Network Management of Cognitive Radio Ad Hoc Networks

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ABSTRACT
In this paper, we examine the problem of network management for cognitive radio ad hoc networks (CRAHNs). A cognitive radio (CR) is an intelligent wireless communications device based on software defined radio that is aware of its environment and can adapt to variations in its inputs. Cognitive radio ad hoc networks are distinguished from other wireless networks by their distributed multi-hop architecture and dynamic spectrum access, which introduce many challenges in managing such networks. Whereas traditional network management systems typically monitor and report certain network parameters for potential operator intervention, the Cognitive Network Management Protocol (CNMP) is proposed to provide a framework to acquire, predict, verify and autonomously act on network information to essentially learn and respond to network behavior to meet Quality of Service commitments and user-specific needs within CRAHNs. In this paper, a literature review is given where we describe the areas of classic network management and how the management of CR ad hoc networks is different from the traditional management areas for wireline/wireless networks. The three basic management architecture types are then outlined and the discussion proceeds to overview several relevant network management protocols. Then the proposed framework of cognitive radio network management is introduced and discussed.

Keywords
- cognitive radio
- network management

1. INTRODUCTION
Although the increased use of radio frequency devices leads to competition for scarce spectrum resources, the U.S. Federal Communications Commission (FCC) has indicated in a 2002 report that portions of the spectrum are significantly underutilized [5]. The spectrum shortage and the inefficient usage of spectrum has encouraged the development of Cognitive Radio (CR) that is a context aware intelligent radio capable of autonomous reconfiguration by learning and adapting to the spectrum environment [10], [14]. Since the unlicensed or lower priority Secondary Users (SUs) employing CR must limit any interference to the licensed or higher priority Primary Users (PUs) of the spectrum, the SUs must only transmit in the spectrum holes left available by the PUs at any given time. Maximizing throughput for both PUs and SUs then depends largely on the efficient management of the CR network. In contrast to radio resource management typically performed at the physical layer, network management considered here addresses the network-wide situation awareness and decision making, usually in a medium time scale.

1.1 Comparison with Classic Network Management
We start by comparing the inherent differences between managing traditional networks and CRAHNs. Traditional network management of wireline networks as described in [11] is divided into five areas: performance management, fault management, security management, configuration management and accounting management. In Table 1 we contrast the traditional functions to those required by CRAHNs. Managing a CRAHN poses a unique set of problems where the primary differences from traditional networks concern the availability and stability of channels in the wireless CRAHN environment, and in particular the potential channel interruptions due to PU activities.

1. Fault management: Fault management includes identifying, isolating and potentially correcting faults in the network. It is also important to record the process used to solve the problem for future reference. Deciding which faults to manage will be influenced by the scope of control desired over the network, which affects the amount of data gathered from network devices and also by the size of the network [11]. Fault management in a CRAHN environment can be very complex, due to dynamically changing spectrum availability, which can cause severe difficulties to perform fault identification and isolation, when the communication paths for the CR network may be constantly changing.

2. Performance management: Performance management involves measurement of network performance, with metrics such as overall throughput, percent utilization and error rates. Baseline performance levels are then established based on acquired data and performance thresholds are set for various monitored parameters. Network tuning is accomplished by throttling network
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Table 1: Traditional versus Cognitive Radio Network Management System Functions

devices as required to maintain network throughput [11]. In a CRAHN, performance management also includes acquiring additional or better performing channels to meet Quality of Service (QoS) objectives.

3. Security management: Security management ensures that network users are authenticated and authorized by controlling network access points and preventing unauthorized users from spoofing the network as valid users or tampering with network operation. The basic steps in security management are 1) Identify the sensitive information to be protected, 2) Find and secure the network access points, which can be done with encryption and decryption schemes, packet filtering, and host, user and key authentication, and 3) maintain those secure access points [11]. Similar to mobile ad hoc networks (MANET), CRAHNs in addition to the traditional security functions must handle spectrum congestion, where attacks may be waged by malicious jammer nodes to occupy all channels in a geographic area. This denies channel availability to SU users, who sense that it is PU activity, and affects both transmitting and receiving CR nodes.

4. Configuration management: Configuration management traditionally involves locating and setting up the parameters and versions of network devices for operation. The goal of configuration management is to track and manage the effect of device configuration changes on the network [13]. The steps involved in configuration management are 1) gathering information about current network configuration, 2) use acquired information to update and/or correct network device configuration as needed, and 3) maintain a database of network device information, such as operating systems version, firmware version, number of CPUs, interfaces, etc. A network database inventory can aid in future problem resolution [11]. However, in CRAHNs, nodes may be mobile, or may power off intentionally to save power or die from battery discharge. Also, during PU or malicious node activity, there may be no channels to reach some of the CR nodes, effectively altering the topology of the network. Finally, if the network architecture does not include a central manager, there would not be a logical location for a single configuration historical database.

5. Accounting management: Accounting management tracks the network usage of users and groups and may serve as the measurement method for compliance to a service level agreement and for CR user billing. Accounting management steps include 1) gathering data about network utilization, 2) setting usage quotas using metrics, and 3) billing users for their network usage [11]. Managing a QoS agreement on a CRAHN is more complex than using traditional management because the service is not solely dependent on the CR network, but also on the activity of the PU network, which can hamper throughput or completely interrupt service.

1.2 Network Management Architectures

Network management architectures for wireless networks are broadly defined as three basic types as described in [4]. Centralized network management uses a single manager station to gather information from all of the managed nodes and controls the network. While centralized management allows a global view of the network to make management decisions, there are several drawbacks. The central manager is a single point of failure if the manager is incapacitated and no backup manager is in place. The amount of management traffic from all of the network nodes in a wireless multihop network may be prohibitive in a CRAHN environment to provide meaningful management functions in a timely manner.

Distributed network management uses multiple managers who each manage subnetwork of nodes. This decreases the amount of network management overhead and per manager computation compared to the centralized approach. In this architecture, the managers communicate peer to peer, and can provide higher reliability with more networked information among the manager peers.

Hierarchical network management uses intermediate managers, each having their own management domain, to distribute management tasks. This architecture uses a central manager and the intermediate managers communicate up or
down the hierarchy. There is no direct communication between intermediate managers. However, depending on the needs of the management system, any of these architectures can be used in combination.

2. RELATED WORK

2.1 Simple Network Management Protocol

The de facto standard for wireline networks is the Simple Network Management Protocol (SNMP) [9], [7]. This protocol uses a manager-agent architecture where the managed devices implement software agents that collect, store and communicate management data to a central management node. Typically, human interaction is required to observe reported information from the managed devices and implement some corrective action as required.

While SNMP performs well for wireline networks, its traffic overhead and long time scale reporting are not well suited for bandwidth constrained, rapidly changing mobile wireless environments.

2.2 Ad Hoc Network Management Protocol

In order to address some of the shortcomings of SNMP for wireless network management implementation, the Ad Hoc Network Management Protocol (ANMP) was introduced in [4]. ANMP reduces the network management traffic, relative to SNMP, between the network manager and agents by using hierarchical clustering of nodes to lessen the number of messages exchanged between the manager and the agents (mobiles). It is also compatible with SNMPv3, using the same Protocol Data Unit (PDU) structure for management communication.

ANMP uses a cluster architecture separated into hierarchical layers. Here, CR nodes with software agents are at the lowest level, cluster head nodes each manage a group of agents and the network manager node manages the cluster heads. An example of the cluster hierarchy is shown in Figure 1.

While this is a significant step forward in wireless communications management, ANMP was not designed for cognitive radio networks, where the managed devices must contend for spectrum resources dynamically. It extends SNMP for mobility and wireless connections, but because it also operates with somewhat course-grained measurements from Management Information Base (MIB) accumulations, it may not provide the dynamic granularity required for CR networks.

2.3 IEEE 802.22 WRAN Standard

A recent protocol has been introduced for cognitive radio networks that takes advantage of unused channels, or ‘white space’, in the TV frequency spectrum. The Wireless Regional Area Networks Standard (802.22) [1] has a network management architecture that implements a Network Control and Management System (NCMS) that allows independence of the physical (PHY) and media access control (MAC) layers from the network architecture. Figure 2 shows the relationship of the three planes in the reference model: the data plane, management/control plane and the cognitive plane. Additionally, managed nodes, such as the Base Station (BS) and Customer Premise Equipment (CPE), collect and store management information in the format of WRAN Interface MIB and Device MIB that are used with network management protocols such as SNMP. While 802.22 is an IEEE standard for CR, it is geared for a cellular style single-hop network configuration, where the BS is in control of all management functions. In the case of Cognitive Radio Ad Hoc Networks (CRAHN), the SNMP based management would still be insufficient for the same reasons stated earlier.

2.4 Other Wireless Network Management Approaches

Another network management approach is called the Self Organizing Network (SON), whose availability can be expected with 4G network implementation [8]. It is intended to reduce complexity and cost of network management by selectively coupling server and client nodes to exchange information. These networks operate on the principles that various processes must be coupled with one another so that they can interact; secondly that interactions must be self-sustaining, or autocatalytic; and finally that self-organizing system must produce functions that are useful to the system’s stakeholders [3]. The architecture can be based on equal agents, denoted as Distributed Network Agent (DNA), to form a management overlay. While direct network management information exchange between local peer nodes can be power conservative, they lack timely global network in-
Finally, we consider the approach of a system that proposes hybrid schemes for radio resource management where the wireless users are assisted in their decisions by the network, which broadcasts aggregated load information [8]. Central intervention is needed during severe congestion periods where it is assumed that the mobiles follow the instructions of the base stations. Otherwise the association decision is left to the mobiles, which make the decision based on aggregated load information. This is based on IEEE standard 1900.4, which provides a basic architecture for enabling coordinated network-device distributed decision making. This helps to optimize radio resource usage, including spectrum access control, in heterogeneous wireless access networks [6]. This standard replaces the SNMP MIB with an object orientation concept, defining classes for policy, terminals and Composite Wireless Network (CWN). The standard also provides mechanisms for one-hop CR networks with a BS and terminal architecture, but is not designed for multihop CRAHN networks that we will consider.

3. PROPOSED COGNITIVE NETWORK MANAGEMENT PROTOCOL

The proposed approach for the Cognitive Network Management Protocol (CNMP) focuses on the CRAHN network implementation with a cluster architecture, as described in [4]. CNMP also recognizes the value of the combination of global information with local node information for comprehensive, yet efficient management of the network. Overall, a cognitive network management protocol should integrate relevant system characterization parameters into learning algorithms to not only address anticipatory management of the CR network functions but also use them cognitively and predictively in the traditional network management areas of performance, fault, security, configuration and accounting management. Hence, this protocol is novel in that it provides a cognitive management approach to cognitive radio networks.

3.1 CNMP Functionality

A conceptual diagram of the communication layers and the management components that reside on a CR node is shown in Figure 3. The cross layer interfaces between a CNMP agent and the communication layers as well as the connections to the spectrum management components are drawn. The idea is that CNMP would integrate with spectrum management, but would leverage and envelop that information to also perform classic network management in a higher plane of functionality. The CNMP functionality will draw on spectrum management information at the local CR node and communicate with the cluster head to exchange information. The cluster head will communicate with the network manager node for global information that can be used to provide more intelligence for the regional cluster wide decisions as well as to provide specific inputs to individual CR nodes.

Hence, in our hierarchical scheme, the CRAHN uses a central network manager node which communicates with the cluster head nodes of each cluster. Each cluster head, or intermediate manager, has as its domain the group of nodes that are geographically near and are registered with the cluster head. It collects and processes node information of its domain and passes the information to the central network manager as required. It also distributes the messages from the central manager to nodes in its domain, thereby decreasing management traffic relative to all nodes communicating with the central manager. Also, there is no direct communication between cluster heads; their communication is always routed through the network manager. As in [4], we should also note that the formation of clusters for management is to create a three tier hierarchical network management system - it is not related to any routing considerations, and thus bridges the global network state information to local network nodes who have limited overall network knowledge.

For example, if congestion information is gathered by the cluster heads and communicated to the network manager node, the manager can evaluate the relative congestion across the network by cluster. It can then communicate relevant congestion information back to the cluster heads which can then provide the appropriate congestion avoidance information to the routing algorithm on each mobile host node. This effectively provides global visibility to the host nodes to make more effective routing decisions that they would not have had if they were operating solely in a distributed management system, which adds to the fine-grain cross layer management data available to the local nodes for a comprehensive management approach. This combination of global and local fine-grain management information that is readily available in a dynamic bandwidth environment distinguishes CNMP from SNMP and ANMP.

3.2 CNMP Implementation

CNMP is intended to provide the basis for all areas of network management, instead of only focusing on radio resource management (RRM). Therefore, in addition to RRM management of spectrum monitoring, identification and acquisition, CNMP will be able to provide information for performance management, fault management, configuration management, security management and accounting management. The design goals for CNMP include that the protocol provides robust, scalable and adaptable network manage-
ment that is fully autonomic, while having the capability to report management information to an operator and provide the option for manual control. As with the IEEE 1900.4 standard, CNMP will be object oriented, specifying network management information in classes and subclasses. The advantage of this is to allow coherent software development with object oriented programming languages and alignment with the direction of Software Defined Radio (SDR) development [14].

Since the CNMP management approach bridges the information gap between centralized management and local node management with intermediate cluster head processing at the intermediate level of network hierarchy, it provides a more efficient and near optimal solution than the more typical approach to the network resource management optimization problem. In that scenario, the method may include decoupling the optimization and reducing the problem to a set of suboptimal components [12]. The components are then solved heuristically at individual nodes, where the results may be somewhat inferior to the optimal solution.

To further increase management communications efficiency, CNMP uses a succinct and efficient packet (frame) protocol structure to communicate network management information to reduce network management overhead. Network state information will be quantized to reduce the bit count of management messages; for example, 3 bits can be used to represent 8 levels of congestion.

To summarize the motivation for our work on CNMP, we note that CNMP bridges the gap between local resource management methods that do not have global visibility and the central manager that cannot implement real-time network control due to excessive management bandwidth overhead. In related work, we see that network management approaches make assumptions about global data being available, which may not actually be supported. CNMP provides global data via cluster heads to local nodes for better management decisions. And finally, CNMP reduces the network management message overhead with a succinct and efficient packet structure.

4. CONCLUSION AND FUTURE WORK

In this paper we have discussed the need to adapt and extend traditional network management concepts to CR ad hoc networks. The related work as discussed all have innovative approaches to attack some form of problems related to network management, but none of them provide a viable solution for overall network management of multihop cognitive radio networks. While some of those mentioned, [4] and [8], recognize the value of both global information regarding the total network from centralized management and the efficiency of distributed network management, they do not address our cognitive radio ad hoc networks case. In our future work, approaches to the problem of incomplete spectrum data due to limited sensing ability of the CRs will be addressed with a novel scheme and the problem of maximizing throughput as part of performance management will be examined with an optimization technique.

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6. REFERENCES


