



AFRL-RY-WP-TP-2010-1162

CROSS-LAYER DESIGN IN WIRELESS COGNITIVE NETWORKS (POSTPRINT)

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RF Sensor Technology Division**

JUNE 2010

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REPORT DOCUMENTATION PAGE				<i>Form Approved</i> OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YY) June 2010		2. REPORT TYPE Conference Paper Postprint		3. DATES COVERED (From - To) 08 September 2006 – 31 August 2009	
4. TITLE AND SUBTITLE CROSS-LAYER DESIGN IN WIRELESS COGNITIVE NETWORKS (POSTPRINT)				5a. CONTRACT NUMBER FA8650-05-D-1912-0007	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 62204F	
6. AUTHOR(S) Y.B. Reddy (Grambling State University) Clifton Bullmaster (AFRL/Ryre)				5d. PROJECT NUMBER 7622	
				5e. TASK NUMBER 11	
				5f. WORK UNIT NUMBER 7622110P	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Grambling State University Grambling, LA 71245				8. PERFORMING ORGANIZATION REPORT NUMBER	
EW Techniques Development and Analysis Branch (AFRL/Ryre) RF Sensor Technology Division Air Force Research Laboratory, Sensors Directorate Wright-Patterson Air Force Base, OH 45433-7320 Air Force Materiel Command, United States Air Force					
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory Sensors Directorate Wright-Patterson Air Force Base, OH 45433-7320 Air Force Materiel Command United States Air Force				10. SPONSORING/MONITORING AGENCY ACRONYM(S) AFRL/Ryrr	
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S) AFRL-RY-WP-TP-2010-1162	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES Conference paper published in the <i>Proceedings of the 2008 Ninth International Conference on Parallel and Distributed Computing, Applications and Technologies</i> , conference held December 01 - 04, 2008 in New Zealand. PAO Case Number: WPAFB-08-0147; Clearance Date: 12 Sep 2008. © 2008 IEEE. The U.S. Government is joint author of the work and has the right to use, modify, reproduce, release, perform, display, or disclose the work.					
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15. SUBJECT TERMS cross-layer, cognitive radio, blackboard, energy detector, spectrum utilization					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT: SAR	18. NUMBER OF PAGES 12	19a. NAME OF RESPONSIBLE PERSON (Monitor) Nivia Colon-Diaz
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include Area Code) N/A

Cross-layer Design in Wireless Cognitive Networks

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Abstract

The objective of this research is to provide appropriate cross-layer architecture for wireless cognitive networks for efficient resource allocation and improved quality of service. We proposed the blackboard model, which is known for coordinating multiple agents (cognitive nodes) in a real-time manner, receiving the current state of information from these nodes, providing conclusions basing on information received from these nodes, updating these nodes with current conclusions, and suggesting needed actions for these nodes. Each cognitive node is assumed as an agent to the blackboard. The parameter values abstracted from these cognitive nodes to blackboard are structured messages that are optimized with respective to an objective function. This paper introduces the cross-layer design of a cognitive network, the role of the blackboard architecture, and possible applications.

1. Introduction

Spectrum is a rare resource and efficient utilization of spectrum became a central theme of the research in recent years. Ideal spectrum sensing helps the cognitive radio (CR) user to make correct decisions about utilizing unused spectrum efficiently. Spectrum sensing is the detection of the primary user (PU) in the frequency band of interest and helps to assign the CR user in the absence of the PU. Various techniques are used to detect the presence of the PU. In most of the cases, the CRs use the help of energy detectors (ED) to detect the presence of the PU in the spectrum space. It is also possible that CRs may determine the geographical information (current status) of the PU. The research shows that the geographical information of the PU could be done better using collaborative communication in the cognitive radio networks [1, 2, 3]. Various spectrum sensing techniques were discussed by Kataria [4] including collaborative strategies to solve the spectrum sensing problem.

Cognitive radio is considered as spectrum sharing technology and concentrates on spectrum holes without overlapping the primary user signal. For efficient utilization of spectrum holes, the CR must sense the spectrum segments and adapt to use spectrum segments without interference with PU. The

physical layer signal structure helps for such flexible operations including power sensing and waveform sensing. The physical layer issues of wide-band CR systems was studied by Tang [5] and suggested that OFDM (orthogonal frequency division multiplexing) is the best physical layer candidate for wide-band CR systems. Further, Dietterich [6] discussed the machine learning techniques in cognitive networks and their influence for the better performance. The panel session of CROWNCOM 2006 [7] on 'Autonomic Communications and Wireless Cognitive Networks' concluded that the cross layer optimization is likely to bring the most benefits by exploring the environmental awareness and that intelligence/cognition should go first in, to produce the highest return on investment.

Cognitive radio design poses more implementation challenges since it requires the ability to sense the spectral environment and flexibility to adapt transmission parameters. The design of CR must detect the weak signals as well as very strong signals. The solution may include the adaptive notch filtering (similar to ultra wide band designs), banks of on chip radio frequency (RF) filters possibly using Micro-Electro-Mechanical Systems (MEMS) technology such as film-bulk-acoustic-resonator (FBAR), and spatial filtering RF beam-forming through adaptive antenna arrays [8]. The implementation issues in spectrum sensing for CRs are briefly discussed by Cabric [9]. The implementation challenges include a cognitive network where a primary transmitter communicates with primary receivers within the primary exclusive region. The cognitive user transmits and receives outside the guard area of the primary user. Vu [10] discussed the primary exclusive region radius where PUs can transmit safely and where the guard band size protects the primary users from cognitive users. These bounds can help in design of cognitive networks within primary exclusive regions.

To meet the demands of world customers of wireless communications, researchers proposed various models. After exploring the dependencies and interactions between layers it was understood that optimum performance and quality of service (QoS)

can be obtained by sharing of information across the layers of the protocol stack and the potentially powerful results of adaptive cross-layer design (CLD) approaches. The CLD models focus on adaptive waveform design (power, modulation, coding, and interleaving) to maintain consistent link performance across a range of channel conditions, channel traffic conditions, and MAC parameters to maintain higher throughput. The stable condition at a cognitive node may be achieved by radio adaptive behavior (e.g. transmission characteristics). Further optimum allocation of bandwidth to achieve QoS is very important.

CLD is one of the models that the concepts are similar to a software process model design. In the new CLD, all layers must be integrated and jointly optimized (eliminate layer approach) which is not practical, but sharing the knowledge between the layers is practical. Hence by keeping the layered approach and allowing the design violations to be as small as possible, one must allow the interactions between non-adjacent layers.

The cross-layer approach violates the traditional layered architecture, since it requires new interfaces, merging of adjacent layers, and sharing key variables among multiple layers. Therefore, we must select the CLD approach without modifying the current status of the traditional layered architecture. But, the CLD without solid architectural guidelines leads to spaghetti-design. Furthermore, different kinds of CLD design proposals raise different implementation concerns. In wireless communications, the first implementation concern is direct communication between layers through the creation of new interfaces for information sharing. The second concern proposes a common entity acting as a mediator between layers. The third depicts completely new abstractions.

The new wireless networks are using the standard protocol stacks (TCP/IP) to ensure interoperability. These stacks are architected and implemented in a layered manner. Recent work focused on cross-layer design of cognitive networks which is essential in future wireless communication architecture. The cross-layer is to adopt the data rate, power, and coding at the physical layer to meet the requirements of the applications for a given channel and network conditions, and share the knowledge between layers to obtain the highest possible adaptability. It is necessary to implement new and efficient algorithms to make use of multiuser diversity gain and similarly the efficient algorithms for a multi-cell case. The cross-layer design may have the following possible implementations:

- Interfaces to layers (upward, downward, and both ways): Keeping in view of architectural violations, the new interface design (upward, downward, and both ways) helps to share the information between the layers.
- Merging adjacent layers and making super layers. Interface the super layers: Merging two or more layers may not require a new interface, but it is suggested that a higher level interface for these merged layers will help to improve the performance with overheads.
- Coupling two or more layers without extra layers: This facility improves the performance without an interface. For example, design the MAC layer for uplink of wireless LAN when PHY is capable of providing multiple packet reception capability. This changes the role of MAC layer with new design, but there is no interaction with other layers. Sometimes this may hinder the overall performance.
- Tuning the parameters of each layer by looking at the performance of each layer: Joint tuning of parameters keeping some metric in mind during design time will help more than tuning individual parameters. Joint tuning is more useful in dynamic channel allocation.

Keeping in view of these design options there are various issues in the cross-layer design activity. The design issues include:

- the cross-layer (CL) proposals in the current research and suitable cost-benefit network implementation
- the roles of layers at individual node and global parameter settings of layers
- the role of cross-layer design in the future networks and will this be different in cognitive network design

CLD in cognitive networks is an interactive interface between non-adjacent nodes to increase the detection rate of the presence of the primary signal. It allows exploring flexibility in the cognitive nodes by using them to enable adaptability and controlling specific features jointly across multiple nodes. The CLD extends the traditional network topology architecture by providing communication between non-adjacent nodes. Hence the CLD design becomes an important part in relation to flexibility and adaptability of the cognitive network nodes. One of the efficient CLD architecture for cognitive networks includes the following components:

- Cross-layer manager and scheduler of nodes
- Cross-layer interface to nodes
- Cross-layer module of single node
- Inter-node (network) cross-layer module

The CLD using these components needs more care because a CLD node interacting with another CLD node might generate interference. Further, the interaction of a CLD affects not only the layers concerned, but also the other parts of the system. It may be unrelated remotely but unintended overheads may have an effect on overall performance.

2. Cognitive Networks

A cognitive infrastructure consists of intelligent management and reconfigurable elements that can progressively evolve the policies based on their past actions. The cognitive network is viewed as the topology of cognitive nodes that perceives the current network conditions, updates the current status, plan, and schedules the activities suitable to current conditions. The cognitive networks include the cognitive property at each node as well as among the network of nodes. The cognitive wireless access networks interact and respond to requests of a specific user by dynamically altering their topologies and/or operational parameters to enforce regulatory policies and optimize overall performance. Further the CLD in cognitive networks includes the cross-layer property of participating layers and network of cognitive nodes. The CLD does not have learning capabilities but keeps the current status of participating nodes and acts accordingly to increase the overall throughput.

Most of the CLD researchers concentrate on the media access control (MAC) layer, which is one of the sub-layers that make up data link layer (DLL) of OSI model. The MAC layer is responsible for moving data packets to and from one network interface card (NIC) to another across a shared channel. The MAC layer uses MAC protocols (such as Ethernets, Token Rings, Token Buses, and WANs) to ensure that signals sent from different stations across the same channel do not collide. The IEEE 802.11 standard specifies a common MAC layer that manages and maintains communications between 802.11 stations (radio network cards and access points) by coordinating access to a shared radio channel and utilizing protocols that enhance communications over a wireless medium. The goal is to design a topology that can offer maximum network-wide throughput, best user performance, and minimum interference to primary users. The 802.11 MAC layer functions include: scanning, authentication, association, wired equivalent privacy (WEP), request-to-send and clear-to-send (RTS/CTS) functions, power save mode (PSM), and fragmentation.

3. Current status

The objective of the current research is *cross-layer design in wireless cognitive networks*. Three concepts are involved, viz. network nodes must be cognitive, wireless, and use the cross-layer design concept. There are no papers in the current literature, but the

concept close to this idea was coined by David Clark [11]. Burbank [12] discussed the cross-layer design for military networks, but most of the paper was discussed the cross-layer design requirements among the application, transport, physical, and MAC layers. Thomas discussed cognitive networks and application of game theory in his dissertation [13] and results include the power gain with quality of service, but there was no discussion of cross-layer design in cognitive networks. David Clark's proposal of proposed cognitive network was "*assemble itself given high level instructions, reassemble itself as requirements change, automatically discover when something goes wrong, and automatically fix a detected problem or explain why it cannot do so.*" But cross-layer design of cognitive networks goes beyond this concept. The concept is close to the blackboard system design [14] concept for cognitive nodes.

David Clark's knowledge plane has the following components:

- Edge involvement – knowledge generated by devices and applications that use it will be brought to the plane
- Global Perspective – The problem identification depends upon the combination of data from the edges and inside network.
- Compositional structure – merging of unconnected networks to connect their activities
- Unified approach – integrated approach to develop solutions to problems
- Cognitive framework – to take decisions basing on partial or full information.

The David Clark's knowledge frame if implemented will be solving many problems including, fault diagnosis and mitigation, automatic reconfiguration, support for overlay networks, intrusion detection, and finally it is expected to support cyber security.

Keith Nolan [15] discussed the capabilities of cognitive networks of wireless communications and their potential contribution for public safety, entertainment, and military applications. The basic idea is that team of cognitive nodes working together will have the benefit of a shared pool of knowledge to solve the critical problems that appears in the networks. The overall objective of cognitive network is two or more nodes with cognitive functionality will contribute for higher throughput, quality of service, and needed network security, where an individual node may not have the capacity to form and implement an optimal (or near optimal) communications solution. The principles of cognitive radio can be applied to the network to avail of the individual knowledge, resources and individual cognitive abilities of each node in this network. Lee

[16] discussed cognitive network management using reinforcement learning for wireless mesh networks. The system reconfigures its policy strategy around areas of interest with a cross-layer approach and adapt to changes.

The above ideas from these proposed models lead to a new architecture for better network management with higher throughput, and quality of service.

4. Possible models for Cross-layer Architecture

CLD architecture is viewed at two places. First, at node level, where sharing of information is needed among the layers to adjust the capacity of individual wireless links and to support delay-constrained traffic; dynamic capacity assignment in MAC layer for optimum resource allocation among various traffic flows; and intelligent packet scheduling and error-resilient audio/video coding to optimize low latency delivery over ad-hoc wireless networks. Secondly, at the network level, where sharing of information among the nodes help to improve the QoS and efficient utilization of resources.

One of the important factors to consider for a cross-layer approach is rate control. The channel condition normally decided by rate, information communicated across the layers, and delivery mechanisms. If we implement the cross-layer design over the existing layered model, it violates the basic layer structure. Our goal is to develop an architecture that can accommodate the proposed cross-layer property without disturbing the current layered architecture. To achieve this we must preserve the modularity of existing protocol modules to the greatest extent possible, the model must facilitate multiple adaptations in a flexible and extensible manner, and the model must be portable to a variety of protocol implementations.

Most of the cross-layer work focuses on the MAC and Physical layers, but we need to focus on all five layer of TCP for wireless problems. So far there is no systematic way or general considerations for cross-layer adaptations. Our goal is to introduce cross-layer structure at the node level and inter node level.

We propose the cross-layer design among the cognitive nodes for better quality of services and high throughput. Each cognitive node contains a network cross-layer (NCL) component to connect to other participating nodes. The interaction among the cognitive nodes will be done through the NCL component. The interaction between the nodes will be selected as one of the following:

- One node to the next closest node (one-to-one one-to-many). Each node communicates to the next closest node.

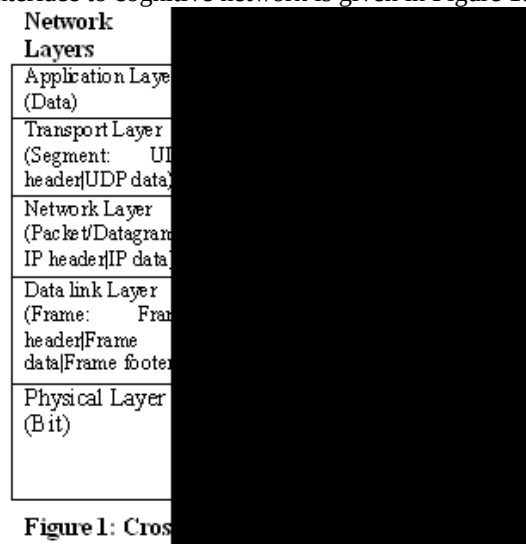
In this process each node communicates to the closest nodes whether one or many. The communication multiplies and the information will be broadcasted to all nodes. It is possible the nodes receive redundant information (more duplication possible).

- each node to all other participating nodes (one-to-many which involves a heavy load on each node)
- all nodes interact through a central node
- closest nodes form a cluster and the cluster heads use cases (a) or (b) or (c)

Each design has its own merits, but (c) and (d) has better benefits. In (c), the central node possesses the current state of all nodes and acts with the current state of information received. For example, if the primary user (licensed user) enters into the network, the central node gets updated and it takes appropriate action to move the current existing secondary channel (cognitive user) from primary channel space. In (d), the closest nodes form a cluster and one of the cluster node acts as cluster head. The cluster head keeps the current state of all nodes within the cluster and appropriate interaction with other cluster heads or creates a central node for the cluster heads and interacts with the central node. Each cluster head acts as central node to the cluster and collaborates with other cluster heads through the main central node.

5. Proposed Node level Cross-layer Architecture

The CLD starts from basic design of TCP/IP at a conventional layered architecture. The OSI model which interacts directly only with the layer immediately beneath it and provides facilities for use by the layer above it. The TCP/IP describes with four abstraction layers and five layers if we include the Physical layer. The TCP/IP model with cross-layer interface to cognitive network is given in Figure 1:



The planned or unplanned activities due to CL interface and management activities may create panic in the current TCP/IP structure. The abstraction of current state may not create panic. But if we try to modify any parameters of one or more layers due to network problems or data transfer problems, it may be a total disaster in the current network. Therefore we plan to implement CLD at the node level by introducing the following components:

- Parameter abstraction – necessary state of layer specific information that is comprehensible for cross-layer optimizer. These are called cross-layer parameters.
- Cross-layer optimization – optimization is carried out with respect to an objective function.
- Destination and respond back – once the cross-layer decides particular parameter tuple, the distributor responds back to the corresponding layers.
- CL Manager – generates needed data from node interface (successful transmission rate, channel rate, etc). This data can be used by for example – the physical layer and network layer to adjust transmission power and to find routes free of congestion and collision. This activity will not disturb the normal activity of the layered protocol. The activity further provides the current status of a node at any particular time.
- The network cross-layer interface - allows the wide adaptations by knowing the local status of other nodes. The advantage of this component is that nodes in the network will adjust their behavior according to the state of the network.

The activities of CLD include: Analyze the type of data to be maintained by interface module. Find the effects of changing the data values in one layer over other layers, which helps to adjust the parameter values as needed (in case of network CLD, the extracted data from different nodes will help the network wide view for further action to fix the transmission problems). This further helps, during the time critical operations to minimize the overheads by directing the callback to the right layer. It is also noted that at the CL network interface protocol reconfiguration will help for efficient packet transmission because it will now switching from one wireless protocol to another as needed by the end node.

6. Blackboard Architecture for Cognitive Networks

The blackboard is a centralized global data structure consisting of a set of knowledge sources called intelligent agents (cognitive nodes). These agents are self sufficient intelligent nodes that interact with the blackboard, write the necessary

information (parameters) to the blackboard and provide updates with the current state of information available from blackboard. The design allows for an opportunistic control strategy. The opportunistic control problem solving technique allows the node (knowledge source or intelligent agent) to contribute towards the solution of the current problem without knowing what other sources use this information. The opportunistic problem solving allows the blackboard control structure and scheduler to determine which knowledge sources (intelligent nodes) are active at a particular time.

The class-layer manager of each cognitive node processes, generates needed parameters, and communicates to blackboard through the network interface. The parameters include current network state information or network behavior across the composite end-to-end communications path (irregular patterns in network or intrusions, overlays, and path status), hop behavior (e. g. transmission characteristics) in a manner that attempts to counter the effects of changing channel, and bandwidth utilization.

The messages will be communicated from the cognitive nodes through a node communication language (NCL). The message must be simple and easy to parse. The NCL can be derived from extended markup language (XML), user generated macros using one of the languages (C, C++, and Java), or use quarry language (SQL). The cognitive node messages can include the node position and status, irregular patterns, transmission characteristics, status of bandwidth utilization, and similar parameters.

With this basic information we will design our blackboard that integrates various knowledge sources (cognitive nodes) around a central data structure known as the working space. The purpose will be served if we can achieve the controlling strategy and real-time performance. Figure 2 depicts the proposed blackboard architecture.

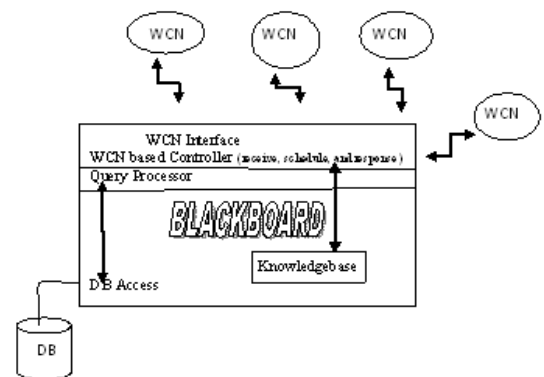


Figure 2: Blackboard Architecture

Wireless cognitive node (WCN) interface connects the cognitive nodes and blackboard. The controller receives the messages, schedules messages, and conducts appropriate actions. The controller interacts with knowledgebase and query processor to process the messages in the form of queries. The knowledgebase consists of set of production rules and inference engine to operate those rules. The workspace is part of the blackboard (not shown in the Figure 2) and stores the messages generated by the agents.

7. Cross-layer concept

The abstraction of critical parameter values from cognitive nodes plays a central role in the current cross-layer design of WCN. The optimization and decision making is part of the blackboard model. The Cross-layer concept is sharing the parameter information of cognitive nodes.

The critical parameters from different WCNs help to solve the problems including a) clearing the cognitive signal when primary signal enters in the domain, b) intrusion detection, c) network deadlocking, d) alternate path selection, e) dealing with malicious and untrustworthy components, f) and many more.

8. Conclusions

The use of blackboard for WCN is designed as multi-agent co-ordination possessing modularity, flexibility, and expressivity. The proposed blackboard approach helps to solve the problems including intrusion detection, jamming, and related network problems.

Recent work for cross-layer design uses MAC layer (normally physical and link layer for wireless communications) for adaptive waveform design (power, modulation, coding, interleaving). The researchers in recent months are extending the concept to Network-layer, Transport-layer, and application-layer. The cross-layer design in wireless cognitive networks is introduced in this paper, which is expected to solve many future network problems (e.g. cyber security).

Acknowledgment

The research work was supported by Air Force Research Laboratory/Clarkson Minority Leaders

Program through contract No: FA8650-05-D-1912. The first author wishes to express appreciation to Dr. Connie Walton, Dean, College of Arts and Sciences, Grambling State University, for her continuous support. The authors acknowledge Dr. Vasu Chakravarthy, Wright Patterson Air Force Base, Dayton, OH, for his helpful discussions.

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