워크 연결성을 증가시킨다. 또한, CA-MAC은 서로 다른 장치들이 다중 채널을 병행 접근하는 것을 허용한다. 성능 평가 결과에 의하면, CA-MAC은 SYN-MAC (비공통 채널 CRAHN을 위한 종래의 핵심 MAC 프로토콜)에 비해 짧은 채널 접근 지연시간으로 높은 네트워크 연결성을 제공함으로써 네트워크 전송률을 크게 향상시킨다.

I. Introduction

Cognitive radio networks (CRNs) were devised to opportunistically access the available spectrum being spared by users who are licensed to use that spectrum. These users are commonly called **primary users** (PUs). FCC pointed out that these licensed spectrums are underutilized by PUs in vast amount [1]. Therefore, a need was felt to utilize this valuable resource. Mitola and Maguire [2] coined **cognitive radio** (CR) which could intelligently find out these spare spectrums and use them for communication. These users are called as secondary users (SUs).

SUs are equipped with cognitive radio capability that can be split into *cognitive capability* and *re-configurability*. Cognitive capability refers to the ability to sense opportunities in spectrum where channels are not utilized by PUs. These opportunities are called *spectrum holes*. Re-configurability means the capability to reconfigure its communication parameters and utilize the spectrum hole. However, SUs should access channels such that there is not any interference with PUs. Therefore, whenever the PU tries to access channel back, the SU should immediately refrain from its transmission.

Due to the requirement of CR devices to sense the opportunities (or spectrum holes) prior to deciding to access a spectrum, CR MAC protocols have additional requirements to the legacy wireless ad hoc network MAC protocols. In addition to this, network structure can vary in different cases such as centralized or distributed and channel access may be done by overlay or underlay mechanism. In addition to this, in general a CR device accessing a spectrum hole should stop its transmission in case the PU licensed to channel reappears. This mandates the SU medium access mechanism to defer the transmission and switch to an alternative channel. Hence spectrum handoff and spectrum switching are also major issues in CR MAC protocols. Chapter II discusses different issues in CR ad hoc network (CRAHN) MAC protocols.

A. Research Objective

A SU can sense a number of available channels before accessing them. Each of participating SUs in a network senses for opportunities. But, as they are sparsely located in certain area and PUs' activities vary location by location, it is likely that a channel available to an SU at one location might not be available to an SU at another location. Therefore, *channel availability* is not common throughout the network. This is the practical scenario for CRAHNs and therefore needs the consideration while designing this kind of networks. In this document, the channel availability is defined as a probability that a channel is accessible to an SU after sensing.

With the "uncommon" channel availability, opportunistic spectrum access cannot be done merely with legacy wireless MAC protocols. Also, it is required that each of the members in a network gains access to utilize the spectrum. Although some of the MAC protocols as in [3]-[5] are designed by taking "uncommon" channels in account, most of the existing MAC protocols for CRAHNs assume that a common channel exists throughout the network to be used as a control channel. In addition, the existing MAC protocols for CRAHNs with uncommon channel availability lag either by adding up high overhead to network or fail to solve the issues with wireless network medium access.

In this thesis, we propose a concurrent access MAC protocol called CA-MAC for CRAHNs capable of concurrent transmissions in multiple channels by different pairs of devices synchronously. The proposed CA-MAC does not require any CCC for transferring control information. CA-MAC alleviates fairness in channel access between SUs and increases network connectivity. The performance evaluation result shows that the proposed CA-MAC provides lesser network wide delay with high network connectivity compared to existing CRAHN MAC protocol. With higher number of network nodes gaining access, network wide average throughput is also shown to be augmented.

B. Thesis Layout

We first study the existing key MAC protocols proposed for CRAHNs in literature. In chapter II, we first discuss on the major issues in designing CRAHN MAC protocols. We classify the study of CRAHN MAC protocols on the basis of common control channel (CCC) requirement. Under each of the categories, we go through the key MAC protocols in terms of their basic operating principles and characteristics followed by the criticism. The classification and study of MAC protocols is followed by discussion and qualitative comparison of each of the categories with respect to major characteristics and achievable performance. These results give the basic guidance in designing different MAC protocol for various potential network environments.

The proposed MAC protocol is discussed in detail in chapter III. Proposed protocol assumes two radio interfaces per nodes. Each of the nodes in network have uncommon set of channels (not necessarily disjoint) accessible and are synchronized with each other in time domain. No common control channel is required for network-wide coordination. Furthermore, Channel access is done in discrete time slots with synchronization. The protocol also implements different new data structures such as node channel matrix (NCM) for simple representation of network.

In chapter III, we present the performance analysis of proposed MAC protocol against key MAC protocol in the same category. The performance analysis is done through simulation results obtained from popular network simulator (ns-2). Major contribution of this protocol is the reduced average network-wide delay in channel access and concurrent transmission in multiple channels. The performance comparison is done on the basis of network-wide delay and achievable throughput. Results show that the proposed protocol has decent characteristics in terms of measured performance metrics.

II. Related Works

Since the term ‘Cognitive Radio’ has been coined in 1999, researches have contributed a lot into the problem. In order to utilize TV white spaces, IEEE has developed IEEE 802.22 standard for CRNs [6]. Some authors like Yuan et al. [7] have proposed a prototype along with MAC protocol and a hardware platform. Pawelczak et al. has illustrated the development of CRN in past years in [8]. The standardization efforts make it possible to provide a protocol stack along with the guideline for developing new protocols.

In the literature, various MAC protocols are proposed for CR networks to address the above-mentioned problems. Centralized MAC protocols consist of a central coordinator (such as base stations or access points) for spectrum access and management. There is no central coordinator in decentralized MAC protocols, however. But because of the heterogeneity of the environment and the behavior of the PUs, channel access and synchronization among the SUs is necessary. This introduces a number of challenges in designing MAC protocols for CR ad hoc networks (CRAHNs). Many of the existing works have tried to solve this problem by using a network-wide common control channel (CCC) for exchanging control signals and synchronizing within/between the networks [9]-[12]. Some has also coined problems in CCC and hence tried to avoid using CCC as in references [13]-[14].

In this chapter, MAC protocols for CRAHNs are classified into three categories as follows: dedicated CCC (D-CCC), non-dedicated CCC (ND-CCC) and non-CCC (N-CCC) on basis of CCC requirement, and reviewed in terms of operational principles and characteristics [31]-[32]. Then, they are compared qualitatively with respect to major characteristics and achievable performance. The comparison shows that D-CCC protocols work well in uncommon available channel environments with sparsely populated network. N-CCC protocols outdo D-CCC protocols in networks with dissimilar channel allocation and ND-CCC protocols are somewhere in-between. However, there is very few, moderate and high reconfiguration and signal transmission overhead in D-CCC, ND-CCC and N-CCC based protocols respectively.

A. Design Issues with MAC Protocols in CRAHNs

In addition to legacy wireless ad hoc MAC protocols, designing a MAC protocol for CRAHN requires serious considerations. The opportunistic spectrum access mechanism in CR networks further introduces a number of challenges. Here, we briefly outline the important aspects of CRAHN MAC protocols.

1. Spectrum Sensing

Spectrum sensing is an important characteristic of CRAHNs [33]-[34]. It has two basic purposes: one is to find out available spectrum and the other is to detect PU activities. Sensing the channel for identification of PU activities is called *inband sensing*; whereas finding a new spectrum is called *out-of-band sensing*. In literature, different sensing methods have been discussed [15] such as *energy detector based, waveform-based, cyclostationary-based, radio-identification based* and *matched-filtering sensing*. The dissemination of sensing results can be done in a centralized or distributed manner. In centralized distribution, a central coordinator transfers sensing information to network members. On the other hand, in distributed method, all members exchange their sensing results among themselves. Spectrum sensing also depends on hardware constraints. The major factors are sensing time and the number of radios. The more time is required to sense, the more spectrum opportunities can be found, but the time overhead is considerable. Having separate radio for sensing and for communications could solve the efficiency problem, but this would involve energy issues. In terms of sensing policies, random sensing policy implements the strategy of selecting a random channel from all available channels to sense for an opportunity. In negotiation based sensing policy, channels already sensed by network members are advised to the other members that don't sense them anymore.

2. Dynamic Spectrum Allocation

The CRAHNs are subject to the heterogeneous environment with different channel availability. This heterogeneity is due to such factors as time and location of different nodes and PU activities. Therefore, spectrum allocation is of critical importance. The method and content of messages exchanged for spectrum allocation within a CRAHN varies according to the scheme of the MAC protocol. In MAC protocols with CCC, channel allocation is advised to the neighbors through CCC. If there is no CCC (e.g. AMAC [16]), channel allocation list is exchanged among sender-receiver pairs. This exchange determines which channel to use for transmission and which for control signal exchange.

3. Dynamic Spectrum Sharing

Spectrum Sharing in CRAHNs means co-existence of CR users with licensed and unlicensed devices. In reference [17], spectrum sharing is classified into three modes: *underlay*, *overlay* and *interweave*. In the underlay mode, SUs utilize the spectrum being used by PUs below some signal threshold level. This threshold level limits SUs transmission from interfering with the PUs transmission. In the overlay mode, CR users try to either cancel or reduce the interference on both SU and PU side by utilizing the information of non-CR users’ messages. Finally in the interweave mode, the SU transmits only within the vacant portions of the spectrum. Therefore, to avoid the interference, it immediately retains its transmission as soon as PU is arrived.

4. Common Control Channel

Because of the heterogeneity of CR networks, CCC has become an important issue to be considered. Although several MAC protocols for CRAHNs are based on availability of the CCC, due to different types of channels available to nodes in a network, MAC protocols without CCC are also used. CCC plays an important role as it is used for coordination and control signal transmission. But this also introduces jamming and contention of the transmission.

5. Other Issues

As CR research is still in its infancy, there are several issues to be addressed in terms of MAC protocol design. The mobility of nodes brings on new challenges as it requires network reconfiguration and extra overhead during signal transmission. Also, it is still an open question how to handle channel switching and spectrum handoff arising from spectrum mobility. In addition, the number of radios in the device can play a critical role in spectrum sensing accuracy and energy constraints at the same time. Also, the capability of a radio to sense the wide spectrum, delays in channel switching and spectrum heterogeneity are still the areas that need to be considered. In dense networks, there is also a problem of hidden terminals (in addition to exposed terminal.)

B. Existing MAC Protocols for CRAHNs

In CRAHNs data transmission is done by opportunistically using the spectrum when an available vacant spectrum (spectrum hole) is found. The access to this spectrum is coordinated by the MAC protocol. Many SUs may contend to access the same spectrum hole at the same time. In legacy MAC protocols, contenders contend on CCC by using protocols like CSMA/CA [18] and get access to the channel upon winning the contention. However, in CRAHNs, the CCC might not be available or can be reclaimed by PUs. Also, the channel availability is not the same for all the SUs throughout the network. Papers [19]-[24] have studied and distinguished MAC protocols in CRAHNs. Here we classify MAC protocols for CRAHNs into three major categories (See Figure 2-1): dedicated CCC (D-CCC), non-dedicated CCC (ND-CCC) and non-CCC (N-CCC).

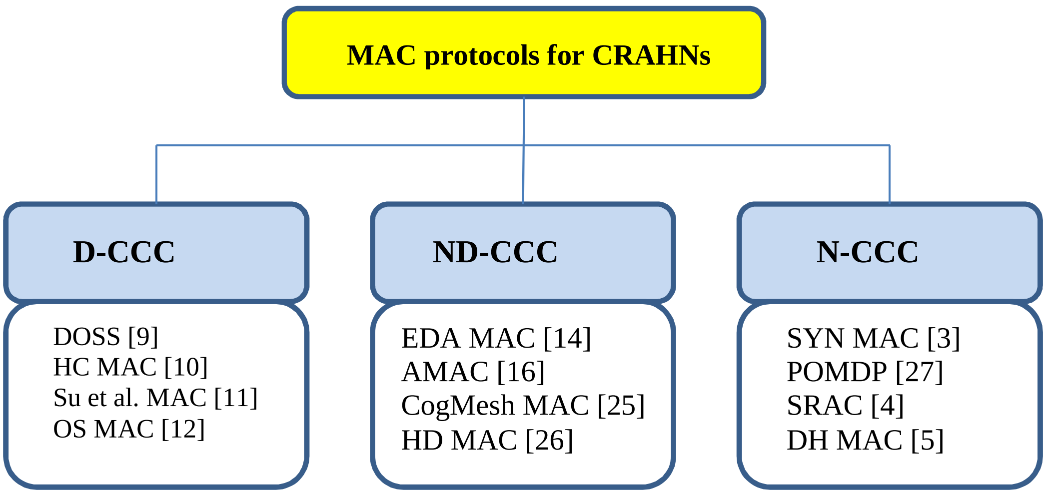


Figure 2-1: Classification of MAC protocols for CRAHNs based on CCC.

1. Dedicated CCC (D-CCC)

The D-CCC protocols assume that CCC is available to all network members. This can be either a channel licensed by the corresponding CRN authority or may as well exist in some unlicensed band such as ISM. SUs contend in this D-CCC for channel access.

Dynamic Open Spectrum Sharing (DOSS) MAC [9] operates by setting three frequency bands for CCC, data channel and for busy tone band. In CCC, control signals are transmitted whereas data band is a wide band used for data transmission. A narrow band called busy tone band has one to one mapping with data band. The corresponding busy tone band is set before data transmission in data channel so that rest of the network elements are well informed about data channel being used.

The **Hardware Constrained MAC** (HC-MAC) considers the existing hardware constraints in practical CRs [10]. It is that the current CR devices can sense only limited range of spectrum with certain duration and can utilize even lesser spectrum out of sensed spectrums. In addition, more of the sensing implies more opportunity in one hand and more overhead in the other. Therefore, a stopping rule is implied for sensing.

It works by dividing time into three phases: *contention, sensing* and *transmission*. With C-RTS and C-CTS signals, intending pairs win a contention and overhearing nodes defer the transmission during contention phase. After that, the pair senses channel till some stopping time which is same for both and exchange S-RTS and S-CTS signal during sensing phase. This is finally followed by data transmission in transmission phase.

The **Cross Layer Based** MAC integrates spectrum sensing policy at the physical layer and packet scheduling at MAC layer [11]. It is based on two transceivers: one for dedicated CCC and another for spectrum sensing and data transmission. The licensed channels are divided into slots which represents either ON or OFF state of PU if it is active or idle respectively. The CCCs time axis is further divided into the slots of the same length as that of the licensed channels and are further synchronized with the licensed channels slots. The slots in CCC are further divided into *reporting phase* and *negotiating phase*. During *n* mini slots in reporting phase, each SUs senses licensed channel and informs to control transceiver whereas during negotiation phase, SUs negotiate for transmitting data using contention based algorithm similar to IEEE 802.11 DCF and p-persistent CSMA.

OS-MAC [12] assumes that each SU is equipped with a single half-duplex radio. A D-CCC and N non-overlapping data channels (DCs) with equal bandwidth are assumed to be available. Time is divided into periodic *opportunistic spectrum period* (OSP). OSP is further divided into three phases: *select phase, delegate phase* and *update phase*. Two or more set of users who want to communicate with each other forms a SU group (SUG). The control frames belonging to different channels is communicated via D-CCC whereas those belonging to same DC (and hence SUG) is communicated via DC.

Each SUG has a delegate SU (DSU) responsible for information exchange between other DSUs of other SUGs regarding state of other DCs. Only one member of a SUG can transmit data at a time using mechanism similar to IEEE 802.11 DCF without using RTS/CTS packets. Rest of the members of SUG would only receive data and one of them send back ACK signal for reception of packet.

2. Non Dedicated CCC (ND-CCC)

D-CCC based MAC protocols are simple but sometimes they cannot be realizable. This is because in some scenarios CCC cannot be guaranteed. In addition, CCC is prone to *common control channel saturation* problem and *jamming* by sending fake signals [3]. In case of large number of contenders, control channel can get saturated. The ND-CCC does not have a dedicated CCC at the network start-up but a CCC is established dynamically. This can be done either by selecting one of the available channels as CCC [14], [16] or by forming groups within a network and selecting different CCCs in each group [25]- [26].

Hsu et al. have proposed the **EDA-MAC** [14] protocol to modify C-MAC [13] protocol for faster join process of network members and increase throughput. If a SU finds a communication group, it can start join process to join that group. Otherwise, it forms the communication group and become the leader. Channel chosen to form a communication group is called *rendezvous channel*. A channel is divided into consecutive superframes each in turn containing a *beacon period* (BP) and a *data transmission period* (DTP). Each BP contains one to several signalling phases (SP), a beacon phase, and a CTS phase. Each SP contains several signalling slots during which host intending to join the group will contend to transmit a signal in one of the signalling slots.

In the dedicated beacon slot, intended sender sends RTS with rate subfield. Leader also assigns a dedicated CTS slot for receiver to avoid collision. After leader listen the CTS signal, it schedules transmission according to the various priorities such as smallest data first or least number of transmissions first etc. For load balancing, leader also manages channel switching of nodes. First node joining new channel becomes leader of that channel which periodically switch back to RC for resynchronization. In addition, it also undergoes primary user detection during quite periods (QP) within DTP.

Joshi et al proposed the **AMAC** protocol [16] which does not need an extra D-CCC throughout the network. Hence, they suggest a mechanism to overcome the *common control channel saturation* problem. The AMAC protocol assumes that there are n available channels in the environment. Every node prioritizes the available channels according to channel reliability: C_1, C_2,...., C_n. Here, C_1 is the most reliable channel, C_2 is the second, and so on, and C_n is the least reliable channel. This list is called the *indexed channel list* (ICL).

When a sender wants to transmit, it sends the RTS signal with its ICL to the receiver. When the receiver receives the RTS signal, it compares the sender's ICL with its own ICL and creates a new list that includes only channels available to the both parties. This list is called ICCL (*indexed common channel list*). The receiver then sends back the CTS signal to the sender with this ICCL. From the ICCL, the most reliable channel is selected as *non-global common control channel* (NCCC) which is used to exchange control signals. The second reliable channel becomes the data channel to transmit the data. Finally, the third reliable channel is used as the data backup channel.

In [25], Chen et al have proposed cluster-based network architecture for CRAHNs and **CogMesh MAC** protocol where the SUs form clusters. There is no global CCC available but each cluster has a local CCC called master channel. A leader forms a cluster and becomes a clusterhead. It invites neighboring nodes to join the cluster. To interconnect the clusters, one node is selected as a gateway node, which may or may not be the common node between two or more clusters. Hence, considering the rest of nodes called ordinary nodes, there are three types of nodes in each cluster. The control signal transmission is done in the master channel. It consists of MAC superframes which are further divided into a number of periods as *beacon period* (BP), *Neighborhood broadcasting period* (NBP), *data period* (DP), *quite period* (QP), *private and public random access period* (Private and Public RAP).

In **HD-MAC**, coordination groups are formed within a network based on available common channels [26]. Members within same group are only allowed for direct communication whereas *bridge nodes* which have common channels to both groups realize communication between those groups. For establishing a coordination group, every user scans the available channels and then beacons its channel list over the available channels. This is called *neighbour discovery* and allows each node to accumulate information on its neighbouring nodes and channel availability. Among the available channels, a channel with the highest connectivity (i.e. channel shared by the maximum number of nodes) is selected as a local coordination or control channel for that group through the process of voting. To handle spectrum heterogeneity in the CRNs, authors have proposed a modification to the legacy MAC protocol MMAC (So et al [26]) for ad hoc networks.

3. Non CCC (N-CCC)

Non CCC based MAC protocols does not require separate CCC for control signal exchange. Usually, intending sender would tune to the receivers' data channel and transfer control and data packets over the same channel. In some cases, channel hopping is used. Control signals are passed by hopping on different channels. These mechanisms reduce the overhead of selecting CCC in ND-CCC based MAC protocols, but require additional network-wide synchronization.

In [3], Kondareddy et al. have proposed the **SYN-MAC** protocol. It assumes that each SU is equipped with two radios. One radio is called *listening radio* and is used for listening control signals and another is called *data radio* which is used for data transmissions. The environment is heterogeneous i.e. channel availability is not the same for all SUs.

When a SU wants to start data transmission over a channel, it waits for the time slot represented by the channel. Within that slot, the sender transmits the RTS signal after a back off time. When it successfully receives the CTS signal from the receiver, data transmission starts immediately. As the receiver and the other nodes listen to the same channel at this particular time slot, overhearing nodes are aware that the channel is in use by the specific communicating pair. So, the overhearing nodes avoid to transmit into this channel.

DC-MAC [27] is based on *partially observable Markovian decision process* (POMDP). The spectrum is accessed by combining the spectrum sensing at physical layer and with the past statistics. Channels can be assumed to be in two states based on primary users activity as either in state ‘1’ if it is busy or ‘0’ if it is active. These states of channels are used for POMDP for deducing channel access opportunity. Time is divided into number of slots for data transmission using CSMA protocol by using RTS/CTS packets for handshaking and DATA/ACK for data transmission. For selecting channel the best channel, a decision is made based on sensing results (current and past). As it is assumed that both sender and receiver are subject to same channels environment and are using same decision process, they would select the same channel for transmission for next transmissions.

SRAC proposed by Ma et al. in [4] is based on cross-channel communication in the single-radio multi-hop ad hoc networks. A SRAC algorithm is proposed which provides results based on detection of either jammer or PU and channel load to legacy MAC protocols. Authors propose to avoid interference to transmitter as long as it does not pose interference to PUs.

Every node selects a stable *receive channel* among available channels for receiving data. Nodes also maintain database about *receive channels* of its neighbors. Data transmission can be done using the legacy CSMA/CA MAC protocol on corresponding *receive channels.*

Shih et al. have proposed a non-CC based dynamic hopping MAC protocol (**DH-MAC**) [5] for CRNs. Each node in the network consists of a single CR transceiver. N non-overlapping orthogonal channels in the network are indexed as [0, N-1]. The nodes hop among these channels in a cyclic pattern (called *l* cycles) staying in one channel for T time interval. The channel hopping (CH) sequence of nodes is determined by a parameter set called channel hopping (CH) parameter set. This parameter set is broadcasted in the beacon at the start of each time interval T and also embedded in the packet header.

4. Comparison and Discussion

In the previous sections, we have discussed major MAC protocols in CRAHNs and classified them on the basis of CCC requirements. While designing a MAC protocol for CRAHNs, one should consider a great deal of features. The brief comparison of these protocols is shown in Table 2-1.

The non-CCC based network is easy to deploy as it does not require pre-allocation of channel (CCC). But due to mobility in either the nodes or the spectrum, networks need to be reconfigured with the group based or non-CCC protocols. This would require extra reconfiguration effort and coordination between the nodes. The most advantageous feature of the ND-CCC based and N-CCC based protocols is that they are very flexible, even in networks with heterogeneous channel availability. As discussed previously, however, in D-CCC based protocols, as the number of nodes increases, the demand in control signal transmission increases as well. This leads to a high contention in accessing CCC and results in the CCC saturation problem. This is less probable in ND-CCC based protocol and negligible in N-CCC based protocols. The increased number of users and hence the increased network density renders it more prone to hidden terminal problems. As the neighbourhood discovery is very difficult in non CCC based protocols, hidden terminal problems are more prominent there.

Table 2-1: Comparison of CRAHN MAC protocols based on CCC requirements.

Feature	D-CCC	ND-CCC	N-CCC
Deployment	Difficult	Moderate	Easy
Network re-configuration overhead	Less	High	Very high
Channel allocation	Allocated to all the members	Allocated within groups	Sparsely allocated
Uncommon channel distribution	Less affected	Re-formation of groups	Supported
Synchronization between nodes	Done through CCC	Few protocols implemented (eg. EDA MAC)	Less needed
Control signal transmission overhead	Very high	Moderate	Less
CCC saturation problem	Very high	Few	Very less
Hidden terminal problems	Can be tackled using CCC	Moderate	High

In addition to above, the performance of MAC protocols for CRAHNs is also greatly affected by the number of available radios. The more is the number of radios the better is the accuracy of channel sensing and the multichannel hidden terminal problem is better addressed at the same time, although the cost and power consumption go up. Sensing policies and support of multi-hop networks are also needed to be considered.

III. Proposed CA-MAC protocol

Although the majority of contributions in literature assume the common channel distribution where most of the channels are available to network nodes, this might not be the case in practical scenario of CR networks. In practice, channel availability varies through node to node. We propose an ad hoc MAC protocol in CRNs with varying channel availability within network for concurrent access.

A. Assumptions

Our protocol is based on non-CCC principle. Hence no CCC throughout the network is required. First evident assumption is that different nodes have different set of channels available to access. Therefore, a transmitting pair has very few common channels to transmit in. This channel availability of each node is communicated within network. In CRNs, this is done during channel sensing which also helps nodes in network to synchronize with each other. Thus, every node has information about channel availability of every other network member nodes.

Each of the nodes is assumed to possess two radio front ends. One of the radios is for listening to control signals (*listening radio*) and another is for data transmission (*data radio*). So, data transmission and control signal overhearing is possible at the same time. We want to make channel access such that it is fair to each of the nodes consequently all of the nodes get channel access opportunity and therefore node connectivity is high. Unlike some MAC protocols for CRN, proposed protocol requires only one channel common between a communicating pair to the least. This should not be a problem in most of the cases.

B. Network Architecture

The network consists of cognitive radio users distributed throughout the space. Channel distribution is considered to be "uncommon". This means that out of total *N* channels, only *n* ($n \leq N$) channels maybe available to particular node as shown in Figure 3-1. At the beginning of network formation, each of the nodes gains knowledge about channel availability of other member nodes. Each of member nodes is synchronized with each other in time domain.

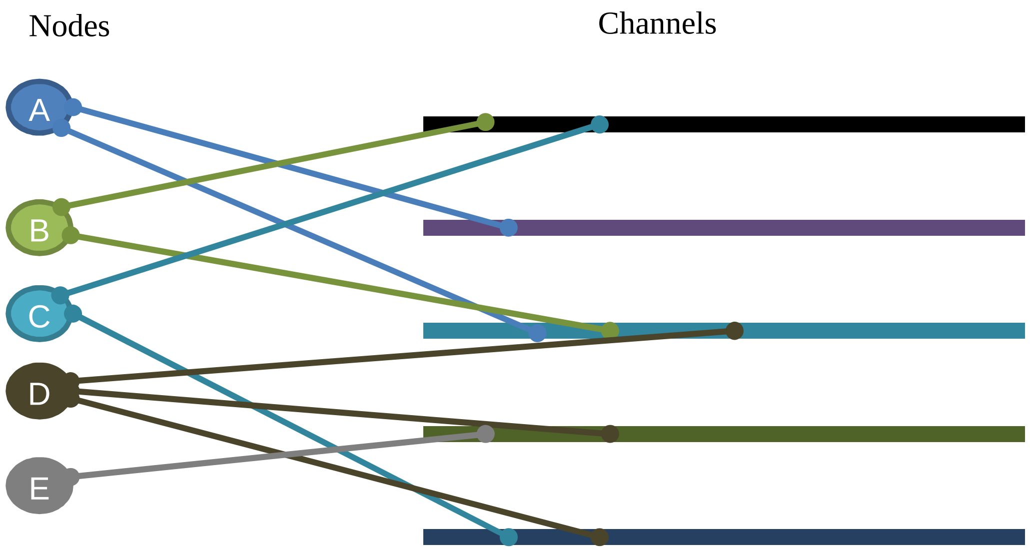


Figure 3-1: A sample network architecture showing different nodes with dissimilar available channel/s.

C. Channel structure

The channel structure of CA-MAC is basically based on split phase multichannel MAC protocol described in [28] and [29] where time is divided into number of phases for control and data transmission as shown in Figure 3-2. CA-MAC differs from this by not using a CCC and having two radio interfaces therefore being able to overlap control and data transmission phase in different channels at the same time slot.

There may be N number of available channels. These channels are ranked according to defined priority and reordered according to their rank with high-ranked channel first, and so on. The ranking and ordering mechanism is described in details in later. All the channels are divided into number of synchronized time slots. Every slot starts at the same time in each of the channels. For a cycle, number of time slot is equal to the number of channels. Each slot represents a channel. Rank 1 channel refers to time slot 1, rank 2 channel refers to time slot 2 and so on.

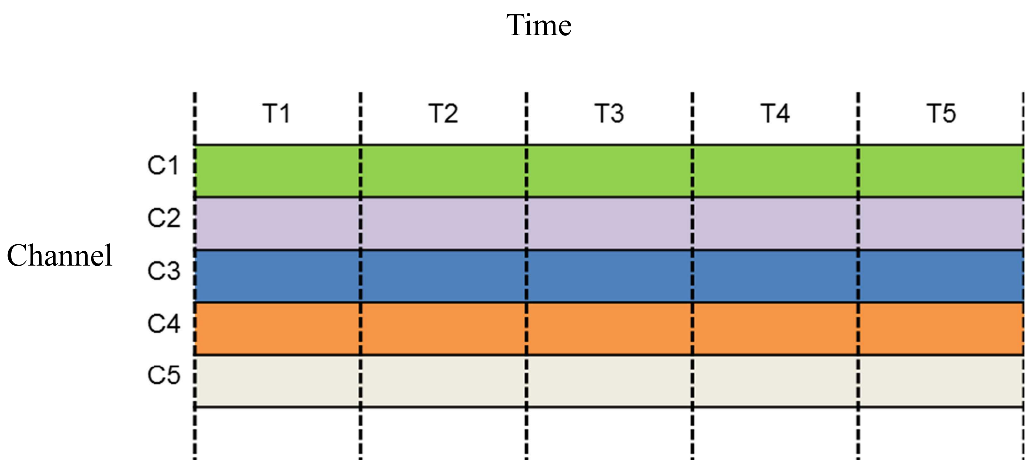


Figure 3-2: Channel structure of the system with five channels (=five time slots.)

Figure 3-2 shows the channel structure of CA-MAC. The representative slot (i.e. when the slot number equals the channel rank number) of the channel starts with a signaling period. For example, for channel ranked as 1, first slot starts with a signaling period (channel C_1 in Figure 3-2); similarly for channel ranked as 3, signaling period is at third slot (channel C_3 in Figure 3-2). Rest of the period in a channel is data transmission period. Signaling period consists of the number of signaling slots for negotiation. These signaling slots are used by intending transmitting pairs to contend for reserving a channel. These slots can also be used for transmitting other control information such as PU arrival notification.

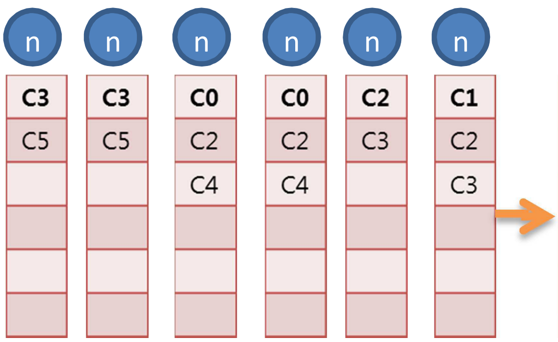
D. Node-Channel Matrix

Before explaining the node-channel matrix, it is necessary to define some new terms. The *channel indicator* or *channel access indicator*, λ_i^j is the bivalent which represents whether node *i* can access channel *j* (1) or not (0). Hence, for node *i*, for *m* number of channels, we can form a list of channels as $\{\{C_1, \lambda_i^1\}$, $\{C_2, \lambda_i^2\}$, $\{C_3, \lambda_i^3\}$, …, $\{C_m, \lambda_i^m\}\}$. Where, for each *j* from 1 to *m*, λ_i^j equals 1 if node *i* can access channel C_j and 0 otherwise. Again, for *n* number of nodes in a network, these lists can be combined to form an $n \times m$ matrix called node-channel matrix (NCM) as shown in Figure 3-3 and 3-4.

	C_1	C_2	C_3	…….	C_m
N_1	$\lambda_1{}^1$	$\lambda_1{}^2$	$\lambda_1{}^3$	…….	$\lambda_1{}^m$
N_2	$\lambda_2{}^1$	$\lambda_2{}^2$	$\lambda_2{}^3$	…….	$\lambda_2{}^m$
N_3	$\lambda_3{}^1$	$\lambda_3{}^2$	$\lambda_3{}^3$	…….	$\lambda_3{}^m$
.	.	.	.	…….	.
.	.	.	.	…….	.
.	.	.	.	…….	.
N_n	$\lambda_n{}^1$	$\lambda_n{}^2$	$\lambda_n{}^3$	…….	$\lambda_n{}^m$
	$\sum_{i=1}^{n} \lambda_i^1$	$\sum_{i=1}^{n} \lambda_i^2$	$\sum_{i=1}^{n} \lambda_i^3$	…….	$\sum_{i=1}^{n} \lambda_i^m$

Figure 3-3: Node channel matrix.

Now, the *channel availability* or *channel access probability*, p_i^j is the probability that λ_i^j = 1. That is to say, channel availability is the probability that a channel is available to a node. In other words, it is the probability that a PU is active in a channel from the point of view of a node. Each of the entries in NCM takes value either 0 or 1 according to the channel availability. For simplicity, we assume that this probability is same for all the node-channel combinations and can be represented by *p*. For smaller values of *p* (say < 40%), very less or none of the channels are common between nodes and the network is said to be 'harsh'. On the other hand, if the value of *p* is larger (say > 80%), most of the channels are available to almost all the nodes. In this case, channels can be said to be "commonly" distributed among the nodes. Finally, if the *p* lies between smaller and larger values, channels are more or less uncommonly distributed and only few channels are common between nodes but at the same time, there is possibility that none of the channels is common throughout the network.



	C0	C1	C2	C3	C4	C5
N0	0	0	0	1	0	1
N1	0	0	0	1	0	1
N2	1	0	1	0	1	0
N3	1	0	1	0	1	0
N4	0	0	1	1	0	0
N5	0	1	1	1	0	0
	2	1	4	4	2	2

Figure 3-4: An example of forming node channel matrix.

In terms of set-theory, if all the channels in network comprises of universal set, U = {C_1, C_2… Cm}, where m is the total number of channels; each of the nodes, N_n

have its own channel set such that for each n = 1 to N (number of nodes) $N_n = \{C_i | C_i \in U \, and \, i = 1,2...m\}$. For example, from the example NCM of Figure 3-5, N1 = {C3, C4}, N7 = {C1, C4, C5} and so on.

We can gain more information from this last row. If one of the values is large then that means corresponding channel is available to large number of nodes. Therefore probability of accessing that channel by more number of nodes would be higher. On the other hand, if that value is small number, then only few nodes have that particular channel available to access so chances of contention for that channel would be low.

	C_1	C_2	C_3	C_4	C_5
N_1	0	0	1	1	0
N_2	0	1	1	1	0
N_3	0	1	1	1	0
N_4	0	1	0	0	1
N_5	0	1	1	1	1
N_6	1	0	1	1	0
N_7	1	0	0	1	1
N_8	1	1	1	1	0
N_9	1	1	0	1	1
N_{10}	0	1	0	0	1
	4	7	6	8	5

Figure 3-5: A sample NCM with availability, p=60%.

E. Communication Initialization

It would be easier to discuss this mechanism with the help of example of NCM in Figure 3-5. Let's assume that each of the member nodes N_1-N_{10} wants to communicate with each other. Let us say the communicating pairs are corresponding odd and even numbered nodes. That is, N_1-N_2, N_3-N_4, N_5-N_6 and so on.

Now, each of the pair forms a *common channel list* (CCL) as shown in Figure 3-6. The ordering of this list depends on the CCL priority scheme as shown in Figure 3-7. Reason that we have designed this as a modular scheme is that different networks have different objectives. These objectives can be as such as high throughput, lesser delay, seamless connection etc. So, the objectives can be modeled as a certain utility function *u(x)*. In multichannel networks, different channels have different characteristics in different scenarios. Hence, these utility functions differ also based on nodes location. According to a nodes goal, channels can be given different priorities based on the utility function. This can result in a prioritized list with 'best' channel as first entry and so on. We call CCL as a prioritized list of 'best' channels common to the transmitter and receiver. Therefore, a CCL in a node k can be represented as:

$$CCL_k = \{\{Ch_1, u_1\}, \{Ch_2, u_2\}\{Ch_3, u_3\} \ldots \{Ch_l, u_l\}\} \qquad (1)$$

Where u_1 to u_l are the utilities of Channels Ch_1 to Ch_l such that $u_c \le u_{c+1} \forall c (1 < c < l)$ and *l* can take value from 0 to *m* (number of channels). Ch_1, Ch$_2$, etc. in CCL and SCL should not be confused with C$_1$, C$_2$, etc. Although both are the channels, CCL and SCL are the sorted list of C$_1$, C$_2$, etc according to some schemes. Therefore, for example, C$_3$ is not necessarily equal to Ch$_3$ in CCL or SCL. And also, Ch$_3$ in CCL is not necessarily equal to Ch$_3$ in SCL. In simple way, as per set representation mentioned in section D, if S is the channel set of sender and R be the channel set of receiver, then CCL of S and R can be found by intersection of S and R. Hence, CCL (S, R) = {S ∩ R} for each (S, R) pairs.

N$_1$ N$_2$	C$_3$	C$_4$
N$_3$ N$_4$	C$_2$	
N$_5$ N$_6$	C$_3$	C$_4$
N$_7$ N$_8$	C$_1$	C$_4$
N$_9$ N$_{10}$	C$_5$	C$_2$

Figure 3-6: An example of common channel list.

Statistically, the probability that the channel (c) is common to both the transmitter (t) and receiver (r) is given as

$$P(c) = p_t^c \times p_r^c \tag{2}$$

Our policy is to give higher priority to channel that is least common such that there is lesser chance of contention between nodes for same channel. This can be found out from last row of the NCM. Entries in CCL are in ascending order of the values in last row of NCM and thus it is common to both the nodes in a communicating pair. The numerals in the last row can be taken as the representation of the "commonness" of the channel in a network as explained in previous section.

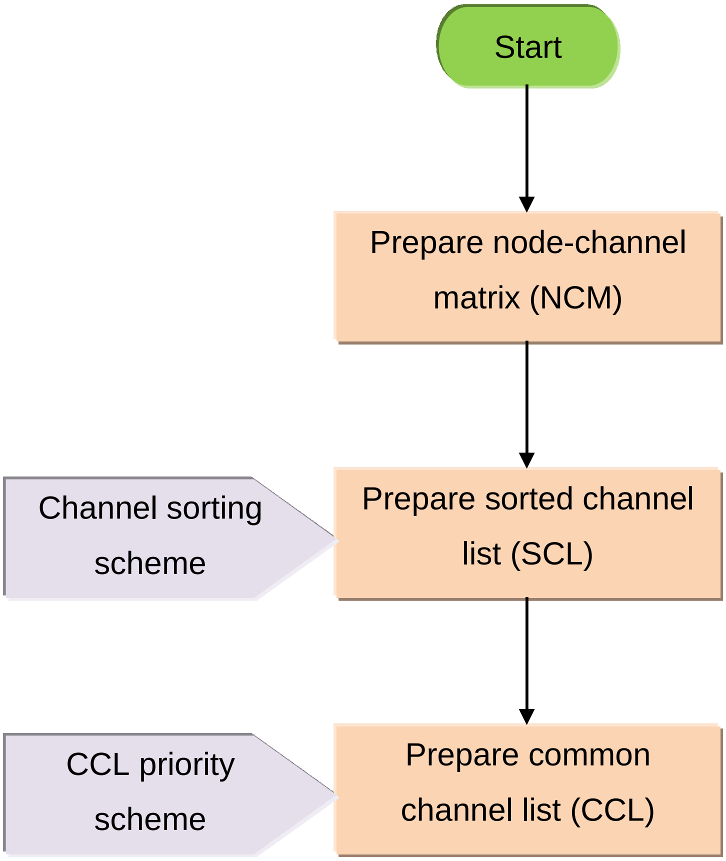


Figure 3-7: Initialization procedure of nodes.

Let us consider for a communicating pair N_1-N_2. Looking at last row, least value is 4 corresponding to channel C_1. But this channel is available to neither N_1 nor N_2. Next value is 5 for channel C_5 which is also not common to both of these nodes. Finally, channels C_3 and C_4 have values 6 and 8 and are common to both N_1 and N_2 nodes. Going on this manner, CCL of N_1-N_2 pair would include channels C_3 and C_4 in same order. CCL of all the communicating pairs is shown in Figure 3-6. Note that some communicating pair/s might not have common channels to transfer.

As we have considered the network such that the available channels set are not common between the nodes in a network, entries in CCL vary for each communicating pairs. For channel access, each node will attempt to access channels on the order they appear in the CCL. If first channel can be accessed, it will be used if not, second and so on. Figure 3-7 shows the initialization phase of both sender and receiver.

F. Channel Access

In CA-MAC, channels are accessed in time-slotted manner. Hence, the entire channels and nodes timer is synchronized. As shown in Figure 3-7, the sorted channel list (SCL) is prepared according to a channel-sorting scheme. This scheme can be designed in various ways according to the objective of the network. Currently, the scheme is such that the maximum control signals are exchanged as early as possible and channels are reserved in advance. This is advantageous as there is lesser channel access delay throughout the network.

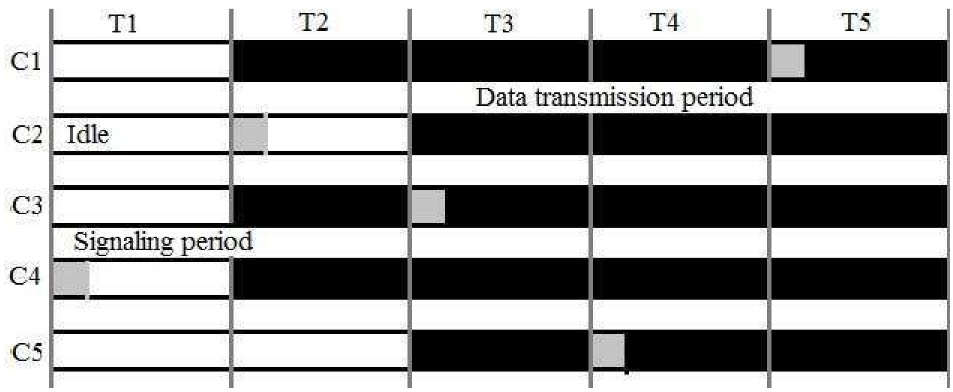


Figure 3-8: Channel access in CA-MAC protocol (dark shades: data transmission, light shades: signaling period and no shades: idle period.)

First of all, channels are ranked. A channel ranks highest if it is common to maximum number of nodes in the network. In our scheme SCL is prepared with the help of NCM. In Figure 3-3 of NCM, we can see that the last row is the sum of all the values (1's and 0's) along the column. As the columns represent channels, hence these values give the 'commonness' of the channel in the network. Larger is this value, channel is available to more number of nodes. Hence by selecting channel common to maximum number of nodes as a first channel for contention, most of the nodes can reserve the channel for data transmission in advance and reduce the channel access delay. SCL is the sorted list of channels and time slots such that each channel is used for control signals transmission at the corresponding slot. It can be shown as

$$SCL = \{\{t_1, Ch_1\}, \{t_2, Ch_2\}, \{t_3, Ch_3\}, ...\{t_m, Ch_m\}\} \quad (3)$$

Where t_1 to t_m are the time slots Ch_1 to Ch_m are the channels such that for every k (1 to m)

$$\sum_{i=1}^{n} \lambda_i^k \geq \sum_{i=1}^{n} \lambda_i^{k+1} \quad (4)$$

Note here that the number of time slots equals the number of channels, m.

For NCM of Figure 3-5, SCL would be $\{C_4, C_2, C_3, C_5, C_1\}$. As there are 5 channels, time is divided into five slots. Each of the 5 slots is associated with a channel according to channels rank. In our example, time slot 1 is for channel C_4 (ranked 1), time slot 2 is for channel C_2, time slot 4 is for C_5 and so on. Each of the associated time slot associated with channels differs with other slots in that channel that it starts with signaling period as shown in Figure 3-8.

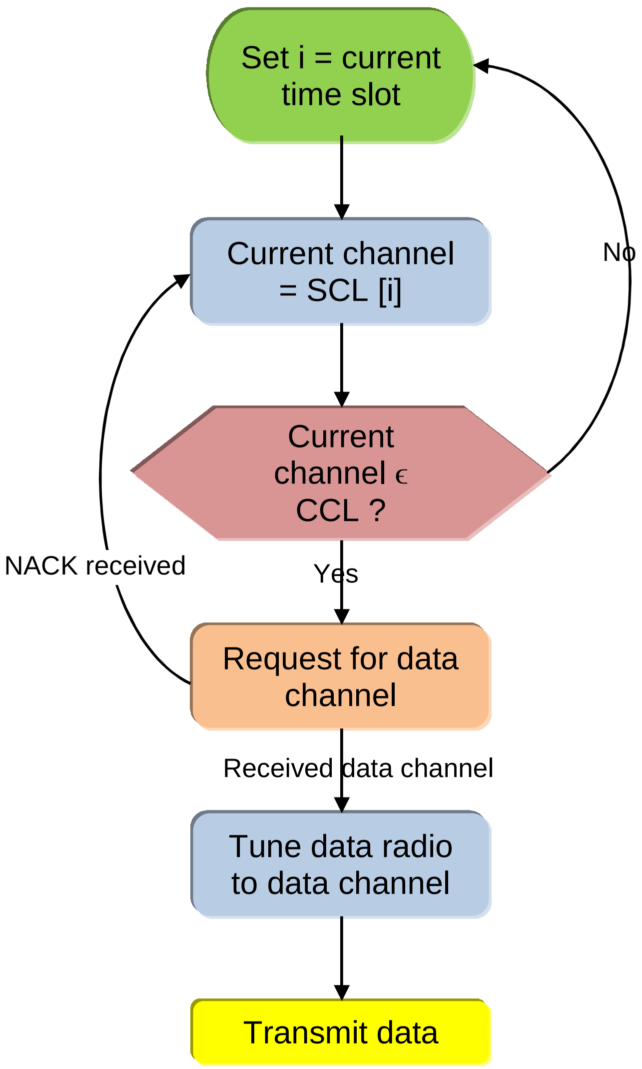


Figure 3-9: Channel access mechanism of sender

All of the nodes tune their listening radio to the channel associated with the current time slot. Hence, on every time slot, listening radio hops to every channel according to their rank on respective time slot. If a node intends to transmit and has channel represented by the slot in its CCL (that means, both transmitter and receiver have this channel in common), it would contend for intended channel during the signaling period. First choice for the intended channel would be first entry on CCL in case it is not reserved by any other pairs; otherwise second entry and so on.

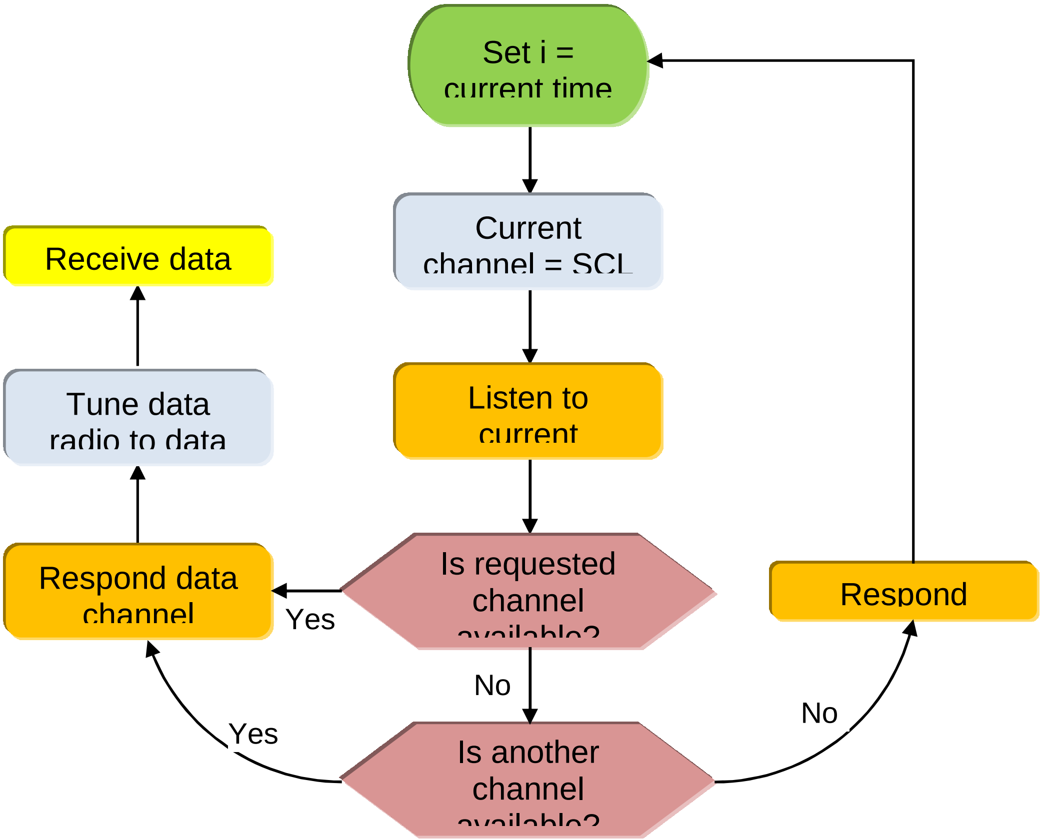


Figure 3-10: Channel access mechanism of receiver

On receiving channel reservation request from transmitter during signaling period, receiver sends acknowledgement to sender if the channel is not reserved. Otherwise, it will offer next entry in CCL as the candidate channel. As rests of the nodes are overhearing this reservation, they update their information that the channel is reserved by other pairs and would not attempt to access the channel in a similar way as the network allocation vector (NAV) is used in 802.11 MAC protocol. The medium access procedure of receiver and sender is shown in Figure 3–9 and 3-10.

After reserving a channel for transmission during signaling period, transmitting pairs tune their data radio to reserved channel and start data transmission in next slot. It should be noted that, during a signaling period multiple pairs can reserve disjoint channels and hence multiple transmissions can start at a same time (concurrent transmission in multiple channels). For instance, for a transmitting pair to transmit after a first slot, following criteria is to be met:

1. Channel is common to both the transmitter and receiver.
2. Channel is the first entry in the SCL.

First criterion has been derived in previous section. Since all the channels have equal chance to be the first entry in SCL (for simplicity), probability of transmitting pair to transmit after first slot is

$$\frac{1}{m} \times P(c) = \frac{1}{m} \times p_t^c \times p_r^c \qquad (5)$$

As per our example, first time slot is for channel C4. All the nodes tune their listening radio to this channel. As channel C4 is in CCL of nodes N1, N2, N5 to N8, pairs N1-N2, N5-N6 and N7-N8 reserve channels C3, C4 and C1 for transmission respectively. Rest of the nodes (N3 and N9) overhears the current reservation. During time slot 2, signaling period is on channel C2 which is in CCL of N3-N4 and N9-N10 where they reserve channels C2 and C5. Note that during signaling period in first time slot, N5 would have requested N6 to reserve channel C3 (first entry in their CCL). But during same time slot, it have already overheard that C3 is reserved by N1-N2, it requests N6 to access channel C4 (second entry in

CCL). During the slot 2, pairs N1-N2, N5-N6 and N7-N8 start their transmissions (see Figure 3-8). During slot 3, nodes N3, N4, N9 and N10 start their transmissions. This way, number of parallel transmissions in different channels has been made possible.

G. Probabilistic Analysis

Now we analyze the channel access delay of CA-MAC by building a Markovian model. The channels are opportunistic in cognitive radio environment. Due to this nature, the i^{th} channel is available to a node following a Bernoulli process with time invariant probability p_i. And the indicator function can be defined as

$$\lambda_i^j = \begin{cases} 1 & \text{if channel } i \text{ is available to node } j \\ 0 & \text{otherwise.} \end{cases} \tag{6}$$

Hence, p_i can be simply stated as the probability that λ_i^j takes value 1.

Time is divided into the number of slots. During each slot, one of the channels is used for the control phase by the nodes which hold the channel and contend for data channel reservation. The channels for the control phase are assigned in round robin fashion, and each device tunes its control radio to the channel used for the control phase and its data radio to its data channel.

Let the number of channels be M and the number of nodes be N. We form a Markov chain with states $\{X_t\}$ as shown in Figure 3-11. Here, X_t denotes the number of communicating pairs during time t. Note that it is the same as the number of busy channels and if $X_t = k$ (the number of communicating pairs), the number of busy devices is $2k$ and $N - 2k$ idle devices. The maximum number of communicating devices is bounded by $\min(M, N/2)$. Now, the state space of X_t can be given as

$$S := \{0, 1, \ldots, \min(M, N/2)\}. \tag{7}$$

At any state, the probability p_i that i ($0 \le i \le \min(M, N/2)$) agreements are made is given by

$$p_i = p_{SR}\, p_{idle}\,, \tag{8}$$

where p_{SR} is the probability that a pair of sender device (say S) and receiver device (say R) have the current control channel and thus $p_{SR} = p_S\, p_R$, and p_{idle} is the probability that i exclusive channels are idle and thus p_{idle} is given by the product of the probability that $M - i$ channels are busy (i.e., $({}^{k}C_{(M-i)} \times {}^{M-k}C_i)/\,{}^{k}C_M$ since k channels are busy) and the probability that i channels out of k available channels are exclusive (i.e., ${}^{k}C_i/\,{}^{k+i-1}C_i$), resulting in $p_{idle} = (({}^{k}C_{(M-i)} \times {}^{M-k}C_i)/\,{}^{k}C_M) \times ({}^{k}C_i/\,{}^{k+i-1}C_i)$.

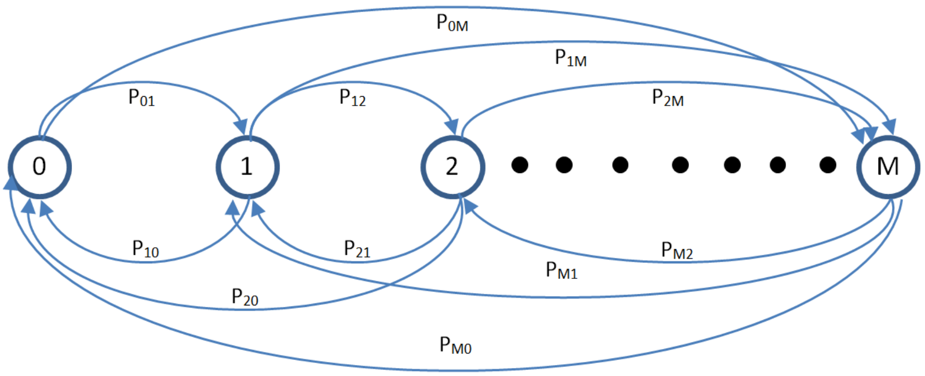


Figure 3-11: Markovian model with M states of the system.

Whenever a new agreement is made or the current transmission ends, a state transition would occur. If S_k^i is the probability that i new agreements are made at the current state X_t (or k) in the next slot and T_k^j is the probability that j transmissions terminate at the current state X_t (or k) in the next slot, the transition probability from state k to state l, p_{kl}, can be expressed as

$$p_{kl} = \begin{cases} \sum_{m=0}^{k} S_k^{m+l-k} T_k^m & \text{for } l \geq k \\ \sum_{m=k-l}^{k} S_k^{m+l-k} T_k^m & \text{for } l < k \end{cases} = \sum_{m=(k-l)^+}^{k} S_k^{m+l-k} T_k^m. \quad (9)$$

We can simplify the above equations by using set theory notation to make the equations more understandable. In every time slot t, a representative channel is used for control signal exchange by the nodes which tune their listening radio to this particular channel. Hence, if the current channel is C_t, then transmitting pairs *(S, R)* would contend for reserving a channel if $C_t \in CCL$ (*S, R*). Note that *CCL* (*S, R*) is obtained by set intersection of sender's and receiver's channel sets. Now, let us say that R_t is the set of the channels reserved by the contenders until time slot t, the total number of channels utilized in the next slot would be equal to cardinality of set R_t given as $|R_t|$. This is also the channel utilization of the network. Hence, throughput $Th(t)$ in time slot t can be obtained by

$$Th(t) = |R_t|\text{*(total packets)/(slot duration)}. \quad (10)$$

And, overall system throughput, Th_s is obtained by

$$Th_s = \sum_t Th(t). \quad (11)$$

At time slot t, $|R_t|$ pairs out of N number of nodes would be busy accessing the channels. As a result, $N/2 - |R_t|$ pairs would be idle. Therefore, the average network access delay of the system, D_{avg}, is given by

$$D_{avg} = \frac{1}{|t|}\sum_{t}(N/2 - |R_t|). \tag{12}$$

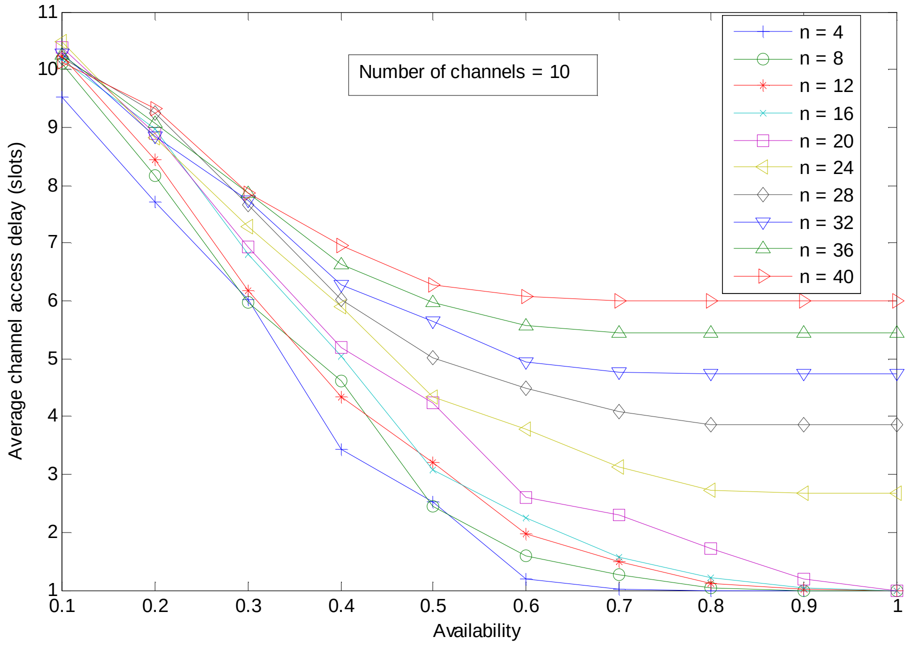


Figure 3-12 Expected average access delay versus channel availability with varying number of nodes.

We have done mathematical analysis in MATLAB to get the expected performance of the system. The channel availability is varied from 0.1 (10%) to 1 (100%) and the average channel access delay is obtained by varying the number of nodes (with 10 channels) as shown in Figure 3-12 and by varying the number of channels (with

10 nodes) as shown in Figure 3-13. These analysis results will be validated by the ns-2 simulation results which will be discussed in chapter IV.

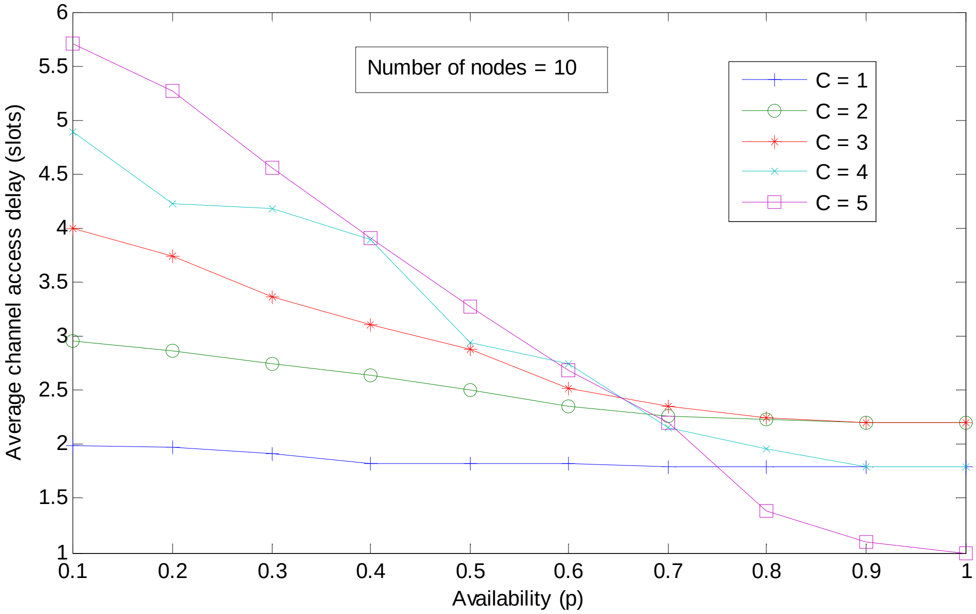


Figure 3-13 Expected average access delay versus channel availability with varying number of channels.

IV. Performance Evaluation

A. Simulation Environment

The performance study of CR MAC protocols is challenging due to the unavailability of a reliable evaluation tool even though special features are added above legacy wireless MAC protocols. In our performance study, the network simulator ns-2 is used. The “cognitive radio cognitive network simulator” CRCN patch [30] is combined in ns-2 for CRN simulation. It provides additional functionality to ns-2 with cognitive capabilities of multichannel environment, channel selection at MAC or routing layer and multi-radio interface. We have used ns-2.31 version with CRCN patch for our simulation. Although some sample MAC protocols have been provided for tests, we have modified the existing 802.11 MAC protocol to suite CA-MAC characteristics. The simulation parameters are summarized in Table 4-1.

Table 4-1 Simulation parameters

Description	Value
Simulation tool	Ns-2 (with CRCN patch [18])
Network area	1000m × 1000m
Number of nodes	40
Number of sessions at a time	5
Propagation channel model	Two-ray ground reflection model
Number of interfaces per node	2
Number of channels	10
Channel availability	10% to 100% (steps of 5%)
Maximum signal period length	10ms
Simulation time	50s
Number of NCMs per the examined value of channel availability	50 (950 in total)

Figure 4-1 shows the overall simulation and analysis procedure. We assume that channel sensing phase has passed and hence feed the nodes with channel information through NCM files. The number of NCMs is created for each of channel availability for more number of runs to mitigate effect of randomness. For each NCM network scenario and both the protocols, huge number of simulation runs is to be undergone. We therefore do this through batch simulator built using Linux operating systems bash. Finally large amount of trace files through these runs are processed to form data files by trace analyzer using perl script and finally these data files are plotted by appropriate plotter.

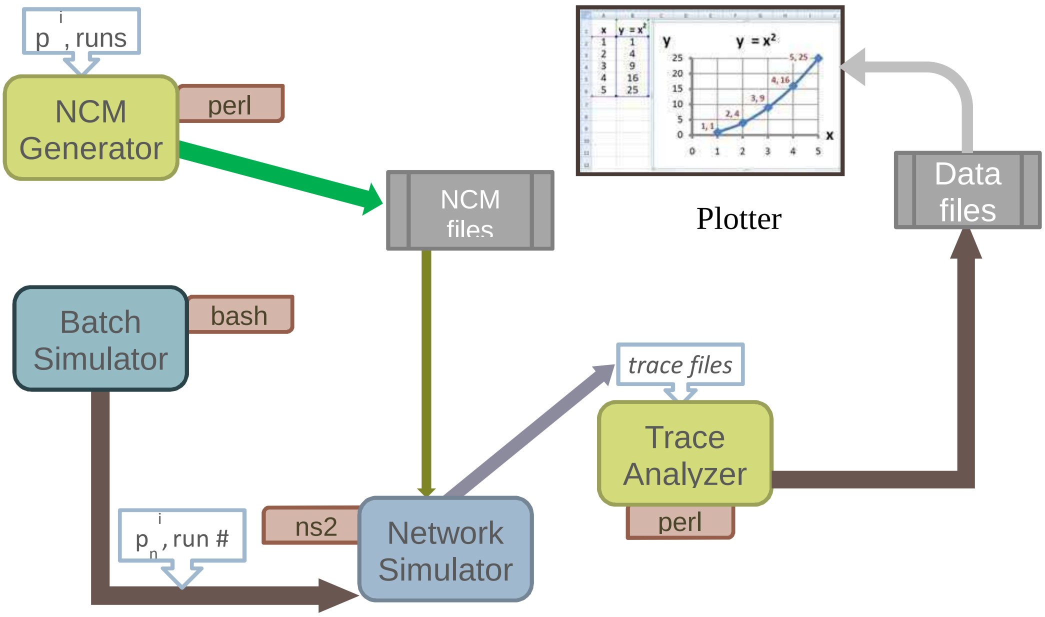


Figure 4-1: Simulation and analysis methodology.

The CA-MAC requires node-channel information obtained through sensing phase, or exchanged between the nodes. This phase is assumed to be passed. The channel availability (as described in Chapter III) is varied from 10% to 100% with the steps of 5% to represent harsh, “uncommon” and “common” channel environment as explained earlier. So, there are 19 examined values of channel availability (i.e., 10%, 15%, …, 100%) in total. For each value of channel availability, 50 NCMs is generated to create total of 950 NCMs. This number of sample NCMs is enough to validate the outputs due to randomness. The 802.11 MAC protocol is modified with the input of these NCM values and prepare all of the data structures as per our protocol such as SCL and CCL. Around 40 nodes are deployed randomly in 1000m x 1000m area. Out of them, 10 nodes are selected in random as transmitter and receiver. The transmission range and other values were kept to default settings. The number of channels is set to 10 with the availability probability varying from 10 to 100 percent with steps of 5 as mentioned earlier for each of the nodes. For making multiple numbers of users able to contend in a single slot, slot length is set to 10 milliseconds.

B. Simulation Results and Discussion

In this section, we present the simulation results obtained and comparison with the SYN-MAC protocol. SYN-MAC protocol is similar to CA-MAC protocol but differs in the sense that channel hopping order is according to channel index and only one new transmission can be started in a time slot [7]. It offers the good connectivity between network nodes and outperforms the existing CCC based protocols. Hence, it can be considered as a key MAC protocol for uncommonly distributed channel architecture in CRAHNs. Although it solves the several problems related to CCC, it has a shortcoming as in one slot; only one transmission can be started. Our target in CA-MAC is to overcome this by allowing multiple transmissions to start at a time and hence decreasing the overall channel access delay in the network. SYN-MAC was simulated using the same procedure under same network environments with same inputs as CA-MAC for comparison.

Figure 4-2 shows the observed end-to-end delay in terms of slots in SYN-MAC and CA-MAC under the same network scenarios (i.e. the same NCMs). We can observe that CA-MAC has less delay in channel access compared to SYN-MAC. Gap between the trends of CA-MAC and SYN-MAC is found to increase as more number of channels is available throughout the network. In SYN-MAC, as only one new transmission is allowed per slot, for n transmissions, at least $n \times (n - 1)/2$ slots are lost in total. Hence, average delay for n channels is at least $(n - 1)/2$ slots. However, as in CA-MAC, multiple transmissions can start in a same slot, minimum delay would be one slot per every transmissions. Hence average delay would be around 1 slot for an ideal case where all the transmissions start from the beginning.

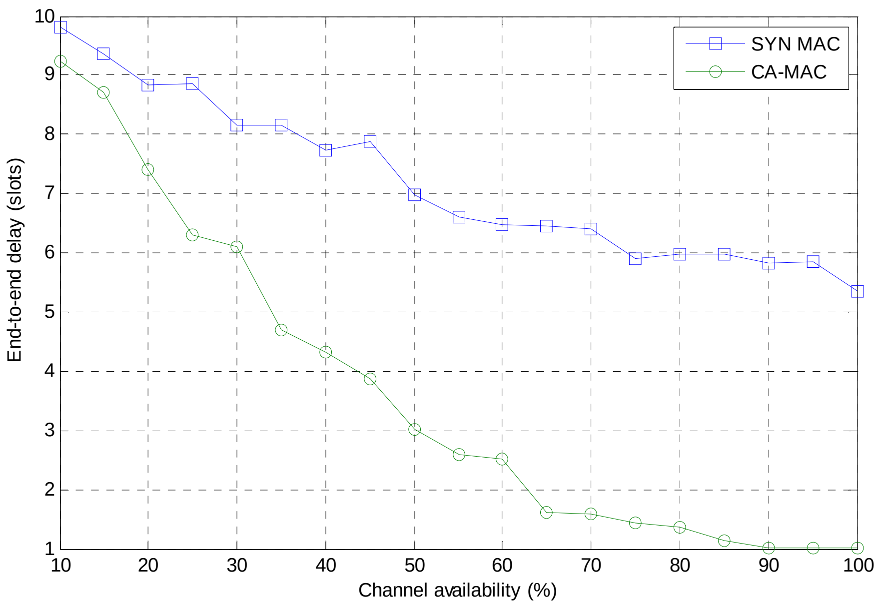


Figure 4-2: End-to-end delay at different channel availability.

Figure 4-3 compares SYN-MAC and CA-MAC in terms of session connectivity. In this paper, session connectivity in a network is defined as the ratio of the number of communicating pairs over the total number of enabled sessions. We can see that session connectivity is high in CA-MAC compared to SYN-MAC because, in SYN-MAC, a node selects a channel randomly out of available common channels. And if it loses the contention, it has to wait for next available common channel with its intended receiver. However, in CA-MAC, transmitter can contend for any channel in any slot and receiver could even notify the transmitter of next available channel during same slot. For an instance say $\{C_1, C_3, C_5\}$ be the CCL and current slot be 3rd slot. In SYN-MAC, nodes would contend to access channel 3. If they lose, they need to wait till 5th slot for next contention (where there is no guarantee of winning). On the other hand, if C_5 was not available, it cannot contend for C_1 after losing C_3 because 1st slot representing channel C_1 has already passed. But in case of CA-MAC, nodes can contend for C_3 in current slot in current channel and if it loses, it can claim C_1 to be accessed in next slot.

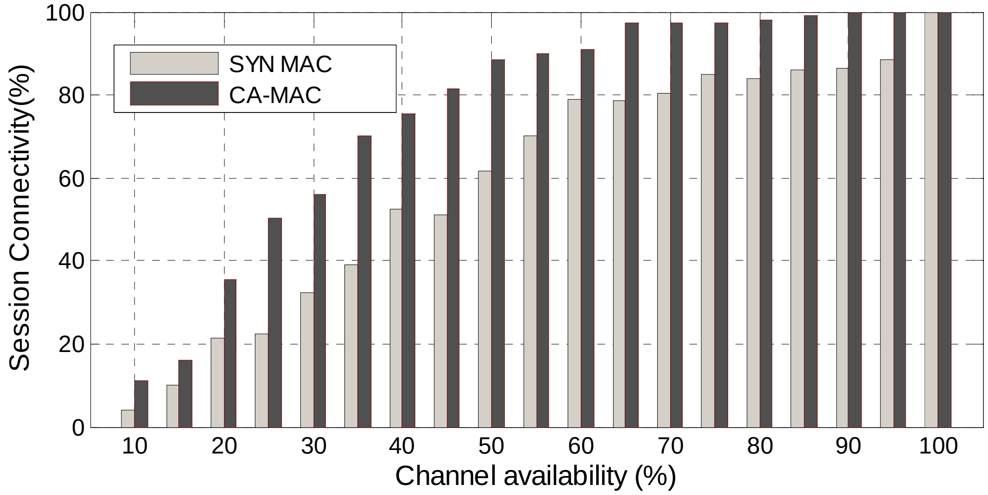


Figure 4-3: Session connectivity at different channel availability.

Figure 4-4 highlights that, through lower access delay and high connectivity, CA-MAC offers better throughput compared to SYN-MAC. In Figure 4-4, *normalized throughput* represents the normalized ratio of the maximum throughput obtained in all the examined values of channel availability over the throughput obtained at a given channel availability. We can see from the graph that the normalized throughput equals one when channel availability is around 100% for both protocols which corresponds to the maximum throughput obtained. Rests of the plots are the relative throughput to that maximum obtained throughput at this point. There are some rise and falls in the plot of throughput because the channel selection is a random process and channel availability itself is random. Hence, due to randomness, the output is not smooth. However, this effect is compensated through multiple iterations.

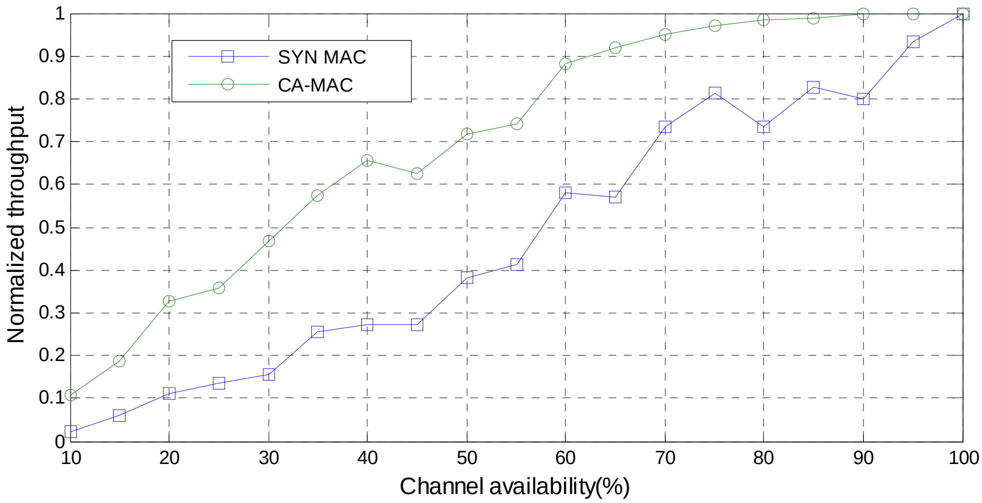


Figure 4-4: Network throughput at different channel availability.

V. Conclusions and Future Works

We presented a MAC protocol for CRAHN where the channel is uncommon between nodes. This is the practical case in the CR networks where channels available might not be same to all of the nodes in the network. Proposed CA-MAC protocol does not require any CCC. Hence it is possible for network connectivity even one channel is not common throughout the network. In addition, several problems of CCC can be avoided. We simulated the protocol using ns2 and CRCN patch for CRNs and compared it against SYN-MAC protocol. We have shown that CA-MAC outperforms SYN-MAC by improving overall network access delay and network connectivity by allowing multiple device pairs to transmit data concurrently in different channels.

As the future works in CA-MAC, we plan to add additional optimizations such as minimizing the NCMs size to optimal dimension. This is to form an abridged NCM which could simplify the processing overhead required in each of the node-ends. Also, as explained, in CRAHNs MAC protocols, choice of channel to be selected depends on the kind of network implemented. Therefore, we plan to study and identify an appropriate utility function for various kinds of networks. Several utility requirements such as QoS, PU interference preservation, delay tolerant network, intra-SU congestion can thus change the channel sorting schemes. In addition to this, in future work, a priority classes can be created by a node in order to access channels. This could have one or more targets such as PU interference preservation, fairness, and delay sensitivity or for some multimedia applications. The channel selection schemes popular in literature such as: game-theoretic selection or statistical prediction can be implemented in the system in future.

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ABSTRACT

A MAC Protocol for Concurrent Channel Access in Cognitive Radio Ad Hoc Networks

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Cognitive radio ad hoc networks (CRAHNs) consist of autonomous devices that operate in ad hoc mode and aims to perform efficient utilization of spectrum resources. In cognitive radio (CR) networks, unlicensed users sense the licensed spectrum bands and opportunistically access them without interfering operations of licensed users. This requires serious attention on MAC layer design for spectrum access. Especially, in ad hoc networks with no central coordinator, the MAC layer plays an important role in coordinating unlicensed users' access to the licensed spectrum. Recently, a number of works on designing MAC protocols for this purpose have been published. Most of them, however, are restricted with numerous limitations and assumptions. In this thesis, we examine MAC protocols in CRAHNs and propose a new MAC protocol called CA-MAC (Concurrent Access MAC) in this category.

First, we categorize the protocols on the basis of common control channel (CCC) requirements and further review major implementations for each category. Then, we make a qualitative comparison of the protocols in terms of inherent characteristics and performance. Usually, cognitive devices exploit a vast number

of available channels. In general, all or some channels are not common to the nodes in a CRAHN. Such a network environment poses the problem of establishing a common control channel (CCC), as there might be no channel common to all the network members at all.

Then, we propose a MAC protocol named CA-MAC which operates on this kind of channel environment without requiring any CCC. The two devices in a communicating pair can communicate with each other even if they have only one common channel available. Therefore, the problems with CCC (such as channel saturation and denial of service attacks) can be also resolved. CA-MAC distributes the channel access between communicating pairs and, thus, it increases network connectivity. In addition, CA-MAC allows the concurrent access to multiple channels concurrently. According to our performance study, CA-MAC provides the higher network connectivity with shorter network-wide channel access delay compared to SYN-MAC (which is the conventional key MAC protocol for similar “uncommon” channel architecture in CRAHNs), resulting in better network throughput.

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