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Cognitive Radio Network with a distributed control channel and quality-of-service solution

Urban Terrell Wiggins
Louisiana State University and Agricultural and Mechanical College, uwiggi1@lsu.edu

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COGNITIVE RADIO NETWORK WITH A DISTRIBUTED CONTROL CHANNEL AND QUALITY-OF-SERVICE SOLUTION

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

the Department of Computer Science

by
Urban Wiggins
B.S., Southern University, 1994
M.S., Southern University, 2002
December, 2011

DEDICATION

TO MY FATHER,
WHOSE SHOES NOW FIT (JUST LIKE YOU SAID THEY WOULD).
I WISH YOU WERE HERE TO SEE THEM ON ME.

TO MY MOTHER,
WHOSE SOFT WORDS AND SUBTLE BUT INDOMITABLE SPIRIT GIVES ME COURAGE.

TO MY SON, BRANDON, AND DAUGHTER, LONDYN,
WHOSE SMILES AND HUGS ARE INSPIRING AND ALLOWED ME TO PERSEVERE.

TO MY WIFE, WENDY, MY SPECIAL LADY,
WHOSE BELIEF HAS PROVIDED MY LIFE WITH HAPPINESS AND LOVE.

ACKNOWLEDGEMENTS

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Finally, to my family that has walked this road along my side. You have been my inspiration and support. I can’t express how much you mean to me. You have made my life, and at times my house, chaotic and I would not have it any other way.

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ABSTRACT

The proliferation of wireless access and applications to the Internet and the advent of a myriad of highly evolved portable communication devices; creates the need for an efficiently utilized radio spectrum. This is paramount in the licensed and unlicensed radio frequency bands, that spawn an exponential growth in Dynamic Spectrum Access (DSA) research, Cognitive Radio (CR) and Cognitive Radio Networks (CRN) research.

DSA research has given way to the paradigm shift toward CR with its dynamic changes in transmission schemas. This paradigm shift from a fixed and centralized frequency spectrum environment has morphed into a dynamic and decentralized one. CR provides wireless nodes the capability to adapt and exploit the frequency spectrum. The spectrum information obtained is scanned and updated to determine the channel quality for viability and a utilization/availability by the licensed (primary) user.

To take advantage of the CR capabilities, previous research has focused on a Common Control Channel(CCC) for the control signals to be used for spectrum control. This utilization generates channel saturation, extreme transmission overhead of control information, and a point of vulnerability. The traditional designs for wireless routing protocols do not support an ad hoc multi-hop cognitive radio network model.

This research focuses on a real world implementation of a heterogeneous ad hoc multi-hop Cognitive Radio Network. An overall model, coined Emerald, has been designed to address the architecture; the Medium Access Control layer, E-MAC; and the network layer, E-NET. First, a Medium Access Control(MAC) layer protocol is provided to avoid the pitfalls of a common control channel. This new design provides CRNs with network topology and channel utilization

information. Spectrum etiquette, in turn, addresses channel saturation, control overhead, and the single point of vulnerability.

Secondly, a routing model is proposed that will address the efficiency of an ad hoc multi-hop CRN with a focus on the Quality-of-Service(QoS) of the point-to-point as well as end-to-end communication. This research has documented weaknesses in spectrum utilization; it has been expanded to accommodate a distributed control environment. Subsets of the model will be validated through Network Simulator-2(NS/2) and MatLab© simulations to determine point-to-point and end-to-end communications.

Chapter 1

Introduction

1.1 Overview of Cognitive Radio

Wireless communication is not a new paradigm to the technological world of today. It may be viewed in different ways and generically defined as the means of conveying a message from one point/person to another by means of some tool that may be understood by the receiver of said message. This opens the concepts of wireless communication to literally mean without wires and have an addition of some type of tool or device to convey the message from sender to receiver.

This work will delve into the world of radio-based communication with the transmission of an electrical signal via the air from sender to receiver. The evolutionary track of the wireless communication will also be based with the technological usage of the 21st century computer-based devices. This brings forward and introduction of the software-defined and cognitive radios. Figure 1 is an illustration from [1], of what will be covered in the paper: the traditional, software-defined, and cognitive radios.

1.1.1 Traditional Radio

An easy familiarity may be sparked when conversation is, "How does a traditional radio frequency communication behave?" This question is not very profound in this current day and age. Most middle school students can explain, in their own words, how the radio works.

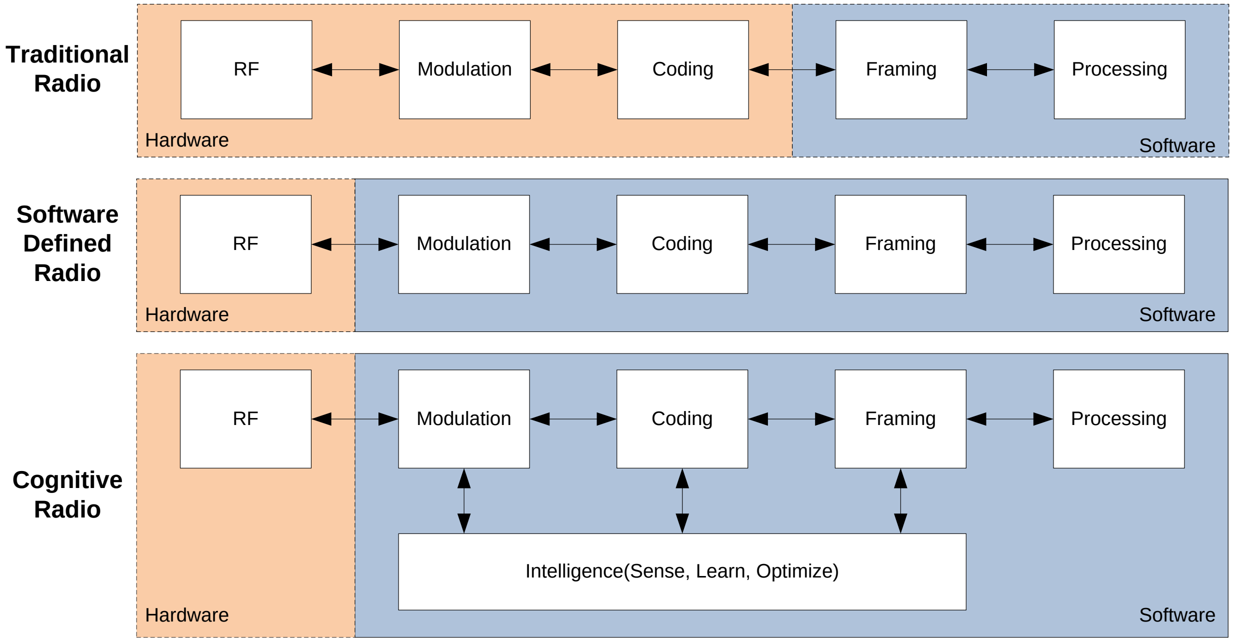


Figure 1: Logical diagram contrasting traditional, software defined, and cognitive radio

A simple explanation of conventional communications would be that an antenna broadcasts a signal on a specific frequency and another antenna receives that signal. Albeit simplistic, this is the fundamental basis of a broadcast which is a unidirectional communication paradigm.

1.1.2 Software Defined Radio

Software Defined Radio(SDR) served as the predecessor to cognitive radio. Due to the diversity of opinions in the research arena regarding the definition of an SDR, even for the sake of conversation, the SDR Forum collaborated with the Institute of Electrical and Electronic Engineers(IEEE) P1900.1 working group established several definitions for SDR and Cognitive Radio terminology. The resulting definition of SDR is a "*radio in which some or all of the* *physical layer functions are software defined(-- radio system software processing for operational functionality but not control functionality.)*". [2]

The FCC defined SDR as

> **"…a transmitter in which the operating parameters of frequency range, modulation type or maximum output power …can be altered by making a change in software that controls the operation of the device without making any changes in the hardware components that affect the radio frequency emissions."** [3]

The FCC's definition is more specific with regards to the physical layer aspects of operations; however, this definition is basically the same as that derived by the SDR Forum and IEEE.

1.1.3 Cognitive Radio

There have been several definitions as well as concepts that are involved in the introduction of Cognitive Radio or intelligent radios. The Spectrum Sensing involved in the Dynamic Spectrum Allocation concepts are truly diverse; however, they are all rooted with dynamic ad hoc spectrum manipulation while remaining non-obtrusive to the primary users.

1.1.3.1 What Is Cognitive Radio?

Mitola's Definition [4]***:***

Cognitive Radio is an extension of the Software Defined Radio. [4] goes on to define CR as:

> **"… the point at which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to:**
>
> **a) detect user communications needs as a function of use context,**
> **b) to provide radio resources and wireless services most appropriate to those needs."**

Cognitive radio adds interfaces, applications, and other cognition functions such as behavior and components. Mitola presents two primary CR functions; (1) the recognition of the communications context and (2) the mediation of wireless information services.

Communications context recognition is the interpretation of user action process streams with their respective applications. This function utilizes, as a last resort, input regarding the communication context from the user interface. In this research, we have extended this definition to incorporate the minimum network requirements with respect to the application's network footprint as proposed in previous research. [5] This serves as the foundational basis for the Quality-of-Service aspect of this research.

The mediation of wireless information is the record maintenance of the other users in the geospatial radius of the CR node. Incorporated within the mediation are additional factors regarding the overall network, such as, spectrum availability, spectrum occupancy, time and space utilization, and also cost. This research advances this by its routing table information.

Federal Communications Committee (FCC) Definition:

The FCC references CR by its capabilities. [3] defines CR as "… a radio that can change its transmitter parameters based on interaction with the environment in which is operates." This definition of CR is broader with respect to the environment which infers both the interference levels in a frequency band but also data traffic patterns relative to the volume of simultaneous communications set forth via other nodes in the same temporal and geographic region. [3] further explains CR by noting that "this interaction may involve active negotiations or communications with other spectrum users and/or passive sensing and decision making within the radio."

Although the FCC's recognizes the dynamic faculties of CR; the full scope of CR involves additional phases that address the transmission patterns of the primary user or any recurring natural environmental interferences that must be acknowledged in the spectrum utilization for example.

Regarding the capabilities of the CR node, [3] provides for five(5) basic features for incorporation:

1. Frequency agility – a radio's ability to alter the operating frequency plus a methodology for dynamically determining the appropriate frequency.
2. Adaptive modulation – the strategic modifying of the transmission characteristics and waveforms.
3. Transmit power control – transmissions at appropriate limits, higher or lower power levels for equity or better bandwidth optimization.
4. Geographic consciousness – the awareness of its physical location as well as the physical location of other CR's. The CR can then adjust the power and the frequency levels to accommodate the geospatial information attained and analyzed.
5. Spectrum sharing policy – A policy that provides the terms a primary user may allow a secondary user access to its (primary user) frequency spectrum.

An addendum to these capabilities is the incorporation of a security feature restricting "only authorized usage" and preventing "unauthorized modifications".

Next Generation(xG) Definition:

As noted in [6], the definition of cognitive radio has expanded beyond serving as the expansion of software defined radios. The concept has been broadened to cover dynamic spectrum access along with expanding the inference of the CR footprint with Multiple Input

Multiple Output and multiple antennas as a means to fully incorporate the phases of the cognition cycle. This research utilizes the broader definition of CR where the primary functions are keystones in the design and architecture.

After the referencing of several sources such as Mitola, FCC, ITU-R, and IEEE-USA, Neel's dissertation [7] determined that a Cognitive Radio is a radio that has a control process that utilizes knowledge and analysis to modify its transmission parameters in an ad hoc manner.

Akyildiz et al [8] defined CR as a "radio that can change its transmitter parameters based (up)on the interaction with the environment in which it operates." This definition focuses on the interaction of communication between multiple nodes without respect to the primary user's frequency ownership or etiquette policy with any secondary users in the geographic or temporal area.

Cabric [9] defines a CR as a "network of radios that co-exists with higher priority primary users, by sensing their presence and modifying its own transmission characteristics in such a way that they do not yield any harmful interference." The focus of [9] is spectrum awareness and spectrum agility as related to the physical and network layers.

1.1.3.2 What Are Spectrum Holes?

As noted in Chapter 2, the frequency spectrum has been assigned to its licensed users; therefore, the CR node is faced with the problem of utilization of a frequency spectrum without interfering with those whose usage may be described as discretionary at best. In [10], Haykin described the *spectrum holes* or *white spaces*. He defined spectrum holes as " *…a band of frequencies assigned to a primary user, but, at a particular time and specific geographic location, the band is not being utilized by that user."* Whenever the primary user attempts to utilize the frequency it has been assigned, the cognitive user must discontinue its transmission as to not create interference with the primary user's transmission. The CR node then accomplishes this by then altering its transmission characteristics, such as transmit power level and modulation scheme. This concept is illustrated in Figure 2 [11] below.

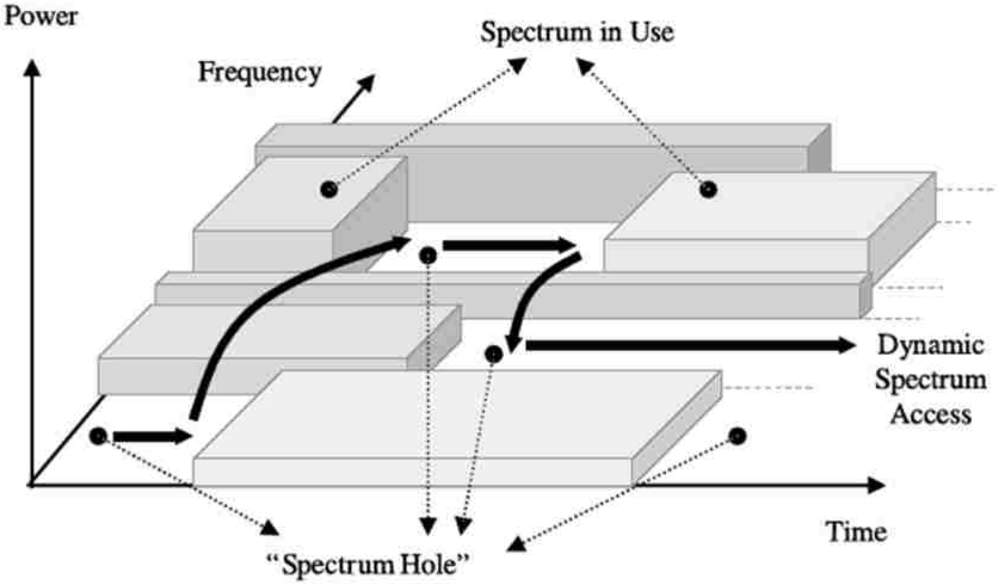


Figure 2: Time-Power-Frequency diagram illustrating "Spectrum Holes"

1.1.3.3 What Is the Cognition Cycle?

The Cognition Cycle in Figure 3 illustrates the phases of the cognitive radio as presented by Mitola in [4]. The cognition cycles phase are orientation, planning, decision, learning, acting, and observation, in no particular order. The CR node adjusts**(orient)** its operating conditions based upon information obtained regarding the **outside environment**. The **observed** conditions priority based evaluations in this research leverages the network footprint of the application's transmission characteristics as in [5] to establish these priorities. The CR node then **plans** its options based upon the observations. The chosen (**decide**) frequency may generate a decision collision or upon implementation**(act)**, the transmission may generate an actual network collision [5]. The operating environment of the outside world is again observed to complete the cognition cycle. Amidst the observing, planning, deciding, and acting is **learning**; where recurring factors are noted and patterns of spectrum availability or unavailability may be recognized. This pseudo-consciousness denotes the cognition factor.

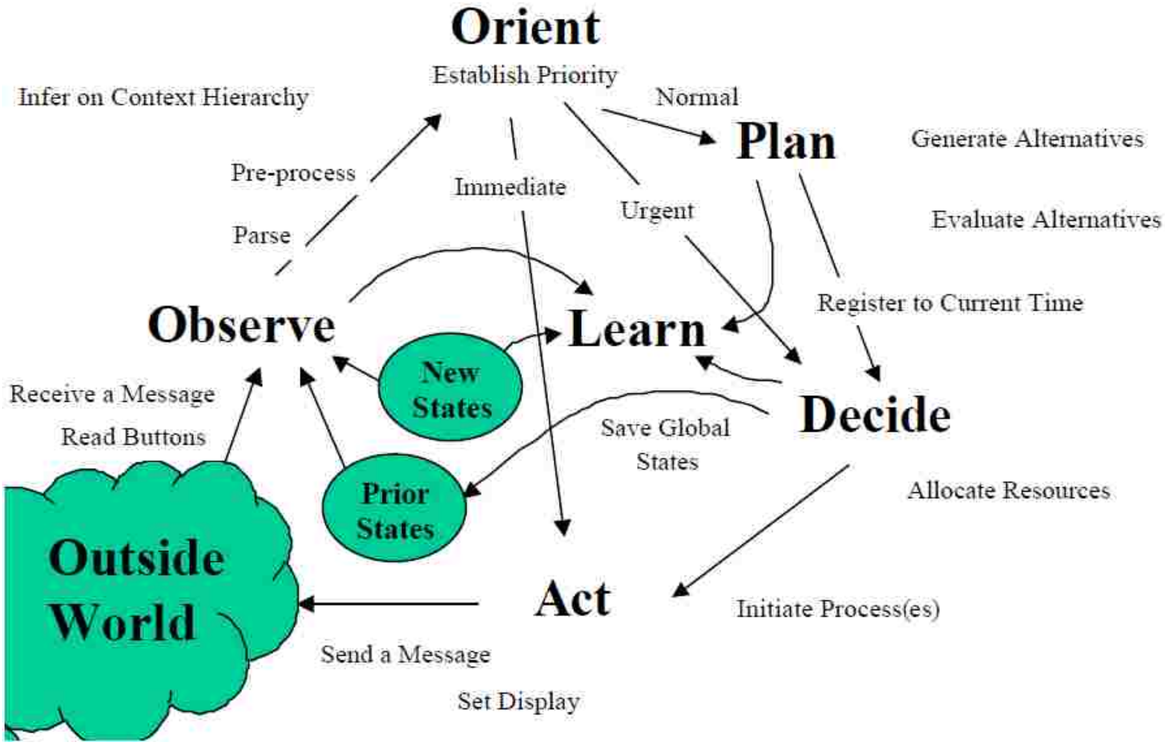


Figure 3: The Cognition Cycle (c) 2009 Joseph Mitola III, Reproduced with Permission **[4]**

1.1.3.4 What Are Cognitive Functionalities

The main functions of the CRN are: [4] [12] [13]

- Spectrum Management (also known as Spectrum Decision) – provides the best channel for the secondary user by analyzing the spectrum deterministically based upon the physical layer network transmission demands or requirements. As noted in our previous research [5], the spectrum determination for a “best fit” frequency is redefined to be the “most appropriate” frequency for this transmission.
- Spectrum Mobility – Since CR nodes are viewed as “visitors” or “seat fillers” in the frequency spectrum; the CR nodes must be able dynamically alter its communicating frequency. The primary user’s transmission must always take precedent over a secondary user.
- Spectrum Sharing – a coordinated effort/policy to provide equity amongst CR nodes within the frequency spectrum, also noted as similar to a wired networks MAC problem of equity.
- Spectrum Sensing – evaluates the frequency spectrum denoting the location of the unused and / underused frequencies that will not be harmful to other users. In [14] the manipulation of spectrum sensing is subdivided into three categories of detection: interference-based, cooperative, transmitter detection.

1.1.4 Cognitive Radio Network

The Cognitive Radio Network (CRN), as the cognitive radio, is extremely diverse in definition and understanding. Most of the definitions of a CRN incorporate a CR node or nodes as featured concept solution as a frequency spectrum opportunistic device with or without prior knowledge of itself and environment. At this point the consensus diverges. Throughout much of the CR research industry, a CRN and a Cognitive Network (CN) are terms often used interchangeably. This paper will use CRN except in places a direct reference is made.

Kondareddy et al [15] defines a CRN as "a group of opportunistic users communicating with each other using the spectrum holes." [15] indirectly classifies the CRN as a composition of CR nodes and a management member. [15] extends the definition to address infrastructure based and infrastructure less based networks. infrastructure based networks introduce the Cognitive Base Station(CBS) as a centralized controller. The CBS gathers and processes the free channel list from the CR nodes or it senses the entire frequency spectrum domain itself.

Akyldiz et al [12] references the CRN as a Next Generation network (xG network) that is comprised of both primary users(those with spectrum licenses) and secondary users(those without spectrum licenses). This composition of users with their opportunistic spectrum access and dynamic transmission modulation references the definition presented in [16].

In [17], the distinction between the cognitive network and the cognitive radio is described as a factor of the scope each technology perceives. The scope of the cognitive radio is described as the "customization of the wireless channel(s) access". The scope of the cognitive network is the "network-wide optimization and end-to-end network-wide goals."

A formal definition was presented in 2005 at the IEEE DySPAN conference by Thomas et al. [16] This definition is supported in kind by [18], [19] [20] and [21], for example. Thomas defined a CN as a network

> "…that can perceive current network conditions, and then plan, decide and act on those conditions. The network can learn from these adaptations and use them to make future decisions, all while taking into account end-to-end goals."

Thomas et al continued the distinction between the Cognitive Radio and the cognitive network. First, the overall goal of a cognitive radio is localized to communication between the cognitive radios communication; while the cognitive network seeks an end-to-end solution of communication with all devices as a whole. The difference is between a localized versus global view of communication. Next, the cognitive network is not restricted to the wireless environment and only with CR nodes. This promotes a greater heterogeneity within the network. As such, there is no limitation to the type of network as wired or wireless, further distinguishing the cognitive network from the cognitive radio. This research will reference the definition from [22] throughout this paper with a conscious addition of Quality of Service into the definition.

1.1.5 Cognitive Radio Applications

Real world application of CR nodes traverses emergency management/implementations, military operations, and high volume low availability environments. [12] The emergency management arena relies on the existence of an infrastructure for functionality. As noted in 2005, during Hurricane Katrina in Louisiana, communication was a premium commodity.

The paradigm shift is the concept of providing for every wireless networking device the Cognitive Radio design features. This concept supports the frequency spectrum limitations as well as the support for the constantly increasing number of active wireless network devices in the market and on the people of today all requiring network connectivity.

1.1.5.1 Emergency Application

In [23], the emergency application of the CRN is noted as a functional component as from [24] an **Incident Area Network(IAN)** or as in [25] an **Incident Communications Network(ICN)**. As these two network types are essentially the same, this paper will use IAN moving forward. The IAN is a network created due to an unexpected event which has occurred in an environment.

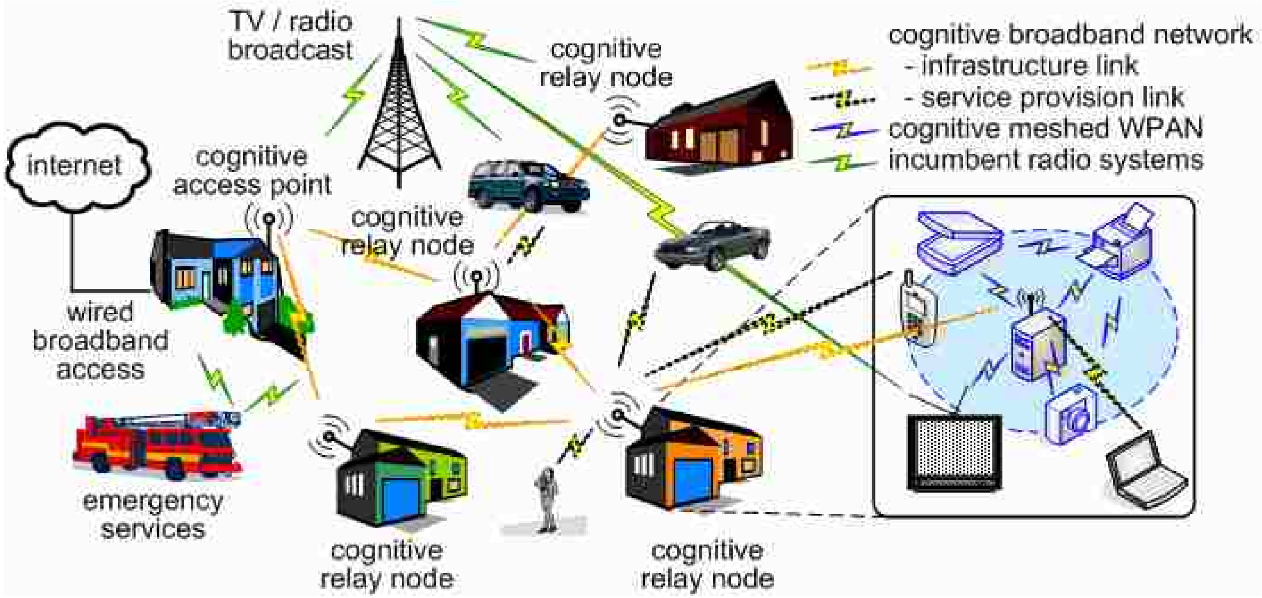


Figure 4: Real-life example of CR nodes operating in conjunction with PUs **[18]**

As noted earlier, Hurricane Katrina in the Gulf Region left the area devastated and the traditional wired network solutions were completely unavailable. Although these devices were physically in place, relatively, they were inoperable. [26] This event fostered the creation of an ad hoc CRN for emergency and evacuees in the area.

Another situation that finds a fit for CRNs would be in the case of a forest fire as often experienced on the western coastal region of the United States. In this case, there is limited to no wire structured communication system to utilize. An ad hoc CRN is necessary to establish or even maintain communication with emergency personnel.

Certain services are noted, in [23], as required services for the emergency communications situation: video calls, voice calls, and text messaging and alarm services. These services are often found to be completely absent or inoperable in cases of emergency situations.

1.1.5.2 Military Application

The ability of the military organizations such as the U. S. Department of Defense and the U. S. Department of Transportation are supporters of the efficient utilization of the frequency spectrum. A contributing factor may be due to the utilization of next-generation spectrum dependent devices for communications, weapons, logistics, sensors, munitions, radars, navigation, and geo-location systems. [27] [28]

The military application of a CRN provides a dynamic spectrum flexibility that can be employed in multiple international locations. [26] Spectrum availability or even utilization will be governed by various international entities with their own respective requirements. This flexibility is also extended into more combative/hostile environments; where standard wireless communications may be intercepted or even jammed.

1.2 Motivation

In 2002, the FCC determined that almost 90% of the radio spectrum at different time and different locations is either underutilized or not utilized. This inefficiency of the radio spectrum represents a challenge and an opportunity for researchers. [29] As noted in Figure 5 , the frequency spectrum that has been allocated by the United States.

Research has been done in single Cognitive Radio communication. This communication addresses the first question of (***Question #1***) how does a node communicate with another node? As noted in the IEEE specification 802.22 [30], as a point-to-multipoint communication design with the usage of a base station. This base station manages the cell/cluster of CR nodes providing channel control information. [31]

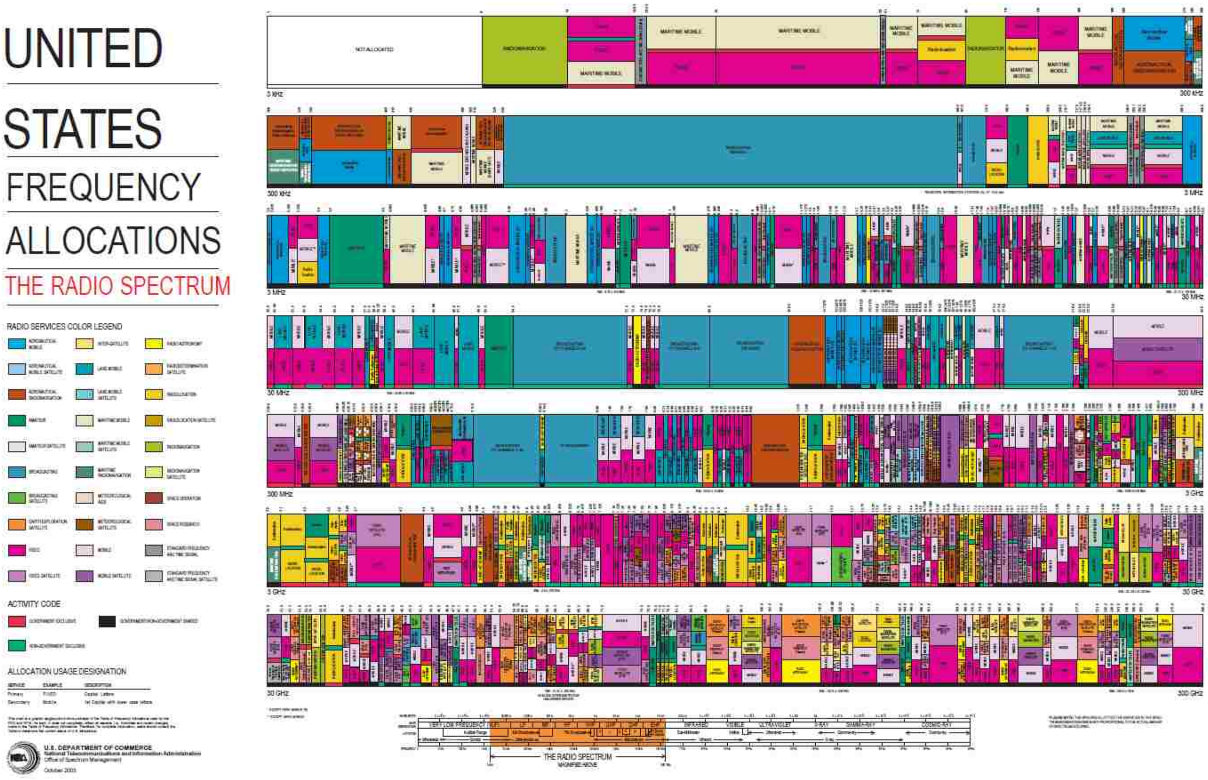


Figure 5: United State Frequency Allocation Table

Additional research has been done designing routing methodologies that allow nodes to create a multi-hop network path. [32] This presents another question in CR communication: (***Question #2***) What type of routing algorithm should be utilized that not only addresses the shortest hop problem but also includes the multiple frequencies and temporal variances that are maintained by each node.

Research has also been done in the opportunistic allocation of spectrum or spectrum management for CR networks. Spectrum management is not a new area of research, but it has been augmented by the CR concept. Game theoretic [10] [33] [34] [7], Genie-aided dynamic spectrum allocation [35] and frequency reservations [10] [21] are proposed examples of spectrum management solutions. Many of these algorithmic designs are employed with routing as well; however, the infrastructural design manages via a common control channel, a base station/clusterhead, or some other entity that services as an overarching manager and, as this paper has note, a single point of failure.

With the desire to eventually communicate through a CR network onto a wired network some topological design relative to the OSI model must be established. It will serve as the basis for any standardization of any CR protocol.

Existing research efforts have expanded upon or generated new algorithmic techniques based upon the CR conceptual design; however, the setup or initialization of nodes in for a CR network has not been clearly defined, [21] has an assistance system with a “genie-aided” device that provides for a truly ad hoc CR network with an assumption of an established network setup.

While routing has been addressed; CR nodes must also act as a gateway to provide communication for nodes that cannot communicate directly to one another due to interference, distance, or attenuation; while still managing the myriad of frequencies and relative time slots of each nodes communication sequence.

Researchers have proposed several solutions to address a few of the nuances of a CR network. Many proposals focus on the development of a common control channel; for synchronizing communication or clustering; creating a clusterhead for the management of the spectrum.

In summary, the critical design problems for a CR network are

- Network Setup problem [15]
- Common Control Channel Problem [15]
- Hidden/Exposed Station problem [12]
- Routing in a CRN

1.3 Problem Statement

We consider the challenges of communication between point-to-point or end-to-end cognitive radio nodes. There are major implications of the CR technology and a few are as follows:

- Synchronicity – CR nodes can frequency hop throughout the entire radio spectrum via spectrum holes based upon the spectrum's availability at the time of transmission. The CRN provides for nodes to route traffic between nodes that are either geographically distant or frequency unavailable.
- Fairness – Since secondary users are opportunistic by design, frequency utilization can be competitive, which lends itself to "frequency squatting". Frequency squatting shall be defined as the act of a secondary user monopolizing a frequency by continually transmitting on that frequency making it appear as occupied to all other secondary users.
- Scalability – The increase of CR nodes in the same geographic area increases competition for the same spectrum white spaces. This competition may result in network overhead and failed communications between nodes.
- Manageability – The majority of research in the CR domain when addressing the management service lean upon the current cellular paradigm that provides for a common control channel and a single leader or management entity. As previously noted, presents a single point of failure.

- Flexibility – In lieu of the dynamic nature of CR technology, the types of nodes and there mobility must be accommodated especially noting the changes in modulation that may also be utilized in an attempt to exploit the spectrum holes and complete communication.
- Efficiency – Any process that results in an inefficient utilization of the spectrum; such as a brute force method of continual broadcasts of message, may complete the communication; however, the fundamental goal of CR is to better utilize the frequency spectrum.

Cognitive Radio presents many opportunities to advance the current radio communication paradigm. New policies for standardization and logistics of operation are the focus of this research. We focus on several problems in the CRN domain; however, the research questions are base in nature with complex solutions. A great deal of research has been done to address many of these issues separately. *This research focuses on three key components to address the overarching goal of a real world deployment.*

(1) How do CR devices communicate between spectrum holes?

(2) How can distributed control channels be developed?

(3) How can Quality-of-Service be implemented based upon Questions #1 and #2?

Additional sub questions are spawned based upon the solutions to any of the three base questions. These additional research questions fit within any one or multiple base question above.

(1) How is initialization/setup achieved without a common control channel?

(2) How do CR nodes communicate their respective available frequencies?

(3) How do CR nodes synchronize next spectrum hole information?

(4) How can fairness be attained?

(5) How is multi-hop routing accomplished?

(6) How is a level of QoS maintained with multi-hop routing?

1.4 Delimitations

This research requires simultaneous multiple antenna support and interpretation for all CR devices. As previously noted, a significant gap with many variations, between the original definition as presented in [4] and the next generation definition in [12], has arisen that is interpreted as a logical evolution of the cognitive radio technology. This research bridges the gap by managing the additional dynamic aspects and exploits the multiple phases of the cognition cycle where simultaneous activity by the antenna such as scanning and transmitting is necessitated.

1.5 Research Contribution

The contribution of this research is to provide an end-to-end cognitive radio network solution for an infrastructure and an infrastructure less ad-hoc network that does not overlook the network setup problem, include the bottleneck of a common control channel and also provides a Quality-of-Service communication path.

1.6 Dissertation Organization

This document is designed as follows:

Chapter 2: Provides a proposed explanation of the evolutionary path of the technological innovations, products, and services that has spawned the current demand and necessity of wireless communication devices.

Chapter 3: Describes the conceptual designs that promote the development of a complete cognitive radio network system. The architecture and protocols that have been proposed in previous research is discussed.

Chapter 4: Introduces a CR model that emphasizes a Quality-of-Service modeled network. The QoS model, called Data-centric Prioritization, uniquely pairs the application type and its network characteristics with an appropriate frequency derived from the spectrum sensing completed by the CR node. This chapter presents a routing model with the QoS emphasis.

Chapter 5: Introduces the Emerald model. The Emerald model is the two(2) phase solutions to the problems previously discussed. The Emerald model has a MAC layer component called the E-MAC and a Network layer component called the E-Net. It also provides the system adaptation model to incorporate data-centric prioritization(DCP).

Chapter 6: Provides the conclusion of the solutions relative to the problems that have been posed.

Chapter 2

Background

Here, we provide a brief explanation of the technological path that has spawned the telecommunication devices and demand of today. Next, the spread spectrum concepts that have accomplished these advances are discussed. Finally, we present the application to quality-of-service factors that complete an end-to-end solution to promote and further exploitation this wireless industry by the advancement of this research.

2.1 How Did We Get Here?

The computer based communication environment has undergone dramatic advances over the last few decades. The wireless computer networking environment began to flourish with the development and distribution of the IEEE standard 802.11b, 802.11g, and 802.11n protocol devices. These devices served as access points(ap) or customer premise equipment(cpe) in the home providing broadband access to the internet via telephony based, coaxial cable based or satellite based service provider.

Wireless networks have evolved and truly transitioned from the 3rd to 4th generation devices very rapidly over the past 10 – 15 years. There are arguably several contributing factors for this accelerated advancement and public proliferation as well as acceptance in both the technological as well as the infrastructural arenas.

The first factor can be attributed to Moore’s law. Moore’s law was created by Intel co-founder, Gordon Moore, presented during a speech in 1988. As illustrated in He surmised that the "… *number of transistors incorporated in a chip will approximately double every 24 months."* This resulted in a progressively cheaper and smaller microprocessor. This chip advancement applied in a myriad of industrial arenas where electronics and thus microelectronics are prevalent.

In the telecommunication industry, the original cellular phones where heavy and bulky devices to the more recent cellular phones that are small enough to fit into the palm of your hand as seen in Figure 6. The complexity of the cellular phone has evolved from a single purpose device (audio only) to a multi-purpose device (smart phone) in which many include an Internet browser, camera, a clock – digital and analog, an address book, a calculator, and many other features that are not voice communications. In the computing arena the flash memory and microprocessor industry was dramatically reinvented. These advancements have revolutionized several industries as well as redefined a new generation in society where online accessibility is standard.

A second factor for these advancements is the "boom" of the Internet. A more specific analysis would be the availability of "access to" the Internet. As more users began accessing the Internet from their homes and via their cellular phones; there were many industries that were redefined. One new industry such as the stock market's day traders generated various new industries such as the online service providers and online brokerage firms such as E-Trade or Fidelity Investments. This multifaceted event rearranged the telecommunication Industry as well as an unprecedented explosion of activity in the stock market.

This introduction mandated businesses practices to be updated in an effort to remain competitive. The Internet fostered a paradigm shift from a more geographically based economy to a global economic basis. The magnitude of Internet users grew exponentially and so did the

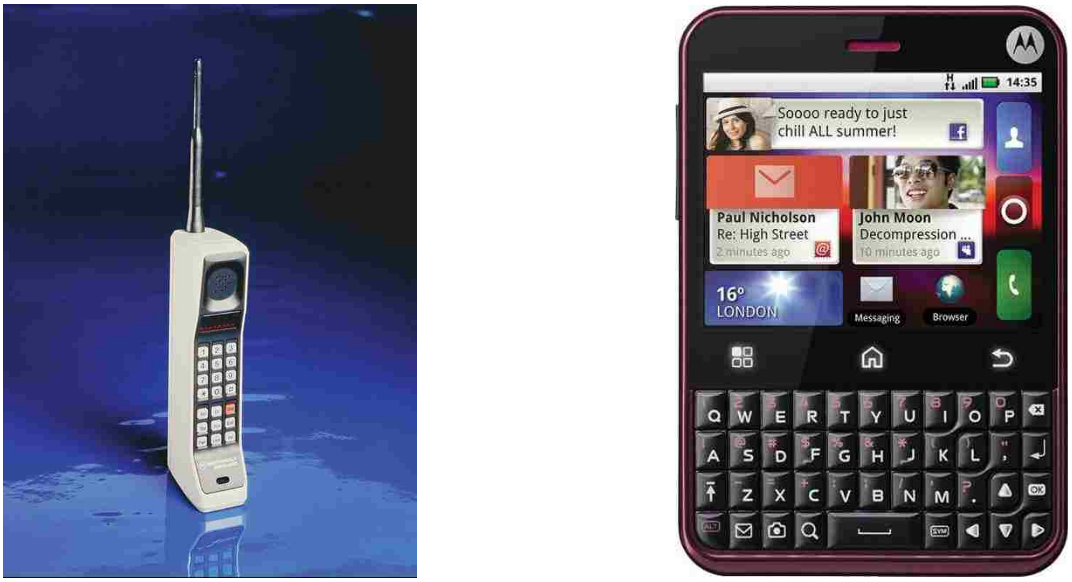


Figure 6: Motorola DynaTAC 8000X, 1983(left) and the Motorola Charm MB502, 2010(right) portable cellular phones (Courtesy of Motorola Co.)

desire for greater accessibility, services, and bandwidth. The Digital Subscriber Line and Cable modem technologies in conjunction with the wireless access points/router were facilitators of this accessibility request demanded by consumers. There were limited devices competing in the 2.4 GHz operating frequency at the time promoting the devices built upon the IEEE’s 802.11 standard.

2.2 What Sparked This Frequency Mobility Thought?

A standard baseband form of modulation simply transmits a single digital signal across a medium. While a broadband modulation technique divides the frequency into several channels that can transmit several signals simultaneously. A broadband network supports video, voice, and data via frequency division multiplexing. The Spread Spectrum techniques provide a better utilization of the spectrum. (18) The true CRN must manage and exploit the multiple functionalities inherent in Cognitive Radios while providing frequency, equity, policy, modulation, and spectrum management. The three basic means of transmitting data wirelessly are narrowband, wideband, and infrared light. While narrowband and infrared light are viable means of transmission, this research focuses on wideband transmission techniques as it best capitalizes on the dynamics of the cognitive radio technology.

Wideband, commonly known as Spread Spectrum, (this will be the terminology used throughout this dissertation) is a technique of transmitting radio signals utilizing a broad frequency spectrum. Spread spectrum allows two of its primary signaling techniques to utilize the same frequency without causing major interference. The major spread spectrum techniques are Direct Sequence Spread Spectrum(DSSS) and Frequency Hopping Spread Spectrum(FHSS). The baseband spread spectrum techniques as described in the IEEE 802.11 standards are FHSS, DSSS, and Infrared (IR). Since IR is not a typical wireless method of transmissions; although it is a viable method, it is outside the bound of this research.

Direct Sequence Spread Spectrum (DSSS): DSSS is a spread spectrum technique that modulated the carrier and data signal waveforms to reflect the rise and fall patterns of the original signal.

Frequency Hopping Spread Spectrum (FHSS): FHSS is a spread spectrum method that transmits the signal hopping between frequency channels in split second intervals; switching between the carrier signals. This rapid transmission switching uses a unique channel sequence scheme that is known to both the transmitter as well as the receivers. To avoid collisions with other communicating nodes, the channel sequence is unique.

2.3 Application to Quality-of-Service Factors

The cognitive network, as with any other network, is designed for performance. The performance of the network may be subdivided into several components, this research shall focus on two(2) components, the software application and its respective spectrum characteristic. The software applications that are generated possess various performance and spectrum characteristics on the network. These performance characteristics shall be referenced as the application's *network footprint* as noted in [5].

The network footprints vary from application to application and definition to definition. The Data-Centric Prioritization (DCP) algorithm in [5] provides for the user customization of the metrics defining the network footprints. Using the tables in [36] and [5] we note the application's network footprint on the network with these matrices of user defined dynamics.

The definitions prescribe by DCP denotes level of need as follows: 1-Very Low, 2-Low, 3-Medium, 4-High, 5-Very High. The matrix is prescribed in Table 1.

Quality of Services as defined by [37] is " …set of service requirements to be met by the network while transporting some network traffic flow." In the case of a CR node with a point-to-point connection the overarching goal is to communicate as quickly and efficiently as possible while minimizing the number of retransmissions. The QoS aspects are designed to facilitate a true end-to-end, multi-hop ad-hoc communication path. This dynamic path is obliged to meet the overarching needs of the CR node while tailoring to the network based demands of the application in use.

A general Quality of Service(QoS) service level agreement(SLA) has to be established to create baseline for the end-to-end communication path. The SLA for this CRN will be defined as a service contract amongst all CR nodes. The format of the contract will be user defined with a lower bound of providing communication success, ie. In the event that the established desired application to frequency correlation may not be provided, the "next best fit" frequency will be chosen. The overarching goal of providing communication between node(s) must be maintained.

Table 1: QoS Network data type and Sensitivities

Transmission Type (T)	Bandwidth (B)	Loss (L)	Delay (D)	Jitter (J)
Voice	1	3	4	4
E-commerce	2	4	4	2
Transactions	2	4	4	2
E-mail	2	4	2	2
Telnet	2	4	3	2
Casual browsing	2	3	3	2
Serious browsing	3	4	4	2
File transfers	4	3	2	2
Video conferencing	4	3	4	4
Multicasting	4	4	4	4

The QoS parameters as discussed by [18] and [38] are utilized not only to provide a Service Level Agreement for the CRN, but may also be expand the network's end-to-end design goal. One of the overarching network design goals is to effectively and efficiently transport data from a source to a destination. [38] aim of an intelligent wireless network marks a continued direction with the CRN to provide more information amongst the nodes themselves as well as provide the network itself the ability to coordinate solutions, such as congestion and repeat failure, in an effective manner.

Chapter 3

Cognitive Radio Fundamentals

As with many complex systems there are primary components that are deemed fundamental. In this chapter, we will address the fundamental components of a cognitive radio network. Section 3.1 provides aspects of the CRN Architectural design. The certain weakness and attributes of other CR MAC layer protocols are noted in section 0. Section 3.3 delves into the varied types of CR Network layer protocols.

3.1 Cognitive Radio Network Architectures

The Cognitive Radio Architecture (CRA) has a basic structure that must accommodate the dynamics of a CR. The CRN architectural design has evolved from an initial concept of point-to-point where the nodes simply communicate with one another to a fully integrated multi-hop network.

With the attributes offered by the CRN; the intelligence of the network, or rather the artificial intelligence of the network, has been made possible. No longer will the intelligence of communication reside solely within the network layer devices on the network. The CRA design promotes an overall intelligence within the packets, its respective interpretation of the network, and a consciousness of the nodes within the network. This intelligence is extremely beneficial in ad hoc networks where the nodes themselves serve as routers and gateways.

3.1.1 Safari

In [39], the Safari architecture forms a recursive organization of nodes into subgroups that are integrated into larger subgroups which are subsequently integrated into even larger groups. This architecture is called *Masai*, "…the hierarchical routing protocol for scalable ad hoc networking". The Safari architecture provides scalability by self-organizing, scalable routing, decentralized operation, and local view. In contrast, our research addresses a global perspective as well as an end-to-end quality-of-service guarantee.

3.1.2 Heterogeneous Reconfigurable Architecture for CR

In [40], the CRA is designed to facilitate a reconfigurable hardware design to address both the functional as well as the system specific requirements of CR. This architectural design leverages the evolutionary growth of the semiconductors. This is accomplished by the development of a reconfigurable platform on a chip/tile called the System-on-Chip(SoC). The various processing element modules such as the General Purpose Processor(GPP), Application Specific Integrated Circuit(ASIC), and the Field Programmable Gate Array(FPGA), as illustrated in Figure 7 below, creates the heterogeneous tiled SoC. This is expanded by the interconnection of SoC tiles into a Network-on-Chip(NoC).

The key design methodology has two(2) features. One feature models the transactions at each level of the application into a graph of parallel tasks. The second feature provides the spatial mapping of tasks done at run-time onto the processing tiles heterogeneously designed.

This architecture's design focuses on the hardware performance capability, albeit reconfigurable hardware and supports the dynamics of CR but is outside the scope of this research. This research does have the capability to lend itself to this integrated hardware design architecture of a SoC.

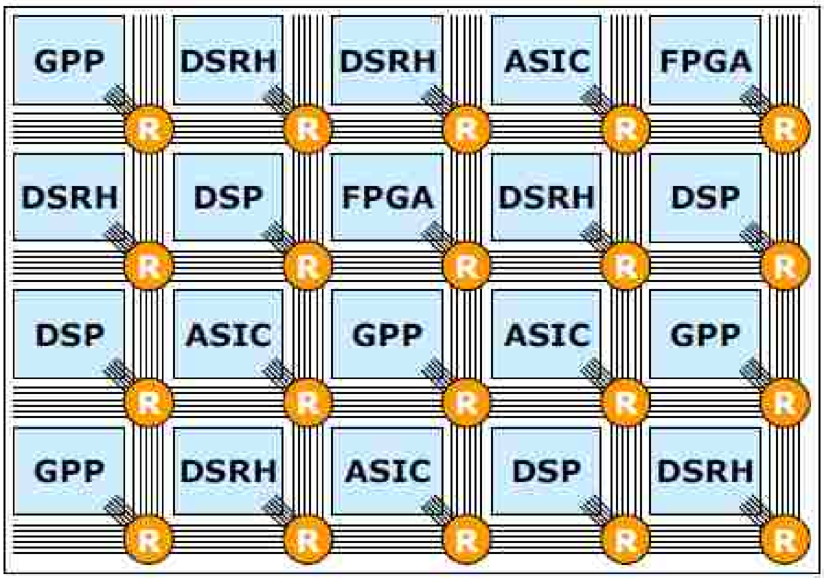


Figure 7: Heterogeneous System on Chip (SoC).

3.1.3 E^{2}R Architecture

The End-to-End Network Architecture [41] for Cognitive Reconfigurable Mobile Systems project is a design architecture for the cognitive networks where the overall performance and capabilities of the services are addressed in a hierarchy in two tiers. The upper tier manages the network and its backbone. The lower tier manages the device-specific reconfigurable attributes.

3.1.4 CogNet

The CogNet [42] is an architectural design framework that supports spectrum agility, physical-layer waveform manipulation, a spectrum etiquette protocol, a programmable MAC layer, a physical-MAC cross-layer protocol implementation, and ad hoc clustering with multi-hop packet forwarding. The CogNet architecture was designed to be a framework for a research into performance balances and introduces protocol concepts for local and global networking. [43]

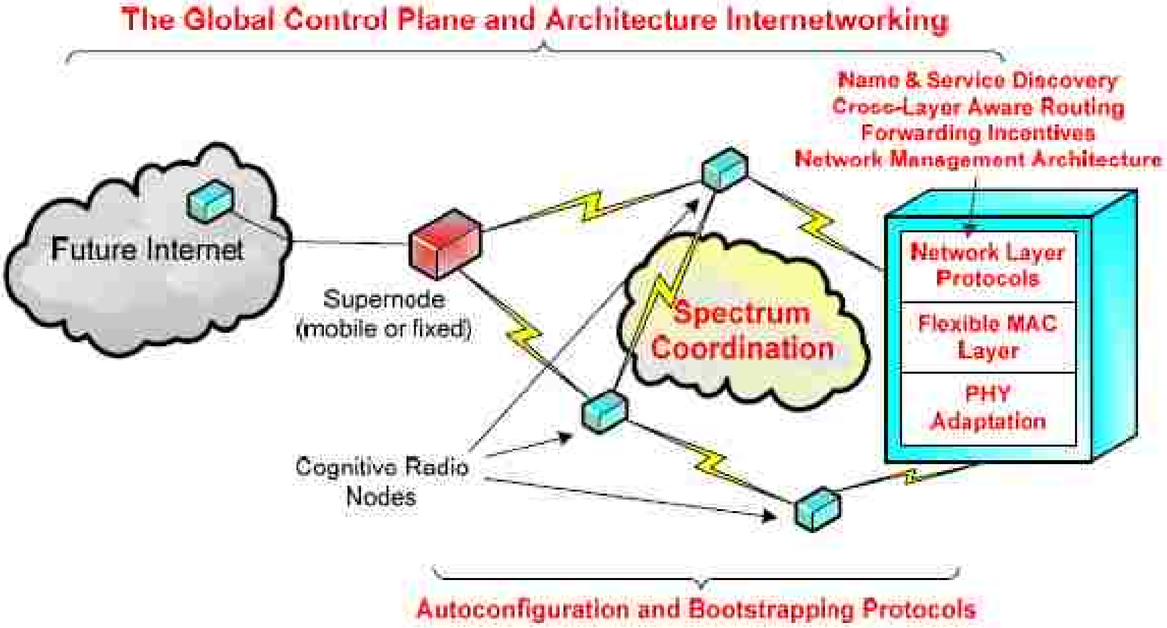


Figure 8: CogNet Architectural framework

The CogNet architecture also provides a network protocol designed as an overlay-based mechanism within the CN. This opportunistic overlay design supports user/network defined overlay layers for application and communication flow as illustrated in Figure 9 below. A “supernode” is also introduced that serve(s) as a group manager, communications gateway, or spectrum manager.

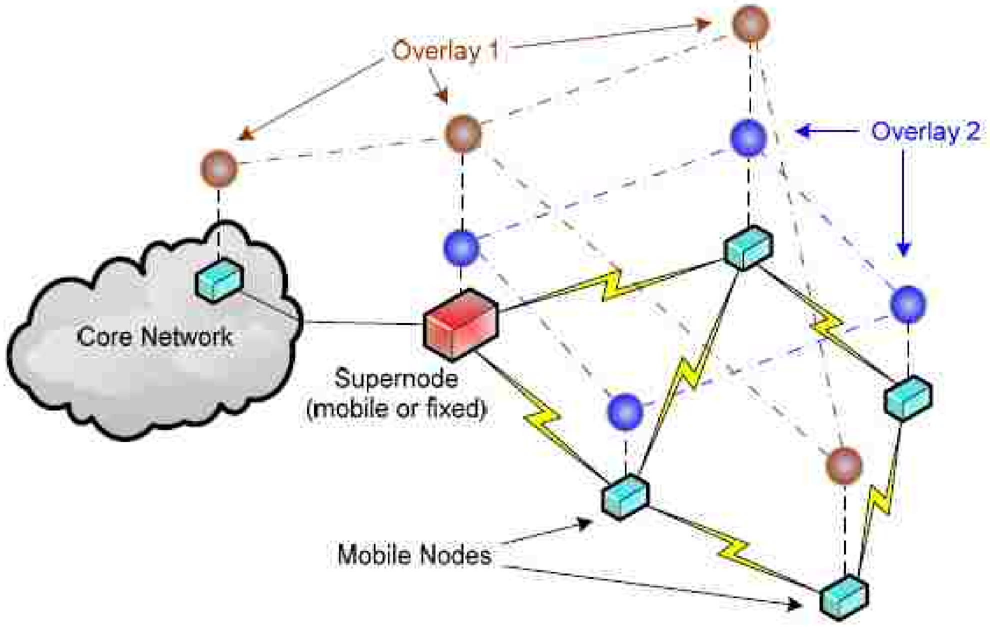


Figure 9: Cognitive Wireless Network with Multiple Network- Overlays

3.1.5 Cultural Algorithm Based Cognitive Node Architecture

In [44] [45], a modular architectural design with several components that allows the CR nodes to reconfigure their protocol stacks. The independent components of the architecture manage the following tasks: (1) exchange of data and knowledge amongst nodes, (2) manage the exchange of information, (3) network performance monitoring, and (4) overseeing the distributed process of reasoning.

3.1.6 Public Safety CR Node

In [46], also presents a design path to apply in a public safety environment. Here, the CR node's definition focuses on environmental awareness, application level requirements, and optimization capabilities A platform independent architecture called a Cognitive Engine is

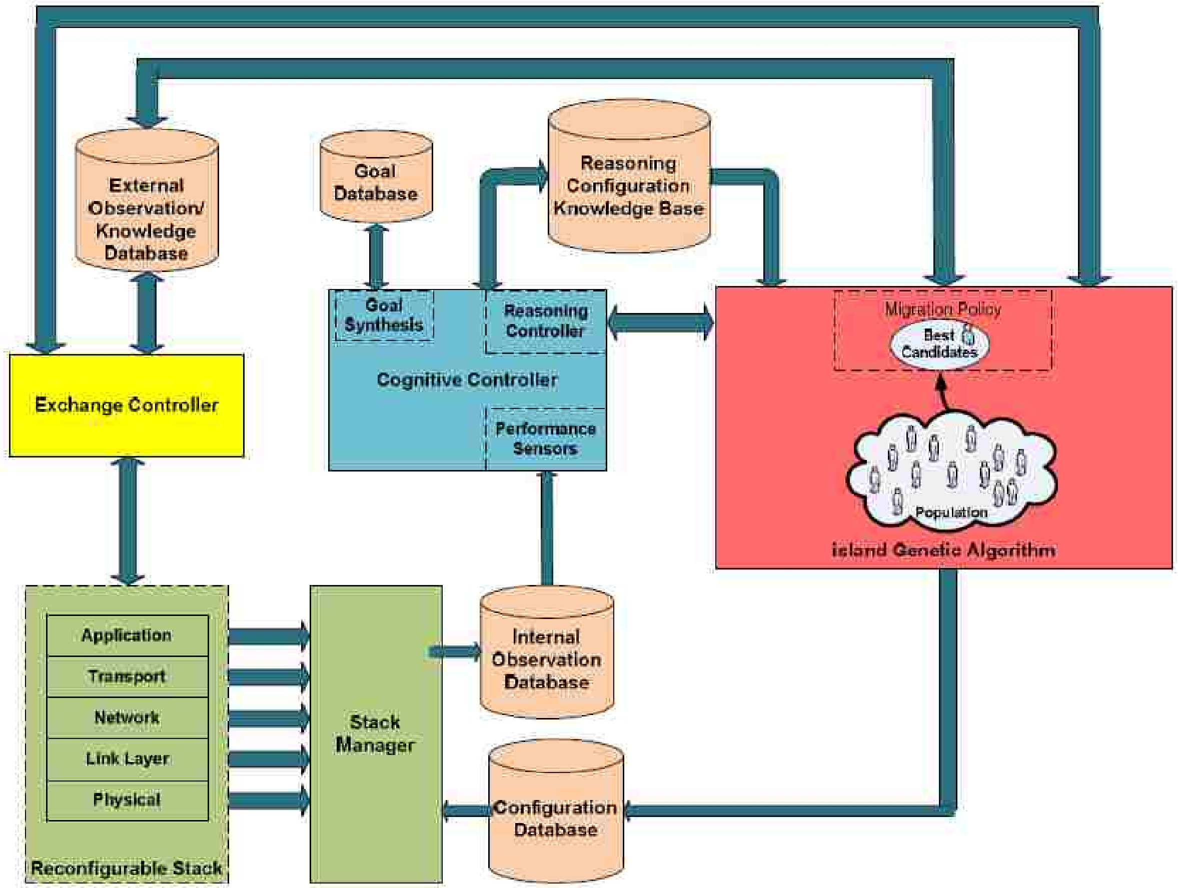


Figure 10: Cultural Algorithm-based Cognitive Node Architecture

created to support an algorithmic software package designed to manage the cognitive functionalities as noted Figure 11 below.

Cognitive functionalities address layers 1 thru 3 of the OSI model for optimization across the layers. The CR node works independently or in a group with a three-step learning structure of recognition, reasoning, and adaptation. This CRA design may be implemented in a centralized or distributed environment with different levels of intelligence and optimization. This functional structure is illustrated below in Figure 12.

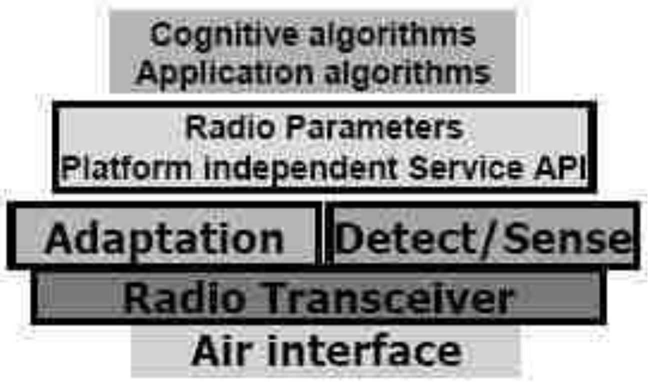


Figure 11: Cognitive radio system model

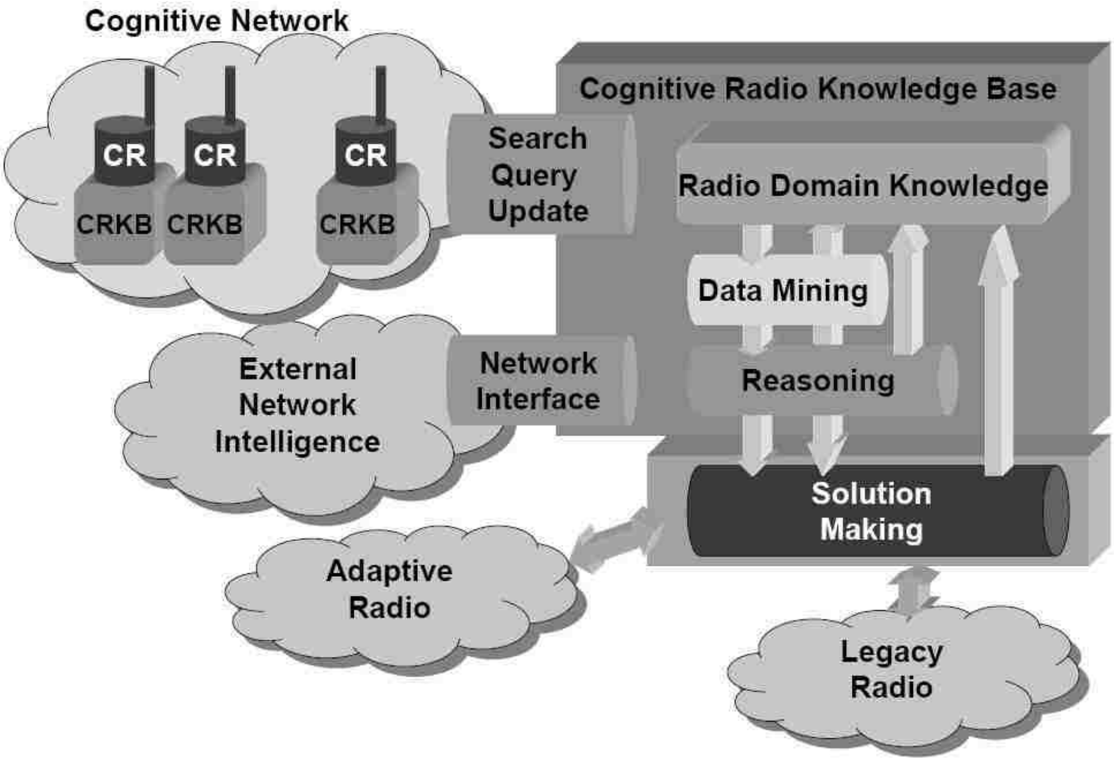


Figure 12: CRN functional architecture

3.1.7 CogMesh

The CogMesh [20] architecture is designed to provide operational coexistence between primary licensed users and secondary unlicensed users with a distributed cluster environment. This network supports the grouping/clustering of nodes for manageability of the radio spectrum maintained by the clusterhead. The clusterhead is a pre-defined node which in turn reduces the dynamic ad-hoc capabilities of the Cognitive Radio as well as the creation of a single point of failure that when exploited, renders the cluster vulnerable to inoperability and spoofing.

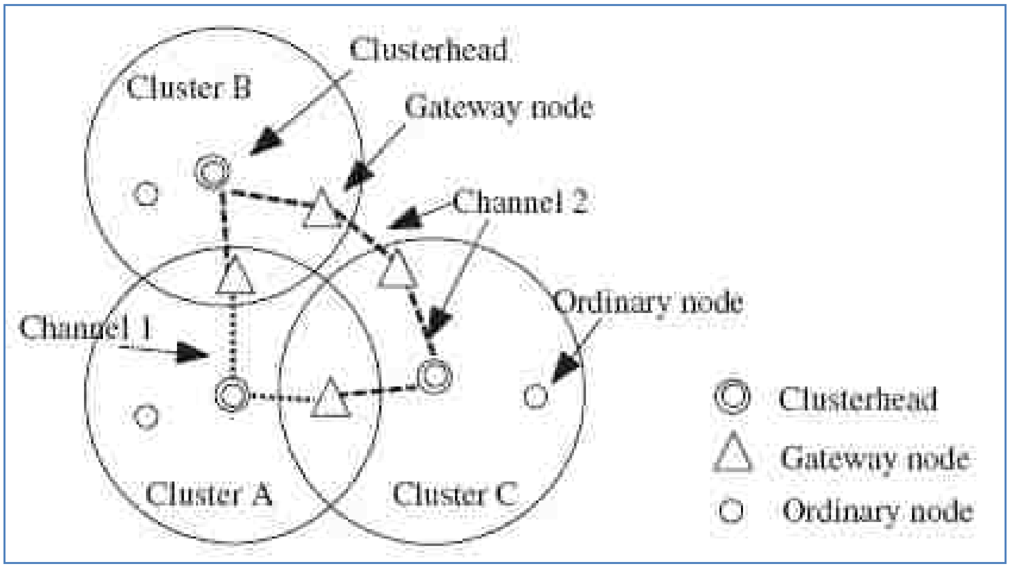


Figure 13: CogMesh Network Architecture

3.2 Cognitive Radio MAC Layer Protocol

The Media Access Control layer of the Open System Interconnect model is responsible for the sharing of the channels.

3.2.1 Cognitive-MAC

In [47], a cognitive MAC layer is designed for distributed multi-channel wireless networks. This protocol utilizes a dynamic rendezvous channel for multi-channel resource reservation. This rendezvous channel is a determination from all available channels of each node. A backup channel is also created for supporting the RC. A beacon packet is used for communication. The protocol divides each channel into logical “superframes” beginning with a slotted beacon period followed by a data transfer period. This MAC protocol contains overhead in the rendezvous channel thus the necessity of the backup channel and also provides a single point of failure with the common control channel.

3.2.2 Cognitive Autonomous-MAC

The Cognitive Autonomous-MAC(CA-MAC) as designed in [48] for autonomous Impulse Radio Ultra-wideband networks in industrial environments and for logistical applications that require a high degree of configurability for ad hoc environments. The CA-MAC operates by configuring the error code rate, the modulation, and the average pulse period per link. It operates with a combination of two blocks that function by creating a medium sharing block and a link parameter control block. The medium sharing block serves as a combination of user defined, time hopping sequences. The Request-to-Send(RTS) and Clear-to-Send(CTS) handshake is used to address the hidden station problem. The link parameter control block optimizes the error protection level by switching the pulse repetition period for the channel load reduction.

3.2.3 Cognitive-Carrier Sensing Multiple Access/Collision Avoidance

In [49], a generic cognitive MAC protocol is presented based upon Carrier Sensing Multiple Access/ Collision Avoidance(CSMA/CA). This Cognitive-Carrier Sensing Multiple Access/ Collision Avoidance(C-CSMA/CA) protocol is designed to support the Basic Service Set from the IEEE 802.11 standard model and by extension the extended service set(ESS). This protocol's focuses on inband and outband sensing where the C-CSMA/CA is used to determine spectrum availability and cooperative sensing is done by the idle stations to exploit the duration of the network allocation vector, respectively.

3.2.4 Cognitive Radio – MAC Protocol

The Cognitive Radio – MAC(COMAC) protocol [50] focuses on providing a statistical performance guarantee for the primary user by limiting the interference. Interference performance probability models are developed for primary users-to-primary users (PR-to-PR) and primary users-to-cognitive users (PR-to-CR). A contention-based handshaking mechanism is used to handle the exchange of the control channel information. The protocol's algorithm specifically addresses a single-hop and a multi-hop environment.

3.2.5 Dynamic Open Spectrum Sharing Protocol

The Dynamic Open Spectrum Sharing(DOSS) protocol from [51] allows CR devices to establish their own frequency hopping sequence. This sequence is known by other CR nodes. Whenever a CR nodes wants to transmit to another node, the node wishing to transmit simply tunes into the frequency hopping sequence of the destination node. This type of negotiation requires universal synchronization and there appears to be an assumed lack of mobility with the CR nodes in this network.

3.2.6 Opportunistic Cognitive-MAC Protocol

The Opportunistic Cognitive - MAC protocol (OC-MAC) [52] is a policy focused protocol that operates by generating a traffic prediction model and transmission etiquette rules. The OC-MAC protocol requires all secondary cognitive radio users to transmit politely as to not interfere with the primary user. Secondary users transmit via white spaces. Also, after the handshaking has been established between nodes the "best common" control channel is established while sending traffic across the maximum overlapping spectral vacancy. These factors contribute to the weakness of this protocol since the setup problem is simply skipped altogether; along with the common control channel and "best common" control channel.

3.3 Cognitive Radio Network Layer Protocol

3.3.1 SAFARI's Ad hoc Scalable Overlay Routing protocol

As previously discussed the routing protocol in the SAFARI CRN architectural design addresses a scalable ad-hoc routing network environment with the Ad hoc Scalable Overlay Routing protocol (ASOR). The ASOR protocol routes packets through a hierarchical design of levels to an on-demand method to its destination. Buoy packets are used to provide self-organization, structure dissemination, and route information delivery. This buoy packet is used to mark a cell of CR nodes and presents vulnerability in the network design. Routing is also reinforced by local on-demand route repair.

3.3.2 Multi-hop Single-transceiver CRN Routing Protocol

In [53], the Multi-hop Single-transceiver CRN Routing Protocol (MSCRP) provides a table driven CRN routing protocol. This protocol, while initially based on the Ad hoc On-demand Distance Vector(AODV) protocol, seeks to address the spectrum opportunity problem.

The MSCRP utilizes the RREQ-RREP mechanism to establish paths from source to destination nodes and as such, is subject to inherent problems associated with a table driven routing methodology such as stale routes or even dead paths. This protocol addresses connective alone not the quality of the service provided.

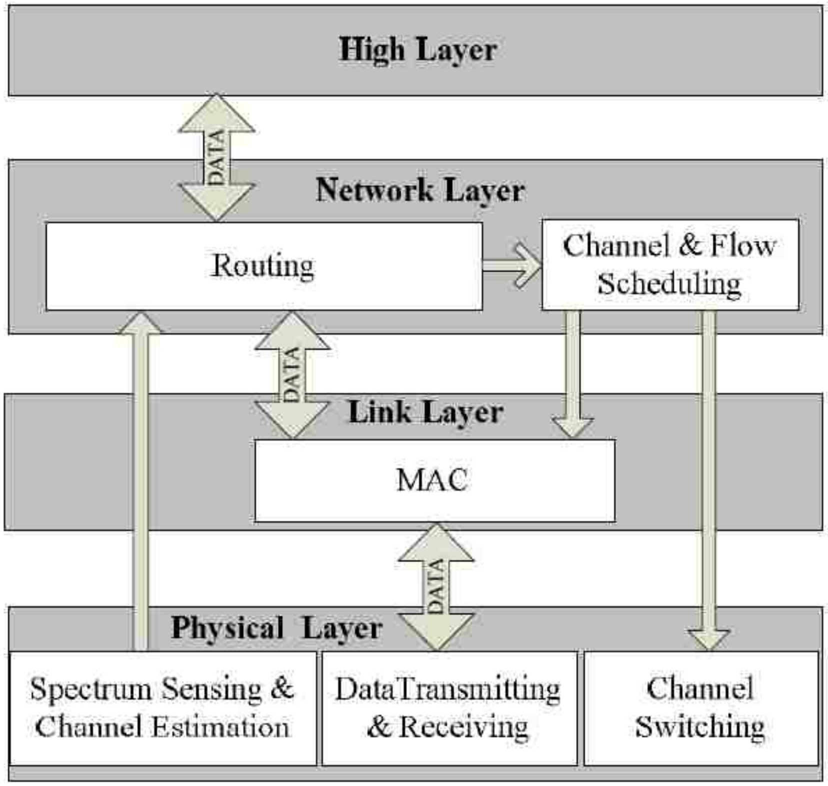


Figure 14: MSCRN Protocol Stack Model

3.3.3 Cognitive Radio Ad Hoc Network

The Cognitive Radio Ad Hoc Network (CRAHN) routing protocol [54] focuses on joint spectrum and routing decisions as essential components. An added emphasis is place on the transparency of the protocols from each layer; therefore the physical switching and reconfiguring of the communication parameters as well as the QoS of the quality degradation is minimized during the spectrum switching. Although a differentiation is made between a common control channel's utilization as exclusive or not, this single point of vulnerability exists.

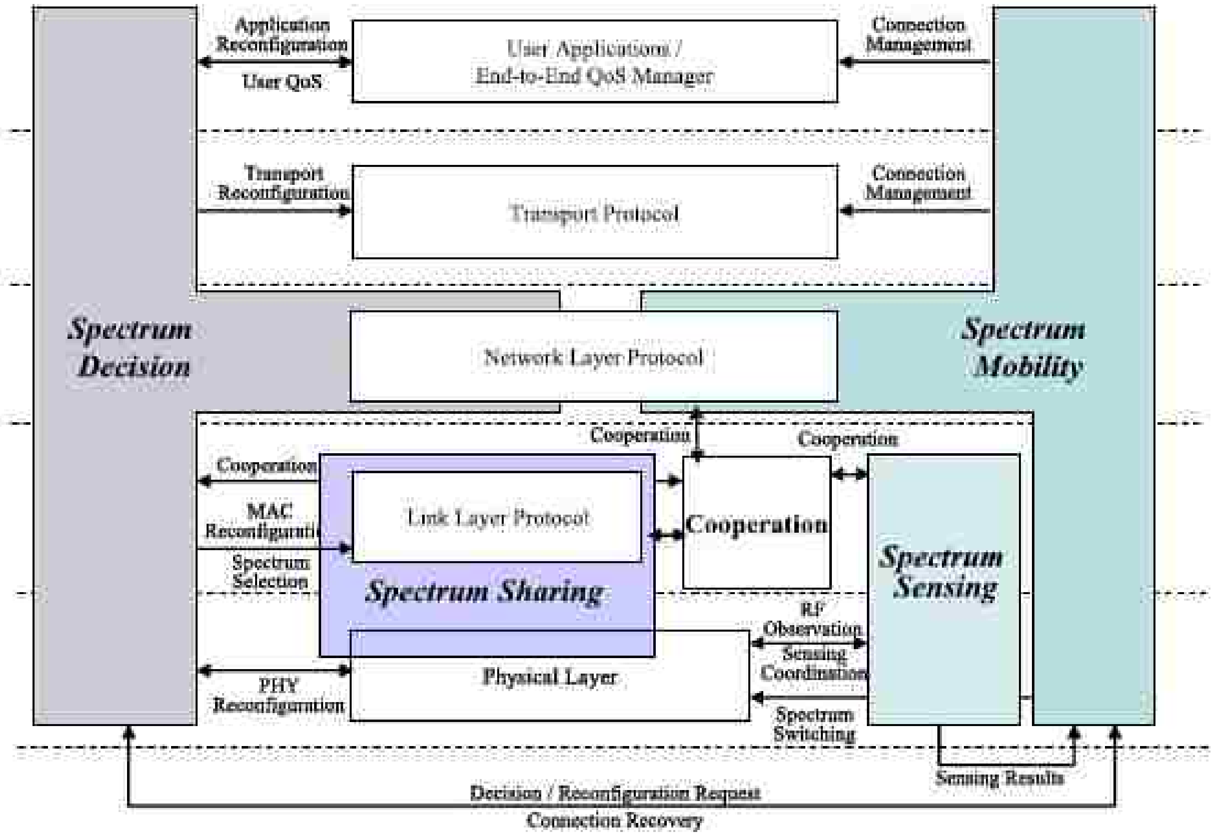


Figure 15: Spectrum Management Framework of CRAHN

Chapter 4

Data-Centric Prioritization in a Cognitive Radio Network: A Quality-of-Service Based Design and Integration

4.1 Introduction

The radio frequency spectrum has become a topic of major conversation since the November 2002, release of the FCC study from the Spectrum-Policy task force which noted amongst its findings, the underutilization of the frequency spectrum. [3] Simon Haykin noted that a study of the radio frequency spectrum would derive the following: (1) the frequency spectrum is largely unutilized; (2) the frequency spectrum is partial occupied; and (3) the frequency spectrum is heavily utilized. As such, Haykin coined the term, ***spectrum hole*** – *a band of frequencies assigned to a primary user, but, at a particular time and specific geographic location, the band is not being utilized by that user.* [10]

The unutilized spectrum is targeted as an area of emphasis and potential in the communication arena in an effort to increase spectrum utilization without interfering with the primary users. [11] The primary users are those that have current license agreements with the FCC which have yet to expire. Several other solutions have been proposed to optimize the utilization of the available radio spectrum, such as ultra-wideband technology and cognitive radio. [4]

Cognitive Radio is perceived as a viable solution for the underutilization of the radio spectrum, due to its flexibility, efficiency, robustness, and reliability in frequency spectrum utilization. A key concept of cognitive radio technology is its ability to be environmentally aware and adaptable to change based upon the statistical variations it encounters. [4] [7] [55]

The application data type being transmitted during the normal operations of a wireless device varies from user to utility to need. These applications have various network performance characteristics to provide normal operations that appear transparent to the end user. Not only are the application-specific network handling requirements varied, but the impact to the overall network is varied. The network must be able to seamlessly support this diversity.

The concept of associating application-specific design requirements with the network dynamics of the frequency spectrum lends itself to a Quality-of-Service (QoS) methodology. This paper delves into the usage of a QoS methodology which addresses the “best-fit” concept with a “true best fit” methodology within the cognitive radio cognition cycle. This new methodology facilitates the introduction of commercial performance controls akin to that of a service level agreement (SLA). The dynamics of the frequency spectrum and its inherent capabilities and limitations serve as the quantitative and qualitative groundwork for sales, marketing, and support opportunities. Current support differentiation and pricing points are simply separated into two core type: voice and data transmission types.

The SLA for the transmission performance is a simplistic binary model; either it works or not. The quality of how well or efficiently it works is an open issue. This paper provides the foundational basis of how and where SLAs may be introduced and how they may it be technically implemented. This paper; however, does not address any pricing points or methodologies for the development of SLAs for a cognitive radio environment.

The contribution of this paper is twofold. (1) The introduction of a new matrix into the frequency determination algorithmic methodology to reduce the probability of multiple nodes choosing and transmitting on the same available channel to reduce collisions. (2) The presentation of distributed process architecture for the integration and behavior of a cognitive radio network in a legacy rich environment.

4.2 Cognitive Radio Terminology

The major components of the community are as follows:

Cognitive Radio Network (CRN) – several Cognitive Radio Communities.

Cognitive Radio Community (CRC) – a geographically located group of nodes which have agreed to work together.

Cognitive Radio Community-Community Leader (CRC-CL) – a CR node that manages the frequency spectrum of the community and new CR nodes.

Cognitive Radio nodes – the members of the community but not the CRC-CL.

Frequency Availability Table – a table of the frequencies that are accessible by a cognitive radio node.

Cognitive Radio Community Frequency Availability Table – a total list of all frequencies that are accessible within a community. (It should be noted that all frequencies in the list may or may not be accessible by all nodes within that cluster.

Ledger Frequency – a secondary frequency determined by the CRC-CL for each particular cluster that is unique to adjacent clusters providing interoperability.

Dynamic wireless ad hoc virtual circuit – refers to the dynamic communication links between source and destination CR nodes.

4.3 Data-centric Prioritization

Cognitive Radio Networks (CRNs) are touted to support various network environments. This paper introduces a new *data-centric prioritization (DCP).*

Data-Centric Prioritization is an intrinsic understanding of the QoS sensitivities of the desired application type's transmission characteristics in combination with an open system of current and future algorithms deployed in a dynamic spectrum environment in an opportunistic effort to determine and utilize the *"best fit for this transmission"* Cognitive Radio Network.

There are several cognitive radio algorithms which are designed to determine the "best" frequency to select as a secondary user. Currently, cognitive radio frequency selection algorithms use varied methods to determine the "best" frequency to operate on and when. Many methods employ variations of a game theoretic approach, for example.

These approaches evaluate the entire frequency spectrum and rank/rate them according to some performance threshold or matrix. The type of transmission being employed by the user is not considered as a factor to be considered as part of the ranking and rating system. Simply, the need to transmit is addressed. By addressing the type of transmission, the number of users evaluating a particular spectrum is statistically divided into several components with distinct characteristics and based upon application sensitivities.

The network characteristics are a result of the dynamic spectrum hole availability for a CR node at any particular time *t*. The goal of the DCP algorithm is to:

1. Maximize spectrum efficiency
2. Minimize network decision and network collisions
3. Optimize radio frequency carrier quality
4. Provide foundational basis for CR Service Level Agreement

Table 1 illustrates the varied application data types and their respective network sensitivities regarding bandwidth, packet loss, delay, and jitter; i.e. Quality of Service sensitivities as note in [36]. The characteristics of the data types are denoted as very high – 5, high – 4, medium – 3, low – 2, and very low – 1. This numeric conversion of sensitivities allows for a discrete implementation of DCP. This serves as the foundation basis for the DCP algorithm. This environmental logistic advocates a non-Poisson distribution of the radio frequency spectrum.

The cognitive radio senses the frequency spectrum evaluating capabilities based upon the respective sensitivity of the application data type to be transmitted. [10] The deterministic analysis of the frequency spectrum's available channels for transmissions are denoted as available and also added into the FAT. At the point of choosing a frequency for transmission, several methodologies have been employed such as game theory, randomization, or even first-come first-serve. In this paper, we will address a randomization and FCFS algorithmic method. This decision was made to illustrate how the effectiveness of a simplistic algorithm results in great advances in efficiency and performance, therefore, an assumption is that a more comprehensive algorithm may result in even better results. This assumption is an area of future research.

The evaluations and ranking of the frequency band will be based upon the application's QoS sensitivities providing for the *"best fit for the application's need"*. This is a departure from previous research areas where the "*best fit*" was simply the goal of these research efforts. The research into dynamic spectrum allocation(DSA) limits its effort to the medium to be utilized; the application network characteristics are not a facet of recognition. We view this as a limitation of the research into DSA. Simply treating all transmission as the same thing is a beginning however; the future may view this as short-sighted. Amidst a myriad of wireless communication applications being utilized today as well as those unique wireless applications that have yet to be developed may be severely impacted due to this limitation in much of the DSA research.

After the evaluations of the frequency spectrum are quantified as those frequencies that meet the minimum qualifications moving to those that exceed the qualifications. The rankings are user definable as discussed earlier, wherefrom, an evaluation and qualification results in 100 frequencies, a 50% beginning allows for the first frequency attempt to use is the 50th of 100 available. This algorithm provides the cognitive radio the ability to choose the frequency that may be an average frequency rather than that of a minimum or maximum basis.

4.3.1 The DCP Algorithm

Consider some application with a network data-type, d; corresponding to a set of network sensitivity, *v*. Let f_x be the frequency number and $f_x(v)$ be the frequency sensitivity determined during the scanning process. The λ is the set of f_x choices based upon d_v..

Table 2: DCP Algorithm

```
1.  Determine application data-type, d, and $d_V$.
2.  Repeat for all available frequencies, $f_x$.
3.          If $[1 \leq (f_x(v) - d_V)]$ then add $f_x$ to $\lambda$
4.          Else move to next $f$, $f_{x+1}$
5.  Sort $\lambda_a$ where a is the item number
6.  Execute implementation algorithm.
```

The Euclidean Norm of all frequencies in λ shall be the vector – scalar conversion method used to then sort all λ_a. In case of a tie, the frequency number itself will be the determinant factor to resolve any ties. The scalar ranking system derived from the Euclidean Norm of

Equation 1: Scalar Ranking derived from Euclidean Norm

$$\lambda_{a,x} = \sqrt{\sum_{1}^{k} (f_{x,k})^2}$$

Unsorted sequence number

Frequency number

Vector sensitivity

The Euclidean norm of all λ relative to the Euclidean norm of d_v is the foundational basis of the ranking system, i.e. the priority ranking is the absolute difference between the two Euclidean norms from the minimum to the maximum delta.

Equation 2: Priority ranking's absolute difference.

$$d_k = \sqrt{\sum_{1}^{k} (d_k)^2}$$

$$\Delta_a = \lambda_{a,x} - d_k$$

Again, in a case of a tie during the ranking process, the minimum of the frequency number serves as the tie breaker.

4.3.2 Example of DCP

Based upon the application being utilized, the cognitive radio device chooses the frequency spectrum that will best correspond with that respective application.

Figure 16 illustrates the cognitive radio transmissions of a file transfer, casual web browsing, a voice call, and a video conference taking place utilizing a PDA, tablet pc, cellular phone, and a laptop, respectively. The application and integrated cognitive radio device processing the preference of sensitivities needed for an assumed service level agreement of acceptability. This by no means limits the capabilities of the CR device; it merely denotes a specific action being implemented by the CR device at a specific interval of time *t*.

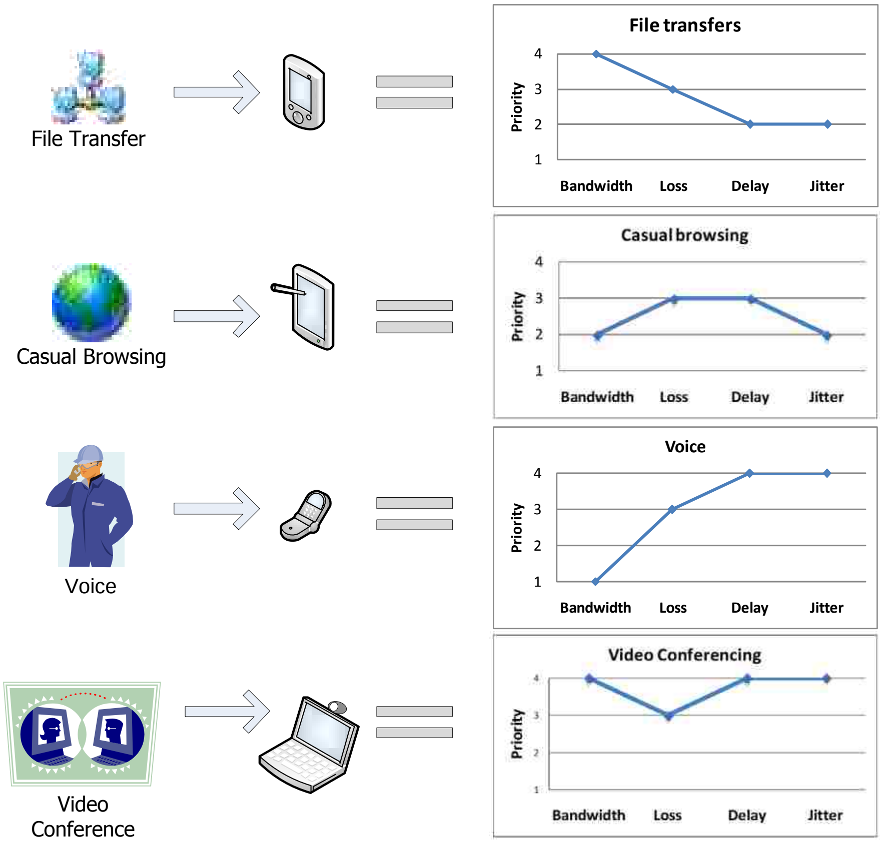
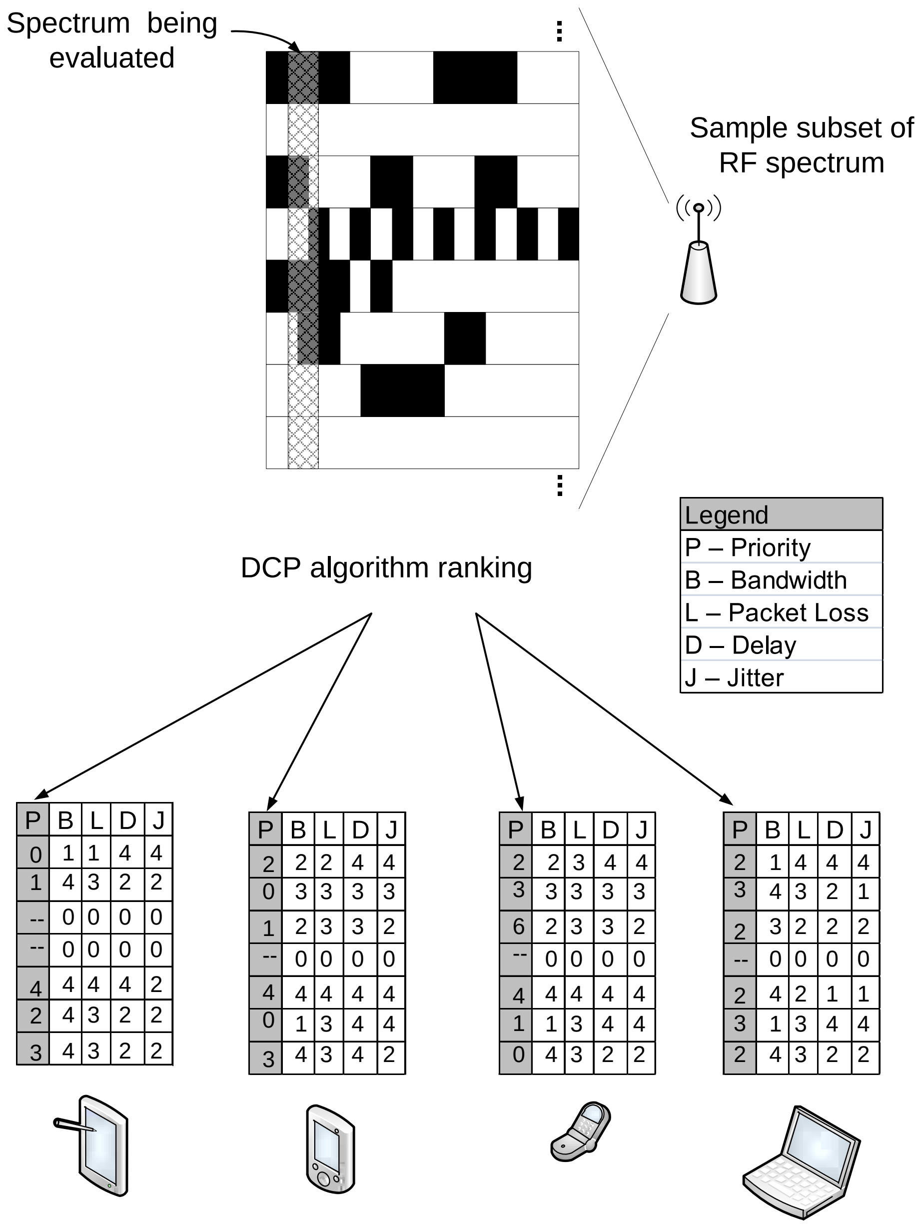


Figure 16: Examples of the DCP decision process with different application types illustrating their network footprints

The QoS sensitivities are referenced as the frequency spectrum is sensed. This provides an environment that emulates the heterogeneity of current Internet traffic wherein the target frequency is that which best fits the desired performance sensitivity.



P	B	L	D	J
0	1	1	4	4
1	4	3	2	2
--	0	0	0	0
--	0	0	0	0
4	4	4	4	2
2	4	3	2	2
3	4	3	2	2

P	B	L	D	J
2	2	2	4	4
0	3	3	3	3
1	2	3	3	2
--	0	0	0	0
4	4	4	4	4
0	1	3	4	4
3	4	3	4	2

P	B	L	D	J
2	2	3	4	4
3	3	3	3	3
6	2	3	3	2
--	0	0	0	0
4	4	4	4	4
1	1	3	4	4
0	4	3	2	2

P	B	L	D	J
2	1	4	4	4
3	4	3	2	1
2	3	2	2	2
--	0	0	0	0
2	4	2	1	1
3	1	3	4	4
2	4	3	2	2

Figure 17: DCP based evaluation of frequency spectrum

As illustrated in Fig.2 noting that there may exist several differences between sensing results between cognitive radio nodes at any given time and frequency in a CRN. Also noting that the geographic location and arbitrary interference impacts sensing results directly, i.e. the sender may evaluate a specific channel to a difference performance matrix; however, the destination node may not evaluate it the same. .

These examples are designed to emulate a typical CR environment where the frequency qualifications may be different between any time and geographic location. This paper does not address the qualification methodologies used to derive the scanning solutions noted here; that is outside the scope of this paper. The scanning and qualification process of a CR node in respect to the CR cycle as illustrated by Mitola is a constant atomic action. This is to provide for the immediate functionality of any application and its performance.

The implementation of the DCP algorithm for a voice call follows for the DCP algorithmic process with the following values.

Equation 3: Calculation example of DCP implementation

$$d = voice$$

$$d_{voice} = \begin{cases} Bandwidth_{v=1}, & d_1 = 1 \\ Latency_{v=2}, & d_2 = 3 \\ Delay_{v=3}, & d_3 = 4 \\ Jitter_{v=4}, & d_4 = 4 \end{cases}$$

$$d_k = \sqrt{\sum_{1}^{k} (d_k)^2} \qquad = 6.48$$

Table 3: DCP implementation example of CR node

		Vector *x*				λ	Δ	Priority Ranking
		1	2	3	4			
Frequency *a*	1	2	3	4	4	6.71	0.228	2
	2	3	3	3	3	6.00	0.480	3
	3	2	3	3	2	5.10	1.381	6
	4	0	0	0	0	0.00	---	---
	5	4	4	4	2	7.21	0.731	4
	6	1	3	4	4	6.48	0.001	1
	7	4	3	2	2	5.74	0.735	5

A frequency with vectors of all 0 is denoted as an prohibited frequency and thus is not included in the ranking; therefore any ranking number is misleading. As noted, the frequency prioritization for the CR node implementing a voice data-type transmission, illustrates the λ ranking of each frequency *a*. The Δ is calculated and the priority ranking is concluded.

Our research effort utilizes a prioritization of the frequency spectrum; however, DCP does not mandate the order of usage. The design of DCP facilitates a definable platform where the myriad of algorithmic approaches such as game theory, or first-come first serve or even a randomization may be explored. [34] It should be noted that during our simulations, those CR nodes that chose frequencies with a higher (1 is highest) priority ranking, seems to maximize its transmission efficiency due to the fewer number of decision and network collisions.

4.4 Cognitive Radio Collisions

Since the cognition cycle makes a distinction between decisions and actions that are made regarding utilization of the frequency spectrum and transmissions, thereof. We make a distinction between the types of collisions which may occur within a CR Network environment. We also note the lack of explicitness regarding the immediate transmission of data, after a frequency decision has been made. We will differentiate between the types of collisions in a cognitive radio network both implicitly and explicitly by the following:

a) Decision Collision – a collision which occurs when two or more CR nodes have decided on the same frequency.
b) Network Collision – a collision occurring when two or more nodes transmit at the same time on the same frequency.

4.5 Cognitive Radio Network

The CR nodes will create a “friendly” community where frequency negotiations and management will take place. Much research has been done regarding wireless ad hoc networking from the development of clustering networking protocols such as LEACH [56] and the more specific cognitive based clustering architectural design such as CogMesh. [20]

A feature of our research is the development of a design architecture that may be seamlessly added to another cognitive radio environment as a means of enhancing said environment without deviating from its overall goal.

4.5.1 Cognitive Radio Community(CRC)

The CRC will serve as finite groups of nodes that have been formed together as a community promoting a CR network of cooperation and fairness. [57]

4.5.2 Community Leader

The CRC-CL maintains the community’s frequency availability lists and the frequency availability list of the adjacent clusters. This will be done to promote interoperability in a CRN, in that a CRC-CL can communicate specific frequencies that are to be deemed inaccessible. The CRC-CL will select a secondary frequency accessible by all nodes in its community as a “ledger

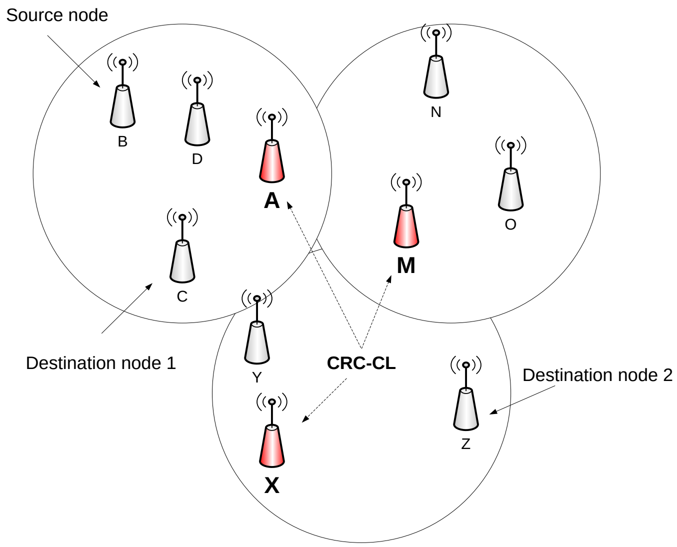


Figure 18: Cognitive Radio Community cluster

frequency” (LF). The CRC-LF must be a secondary channel accessible by all nodes in the CRC and it must be unique between adjacent CRCs.

The CLs will negotiate between each other a frequency for adjacent cluster communication. The respective CRC-FAT will be intermittently transmitted between adjacent CLs as to promote interoperability throughout the entire CR network.

The CRC-FAT should be comprised of a unique set of frequencies between adjacent CRCs, wherever possible. Due to the dynamics of DCP, this rule is not mandated rather strongly recommended.

After a period of time has elapsed without receiving a still alive beacon transmission from a node, any frequencies unique to that node only should be removed from the cluster frequency availability table and an updated frequency availability table message should be transmitted to the adjacent CLs.

4.5.3 Cognitive Radio Node

The cognitive radio, once within a cluster, should intermittently transmit a “still alive” beacon message to the CL on the LF. The CL acknowledges receipt of the message and updates its status table.

If the CR does not receive a beacon message after a predetermined number of failed attempts; the CR must seek a new CRC or become a CRC-CL itself, if communication with another CL cannot be established.

4.6 Introduction of a New CR Node

When a new node is brought online, it must broadcast a request for the LF from the nearest CLs (Figure 19-1). It is the CLs responsibility to communicate with the new node on the same frequency, providing the new node with the LF for its CRC as well a unique CRC identification (Figure 19-2). The new node must respond in kind to all CRCs that have responded to its request on the LF with its respective identification providing its available frequencies table (Figure 19-3). The CL will calculate the number of duplicated frequencies currently in the CL’s frequency availability table. The CL will then transmit the total number of duplicated frequencies to the new node with a CRC-Invite (Figure 19-4).

The goal of each new node is to join a CRC that best fits its own operating environment. As noted earlier, the geography plays a role in the cognitive radio environment; therefore, simple geographic location does not always relegate a node to a CRC due to distance. If the new node deems the CRC acceptable, i.e. this CL has a community with a greater number of shared frequencies, the new node will respond to the CL accepting the CRC-Invite (Figure 19-5). The

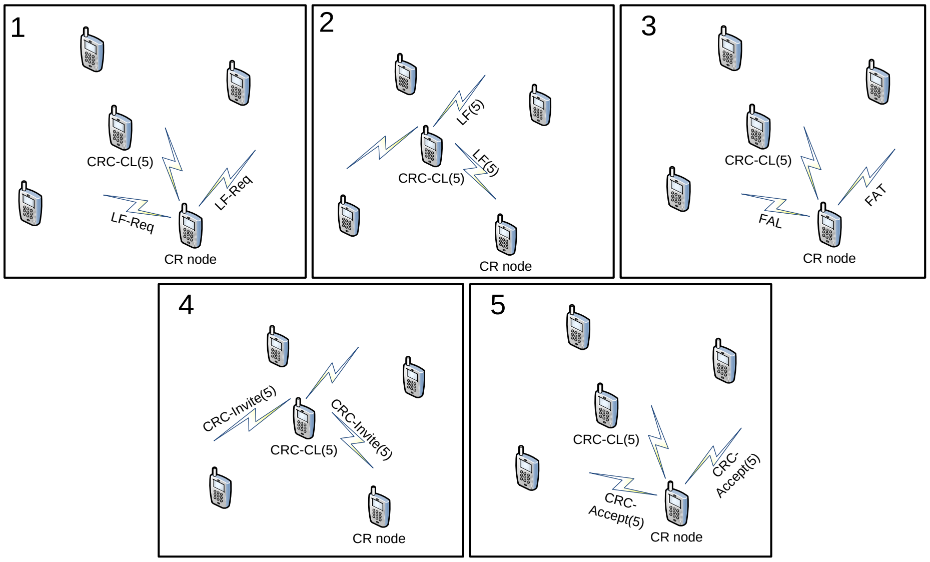


Figure 19: CRC introduction of a new Cognitive Radio node in a current CRC

CL must append any unique available frequencies accessible by the new node, to its frequency availability table.

In a case where multiple CLs respond to the broadcast from the new node; the new node chooses the CL with the maximum number of duplicated available frequencies amongst the different CRC-Invites received. In cases of ties, the new node then evaluates the maximum receive power level. If there is yet another tie the choice will be on the first come basis.

The design of the intra-communications algorithms is to promote a distributed ad hoc communication environment. The CL's job is merely to facilitate the initial communication linkage. The design of these algorithms is to emulate a type of dynamic wireless ad hoc virtual circuit between the source and destination CR nodes. The continued establishment of the link is maintained by a forward cognition of available next frequencies to support both transmitting and receiving data.

4.6.1 Flowchart of the Initialization in a CRC

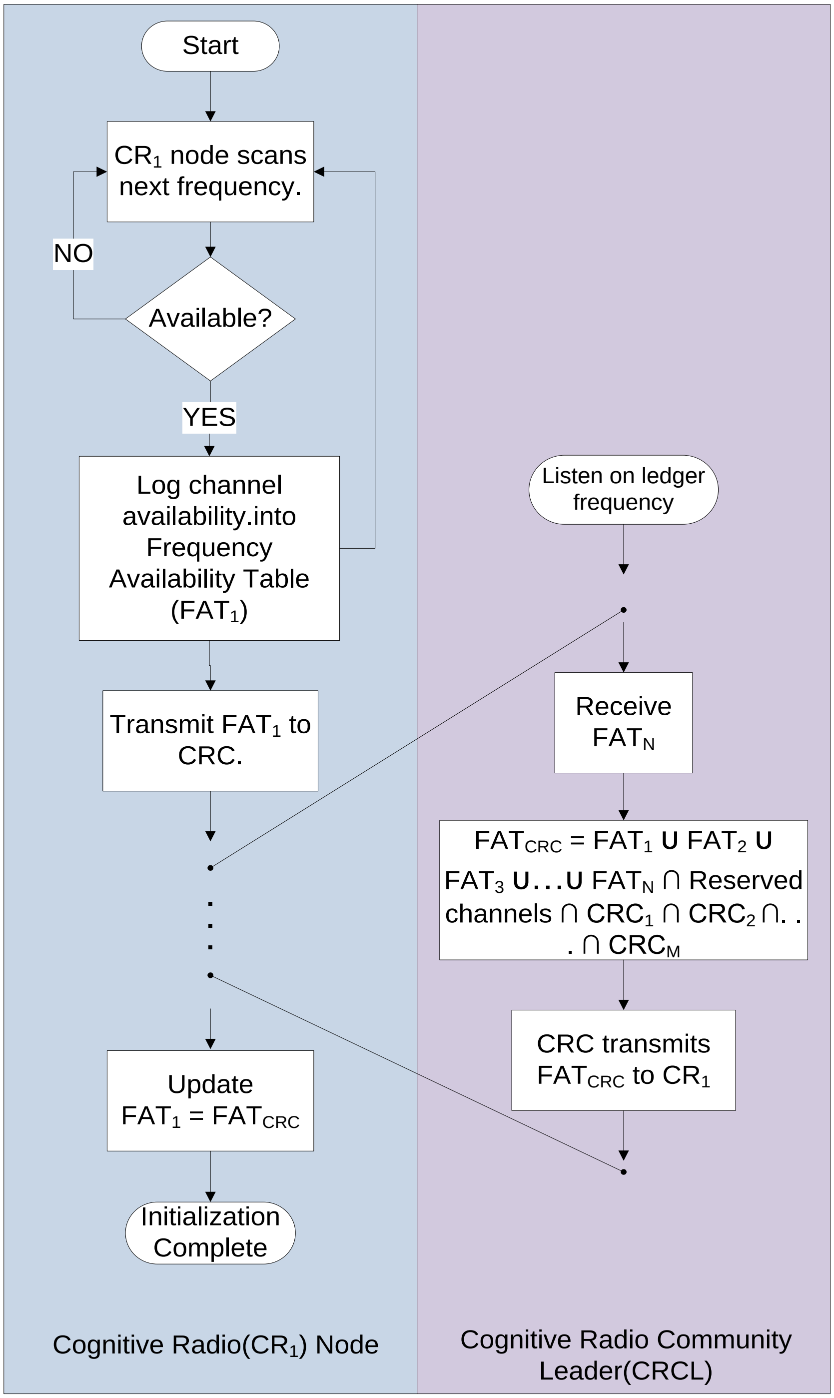


Figure 20: Flowchart of the initialization of a CR Node and CRC-CL

4.7 CRC Communications

4.7.1 Intra-CRC Communication

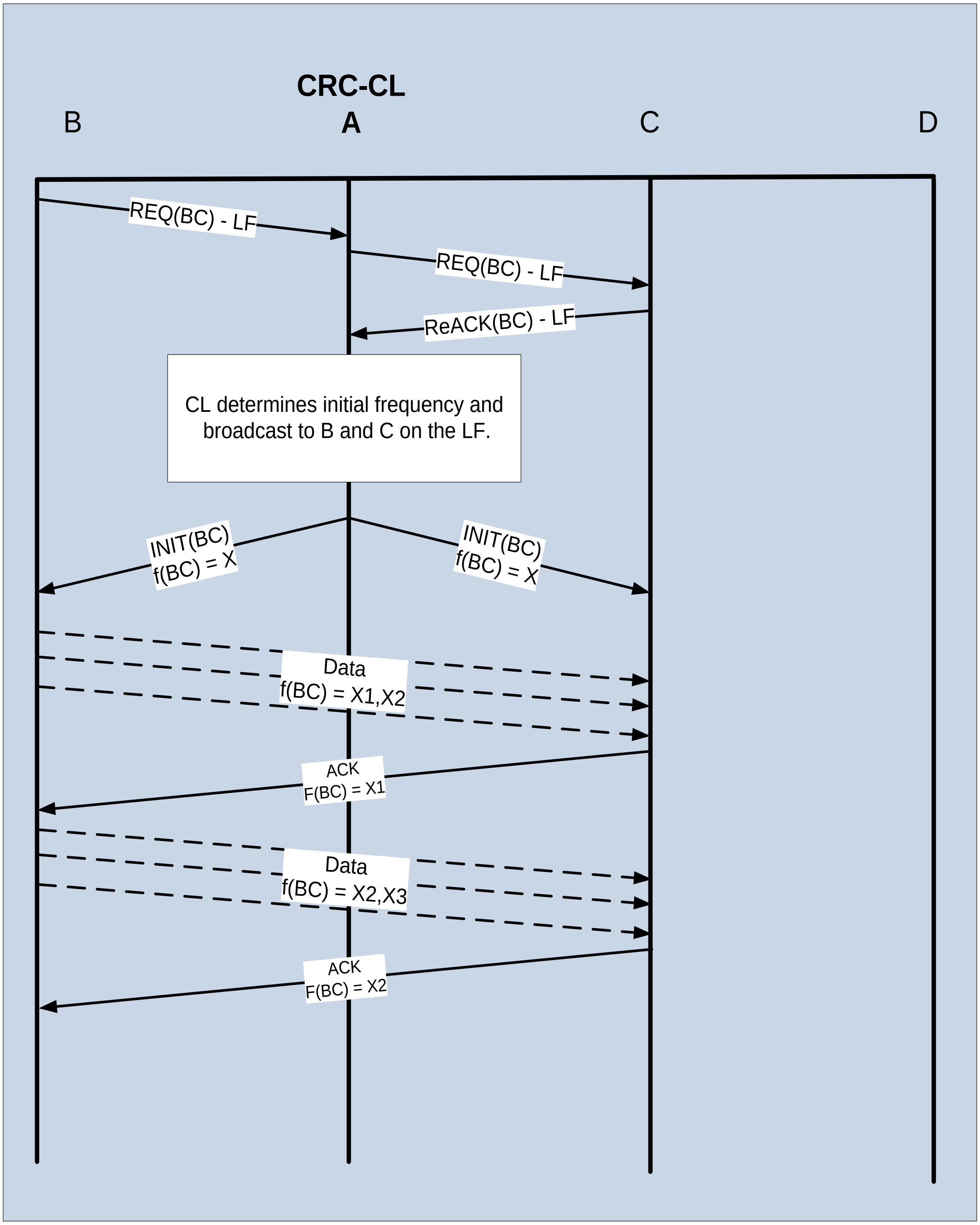


Figure 21: Intra-Communication of CR Nodes using DCP algorithms

Table 4: Transmitter CR Node Algorithm

```
Upon completing DCP algorithm and CRC membership.
1. Transmit REQ(Source,Destination) on LF.
2. Listen for $INIT_f$(x,y).
3. Repeat
4. Tx data, $Data.Next_f$ and $Data.Next_{f+1}$ on frequency $f$
5. If no ACK before timeout then retransmit(at most twice)
   on frequency $f$
    If still no ACK then retransmit once on frequency $f+1$
      else return to 1 at most twice
    Upon receipt of ACK, $f = ACK.Next_f$ , $f+1 = ACK.Next_{f+1}$
6. Until Tx data = {EMPTY}
```

Table 5: CRC-CL Communication Algorithm

```
Listen on $LF_{CRC}$ and $LF_{CL}$.
Upon receipt of REQ.
    1. Forward REQ to Destination.
    2. Upon receipt of ReACK from Destination.
    3. Randomly choose a frequency $f$ from $\lambda_{Source}$ υ $\lambda_{Destination}$
    4. Transmit $INIT_f$ to Source and Destination
    5. Add $f$ to InUse set of frequencies.
```

Table 6: Receiver CR node Algorithm

```
Upon receiving INIT(x,y)
1. Repeat until $Data.Next_{f+1}$ = {EMPTY}.
2. Execute DCP Algorithm.
3. $f = ACK.Next_f$ , $f+1 = ACK.Next_{f+1}$
4. On receipt of data
5. Tx ACK, $ACK.Next_f$ and $ACK.Next_{f+1}$ on frequency $f$
   ACK.
6. If no data received before timeout then
        move to frequency $f+1$ return to #2 at most twice
    else upon receipt of ACK
```

4.7.2 Inter-CRC Communication

The communication between CR nodes in different CRCs requires the facilitation from the CR nodes involved respective CL. The concept of the CR environment becomes more complex addressing the basic tenet of the spectrum hole during inter-community communication. We reiterate that the frequency spectrum of a CR node at any time t cannot be assumed to be the same at the receiver; hence, the need for a moderator to facilitate the initial communication link.

The design methodology being employed is again designed to facilitate a dynamic wireless ad hoc virtual circuit. A dynamic virtual circuit is a virtual communication link via gateway CR nodes, if necessary, between multiple CRCs. If the sender and receiver is out of the transmission ranges of the CRCs, a gateway node is utilized.

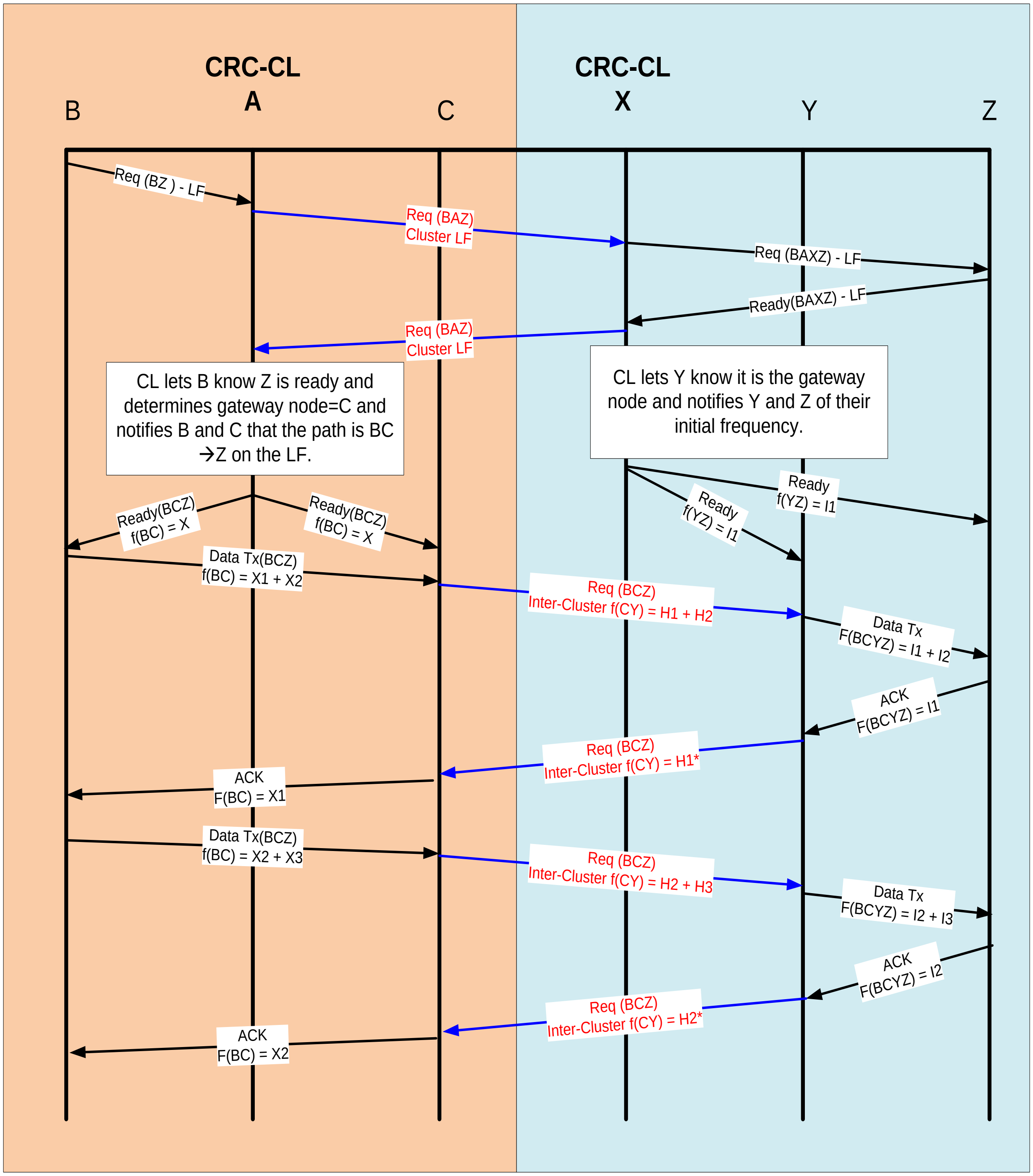
4.8 Simulation Environment

The emphasis of the DCP methodology is evident in the analysis of the simulations performed for varied nodes at multiple frequencies. In our simulation the links types are the emphasis of the QoS attribute not the nodes themselves. This again illustrates the complexity involved in the simulation of a Cognitive Radio Network.

The simulations were executed under the following conditions.

Parameter	Value
Frequencies Available	10, 50, 100, 250, 500
Nodes	100, 250, 500
Mobility	None
CRC	None

- **noDCP** – This process utilizes the basic "best fit methodology
- **DCP** – This process utilizes the data-centric prioritization methodology where the 1st of n available frequencies is decided upon.



CL lets B know Z is ready and determines gateway node=C and notifies B and C that the path is BC →Z on the LF.

CL lets Y know it is the gateway node and notifies Y and Z of their initial frequency.

Figure 22: Inter-Communication of CR Nodes using DCP algorithms

- **DCP w/Random Choice** – This process utilizes the data-centric prioritization methodology where a random frequency is chosen amongst the n available frequencies. Since the CR node evaluates all scanned frequencies, the algorithm to determine the frequency for simulation results is a randomization algorithm that chooses the frequency availability table.

Resulting Values
Number of Frequencies Chosen
Number of Frequencies Duplication (Decision Collisions)

The following rules have been applied to emulate a realistic CR environment while maximizing a variance of complex yet well-defined deterministic algorithms. The more obvious concept purveyed throughout the simulation rules is that a more simplistic design may not present a viable solution set, i.e. if there are five CR nodes and five frequencies available, each node will choose a unique frequency repeatedly.

Rule 1: Frequencies determination algorithm: First Come First Serve (FCFS).and Random choice of the first four frequency solutions.

Rule 2: We assume that transmission will occur on the next time interval for all CR nodes.

Rule 3: To increase the complexity of possible solutions and minimize the collision domain; worst case scenario, only the first four frequencies in the frequency available table are open choices.

4.9 Simulation Results

In the illustration below, the number of frequencies that are chosen and of those that are chosen (Decision collisions). The DCP algorithm increases the number of frequencies choices available; thus reducing the number of decision collisions. The DCP algorithm using a randomization algorithm for additional complexity adds even more available frequencies into the frequency availability tables for the CR nodes.

Table 7: Standard Data-centric Prioritization with first-come first-serve algorithm denoting the frequencies chosen and the duplicates(collisions).

Chosen Collisions		Frequencies Available				
		10	50	100	250	500
Nodes	100	3 2	3 3	3 3	6 6	2 2
	250	3 3	3 3	4 4	3 3	4 4
	500	4 2	3 3	6 6	3 3	6 6

Table 8: DCP with randomizaion algorithm denoting the frequencies chose and duplicates(collisions)

Chosen Collisions		Frequencies Available				
		10	50	100	250	500
Nodes	100	7 2	3 3	3 3	6 6	2 2
	250	7 2	6 6	9 8	7 6	8 8
	500	4 2	6 5	9 8	6 6	10 10

The analysis of the simulation displays the number of frequency decision collisions during an execution of the DCP algorithm. The number of frequencies chosen without the implementation of the DCP algorithm is close to a first choice when the choices are extremely restricted.

The DCP algorithm shows a performance output providing double the number of frequencies choices when the application data-types are relatively close to one another. As the number of nodes increases, the number of frequency choices does as well.

4.10 Conclusion

This chapter illustrates the success of DCP in priori of the frequency determination algorithm in the cognitive radio cycle while also providing for an ad hoc distributed management system. The cognitive radio community (CRC) system ensures unique frequency availability

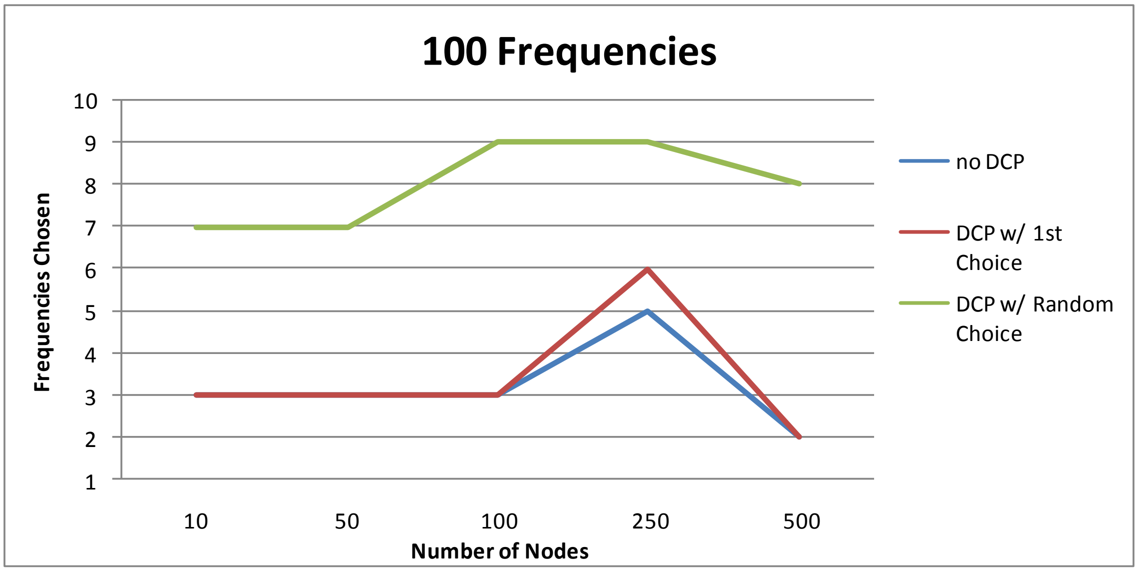


Figure 23: Total of Decision Collisions relative to 100 available frequencies and number of nodes.

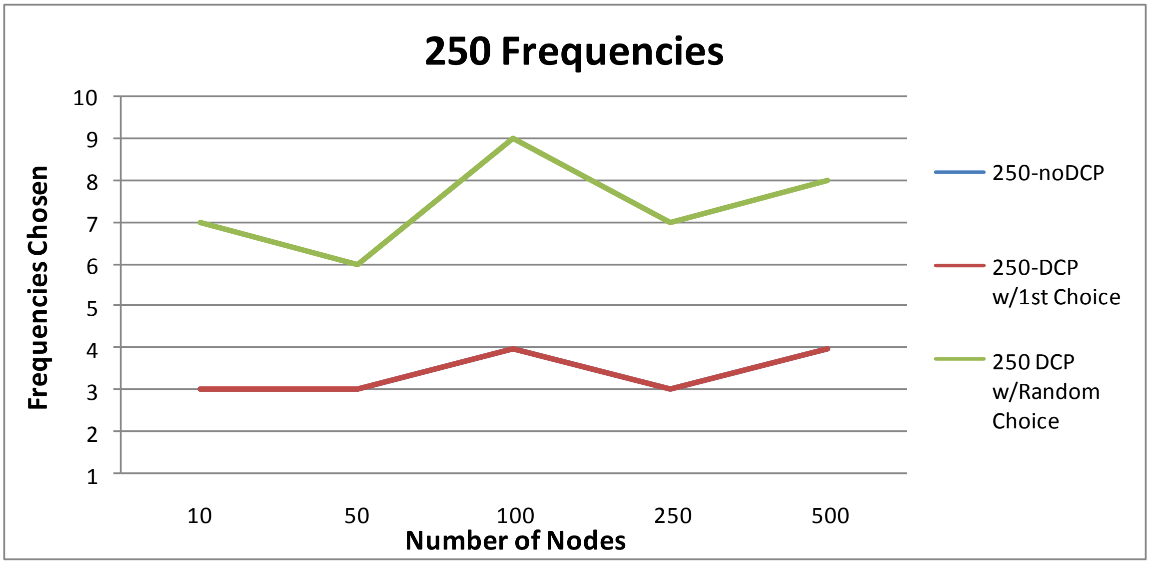
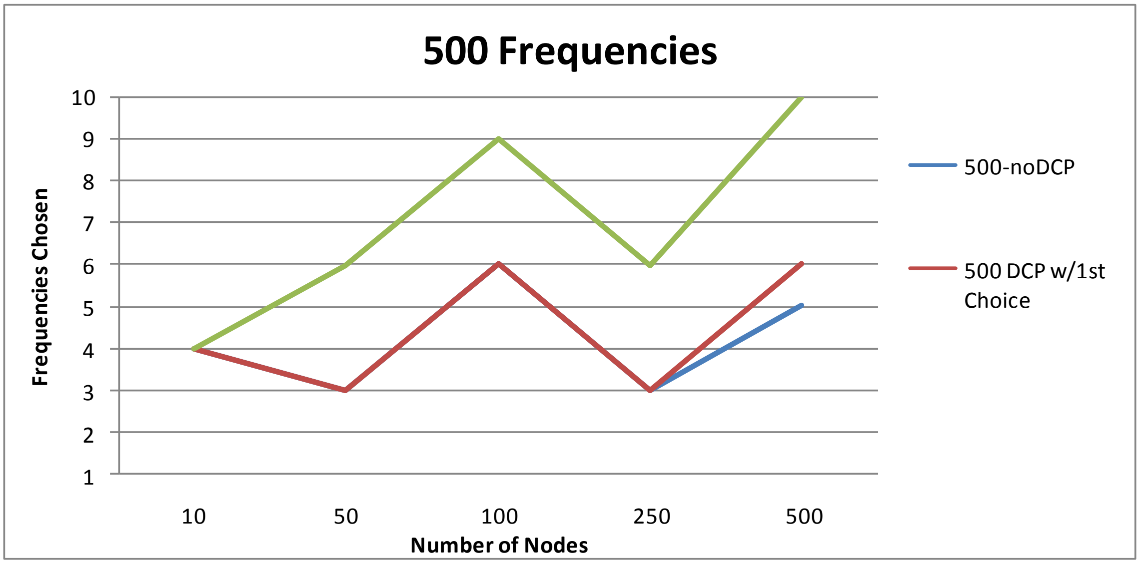


Figure 24: Total of Decision Collisions relative to 250 available frequencies and number of nodes.



(c)

Figure 25: Total of Decision Collisions relative to available frequencies and number of nodes.

tables between adjacent CRC-CL supporting a highly dynamic inter-community non-overlapping communication environment.

The DCP may be implemented as a standalone component in a cognitive radio network but greater efficiently is obtained in a clustered environment where the frequency spectrum has a management component. The CRC provides for fewer decision and network collisions in the CRN; hence, adding to its overall performance by minimizing the network overhead due to collisions, missed connects, and or retransmits, for example.

Chapter 5

Emerald: A Cognitive Radio Network System Model

In this chapter, we present Emerald, a multi-phased solution for the transmission and reception of data for direct, node to node, and indirect, multi-hop node to node communication in an Ad Hoc Cognitive Radio Network without prior knowledge of frequency spectrum and network neighbor information. Emerald's multi-layer solution encompasses, Media Access Control(MAC) and Network layers from the Open System Interconnect(OSI) model, for usage in an infrastructure and infrastructure-less based CRN. The first phase of Emerald is E-MAC, a MAC layer solution designed to resolve the Network Setup Problem and the Common Control Channel Problem. The later phase, E-NET, builds upon the Network layer, providing multi-hop routing with a node managing multiple communication links almost simultaneously. A key feature is that the node must not only route between two nodes for one communication link; but also, manage communication links that vary between separate(or the same) nodes at different times as well as different frequencies. This level of complexity is unique to CRNs.

We describe the Emerald system architecture in section 5.1. Section 5.2 provides the parameters used to describe the Emerald model. The algorithm to address the network setup problem is provided in section 5.3. The Emerald components are expounded upon in section 5.4. Section 5.5 provides the simulation environment and a step by step simulation of our Emerald model

5.1 Emerald System Architecture

As noted in section 3.1 there are several CR architectures designed a CRN. Some are state-based CRN architectures such as Safari and the Adaptive Cognitive Network layer model while others like CogNet and CogMesh are derivatives of a layered model approach from OSI. A key attribute to the Emerald System Architecture Model is its ability to serve as a stand-alone function or as an addition module or function to an already established architecture. Since the Emerald model provide solutions to several Cognitive Radio and Cognitive Radio Network problems; adding it will serve as an enhancement. Again, we note that the common control channel problem and the network setup problems are not completely resolved or even provisioned in the CRN architectures previously established.

Therefore, the E-MAC and the E-NET functions of Emerald are designed to be encompassed as illustrated in Figure 28 below.

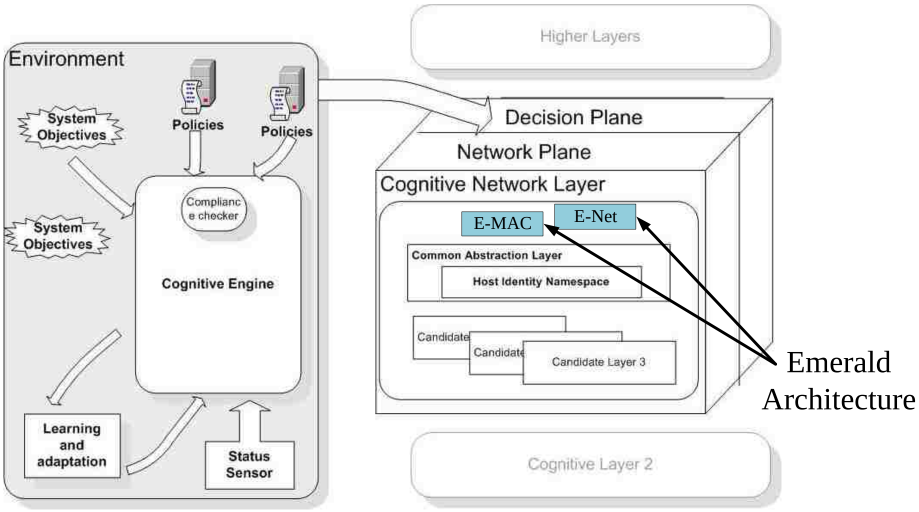


Figure 26: Proposed introduction of the Emerald phases E-MAC and E-NET in the Adaptive Cognitive network layer model

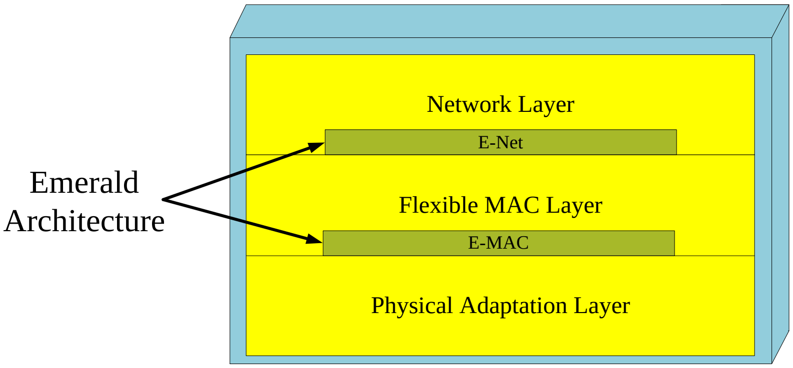


Figure 27: Proposed introduction of the Emerald phases E-MAC and E-NET in the CogNet Architecture

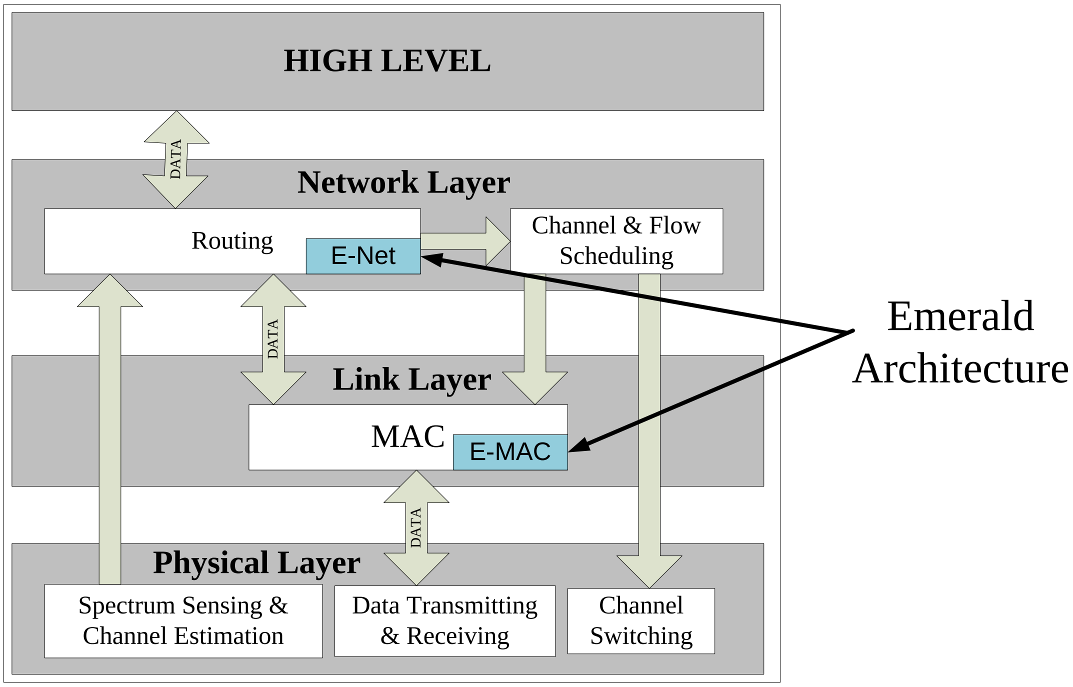


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Figure 28: Proposed introduction of the Emerald phases E-MAC and E-NET in the MSCRN Protocol Stack Model

Here we illustrate the logical location of the Emerald components. The next sections will denote its unique functionalities. This does not imply that the current systems models should be totally abandoned, merely enhanced.

For example, a modification to the CogNet Architecture stems from one of the support capabilities within its' design framework. CogNet was designed to support a "fully programmable MAC layer,…"; therefore, E-MAC may serve as a component of this programming. The adjustment to its' design will allow for removal of the common spectrum coordination channel as a mechanism of spectrum etiquette since E-MAC provides for a distributed spectrum control channel or spectrum coordination channel, as noted by the author. The next component to be addressed is the incorporation of the bootstrapping and node discovery process that is utilized to gather network neighbor information. A bonus with E-MAC is that the CogNet bootstrapping is a one hop informational process while E-MAC promotes a multiple hop learning environment. Whenever a new node is brought online, the listen and learn approach as noted in both CogNet and E-MAC is implemented. The sheer magnitude of information that can be provided to the E-MAC nodes may be overwhelming by hardware limitations.

5.2 Parameters

$\mathbf{M}$	the total number of nodes
$\mathbf{k}$	$\{ k \in \mathbf{M} \}$ Cognitive Radio node
$\mathbf{N}$	the total number of available frequencies
f	$\{ f \mid (f \in \mathrm{N}) \text{ and } (0 \le f \le \mathrm{N}) \}$ set of available frequencies
$\mathbf{k_n}$	$\mathbf{k_n} \mid (k \in \mathbf{M})$ and $(n \in \mathbf{N}, k \in \mathbf{M})$ the control frequency of node k
λ	set of slots within a communication window
λ_b	$\{ \lambda_b \mid 1 \le b \le (\lambda - 1) \}$ transmission slot within the communication window
λ_r	$\{ \lambda_r \mid (b + 1) = r \}$ receive slot within the communication window

5.3 E-MAC Algorithm

The Emerald model E-MAC module functions initially as a means to address the network setup problem and common control channel problem.

The *listen-and-learn* algorithmic design has two phases. The first phase is the listening phase. As each cognitive radio node comes online it must determine the makeup of its current environment by identifying its immediate, 1-hop, 2-hop, and possibly 3-hop neighbors. (The x-hop neighbor limitation is discussed in section 5.4.3 below.) To accommodate the constant spectrum sensing as noted in Mitola’s Cognition Cycle; the assumption is that the frequency spectrum(f) will be traversed in a sequential manner via top to bottom or bottom to top. As the nodes learn their neighborhood environment through sensing and tracking, the neighbor table that maintains a knowledge base of the neighboring nodes and their respective control channel is produced.

Table 9: Listen-and-Learn Algorithm

```
Upon node $u$ coming online.
Phase 1 - Listen
1.  Randomly choose an initial frequency $f$
2.  If frequency $f$ is occupied move to next sequential frequency
    $(f+1)$ and repeat step 2 $(f=f+1)$
    else
    a)  Update table
    b)  Update frequency spectrum
    c)  Broadcast message on chosen frequency $f$
Phase 2 - Learn
3.  Scan the spectrum
4.  Upon receipt of message from user $v$
    a)  Update table
    b)  Check for one-hop, two-hop, and three-hop neighbors
```

After the initial neighborhood table has been created the utilization of the network may now begin. A beacon frequency and slot is established and the x-hop table along with the source node's information is packaged and transmitted as a beacon message onto the network. A beacon message will be transmitted on the beacon frequency within its determined slot each cycle. In the case where it has been determined another node is utilizing this frequency, the node would perform a beacon back-off.

The second phase is the learning phase. During each interval thereafter, nodes are arbitrarily coming online and listening on multiple frequencies receiving beacon messages from other nodes as well as primary users that are utilizing the spectrum at that time. There are two(2) initial assumptions utilized in our network: (1) every node is within the transmission and receiving range of at least one other node within the cognitive radio network and (2) these, previously referenced nodes, share at least two available(not owned by a primary user) frequencies between them.

5.4 E-MAC Model Components

5.4.1 Communication Window

As illustrated in Figure 29 below, the communication windows are comprised of the beacon transmission period, the control receiving period, and the vacant periods. The beacon transmission period, λ_b, is the period selected within the communication windows to transmit the nodes network and neighborhood information. The network information of the node will contain the nodes control frequency and beacon transmission period with the communication window. The control receiving period is the period where the nodes will listen to receive communication requests as a control message from other nodes containing communication information such as the frequency that the communication will take place.

During the first interval (time slot), the first node, node *k*, comes online and proceeds to listen and learn (receiving state). The frequency spectrum is scanned in a linear fashion from lowest to highest or highest to lowest for primary users and any beacon messages from neighboring node i, $i \neq k$ & $i \in \mathbf{M}$. Node k listens for a beacon message on the frequency n. Node k determines a control frequency n, $n \in \mathbf{N}$.

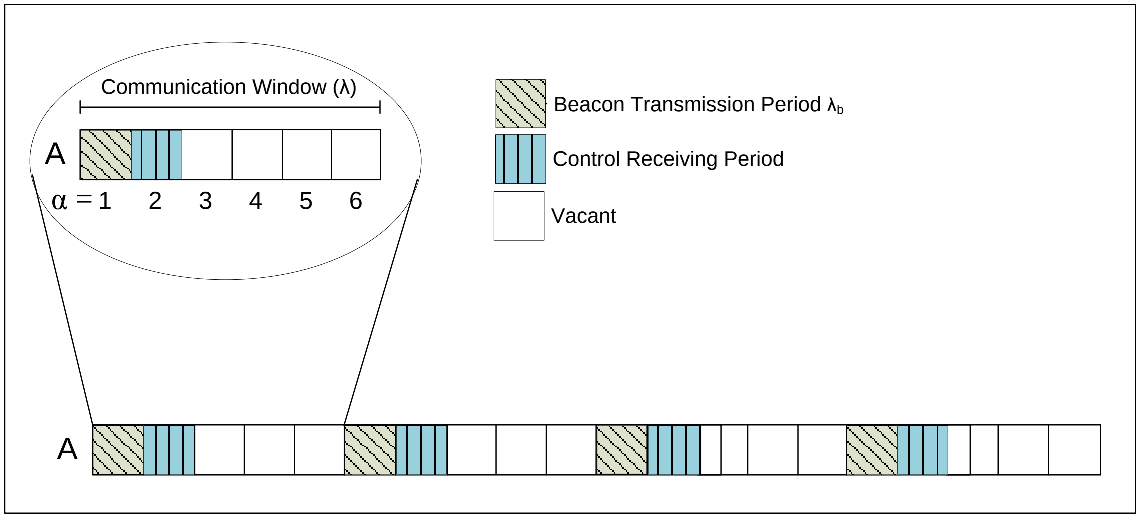

Figure 29: Communication window illustration denoting the beacon transmission, control channel receive and vacant slots.

In [15], their maximum time to exhaustively search the frequency spectrum, identifying Cognitive Radio Base Station and Nodes is basically $(N^2 \times T_S)$ seconds. We provide a learning environment without the Base Station and a maximum time to perform an exhaustive search as $\{(N \log N) \times \lambda\}$ cycles.

There has been a great deal of established research in the field of spectrum analysis and the determination of a frequency [47] [50] [58] [59] [60]; however, this research does not delve into this area.

5.4.2 Beacon Back-Off

The goal of the beacon back-off is to allow CR nodes the time and the ability to establish a beacon slot within an available frequency. However, due to the fact that an available frequency may be available to multiple nodes, a first-come first-serve approach has been established. The beacon back-off behaves the same way as the Distributive Control Function(DCF) of the IEEE 802.11 protocol.

5.4.3 Beacon Transmission Limitation

The neighbor-beacon is transmitted during the transmission slot of the communication window as noted in section 5.3. Although the individual components of the communication window a manufacturer or policy defined variable; it is discrete interval. As the node ***learns*** about its neighbors, its neighbor table size will increase and potentially result in a list of more nodes than can be transmitted within the allotted time of a single beacon slot. Therefore, the beacon transmission number of neighbors, as well as the number of the hops of neighborhood nodes must be less than the transmission slot window.

5.4.4 Beacon Message Format

In our distributed environment, nodes require a means to identify who they are and the specific control channel and slot. This periodic transmission of a beacon message is followed by a receive window for any control setup information requests. The beacon message and the neighbor table are designed to be similar in format for continuity purposes. The Figure 30 below illustrates the format of the beacon message: (a) the initial beacon (upon startup when the neighbor table is empty) and (b) the established neighbors in its neighbor table. This communication concept is similar in framing to [26].

Initial Beacon

(a)

ID	Control Channel

Normal Beacon

(b)

ID	Control Channel	Hop Count	Confirm Status	Next hop	Destination

Figure 30: Beacon message format

5.4.5 Communication Request Format

Control signals must be exchanged when a node attempts to communicate with another node. The control signal requests are designed to behave and appear similar to that of an IEEE 802.11 Request-To-Send(RTS). The control signal design is modified to include the requesting nodes id, control channel and slot, preferred frequency and slot, a secondary frequency and slot and a request sequence number.

Requestor ID	Control Channel	Preferred frequency	Secondary Frequency	Request Sequence	Destination ID

Figure 31: Communication request format

5.4.6 Communication Reply Format

Once the communication request has been received by the destination node, a reply is initiated. The control signal received is deconstructed and processed. Upon reconstruction of the reply to the route request the destination node must generate a route reply that will encapsulate two(2) available frequencies, time slots, and time-listening(TLT), respectively. The two(2) available frequencies and time slot will be denoted in the order the destination node will be listening. The TLT is an adaptation of the time-to-live(TTL) mechanism in IP packets. It addresses the rendezvous problem [61] introduced with the coordination of a communication link by providing a synchronized time to the adjacent node or to the original source node.

Reply Node ID	Control Channel	Preferred frequency	Secondary Frequency	Request Sequence	TLT	Requestor ID

Figure 32: Communication Reply Format

5.5 E-MAC Simulation

We design the simulation environment to address the Common Control Channel Problem and the Network Setup Problem. In doing so, node identification is assumed; much as the MAC address is a unique identifier or a derivative thereof.

Suppose node *a* turns on and begins scanning its available frequency spectrum. It then receives a message from node *b* at a given interval, the following will occur in order.

Table 10: Node processing simulation steps

1. Node *a* will initialize its $table[a][p] = freq_p$.
2. The *frequencySpectrum* is updated, $frequencySpectrum[freq_a] = a$.
3. Node *a* will listen for one-hop, two-hop, and three-hop neighbors.
4. Node *a* will update its table to identify the shortest path to the destination.
5. Node *a* will choose an available frequency and update its table to reflect the choice, $table[a][a] = freq_a$.

If a node is already online and receives a message, its table is simply updated and neighbors are determined. Determining one-hop, two-hop, and three-hop neighbors requires a cooperative effort by the cognitive nodes in the network to sense and share spectrum opportunities. An assumptive level of trust is presumed amongst all nodes. For any node *a*, one-hop neighbors are determined by examining its own table.

Determining two-hop neighbors assumes that CUs remain allocated to their initial frequency selection. Suppose node *a* has neighbor *x*. Node *a* can transmit a message to node *x* requesting its SOPs. This would reveal that node *a* has a two-hop neighbor for all *y*, from 1…M, where node *x*'s table 3 (*table[x][y]*) is not equal to infinity. A similar technique is used to determine three-hop neighbors.

In Figure 33 below, a connected graph is designed to illustrate the connectivity amongst seven(7) nodes. Each link denotes the available transmission range of the node. In that this is a CRN and there are several frequencies that may be shared between nodes, we have delimited the links to be an implied shared communication link with an established albeit assumed availability.

Figure 34 is a step-by-step illustration of the simulation tables for each node and their respective updates to their respective tables relative to the information they have received from a

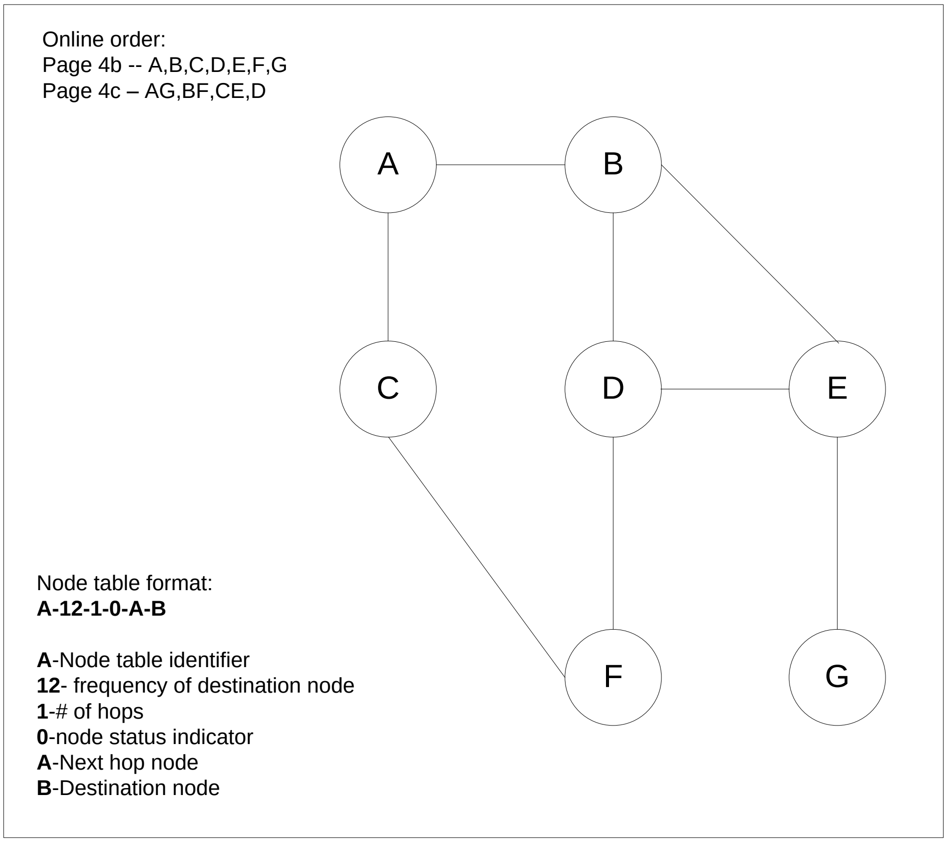

Figure 33: Cognitive Radio Network illustrated as a connected graph

neighboring node. The nodes operate in a truly cooperative manner with an implicit trust relationship. We identify the nodes as “coming online” or “waking up” in a particular order as a means to address the time it will take for a x-hop network neighbor table to normalize. Here we illustrate nodes coming online in the following node order: A, B, C, D, E, F, and G. For this rest of this paper, the online order will be illustrated as {A, B, C, D, E, F, G}. In the case of Figure 35 where multiple nodes come online simultaneously, sets such as nodes A and G, nodes B and F, nodes C and E, and finally node D. It will be noted as {A|G, B|F, C|E, D}.

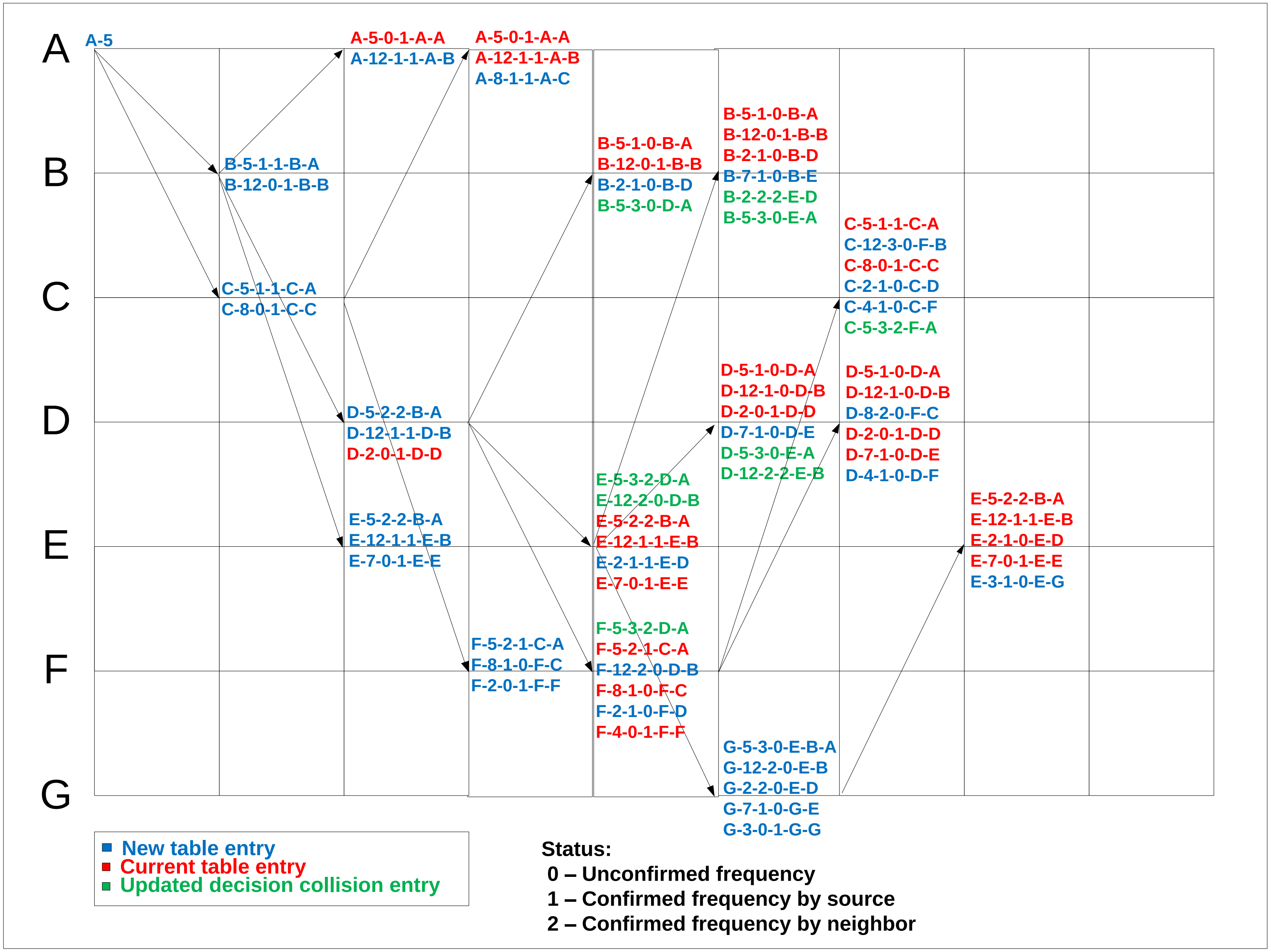

Figure 34: E-MAC's Step-by-Step initialization process illustrated with the online sequence = {A,B,C,D,E,F,G}

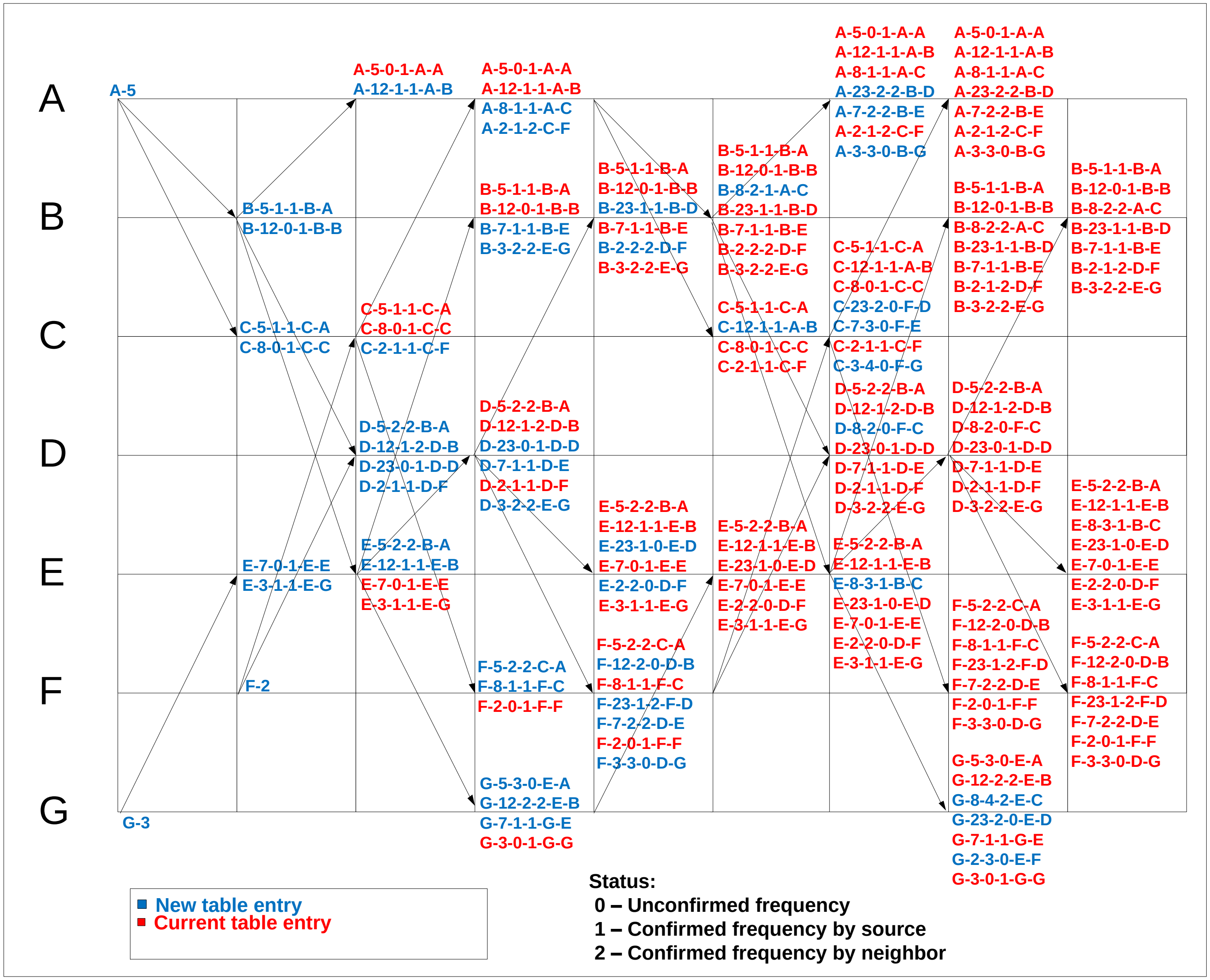

Figure 35: E-MAC's Step-by-Step initialization process illustrated with the online sequence = {A|G,B|F,C|E,D}

As the CR nodes continue to learn their environment of both primary and secondary users and after they have determined their own control channel; they are capable of serving as a source node, establishing a communicating with other nodes; a destination node, receiving communication from another node; and routing node; serving as a circuit point in a message's path.

5.6 E-NET Model

The Cognitive Radio Network experiences an additional dimensional concept traditional not experienced in wireless networking. Within normal wireless networks: home wireless networks or wireless sensor networks, whenever a node attempts to communicate with another node, it is assumed to reside in the same frequency. Therefore, a node merely transmits and all nodes within the signals range can hear the transmission. This is a linear communication scheme.

Wireless routing protocols have been designed to support this linear communication paradigm. The Cognitive Radio Network simply by the dynamics of its operational environment lends itself to an ad hoc network and with the mobility as a factor the mobile ad hoc network(MANET) becomes a more suitable comparative design mechanism. The CRN has many variations that are congruent with ad hoc network. In [62], we note the asymmetric capabilities that are applicable to a CRN.

- transmission ranges and radios that may differ
- battery life at different nodes that may differ
- processing capacity may be different at different nodes
- speed of movement

While these capabilities are applicable, the CRN introduces additional conditions

- frequency availability may differ between geographically neighboring nodes
- frequency availability may differ between non-geographically neighboring source and destinations
- frequency availability may differ in time

5.6.1 Routing Types

Wireless ad hoc routing has several types of protocols such as flat, hierarchical, and geographically based routing. We will address the flat routing protocols as they are more applicable. [63] The flat routing protocols are subdivided into proactive and reactive routing protocols. [64]

Proactive routing – a table-driven routing protocol where nodes maintain several routing tables with information regarding other nodes. The maintenance of the routing table is accomplished via a periodic or responsive activity in the network. A noted advantage is that the source node does not have to perform a route discovery procedure before communication with a destination node. When a message arrives, the node evaluates its routing table and replies along the path that has previously been established. The nodes constantly monitor their neighbors and in the case of a broken link; the nodes then floods its table information throughout the network.

Reactive routing – a dynamic routing protocol where nodes discover routes in an on-demand basis. When a node attempts to communicate with another node, a path has to be established via a route discovery mechanism. A route discovery is accomplished by the source node i floods the network with a request for a path to node j. This is called a route request(RREQ). Each node that receives the RREQ appends its own id to the path and continues to broadcast the RREQ. When node *j* receives the RREQ, it reverses the path and sends a route reply(RREP) along the newly reversed path to the source node *i*. A route maintenance function is necessary for broken links to acquire an alternative path.

The Emerald E-NET is a hybrid routing scheme that utilizes both the table driven methodology from a proactive routing protocol but also the dynamics of a reactive routing protocol. As previously noted, the nodes only transmit *x*-hops worth of table information within its beacon; this does not automatically mean that the entire routing table has been transmitted. (For more discussion regarding the limitation of the beacon transmission, see Section 5.4.3.) This is due to the fact that a node's routing table may contain $x + 1$ table entries.

5.6.2 E-NET Node Environment

The E-NET scheme promotes a source, destination, and relay node environment. The source node serves as the originator of the communication session. The destination node is the receiver of the intended communication. The relay node is a node that will serve as the repeater of a communication packet along a communication path (Possibly, since not all communication paths lead to the destination node.) to its intended destination node. It should also be noted that at any communication window, a node may serve as any one or all of the node types.

E-NET leverages the previously established wireless ad hoc networking protocol such as Ad hoc On-Demand Distance Vector (AODV) [65], Dynamic Source Routing (DSR) [66], and Destination Sequenced Distance Vector (DSDV) [67]. This introduces mechanisms for the functional utilization of its RREQ/RREP/Data/Ack scheme for normal communication, its route discovery for nodes that are not in its routing table, and its route maintenance feature for incorrect table entries. While [68], [69], and [70] all use a derivative of AODV in a cognitive radio network; only [70] is implemented into an environment without a predefined common control channel. In [70], it does generate a version of a common control channel to manage communication, but to its detriment, it introduces a single point of failure in the process also.

5.6.3 Route Discovery

To accommodate routing packets in a cognitive radio network, a communication path that salamanders throughout the frequency spectrum “hop-scotching” through different time slots that may be unavailable because it is already busy or because the communication slot has already passed. The process begins when a source node *i* attempts to communicate with destination node *j*, there are two initial states for node *j* relative to node *i*’s routing table. Node *i* has a path to node *j* or there is no path in node *i*’s table to node *j*.

When the path from node *i* to node *j* is already known, a request-to-send(RTS) message is sent from node *i* to node *j* on node *j*’s control channel and during the receive slot of the communication window. In the cases a busy receive slot, a back-off is implemented. Node *j* will transmit a clear-to-send(CTS) message to node *i* which contains an available and alternative frequency and slot. Node *i* will switch to the available or alternative frequency at the appointed slot time and begin transmitting data from to node *j*. An acknowledgement(ACK) is sent from node *j* at the receipt of the data from node *i*.

When the path from node *i* to node *j* is known but the hop count is greater than one(1), relay node(s) are necessary to facilitate the communication. In this case, the level of complexity is increased since a relay much be developed that behaves like a virtual circuit amongst the nodes along the communication path. As stated previously, there are several factors that must be addressed to establish the communication path.

1. An available frequency must be established between nodes along the path.

2. A transmit and receive window must be established within the available frequency between the relay node and another node.
3. In the case of multiple relay nodes, the transmit and receive slots cannot coincide between adjacent nodes in the path.

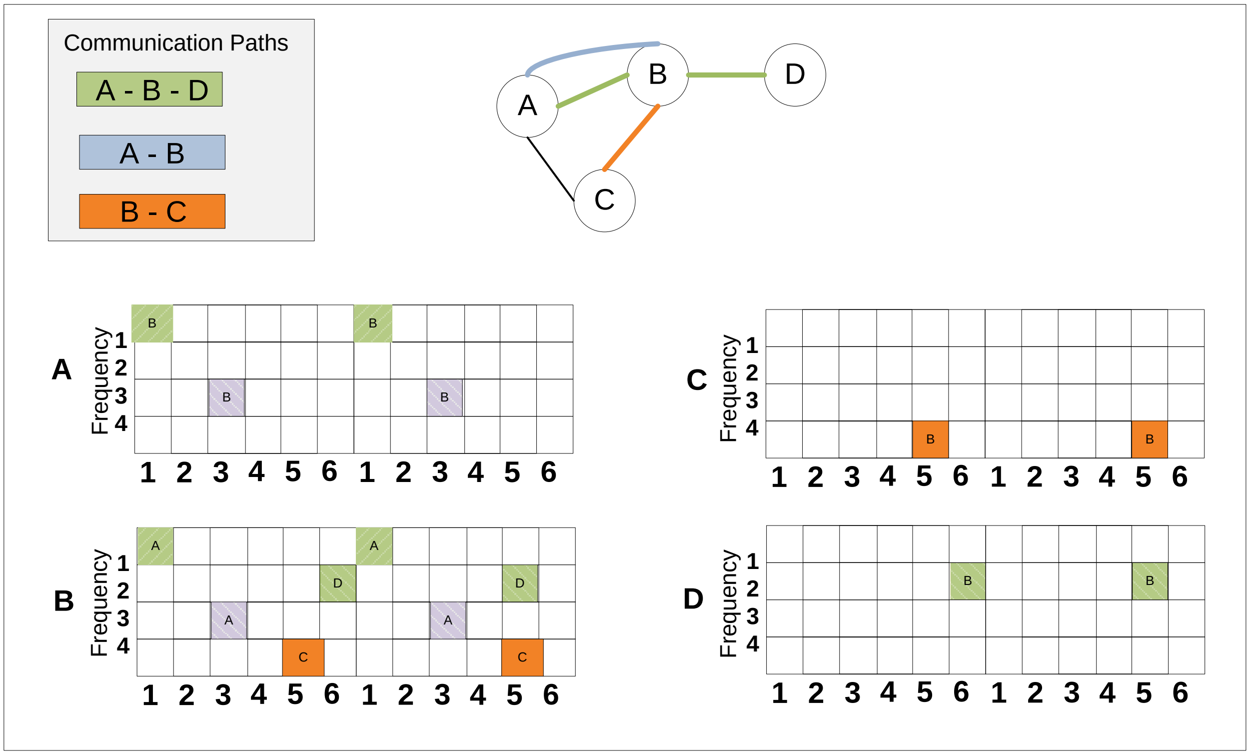

Figure 36: Cognitive Radio Network's routing complexity illustrated.

In the following discussion of the routing protocol, we will assume the initialization has completed successfully and that the network will not introduce any additional nodes. All communication paths are setup successfully via E-MAC and the nodes are ready for the transmission of data.

As illustrated in Figure 36, node A in the source node for a path to the destination node D with node B serving as a relay node. Node A transmit to node B in frequency 1 slot 1; while node B serves as relay transmitting to node D on frequency 2 slot 6.

Also node B establishes a communication path with node C. We will assume that the previous communication link was established prior to this setup. Node B transmits to node C on frequency 4 slot 5.

Finally, node A has a separate communication request with node B. Since this is a different communication path, a separate link must be created. This mandate is designed to address the varied types and size of messages. Also node A transmits on frequency 3 and slot 3.

5.6.4 Route Maintenance

In the case of a broken link in the communication path, a new path must be established. This is accomplished by completing a new route discovery from that point. The node evaluates all of the links along the path to determine if there exists an alternative path. As noted in a previous section, node neighbor tables contain more neighbor information than the amount shared amongst the nodes in their beacon transmission. In addition, the learning process of Emerald coincides with the cognition cycle as initially created by Mitola [4] promoting the constant observing, learning, and deciding nature of a Cognitive Radio.

5.7 Data-Centric Prioritization with Emerald

DCP with Emerald introduces additional capabilities into the Cognitive Radio Network arena. This merge reinforces the flexibility of Emerald by addressing several, previously noted, problems; such as the common control channel problem, while introducing a QoS routing mechanism. DCP also provides a provisioning for clusters and a general infrastructure and infrastructure less implementation.

DCP with Emerald require modifications for the integration of E-MAC and E-NET as noted in section 5.1. These modification are modeled within the construct of the DCP, for example, the cluster in DCP will be manage the domain of

5.7.1 DCP with E-MAC

DCP with E-MAC require minor modifications to the architectural design of the overall Cognitive Radio Network. The utilization of the communication window will not change; however, the beacon format will need to incorporate information regarding the node type for heterogeneous networks. The node types are application type specific but this system also supports a hardware defined type that may be administratively designated. As in Figure 37, the beacon message format is appended to include the node type in both the initial message format as well as the normal beacon message. The node type information is noted in the neighbor table. This additional formatting information provides the infrastructure for the grouping of neighbors

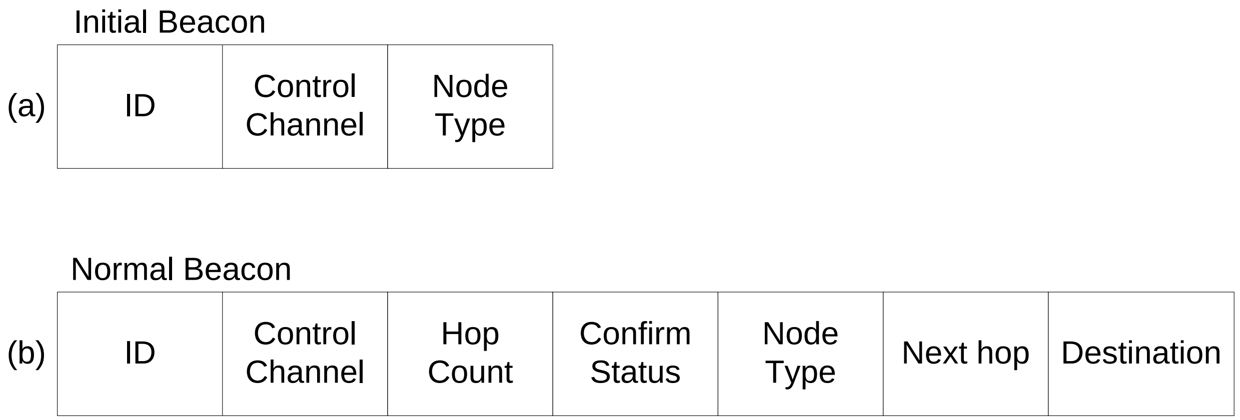

Figure 37: Beacon message format in DCP

by their node type. Again, the node type may be a predefined matric or a user-defined node derived function. For example, the majority of frequency types within the available frequency spectrum may be a user-defined node function.

(As for future work, a beacon message strictly of a specific application type group of neighbors rather than immediate neighboring nodes may be add to the effectiveness of a QoS network.)

5.7.2 DCP with E-NET

In addition to the beacon message format change the route information must be altered to adhere to the modifications from E-MAC.(Figure 38) The QoS solution is obtained via both functions: the node and the communication link.

Requestor ID	Control Channel	QoS level	Preferred frequency	Secondary Frequency	Request Sequence	Destination ID

Figure 38: Communication request format in DCP

The communication path based upon the node type or a delta entails the routing of packets from node to node is controlled during the flooding period. Therefore the communication paths are a directed flooding to support a minimum metric rather than with a brute force approach. In this case as well as others noted, the overarching goal is not the simple conveying of a message from source to destination by any means available. The goal is expand to complete the task of ferrying the message from source to destination but also to accomplish this task with a certain level of assurance as to the services provided by the network.

The communication link will resort to the weight of the path that best supports the application type in the request from the source node. During the request of a communication link from node to node an appropriate available frequency is chosen that best represents the requestors desired format. The establishment of each path from node to node follows the E-NET design and also the DCP routing algorithms. Nodes continually maintain their communication table as noted in section 5.6.3 above.

This bonding of DCP with Emerald illustrates both the QoS and structured system design that is malleable to a variety of environments. Its complexity with the negotiation of spectrum and temporal space is possible and promotes the ad hoc routing capabilities of a heterogeneous Cognitive Radio Network.

Chapter 6

Conclusion

Cognitive Radio Networks present many opportunities to advance the current wireless communication paradigm. New policies for standardization and logistics of operation are the focus of this research. We focus on several problems in the Cognitive Radio Networking domain; however, the research questions are base in nature with complex solutions.

In this dissertation, we developed a heterogeneous ad hoc Cognitive Radio Network System Model called ***Emerald***. First, a Cognitive Radio Architecture model has been created that can be utilized as an enhancement to current CR architectures addressing their limitation. Secondly, a Medium Access Control(MAC) layer algorithm is provided to avoid the pitfalls of the common control channel problem and the network setup problem. Finally, a routing model is proposed that will address the efficiency of an ad hoc multi-hop CRN with a focus on the Quality-of-Service(QoS) of the point-to-point as well as end-to-end communications.

Some of the major contributions of the Emerald system design are the network learning, the frequency spectrum optimization, the Quality of Service provisioning, and the distributed control channel. The derived results from this dissertation will contribute to the policy makers and the research community by providing analytical results of several inherent challenges in Cognitive Radio Networks, such as the network setup problem, the common control channel problem, and the opportunistic spectrum allocation problem, to name a few.

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Appendix A
Permission of Use from Dr. Joseph Mitola III

Urban Wiggins <uwiggi1@tigers.lsu.edu>

Permission of use

2 messages

Urban Wiggins <uwiggi1@tigers.lsu.edu> **Mon, Dec 20, 2010 at 8:15 PM**
To: Joe.Mitola@stevens.edu

Dr. Mitola,

My name is Urban Wiggins and I am a Ph. D. student in the Computer Science program at Louisiana State University.

My dissertation research is based upon Cognitive Radio. I am requesting written permission to utilize your diagram of the cognition cycle(with proper notation) in my dissertation.

Thank you for your time.
Urban Wiggins.
uwiggi1@lsu.edu
225-572-3191

Dr. Joe Mitola <Joe.Mitola@stevens.edu> **Tue, Dec 21, 2010 at 6:52 AM**
To: Urban Wiggins <uwiggi1@tigers.lsu.edu>

Hi, Urban
Thanks for asking. Permission granted. The notation I prefer is to assert my copyright in the figure (c) 2009 Joseph Mitola III, Reproduced with Permission
But if LSU's standard format is different, use your own.
Also, I'd be interested in reading your dissertation.
Best regards
joe

Dr. Joseph Mitola III, Fellow of the IEEE
Distinguished Professor
Charles V. Schaefer, Jr. School of Engineering and Science
School of Systems and Enterprises
Vice President for the Research Enterprise
Stevens Institute of Technology
Castle Point on Hudson, Hoboken, NJ, USA
Cell: 703-314-5709
[Quoted text hidden]

Appendix B
Motorola Photograph Release

Urban Wiggins <uwiggi1@tigers.lsu.edu>

Motorola Collective Asset Order MOT-393183 from Urban Wiggins

1 message

Motorola Collective Administrator <dba-mot@widencollective.com> **Sun, Dec 12, 2010 at 8:20 PM**
Reply-To: uwiggi1@lsu.edu
To: Urban Wiggins <uwiggi1@lsu.edu>

Motorola Collective

Dear Urban Wiggins,

Digital assets have been ordered by Urban Wiggins.
Please click the link below to view and download the assets.

http://www.motorolacollective.com/pickup?key=Sa482fc4a-019d-4a31-ba41-fb8e400e19c3

Asset Order Summary

Order Date: Sunday, December 12, 2010 - 08:20 PM
Order Expiration Date: Sunday, December 19, 2010 - 11:59 PM
Ordered By:Urban Wiggins
uwiggi1@lsu.edu
225-572-3191
Recipient: Urban Wiggins
uwiggi1@lsu.edu
225-572-3191

Asset Conversion Formats: JPEG (with white background)

Assets Ordered

1. CHARM_Cab_Front_Home_EMEA
2. Heritage_1985P0646P
3. i1_Front_Home_Mktng_ENG

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Data-Centric Prioritization in a Cognitive Radio Network: A Quality-of-Service Based Design and Integration

Title: Data-Centric Prioritization in a Cognitive Radio Network: A Quality-of-Service Based Design and Integration

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Author: Wiggins, U.; Kannan, R.; Chakravarthy, V.; Vasilakos, A.V.

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Vita

Urban Wiggins was born on May 2, 1970, in Baton Rouge, Louisiana. He was the first-born son of Corine and Henry Wiggins. After completing his tenure at Southern University High School, he continued on to Southern University and A&M College at Baton Rouge, Louisiana for his secondary studies. He received his Bachelors of Science degree in Mathematics in July, 1994. He continued in his pursuit of higher education at Southern University and A&M College at Baton Rouge, Louisiana obtained a Master's of Science degree in Computer Science with a focus on Digital Data Networks in December, 2002. During his tenure as a graduate student at Southern University and A&M College in Baton Rouge, Louisiana, he held several internships at the Intel Corporation in Santa Clara, California from May 1995 to January 1996, May 1996 to January 1997, and May 1997 to August 1997.

He worked professionally as a Network Engineer and Technical Project Manager at Intel Corporation. He also worked as a Consultant and Subject Matter Expert for Broadband Services at the Home at Telcordia Technologies in Morristown, New Jersey. He moved into academia as a Data Analyst and Student Data Manager at the Baton Rouge Community College in Baton Rouge, Louisiana. He currently works as the Banner/Academic Systems Coordinator at Southern University and A&M College in Baton Rouge, Louisiana.

He is also a candidate for the degree of Doctor of Philosophy in Computer Science, which will be awarded in December 2011.