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Review

Cognitive radio technology: From distributed spectrum coordination to adaptive network collaboration☆

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Abstract

This paper presents an integrated view of cognitive radio technologies for efficient wireless services in dense spectrum environments. The rationale for cognitive radio based systems is discussed, leading to an identification of the available design space that ranges from reactive interference avoidance to spectrum etiquette and eventually network collaboration. After reviewing prior work in the dynamic spectrum area, a specific distributed spectrum etiquette protocol called "common spectrum coordination channel (CSCC)" is introduced. Performance gains achieved with CSCC relative to simpler reactive time/frequency/power control algorithms are evaluated for example in WiFi/Bluetooth and WiFi/WiMax co-existence scenarios. The next level of system performance can be achieved through opportunistic collaboration between radios to form ad hoc multi-hop networks in which neighboring nodes associate with each other at high bit-rate and low power. Adaptive wireless networks of this type will require new protocol architectures which integrate flexible PHY/MAC and cross-layer capabilities with ad hoc network discovery and multi-hop routing. A specific "*CogNet*" protocol architecture based on the concept of a "global control plane (GCP)" is described. Major *CogNet* protocol modules for bootstrapping, discovery, data path setup and naming/addressing are outlined, and representative *ns*-2 simulation results are provided for validation. In conclusion, the paper gives a preview of the network-centric WiNC2R prototype under development at WINLAB as an experimental cognitive radio platform.
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Keywords: Cognitive radio; Dynamic spectrum; Spectrum etiquette protocol; Adaptive wireless network; Global control plane; *CogNet*; Software-defined radio; Experimental cognitive radio platforms

Contents

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1. Introduction

Recent "Moore's law" advances in programmable integrated circuits have created an opportunity to develop a new class of intelligent or "cognitive" radios [1–4] which can adapt to a wide variety of radio interference conditions and multiple protocol standards for collaboration between otherwise incompatible systems. Such a cognitive radio would be capable of very dynamic physical layer adaptation via scanning of available spectrum, selection from a wide range of operating frequencies (possibly non-contiguous), rapid adjustment of modulation waveforms and adaptive power control. In addition, a suitably designed cognitive radio with a software-defined physical layer would be capable of collaborating with neighboring radios to ameliorate interference using higher-layer protocols. These higher-layer coordination protocols could range from multi-node signal combining and coding methods to etiquette mechanisms all the way to fully collaborative multi-hop forwarding between radio nodes. Thus, suitably designed cognitive radios have the potential for creating a next-generation *adaptive wireless network*, [5] in which a single universal radio device is capable of operating in a variety of spectrum allocation and interference conditions by selecting appropriate physical and network layer parameters often in collaboration with other radios operating in the same region. Such a "cognitive network" will lead to increased network capacity and user performance. Perhaps for the first time in the short history of networking, cognitive radios offer the potential for organic formation of infrastructure-less collaborative network clusters with dynamic adaptation at every layer of the protocol stack including physical, link and network layers [6,7].

While the development of cognitive radio hardware and software, especially at the physical layer, has received considerable attention, the question of how one transforms a set of cognitive radios into a cognitive network is much less well understood, and there is a lack of research on protocols for cognitive radio *networks* in the community. As such, *adaptive networks* of cognitive radios represent an important but demanding research challenge for both the wireless and networking communities. The extreme flexibility of cognitive radios has significant implications for the design of network algorithms and protocols at both local/access network and global internetworking levels. In particular, support for cross-layer algorithms which adapt to changes in physical link quality, radio interference, radio node density, network topology or traffic demand may be expected to require an advanced control and management framework with support for cross-layer information and inter-node collaboration. At the wireless local-area network level, an important technical challenge is that of distributing and managing this inter-node and cross-layer information than using this control information to design stable adaptive networking algorithms that are not overly complex. At the global internetworking level, clusters of cognitive radios represent a new category of access network that needs to be interfaced efficiently with the wired network infrastructure both in terms of control and data. End-to-end architecture issues of importance include naming and addressing consistent with the needs of self-organizing network clusters, as well as the definition of sufficiently aggregated control and management interfaces between cognitive radio networks and the global Internet [8].

This paper presents an integrated view of cognitive radio technology as it evolves from autonomous interference avoidance methods to explicit spectrum etiquette protocols and eventually to adaptive wireless networks of collaborating radios. We start with a discussion of the rationale for cognitive radios, leading to an identification of the available design space defined in terms of hardware capabilities and protocol complexity. Different levels of spectrum coordination methods will be introduced, ranging from autonomous *reactive* control [9] of radio parameters (time/frequency/power) to more complex *proactive* coordination schemes [10] based on explicit spectrum etiquette protocols, which define rules or "etiquettes" for how to utilize and share spectrum resources between wireless devices by allowing them to exchange appropriate messages and parameters. The protocol called "common spectrum coordination channel (CSCC)" [11] is proposed as a specific spectrum etiquette solution, and is evaluated using example WiFi/Bluetooth and WiFi/WiMax co-existence scenarios. The next step up from spectrum etiquette is the concept of collaborative networks of cognitive radios, an approach which may be expected to provide significant performance gains in dense usage scenarios. In a collaborative adaptive wireless network, radio nodes avoid interference at the PHY and MAC layers by opportunistically forming or joining an ad hoc network which carries data packets (at relatively high speed and low power) over multiple radio hops. A specific protocol architecture ("*CogNet*") [12] based on the concept of a cleanly separated "global control plane (GCP)" [13] is introduced as a candidate architecture for these adaptive wireless networks. The GCP supports spectrum coordination, PHY/MAC adaptation, ad hoc network discovery and cross-layer routing requirements which arise in a general adaptive wireless network scenario. This paper will provide design and validation results for a baseline *CogNet* protocol design that includes node bootstrapping, discovery, addressing and routing.

Another aspect of importance for the development of cognitive radio networks is the platform technology in terms of both hardware and software. A number of cognitive radio platform development projects are under way in the research community, including the Vanu SDR [14], WARP [15], KU Radio [16], WiNC2R [17] and GNU USRP [18] boards. The WINLAB network-centric cognitive radio (WiNC2R) architecture is aimed at providing a high-performance platform for experimentation with various adaptive wireless network protocols ranging from simple etiquettes to more complex ad hoc collaboration. The WiNC2R board is differentiated from other cognitive radio projects in the sense that the design uses hardware accelerators to achieve programmability and high performance at each layer of the protocol stack. We will present the results of prototype development in progress to give an idea of representative hardware architecture and implementation issues that arise in this emerging field.

The following sections provide more detail on each of the topics outlined above. Section 2 discusses the spectrum coordination problem and alternative reactive and proactive etiquette protocol based solutions. Section 3 describes a specific *CogNet* protocol architecture for cognitive radio networks along with some validation results. Finally, the WiNC2R hardware platform under development is briefly outlined in Section 4. Concluding remarks and future work are given in Section 5.

2. Spectrum coordination for cognitive radios

2.1. Cognitive radio design space

One of the important goals of designing cognitive radio is to improve the spectrum sharing efficiency. Notable approaches for spectrum sharing have been discussed in the technical and regulatory communities, including property rights regimes [19–22], spectrum clearinghouse [23], unlicensed bands with simple spectrum etiquette [24,25], open access [26–29] and cognitive radio. The cognitive radio principles currently under consideration by the FCC and the research community span a fairly wide range of possible functionalities both at physical and network layers. Fig. 1 outlines a number of possible coordination schemes for cognitive radios in terms of their hardware and software complexities.

The "agile wideband radio" scheme shown [30] at the lower right side of Fig. 1 is the most prevalent concept for cognitive radio in which transmitters scan the channel and autonomously choose their frequency band and modulation waveform to meet interference minimization criteria without any protocol-level coordination with neighboring radio nodes. We observe here that although autonomous adaptation of the radio PHY is the simplest method and requires no coordination standards, it suffers from serious limitations due to "hidden node" problems [10,31] that arise in such

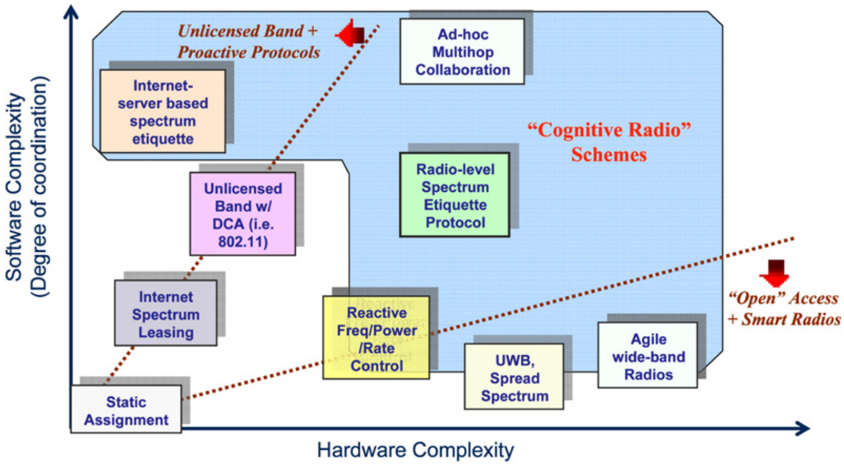


Fig. 1. Cognitive radio design space.

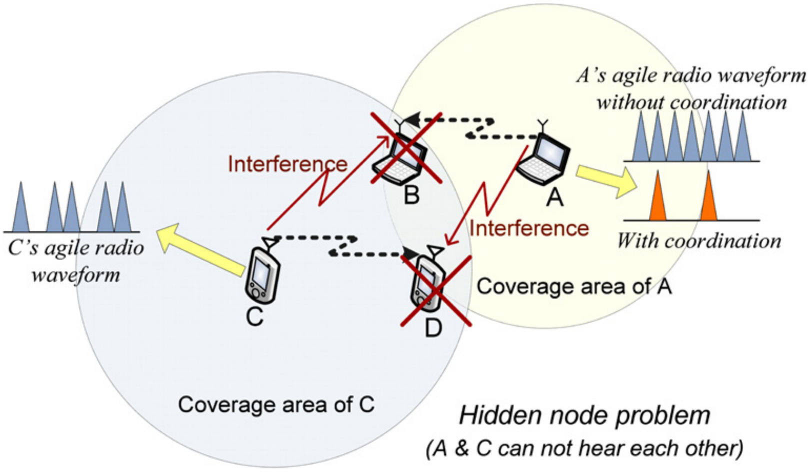


Fig. 2. Illustration of the hidden node problem with agile radios, with and without a coordination protocol.

scenarios illustrated in Fig. 2. When transmission pairs AB and CD are sharing the same spectrum band, the receiver B will suffer from transmitter C's interference (similarly D suffers from A's interference) because of the fact that interference is a receiver property while spectrum scanning alone only provides information about transmitters. That is, node A or C cannot detect the existence of silent node D or B only by performing local channel scanning. Fig. 2 also indicates the fact that this can be overcome by a small amount of explicit protocol-level coordination (which will be discussed in detail in Section 2.4) in which control information is exchanged between transmitters and receivers (if A is explicitly notified the transmission patterns of CD, it can adjust its own waveform to avoid interfering with D).

Another simple technique is "reactive control" of transmit rate/power [9], in which radio nodes do not have any explicit coordination with neighbors but seek equilibrium resource allocation using reactive algorithms to control rate and power, analogous to the way the TCP protocol reactively adjusts source bit-rate over the Internet. At a slightly higher level of protocol complexity in the design space of Fig. 1, it is possible to use proactive schemes such as spectrum etiquette protocols [11] to improve coordination between radio nodes, using either Internet-based spectrum services or a common spectrum coordination channel at the edge of the shared frequency band for distributed coordination. Note that the etiquette approach requires some protocol coordination ability including the use of a common physical layer for coordination, but may not require full-fledged agile radio capabilities with programmable waveforms. At the next level of complexity in Fig. 1 is "ad hoc multi-hop collaboration" which involves a high degree of adaptation at both physical and network layers. In this scheme, radio nodes in a dense environment recognize the mutual value of collaboration and set up an ad hoc network via bootstrapping of a control PHY between adjacent nodes along with appropriate collaborative MAC and network layer protocols that form an adaptive wireless network (vs. just an adaptive radio link) [5,13]. In what follows in this section, we will first review prior work, then focus on introducing reactive and proactive spectrum coordination schemes and further cognitive radio networking protocols in Section 3.

2.2. Prior work on dynamic spectrum

The topic of dynamic spectrum has become an active field during this decade, evidenced by the emergence of specialized conferences such as IEEE DySpan [32] and special issues of journals [33,34]. Many of the early contributions deal with spectrum sensing methods, dynamic spectrum sharing protocols, resource allocation algorithms and spectrum policy issues. Spectrum sensing methods proposed include fast spectrum scanning algorithms [35,36] or interference temperature measurement [37,38]. A number of papers [39–42] examine the scenario with "primary" and "secondary" spectrum users in which frequency agile radios try to dynamically detect "spectrum holes" of primary (or incumbent) spectrum users and opportunistically utilize them in frequency and time. For example, in [43], a dynamic sharing model is proposed with spectrum resource management and policy enforcement algorithms based on measurement of channel busy time for primary spectrum users, with secondary spectrum users fitting into estimated time gaps of each channel. In [44,45], a "spectrum broker" approach is used to share spectrum dynamically in cellular applications. The spectrum broker controls access to a shared frequency band by executing algorithms for globally efficient spectrum utilization based on observed demand. A number of recent results have also been reported on dynamic MAC protocols, e.g. [46–50], which improve spectrum efficiency in the multi-channel access case. Typically, these studies assume an 802.11-like system with a uniform MAC protocol and channelized spectrum (as in [46]), and involve moving MAC control messages to a dedicated control channel separated from the channels used for data transmission. In [51], a "multiMAC" framework is proposed as an integrated approach for dynamically switching between different MAC protocols such as TDMA, Aloha, and 802.11 in response to observed channel conditions and traffic requirements.

In terms of resource allocation algorithms, a variety of analytical frameworks for optimization and control have been applied to the dynamic spectrum problem. Game theoretic models are used in [52–54] for adaptive channel allocation and spectrum resource sharing, where spectrum users are modeled as game players and their strategies determine how to select available channels. In [55], both cooperative and non-cooperative (selfish) scenarios are considered and players try to maximize utility functions related to the received power and interference to other users. Intelligent power allocation strategies are considered in [56] using a game theoretic model. Variable rate link scheduling by a spectrum server is studied in [57] and related pricing and spectrum allocation algorithms are proposed in [58]. There are also other policy related research results, including spectrum regulatory policies for cognitive radio [59] and the economics of collaboration in the spectrum commons [60]. An underlay approach is proposed in [61] to utilize the newly opened VHF/UHF TV frequency band for wireless regional networks, such as IEEE 802.22 [62]. New market and spectrum management concepts enabled by cognitive radio are discussed in [63].

Based on the above discussions, it is clear that significant progress has been reported on several key components of cognitive radio technology, most notably in spectrum policy and related resource allocation algorithms. Much work remains on the technology aspects, both in terms of widely accepted protocol standards needed to enable cognitive radio networks and also in the development of flexible, cost-effective cognitive radio hardware platforms. In the rest of this paper, we draw from our recent work [9,11,13] to present an integrated systems view of spectrum coordination algorithms, protocol software and hardware platforms needed to enable networking of cognitive radios in the future.

2.3. Reactive spectrum coordination methods

Reactive spectrum coordination methods do not require modifications to existing radio hardware or the use of a coordination protocol between nodes. Such schemes are "reactive" in the sense that radio nodes react to observed physical layer parameters and adapt to different interference scenarios by tuning transmission parameters, such as operating frequency, transmit power, packet time scheduling, modulation and coding schemes (for rate control), etc. They are simple to design and implement but there are limitations due to the fact that each radio's adaptation is only based on a local observation of the network interference conditions.

In the scenario shown in Fig. 3, reactive schemes are deployed for spectrum sharing between generic OFDM radios which may use different wireless technologies. Nodes AB and CD have basic capability to tune their radio parameters such as operating frequencies (channels), transmit powers, PHY rates and packet transmission time. As discussed in

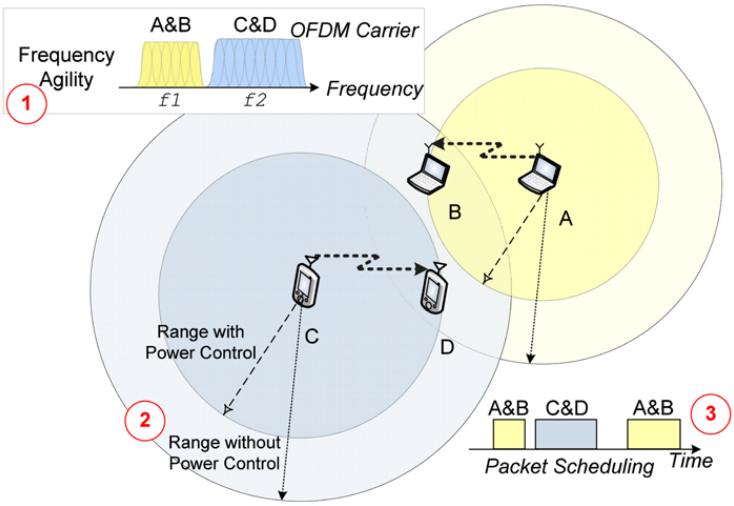


Fig. 3. Reactive spectrum coordination methods.

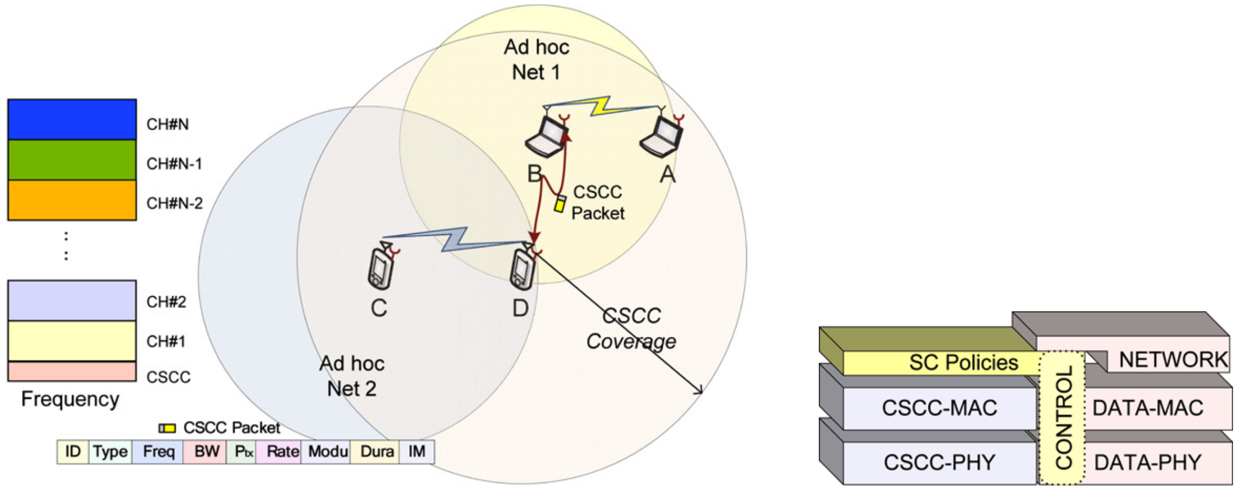
our previous work [9], radio nodes can use reactive methods to explore and fill the gaps in resource dimensions of frequency, space/power or time by scanning each channel and sensing the interference power. Each reactive scheme controlling different resource dimension is identified by (1)–(3) in Fig. 3.

(1) *Dynamic frequency selection (DFS)*: The DFS scheme is based on periodic channel scanning and interference measurement. Each node thus has an estimation of the interference power level at each available channel. When data communication is initiated, the sender will choose the channel with the least interference power to transmit. However, this scheme requires each node to stay in a default channel when it is idle, where sender and receiver can switch to other channels for data transmission. In Fig. 3, node pair AB and CD can choose different frequencies for their OFDM carriers to avoid interference. The drawbacks of this scheme are also obvious: there may be chances that the link is broken due to unsynchronized channel switching; and the hidden node problem where a transmitter may choose a channel which potentially interferes with a receiver nearby due to the inability of detecting such a hidden node. For example, when node B is receiving from A, it may suffer from interference from C because node C cannot sense the existence of node B by only comparing signal strengths and scanning over each channels. Thus more complex coordination schemes are required which will be introduced in Section 2.4.

(2) *Reactive transmit power control (RTPC):* In cases when no vacant frequencies are available, radio nodes can explore the dimension of space by reactively controlling their transmit powers to increase spatial spectrum reuse. The basic idea is that the receiver can estimate the minimum required transmit power to be used by the transmitter for correct packet reception in a packet-by-packet basis, knowing the current interference level at the receiver. As illustrated in Fig. 3, both AB and CD can transmit in parallel at the same frequency band by mutually reducing their transmit powers and thus reducing interference to each other. However nodes using this scheme may be interfered by uncoordinated transmitters because the packet reception is more vulnerable to interference due to reduced signal strength. Hidden node problem still exists in this case when there are uncoordinated receivers in a transmitter's minimum coverage area.

(3) *Time agility (TA):* Another simple technique is reactive control of transmit time by changing transmit probabilities based on interference conditions. As discussed in [9], transmit probability should be reduced when interference level is high to avoid more congested situations in using the spectrum. Otherwise more transmission should be encouraged when interference power is low and channel conditions are good. This kind of adaptation is still based on local channel observation, thus there may be oscillations when nodes control their transmission behaviors based on locally sensing signal strength and interference.

Reactive controls of radio parameters at transmitters are mostly based on local channel scanning, interference sensing and power estimation, thus they also suffer from "hidden node" problems as discussed in Section 2.1, due to the lack of information at receivers who suffer from interference. Transmission parameter adjustment is a reaction of experienced interference changes, which may lead to stability problems. For example, nodes may uncoordinatedly vacate from a congested channel to another same channel which results in congestion in the new channel; Increasing



(a) CSCC etiquette protocol.

(b) CSCC protocol stack.

Fig. 4. Concept of CSCC for proactive spectrum coordination.

transmit power (or transmit opportunities) unilaterally may also deteriorate the interference problems. Therefore, explicit (or proactive) spectrum coordination protocols are needed which will be discussed in the next section.

2.4. *Proactive schemes based on spectrum etiquette protocols*

In contrast to "reactive" (which is passive), "proactive" scheme means nodes can actively coordinate their spectrum usages by following common rules (or etiquettes) and explicitly exchanging information through a common protocol. This kind of "common protocols" (such as CSCC) provides a framework and message exchanging mechanism by which different proactive spectrum coordination algorithms or policies can be executed. Fig. 4 shows the "common spectrum coordination channel (CSCC)" approach [10,11] as a candidate mechanism for implementing such policies. The CSCC protocol utilizes a narrow-band control channel shared by all users intended for spectrum coordination purposes. Each device has a second narrow-band (low bit-rate) radio[1] for exchange of control information over the control channel. When different devices need to use spectrum, the CSCC method requires all users to periodically broadcast spectrum usage information (shown in Fig. 4(a), including: user ID, frequency band used and transmit power as well as optional parameters such as technology type, service type, interference margin, multi-hop forwarding capabilities if any, user priority, etc.) using a simple standardized packet transmission protocol in the pre-defined control channel at the edge of the unlicensed band (both data channels and control channel are shown in Fig. 4(a)). Observation of these announcements permits newly active users to obtain a map of spectrum activity and select available frequencies, if any. In the event that there is contention for spectrum resource request, spectrum etiquette policies can be executed which compose of spectrum coordination algorithms and rules for assigning frequency, power, time etc. among different users, resulting in distributed sharing of radio resources in the congested region.

For example, in the network of Fig. 4(a), devices (AB and CD) with different technologies form into different networks. Similar to Fig. 2, when B transmits to A and C transmits to D, node D is a "hidden node" interfered by B, which cannot detect the existence of node D. This problem can be solved when we apply proactive spectrum coordination schemes using CSCC protocol, where all nodes exchange messages at the CSCC channel and execute etiquette policies to coordinate their spectrum usage. As shown in Fig. 4(a), node D periodically reports its receiving behavior which is heard by node B at the control channel. This is mainly because the control radio using a low-rate PHY usually has a wider coverage than the data radio, which helps to detect the hidden nodes within multiple hops of data radio coverage and a larger area of network can be coordinated. Node B thus can execute certain policies to either explore new unused frequencies or reduce transmit power. Note that the CSCC protocol mechanism is

[1] Note that the control radio for the CSCC may also be implemented as a "virtual link" on a single software-defined radio (SDR) that switches between control and data modes.

independent of the spectrum coordination policy itself, which can be implemented to reflect regional or application-specific requirements. This is further explained in Fig. 4(b) which shows that a separate CSCC control stack consisting of CSCC PHY and MAC operates in parallel with the data service. The spectrum coordination (SC) policy runs on top of the CSCC protocol stack and can be specified in a completely general way as long as necessary parameters are carried by the CSCC packet. The CSCC-MAC utilizes simple CSMA MAC and packet contention can be resolved by periodic repetition with some randomization of transmit time to avoid multiple collisions.

Proactive schemes not only solve the hidden node problem [10,31] in heterogeneous wireless networks, they can also quantify the radio parameter adjustments, which are passively controlled by the reactive schemes. Two proactive coordination algorithms are proposed in [10] where nodes can quantitatively adapt their frequency and power by exchanging interference, power and SINR information using the CSCC protocol. The frequency adaptation algorithm makes sure different transmissions switch to non-overlapping frequencies, and the power adaptation algorithm allows transmitters to calculate the exact upper bound of their transmit power to avoid interfering with the in-range receivers, which report their tolerable interference margins [10]. In Section 2.6, both schemes will be compared with co-existing WiFi and WiMax networks.

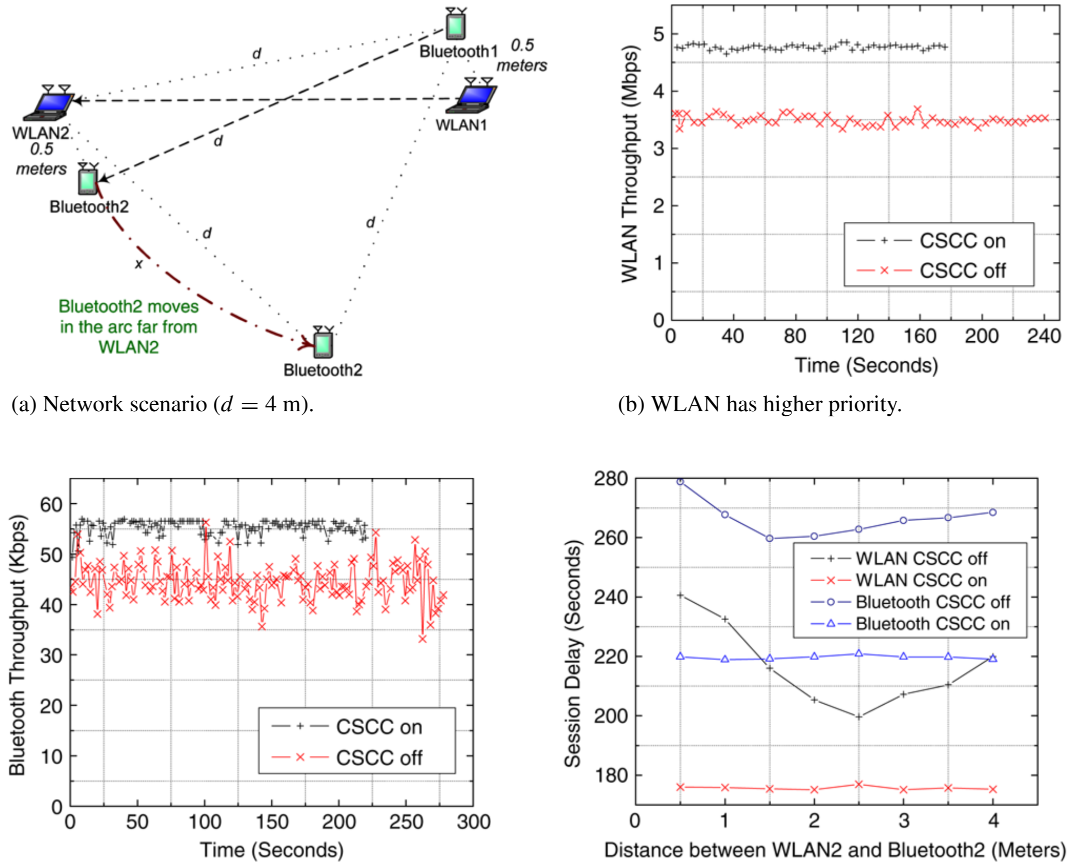
2.5. Validation of CSCC in a WiFi/Bluetooth scenario

We first evaluate the CSCC protocol applied to an IEEE 802.11b and Bluetooth (BT) co-existence scenario in the 2.4 GHz band [11], with a simple priority-based etiquette policy (low priority nodes back off to high priority ones). Two pairs of incompatible radio devices are placed in an indoor environment shown in Fig. 5(a) in which Bluetooth1 and WLAN1 are senders and Bluetooth2 and WLAN2 are receivers. All the nodes are equipped with dual mode radios running the CSCC protocol, using a Cisco Aironet 350 series 802.11b radio at 1 Mbps tuned at a different channel from the WLAN data card, which uses 802.11b 11 Mbps radio. The Bluetooth devices use Ericsson radios (up to 1 Mbps) which hop over the whole ISM frequency band. A number of experiments were conducted to study the benefit of a priority-based ON/OFF etiquette policy for TCP file transfers. The WLAN nodes transfer a file of 100 Mbytes by TCP and BT nodes transfer a file of 1.5 Mbytes.

When the CSCC protocol is used, WLAN and BT devices resolve contentions by using the priority etiquette which has the effect of sequencing the WLAN and Bluetooth transmissions in time, thus avoiding continuous interference associated with a lack of coordination. Two separate experiments were conducted in which either WLAN or Bluetooth has higher priority in using the spectrum. It is observed that when WLAN users are given higher priority, shown in Fig. 5(b), their throughputs can improve ∼35%, and if BT users have priority as in Fig. 5(c), the throughput improvement is ∼30%. It is also noted that without CSCC, BT devices cause periodic interference to WLAN, thus tending to close and open the TCP window repeatedly. To evaluate the total data session delay with and without CSCC etiquette, BT2 was moved away from WLAN2 as outlined in Fig. 5(a). WLAN session delays are reduced by 12%–30% depending on distance, and BT session delays are reduced by 15%–22% as shown in Fig. 5(d). It is interesting to observe that as we move BT2 far from WLAN2 in an arc (while keeping the distance between BT1 and BT2 constant), the session delays for both WLAN and Bluetooth first decrease and then increase without CSCC. This is because BT2 is moving further from WLAN2 but nearer to WLAN1. So their interference first decreases and then increases. When CSCC is turned on, the session delay is almost constant since the two kinds of devices obtain spectrum resources in turn and there is no interference. Overall, these experimental results show the effectiveness of the CSCC approach in the simple scenarios considered, with even larger performance gains anticipated for more complex dense multi-radio environments.

2.6. Comparison of reactive and proactive schemes

To further study both reactive and proactive spectrum coordination algorithms, a co-existing WiFi and WiMax network sharing the 2.4 GHz band is simulated [10,31]. Without any explicit coordination, simple reactive interference avoidance methods introduced in Section 2.3 may be used. Proactive spectrum coordination algorithms using the CSCC etiquette protocol described in Section 2.4 are compared with reactive ones. Specifically, two proactive algorithms [10] discussed in Section 2.4 were studied: one is to adapt in frequency to set up data sessions at different channels, and the other one is to adapt in power to allow parallel transmissions by quantitatively limiting transmit power when there is no vacant spectrum available.



(a) Network scenario ($d = 4$ m).

(b) WLAN has higher priority.

(c) Bluetooth has higher priority.

(d) Average session delay vs. distance parameter.

Fig. 5. Validation of CSCC in a co-existing WiFi/Bluetooth scenario.

A system scenario with co-existing WiFi hotspots in a WiMax cell was simulated in the *ns*-2 simulator [64]. In the typical network scenarios studied, WiMax provides wireless backhaul access which covers a wide area with range of ∼3 km and WiFi hotspots are deployed inside the WiMax cell as wireless local-area networks. In the scenario, WiMax Subscriber Stations (SS) may be clustered with WiFi hotspots in areas with high population. Thus the wide area radio receivers may become hidden when they are close to short range WiFi transmitters. In this case, the CSCC etiquette protocol will help to identify receivers rather than transmitters by explicitly coordinating their spectrum usage.

The WiFi radio uses DSSS with 22 MHz bandwidth, and there are 11 overlapping channels centered from 2412 to 2462 MHz. OFDM is used in IEEE 802.16a radios with 20 MHz bandwidth, and in this study we assume there are three non-overlapping channels centered at 2412, 2432 and 2452 MHz. To simplify the simulation, bandwidth and rate are fixed for both systems, and QPSK modulation is used with 2 Mbps data rate for 802.11b and 14 Mbps for 802.16a radios. We also assume that the CSCC channel is allocated at the left edge of the whole spectrum and is orthogonal to other data channels. Pareto ON/OFF traffic model is applied to both systems where during the on period, CBR traffic is carried using UDP packets.

The network scenario is shown in Fig. 6(a) where the 802.16 Subscriber Stations can be uniformly distributed in region (i) or clustered in region (ii) with 802.11b hotspots. The clustering index C_i is defined as the ratio between the 802.11b hotspot size and the 802.16 SS cluster size ($C_i = R_{11}/R_{16}$), which is an indication of how closely the two systems couple in space and the larger the index, the higher the interference. Fig. 6(b) compares the average system throughput (including WiFi, WiMax uplink and downlink) by using reactive DFS or CSCC with frequency adaptation. Both schemes have a throughput gain of 15%–150% depending on the network topology used because in this case there is only one WiMax cell and both systems can always avoid interference by finding vacant frequencies to adapt to. Fig. 6(c) shows the case when there is no vacant spectrum available and only CSCC power adaptation is used, the

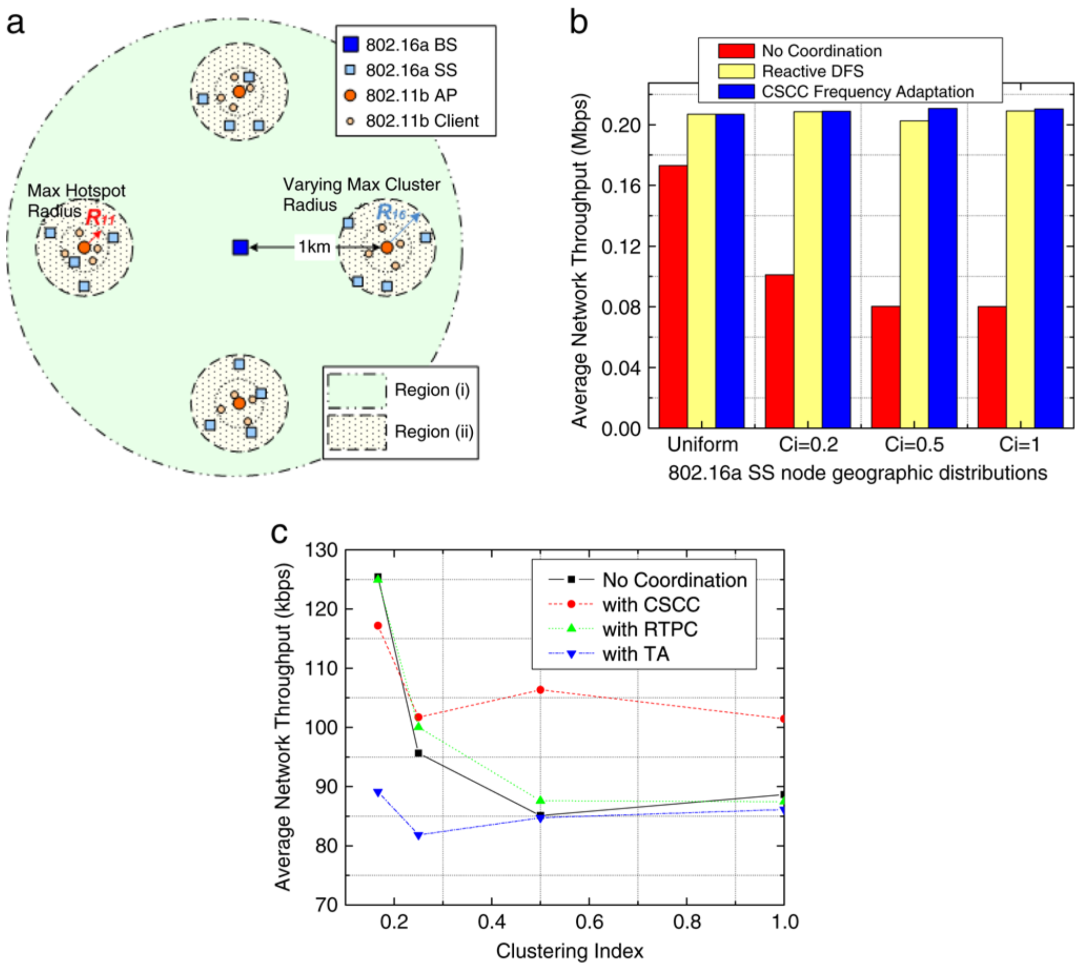


Fig. 6. Simulation results of reactive and proactive spectrum coordination schemes in a co-existing WiFi and WiMax network. (a) Network scenario (b) Throughput for uniformly- and clustering-distributed 802.16a SS with adaptation in frequency, when $R_{\max 11} = 50$ m and Pareto traffic with ON/OFF time = 500 ms/500 ms and traffic load 1 Mbps. (c) Throughputs for power adaptation with clustering-distributed 802.16a SS in region (ii), with Pareto traffic ON/OFF time = 500 ms/500 ms.

CSCC etiquette protocol can help improve the average network throughput by about 20% when the clustering index is large (strong interference scenario), but reactive schemes do not help due to hidden node problems.

3. Cognitive radio networks

3.1. *Architectural considerations*

As discussed earlier, collaborative networks of cognitive radios have the potential of achieving significantly higher performance relative to the reactive or proactive spectrum etiquette protocol approaches discussed in Section 2. In particular, such networks reduce spectral interference by encouraging high-speed/low-power transmissions to nearby radio nodes, with collaborative multi-hop forwarding of packets to their desired destination.

Cognitive radio networks have a number of new and interesting capabilities:

- Spectrum agility and fast spectrum scanning over multiple frequency bands, providing local awareness of radio interference and the ability to change frequency bands on a per-packet basis
- Fast PHY adaptation, or the ability to change physical layer waveforms on a per-packet basis and PHY collaboration modes such as network coding
- Spectrum etiquette protocol and dynamic spectrum policy implementation on a per-session basis
- Fully programmable MAC layer, with the option of dynamic adaptation to meet service needs

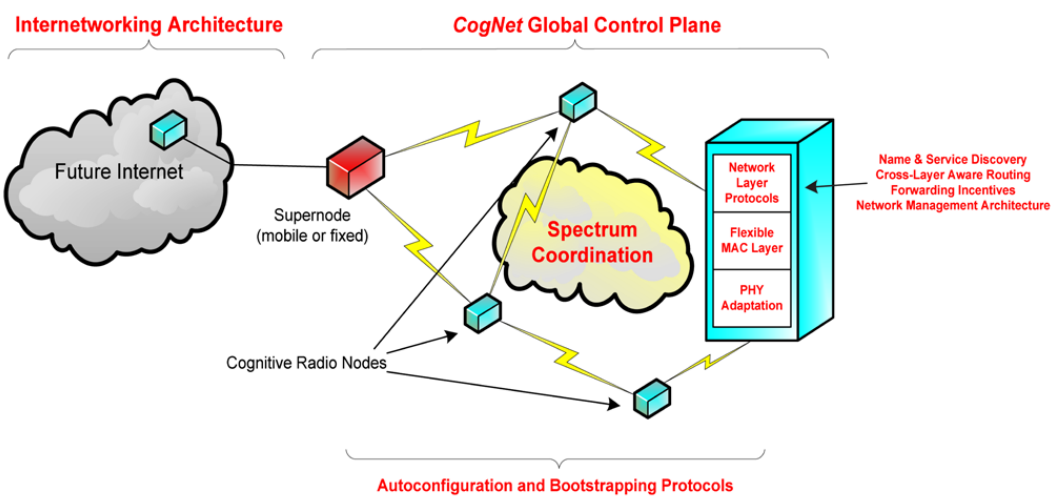


Fig. 7. Overview of cognitive radio protocol architecture and its integration with the future Internet.

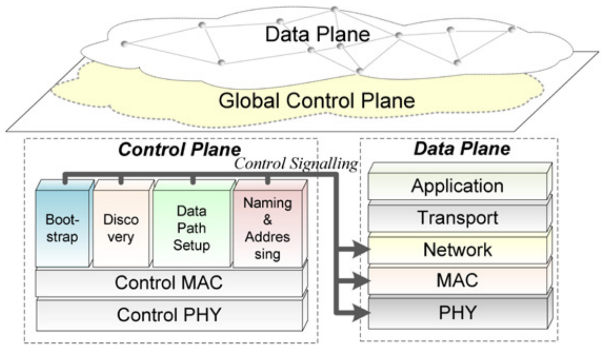


Fig. 8. Global control architecture for cognitive radio networks.

- Cross-layer protocol implementation capabilities based on integrated PHY, MAC, network algorithms
- Ad hoc cluster formation, involving multi-hop packet forwarding among peer groups of radio nodes

Adaptive wireless networks of cognitive radios will require a general protocol framework with control and management support for cross-layer collaboration between radio nodes (see Fig. 7) [12]. For example, collaborative PHY mechanisms such as network coding require control mechanisms to identify participating nodes, specify path diversity routes and eventually indicate (or download) applicable forward error correction algorithms. Similarly, for flexibility at the MAC layer, the control protocol should be able to distribute status necessary to infer current network topology and congestion conditions, together with the ability to coordinate changes in MAC functionality between a selected group of radio nodes. At the network layer, radio nodes should be able to organize into voluntary ad hoc network clusters that agree to forward packets between themselves — this requires control protocol support for neighbor discovery, address assignment and routing table exchange. Cross-layer adaptation algorithms also require exchange of PHY and MAC level status information between nodes which participate in an ad hoc network cluster.

In view of the complexity and range of control and management functions required, it is becoming increasingly clear that we should partition the protocol functionality of the cognitive network in an explicitly-defined control plane and a data plane. The protocol architecture [13] is shown in Fig. 8 which allows individual cognitive radio nodes to organize into adaptive wireless networks by providing a protocol framework with control and management support for cross-layer collaboration between radio nodes.

Global Control Plane: The global control architecture allows cognitive radio nodes to initialize and dynamically adapt their PHY, MAC and network level parameters. The control plane is made up of several key components: bootstrapping, discovery, cross-layer routing and naming/addressing. The radio bootstrapping function allows for detecting local links and configuring PHY/MAC parameters when cognitive radio nodes first boot up. After initialization, nodes execute a discovery protocol based on periodic reporting of local link states of neighboring nodes using a controlled one-hop broadcast mechanism. The discovery protocol also interacts with cross-layer routing module that provides end-to-end reachability and path information across multiple hops, which are dynamically configured with cross-layer parameters including frequency, power, rate, etc. The fourth key component is the support for distributed naming and addressing by which network nodes map their permanent "names" to dynamically assigned network addresses which may change with network structure and mobility. To implement the GCP, we extend the concept of CSCC protocol [11] to serve as the control plane for cognitive radio nodes by utilizing a low-cost control radio (e.g. 802.11b or similar) operating at the edge of the shared spectrum band.

Data Plane: The data plane protocol stack on each node contains modules needed to support data communication between the wireless nodes and it exposes a set of controls for each module which interact with the control plane through APIs to monitor, configure and adapt the data plane modules. The data plane has an agile physical layer which can sense spectrum opportunities, report to GCP and rapidly move to newly available bands. The flexible MAC layer supports for switching between different media access mechanisms to achieve the best performance under different network topology and traffic conditions, e.g., in a sparse network, CSMA-based MAC may be appropriate, while in a dense network, it is preferable to use a TDMA-like MAC for scheduling to avoid excessive channel contention. The GCP provides a generic framework to exchange control information to implement these and other network adaptation functions. The separation of control and data planes gives the flexibility to optimize each function so that the data plane can use a "pipe-like" design to fully utilize radio resources and minimize protocol overheads. The multi-hop "data pipe" from end-to-end source and destination can be established and configured by the control planes of nodes along the "pipe" (data path), where all the control signaling for setting up the pipe is carried through the GCP and data planes just focus on transmit/forward data packets along the pipe (path). The control plane generally uses a low-rate radio PHY with wider coverage than the data signal, and can thus be used to efficiently distribute control information with fewer hops than that would be required during data transfer. The data plane parameters can be optimized for end-to-end performance by setting up frequency, power, bandwidth, rate, etc. at each data forwarding hop to improve spectrum efficiency.

3.2. *Control protocols*

The protocols for control plane operation are introduced in this section, including a bootstrapping protocol, a discovery protocol, a data path setup protocol and a naming/addressing scheme.

3.2.1. *The bootstrapping protocol*

The bootstrapping protocol is aimed for cognitive radio nodes to obtain basic PHY/MAC parameters, local reachability, link states and network service information when they first boot up or move to a network area. In the network of Fig. 9, existing nodes periodically broadcast up-to-date *bootstrapping beacons* (*BSB*) on a specific control channel. When a new node boots up or moves nearby, it will first listen on the predefined control channel using default control plane radio configuration to collect bootstrapping beacons for a random period of time. The bootstrapping beacon can be implemented as a low layer (PHY or MAC) broadcast within only one hop, shown in Fig. 10. The beacon transmit power (quantized using 16 bits from 0 to 50 dBm) is useful for beacon receivers to derive link quality between two nodes. MAC profile includes MAC type and MAC busy indicator, which indicates how busy the sender's data plane MAC is by periodical measurement of data MAC busy time per interval. This quantity is a good estimate of the sender's forwarding ability. A "flags" field usually has control and service information, e.g., "NA" bit indicates naming/addressing service. The collision of beacon messages is resolved by the control plane MAC, e.g. CSMA if 802.11 is used.

From the collected beacons, a local link state table is built up with *link state vectors (LSV)* for each direct wireless link. Each *LSV* is a tuple of destination node ID, link (or end-to-end path) weight, next-hop ID and hop count, e.g., $\langle DestID_k, w_{jk}, NextHopID_k, HopCount_{jk}\rangle$ for node j describing the link from node j to k. The link weight is a performance metric assigned to direct links and end-to-end path weight is a metric of paths involving multi-hop relays. Direct link weight estimates the maximum achievable PHY bit-rate between two nodes by mapping estimated data signal-to-noise ratio (SNR) to physical transmission rate. Node i can estimate the path loss and thus SNR for data packets from a beacon of node j by:

$$SNR_{ij} = \frac{Pt_{\max i} \cdot \Pr_{ji}^{(B)}}{Pt_{ji}^{(B)} \cdot N_0}. \tag{1}$$

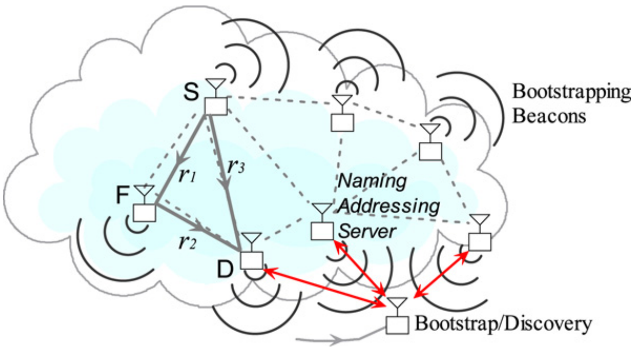


Fig. 9. The bootstrapping protocol.

1	8	16	24 (–32)
MSG Type	Flags	Sequence Number	
Source...			
...Identifier		Max PHY Rate	
Max Transmit Power		Beacon Transmit Power	
Num of Reach	MAC Type	MAC Busy Indicator	

	8		10		12		14	(–16)
Flags:	NA	CF	FD	0	0	0	0	0

Fig. 10. Bootstrapping beacon format.

$Pt_{\max i}$ is the maximum data transmit power of node i, $Pr_{ji}^{(B)}$ and $Pt_{ji}^{(B)}$ are respectively the received and transmit power of the beacon message, and N_0 is the noise power experienced at the data plane (estimated using 20 MHz bandwidth). Here we assume that the path loss between nodes i and j is the same as that of nodes j and i. Note if the data channel is close to the control channel, the path loss estimated by beacon messages is a good estimate for the data channel. Otherwise the path loss estimation is different (e.g., about 8 dB more from 2 to 5 GHz by the Friis model), but this estimation can still be used to evaluate the quality of a link. Note that at the time of estimation there may not be a data transmission so the frequency to be used by data plane is not determined, and thus interference is not counted either in (1). By orthogonal channel allocation, the interference can be minimized or eliminated. The achievable physical bit-rate for data transmission can be estimated by the SNR to rate mapping function f_{map} known to the node's data plane. The maximum achievable link rate $R_{\max ij}$ can be obtained by:

$$R_{\max ij} = \min\{R_{\max i}, R_{\max j}\} = \min\{f_{\text{map}}(SNR_{ij}), R_{\max j}\}. \tag{2}$$

Taking the MAC busy indicator into consideration, if the available bandwidth ($R_{\max ij}$) at a node is shared by transmissions for different data traffic, we define the link weight L_{ij} from node i to j as the "available" portion of the bandwidth as:

$$L_{ij} = R_{\max ij} \cdot \min\{\rho_{\text{MAC}i}, \rho_{\text{MAC}j}\} \tag{3}$$

where ρ_{MAC} $(0 < \rho_{\text{MAC}} < 1)$ is the MAC idle ratio (derived from the MAC busy indicator). The link weight L_{ij} is proportional to the maximum achievable rate from node i to j. The larger the weight, the higher the data rate supported by the link.

3.2.2. The discovery protocol

A node can start the discovery process to achieve the global awareness of the network by exchanging with neighbors its local link states with a polling *link state aggregation (LSA)* message shown in Fig. 11. Upon receiving a poll message ("PR" bit disabled), neighbor nodes then send their *LSVs* in a *LSA* response ("PR" bit enabled), which indicate path metrics to other nodes in the network. A poll message can help to recover link state tables when a node failure happens and all link states are lost. To further reduce control overhead, only changed *LSVs* are propagated to the network.

When a *LSA* response is received, the link state table is updated and new entries are added by calculating E2E path weight if new paths/nodes are discovered. In the network of Fig. 9, when node S wants to transmit data to D, it can

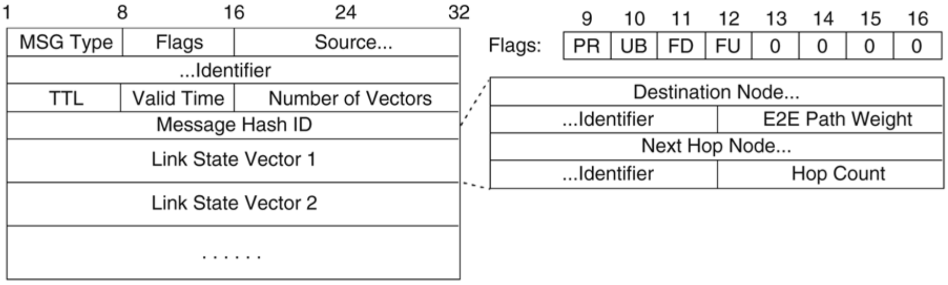


Fig. 11. Link state aggregation message format.

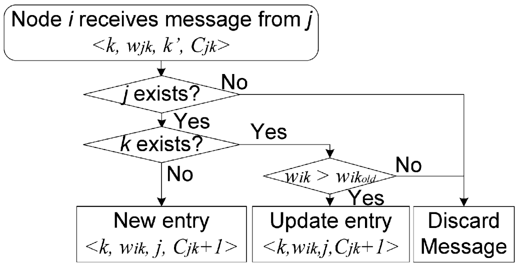


Fig. 12. Flow chart for processing link state vectors.

either directly reach D by rate r_3 or use node F as relay. The estimated per bit delay for both cases are:

$$E(D_1) = \frac{1}{r_3} \qquad E(D_2) = \frac{1}{r_1} + \frac{1}{r_2}. \tag{4}$$

Compared to transmission delay (especially for large data packets), processing/propagation delay and channel switching delay at node F can be ignored. Channel access delay is not counted here either as data forwarding can be completed in consecutive time slots or in orthogonal channels with minimum channel contention. Under the condition $E(D_1) > E(D_2)$, i.e., $r_3 < r_1 r_2/(r_1 + r_2)$, node S would prefer relay rather than direct communication to D. Thus the E2E path weight is defined as the reverse of the summation of the reversing individual link weights along the path. That is, when node i receives a link state vector $\langle k, w_{jk}, k', C_{jk}\rangle$ from j, the new end-to-end path weight from node i to k is calculated as:

$$w_{ik} = \frac{1}{\sum\limits_{m\to n\in\mathfrak{R}_{ik}} \frac{1}{L_{m\to n}}} = \frac{1}{\frac{1}{w_{jk}} + \frac{1}{L_{ij}}} \tag{5}$$

where $\mathfrak{R}_{ik}$ is the link set of all hops (i.e. link $m \to n \in \mathfrak{R}_{ik}$) along the multi-hop path between node i and k. The path weight w_{ik} is a good estimate of the achievable end-to-end rate using intermediate traffic relays. The higher each direct link weight, the higher the end-to-end path weight. The algorithm for updating link state table after calculating the new weight is shown in Fig. 12.

When there is no link failure, this algorithm is loop-free due to the definition of end-to-end path weight. A node will never update with a path going through itself, because from (5), any looping path going through the same link will cause the weight to decrease, while only paths with higher weight are updated. When there are link failures, the discovery protocol can also guarantee loop-free routing. When a link is down, corresponding entries in the link state table will not be deleted immediately; instead, the weight will be set to 0 during the next update interval and propagated to the network. When a zero-weight *LSV* is received, the related path weights will be set to zero and the process is repeated. After the validity interval passes, obsolete *LSVs* will then be deleted. In this way, routing loops may exist but in the long run they will be eliminated after zero-weight *LSVs* are propagated. The *LSV* aggregation is a periodic process where its interval (∼10's of seconds) is usually larger than the bootstrapping beacon interval (2–5 seconds). Note that the aggregation is only a local one-hop broadcast which does not require global flooding. There is a trade-off between the speed of information propagation and control overhead used.

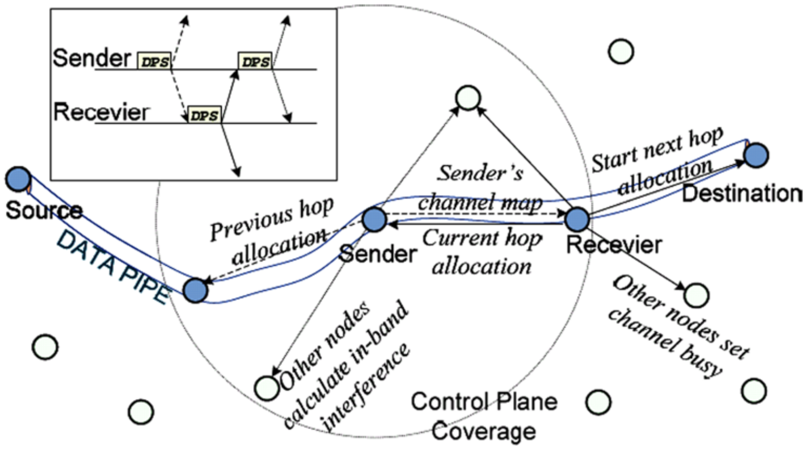


Fig. 13. Multi-hop data path setup.

3.2.3. Data path setup

The *data path setup (DPS)* protocol is used for cross-layer routing when actual data traffic is initiated, and the source explicitly establishes the path to reach a destination, by configuring hop-by-hop cross-layer parameters of the data plane at each forwarding node. This is different from ad hoc routing protocols for the followings reasons: (1) the *DPS* protocol does not only find a path from source to designation (optimized by achievable end-to-end rate), more importantly, it sets up the per-hop data plane parameters (frequency, power, rate, bandwidth, etc.) to utilize local spectrum opportunities to achieve such end-to-end performance; (2) the path setup signaling is carried through the GCP; (3) this protocol utilizes the results from the discovery process. Different radio resource allocation algorithms can be carried in the *DPS* protocol, which is a session-based three-way handshake between hop senders and receivers. Here, we describe a baseline algorithm for joint frequency/power/rate allocation in a channelized cognitive radio system with fixed bandwidth and MAC protocol. As shown in Fig. 13, the traffic source starts by unicasting a *DPS* message (see Fig. 14) to the next-hop node towards the destination (obtained from the discovery protocol). In other cases, the *DPS* message is a one-hop broadcast (indicated by "UC" bit). At each hop, the sender sends its channel availability map (a bit-map of the availability of each data channel) and maximum supported power/rate. The receiver matches the best data channel (with least interference) and calculates the minimum required transmit power for the sender to achieve the maximum PHY rate at the receiver. In the case of no matching channels, the allocation algorithm fails and the source will restart after some random time. The allocated frequency/power/rate values are sent back to the sender with a *DPS* message (with "RV", "SD" and "OT" enabled), which at the same time starts the next-hop allocation process. The sender then repeats the parameter announcement (enabling "OT" bit) and other nodes can calculate the in-band interference of this data session. The algorithm repeats at each hop until the destination is reached. In this way, an end-to-end data path is set up from traffic source to destination and the data plane of each node will forward data traffic in the data "pipe" established. The *DPS* "Flags" field defines the message content, e.g., "RV" or "SD" bit means there is content for a hop receiver or sender, and "OT" bit means the information is for nodes other than a sender or receiver. Thus an intermediate node can use one message to both notify a previous-hop sender and at the same time to start a next-hop negotiation, which expedites the setup process and reduces control overhead.

3.2.4. Naming and addressing

One of the key ideas of the naming and addressing scheme is to elect distributed naming/addressing *(NA)* servers to allocate unique IP addresses to the nodes covered by a server's control plane while also maintaining node name registration and translation to addresses. Fig. 15 shows the *NA* server election process, which guarantees that each node in the network has access to at least one server through the control plane. If a new node fails to collect any beacons (with "NA" bit enabled) from *NA* servers during its bootstrap, it will begin to elect itself as an *NA* server by broadcasting *address pool request (APR)* messages to obtain available IP address pools from existing *NA* servers in the network. Upon receiving any *NA* beacons during the election process, the node will cancel its election and register with the detected *NA* server. The *APR* message uses an expanding ring mechanism which starts as a one-hop broadcast and increases the TTL hop count for subsequent retries. Any *NA* server receiving *APR* will use a binary

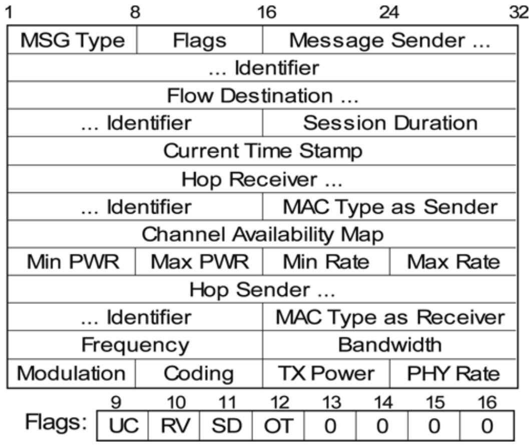


Fig. 14. Data Path Setup (DPS) message format.

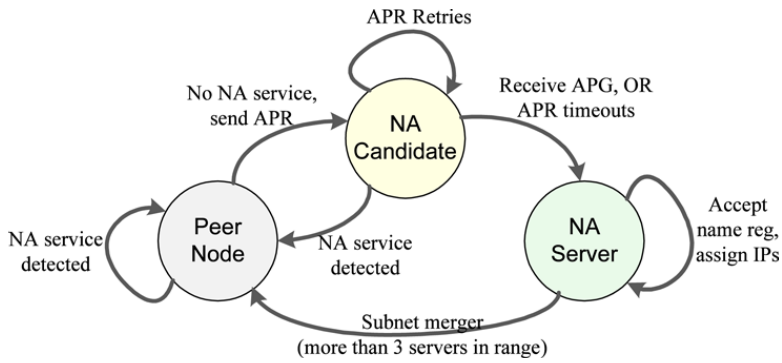


Fig. 15. Naming/addressing server election.

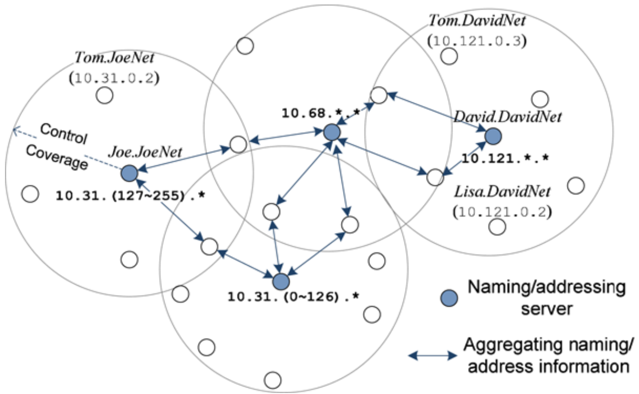


Fig. 16. NA scheme for cognitive radio networks.

splitting mechanism [65] to tentatively allocate half of its own free IP address pool to the requester with an *address pool grant (APG)* message. The accepted pool is committed by an *address pool accepted (APA)* message and non-acknowledged pools will be reclaimed by the owner after an *APG* timeout. If no *APGs* are received after several retries, the requester will choose a random IP segment (e.g. 10.31.*.*) to become an *NA* server by enabling "NA" bit in its beacons. Later during the periodic *NA* aggregation process, name and address information will be exchanged through all distributed *NA* servers to detect and resolve collisions. The network thus is formed into multiple logical subnets, shown in Fig. 16.

If an *NA* server is discovered during the bootstrap, a node sends a *name registration request (NRR)* message to register its name to the server. If the server's IP address pool is non-empty and there is no conflict in node names, an IP address is assigned to the node using a *name address grant (NAG)* message. The server thus keeps the name

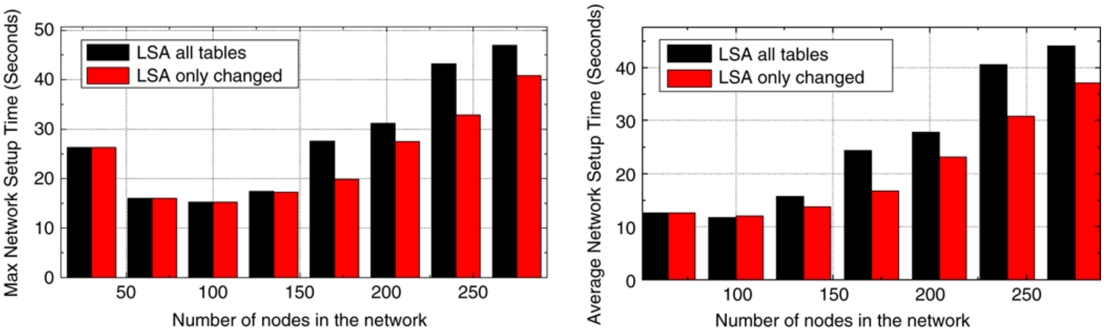


Fig. 17. Network setup time (BSB interval 2 s, LSA interval 5 s).

to address and ID translation information. If there is a name conflict, the server rejects the registration by a *name registration denial (NRD)* message and the requester can retry with another name. If the server's IP pool is empty, an *NRD* message will also be sent indicating that no address is available. If an *NRD* is received or an *NRR* times out after *NRR_Timeout* seconds, the requester can either register to other available servers or retry for a maximum of *NRR_Retries* times. In the rare cases when the server runs out of address, it will restart the *APR* process to get more available addresses from other servers. Each *NA* server periodically aggregates and caches node name/IP/ID translations by *name address aggregation (NAA)* messages. *NA* servers' names (subnet names) are guaranteed to be unique during the aggregation process by the conflict resolution procedure. Thus each node can be uniquely identified by joint node and subnet name. Applications which communicate using node names are thus supported where the resolution of name to address/ID is achieved by distributed *NA* servers.

3.3. Protocol validation results

The global control plane is implemented in *ns*-2, [64] where the control radio uses 802.11b operating at fixed channel 1 with 2 Mbps rate covering about 250 m. The control MAC uses the IEEE 802.11 standard without RTS/CTS. The data radio can be implemented with generic radios (using varying frequency, bandwidth, modulation, power and rate parameters), but without loss of generality, we utilize 802.11a OFDM radio parameters at 5 GHz for data plane with 8 channels of 20 MHz each. PHY rates are 6, 9, 12, 18, 24, 36, 28 and 54 Mbps and transmit power varies from 0 to 20 dBm. A network scenario of 1 km x 1 km with varying numbers of cognitive radio nodes is simulated where nodes are randomly placed in the network and boot up at random times. The bootstrapping and discovery protocols are evaluated in terms of network setup time, control overhead used and estimated achievable end-to-end rate. The maximum network setup time is the time from the start of the first node to the time all nodes in the network achieve global awareness by completing the discovery process. To evaluate the *DPS* protocol, different traffic source/destination pairs are chosen randomly to perform data ON/OFF sessions with ON/OFF duration uniformly distributed from 5 to 10 seconds.

The simulation results are compared for cases in which all link states are sent periodically ("*LSA* all tables"), or alternatively only when changes occur ("*LSA* changes only"). The maximum and average network setup time are shown in Fig. 17 where nodes randomly boot up from 0 to 4 s. With increasing number of nodes in the network, the network setup time first decreases and then increases, reaching its minimum at a node density of about 100 nodes/km^2, because when the network is sparse, more *LSA* steps are needed to discover the whole network, while in a very dense network, the size and number of *LSVs* are large, and it takes about 3–8 *LSA* steps to discover the network. It is observed that when only changed link states are propagated, the network converges faster due to reduced control packets contending for the control channel. The average control traffic per node during the discovery process is shown in Fig. 18 with both bootstrapping beacons and *LSA* messages counted as control traffic. The average per node control traffic rate increases as the node number increases but the curve flattens out when the node number becomes large, converging to about 55–65 kbps, which is well below the control channel capacity. When only changed link states are propagated, the control traffic rate is about 10 kbps less than the case by sending all link states. The estimated theoretical end-to-end rate is also calculated using Eq. (5) during discovery. Each node is randomly assigned a MAC idle ratio to simulate its busy condition. From Fig. 19, each node discovers paths to every other node in the network

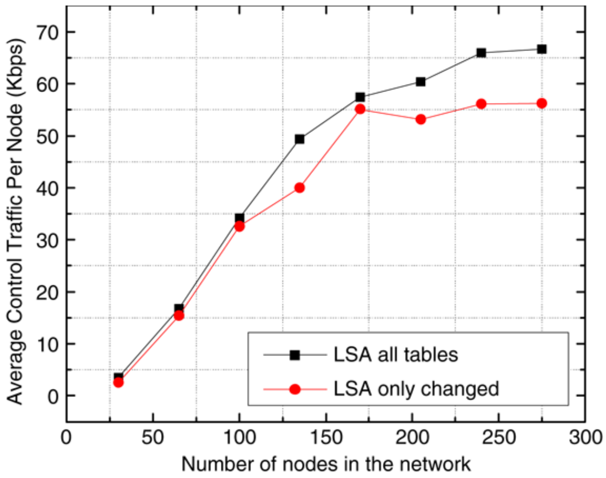


Fig. 18. Average control traffic per node for network setup.

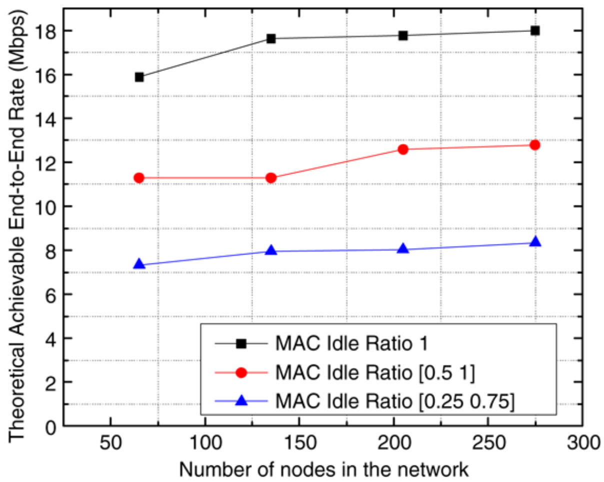


Fig. 19. Estimated theoretical achievable end-to-end rate.

Table 1
Simulation results for the DPS protocol

Node density (per km^2)		65 nodes	135 nodes	205 nodes
Latency (ms)	5 flows	6.49	6.96	7.62
	15 flows	6.52	6.64	7.38
Overhead (kBytes)	5 flows	1.3	1.4	1.5
	15 flows	1.4	1.4	1.3

with average achievable end-to-end rate as high as 18 Mbps for an 802.11a-type network involving multi-hop relays (usually 1–8 hops). The busier a node, the lower the end-to-end rate achieved due to reduced forwarding ability.

Simulation results for the *DPS* protocol and joint frequency/power/rate allocation algorithm are shown in Fig. 20 and Table 1. The average frequency allocation success ratio decreases with increasing numbers of source and destination pairs in the network. The *DPS* succeeds if every hop is configured with a matching frequency between hop sender and receiver. It is observed that with increasing node density, this ratio improves mainly because the joint frequency/power/rate allocation algorithm allocates minimum required power for achieving the maximum supported bit-rate, which potentially increases the space reuse of the limited 8 data channels. The *DPS* latency (the duration from start of source to the acknowledgement of the destination) and control overhead are given in Table 1, where end-to-end path setup only takes an average of 7 milliseconds with modest total control traffic of about 1.4 kBytes.

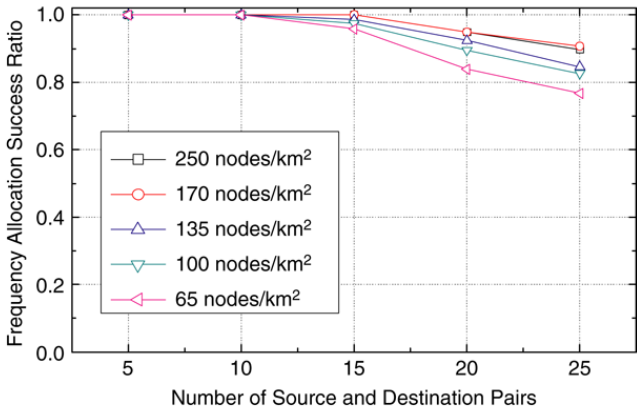


Fig. 20. Frequency allocation success ratio for the DPS protocol.

4. Cognitive radio platforms

A number of software-defined radio (SDR) and cognitive radio (CR) hardware design and prototyping projects have been reported in the past few years. These include the Vanu software-defined radio [14], the WARP programmable radio from Rice University [15], the KU Radio from University of Kansas [16], and the GNU/USRP board from Blossom Research [18,66]. Common to all these platforms is their implementation flexibility, which enables interoperability, upgradeability and future-proofing. Several performance requirements, including RF bandwidth, radio bit-rate, and packet processing speed need to be balanced against flexibility, power consumption and size when designing this type of cognitive radio platform. The implementation of these boards ranges from CPU-centric software processing in the GNU/USRP radio to the FPGA programmable hardware approach used in the WARP radio. The all-software processing approach provides greater flexibility but may be limited in performance due to the complexity of modern PHY and MAC standards such as OFDM and CSMA/CA. As a result, most first generation cognitive radio platforms are implemented around a mix of FPGA and CPUs (and in some cases, programmable DSPs as well to support floating point operations).

4.1. The WiNC2R prototype

As a specific example of a cognitive radio platform, we provide an overview of the WiNC2R platform [67] currently under development at WINLAB. The WiNC2R architecture [17] is aimed at providing a high-performance platform for experimentation with various adaptive wireless network protocols ranging from simple etiquettes to more complex ad hoc collaboration. The WiNC2R board is differentiated from other cognitive radio projects [14–16] in the sense that the design uses hardware accelerators to achieve programmability and high performance at each layer of the protocol stack. The prototype's hardware design provides for fast RF scanning capability, an agile RF transceiver working over a range of frequency bands, a software-defined baseband processor capable of supporting a variety of modulation waveforms, a packet processing engine for protocol and routing functionality, and a general purpose processor for implementation of spectrum etiquette policies and algorithms. The software to be run on this hardware platform uses the GNU software radio code base [18] as its foundation, providing APIs needed for programmability at the PHY and MAC layers. Protocol software used to implement adaptive wireless network capabilities is based on the *CogNet* architecture outlined in Section 3.

4.1.1. Hardware design goals

The goal is to build a flexible wireless platform that will support a range of cognitive radio network scenarios from autonomous agile radios through those that use higher-layer protocols to negotiate and share spectrum. To summarize, the high-level design objectives for the WiNC2R cognitive radio platform include:

- Multi-band operation, fast spectrum scanning and frequency agility;
- Software-defined modem capable of operating at speeds ∼10–50 Mbps with OFDM and QPSK/DSSS class waveforms;
- Spectrum policy processing for dynamic spectrum sharing algorithms and etiquette protocols;

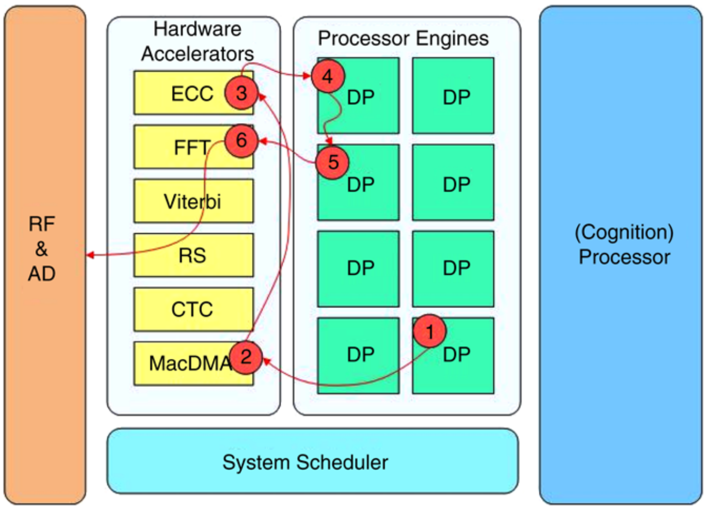


Fig. 21. WiNC2R hardware functions.

- Ability to switch between different MAC algorithms;
- Support for "virtualization" of multiple PHY/MAC instances, for example simultaneous support of different protocols for control and data;
- High throughput networking operations including ad hoc association and multi-hop routing.

4.1.2. WiNC2R platform architecture

The architecture of the WiNC2R platform recognizes differing computational complexity, timing constraints and multiplexing mechanisms at PHY, MAC and network layers, and provides system level control and interconnection mechanisms for customization of hardware and software functions at each of the protocol layers. The logical organization of hardware functions in the platform is shown in Fig. 21. Most of the PHY layer processing is performed by a set of *hardware accelerators* (HA) configurable for the requirements of wireless PHY standard applications. The less processing intensive functions at PHY, MAC and higher layer are performed by an array of *data processors* (DP), which support per-packet protocol selection or change of parameters. The processing sequence and time allocation of HAs and DPs are controlled by the *system scheduler* (SS). The SS is set up and reconfigured by the *cognitive processor* based on observed system load, channel allocation or change of channel parameters. In addition, the cognitive processor is in charge of controlling spectrum sensing, and adaptation of PHY parameters based on system level collaboration algorithms.

During the first phase of platform development we have focused on the implementation of a flexible MacDMA accelerator (block diagram outlined in Fig. 22) which can be used to support dynamic switching between multiple MAC protocols for control and data. We have also developed basic hardware accelerators for both DSSS- and OFDM-based physical layers.

4.2. WiNC2R board implementation

The high-level block diagram of the WiNC2R board is shown in Fig. 23. The board consists of a multiple RF modules with wake-up circuit, wideband analog-to-digital converters, FPGA-based processing hardware for PHY baseband processing, and a second stage of FPGA to support high-speed MAC and network functions. There is also an external general purpose processor (external host) for higher-level protocol and software processing.

The hardware board is organized around three types of modules: RF, Modem and Network.

RF module: The RF module uses double super-heterodyne with switchable shaping filters for a wide tuning range of 30 MHz to 6 GHz with baseband of 0–500 MHz. Dual VCO/PLLs in both IF stages are used for fast switching ($\sim$1 us) thus enabling RF agility. WiNC2R platform allows for attachment of up to 3 RF modules thus enabling flexible CR strategies (e.g. simultaneous use of two communication channels and one agile RF sensor).

Modem module: The modem module performs most of the baseband PHY functions, provides analog input and output interfaces to the RF module as well as the interconnect bus interface towards the network module. Each pair

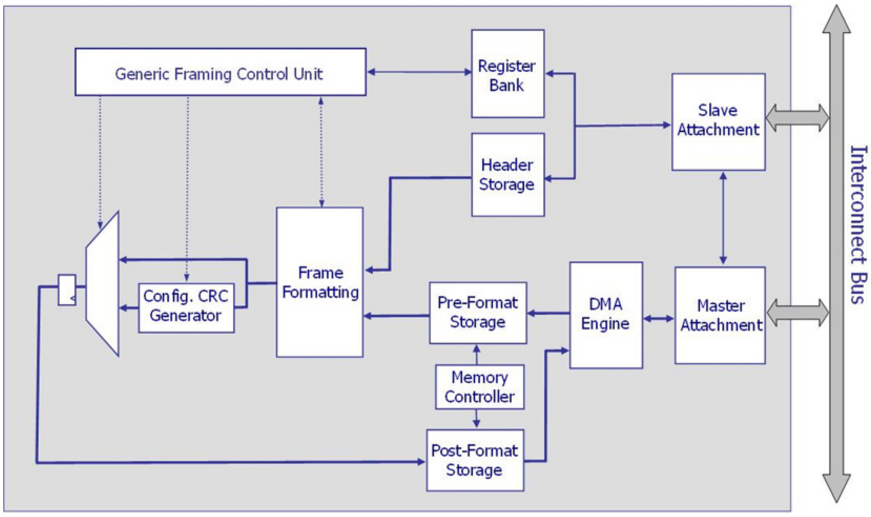


Fig. 22. WiNC2R Flexible MAC Engine Architecture.

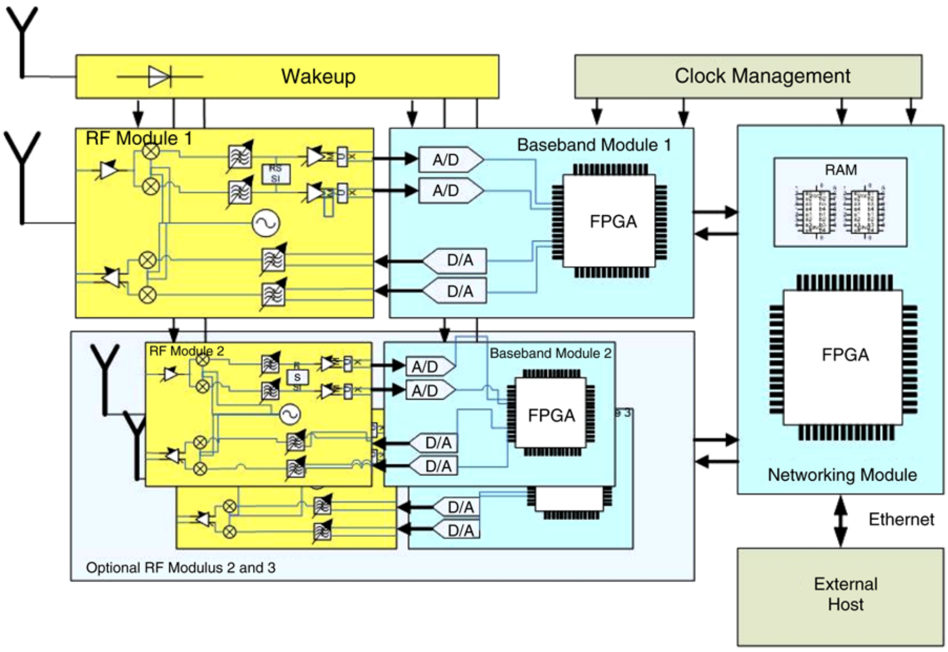


Fig. 23. WiNC2R board implementation.

of analog signals from the RF module is translated to a pair of 14 bit I/Q data streams sampled at a rate of 125 MSPS and further processed by the modem module FPGA. At the outgoing signal path, two 16 bit, 500 MSPS, 2x–8x interpolating dual-channel DACs generate the analog equivalents to the 16 bit I/Q data pair. The core of the module is organized around Xilinx XC4SX35 FPGA as it is geared towards high-performance digital signal processing applications corresponding to the types of functions performed in the PHY block. Data transfers between modem and networking modules occurs through a 16 bit high-speed LVDS bus.

Networking module: Packet and network protocol processing functions are performed using networking module based on a Xilinx 4LX35 FPGA that is geared towards logic processing rather than DSP applications. In addition, this FPGA also supports the Gigabit Ethernet MAC soft-core to support a wired connection to the outside world. The main functions implemented on this FPGA are the MAC accelerator, DPs used for MAC adaptation as well as the system scheduler. All of the DPs from Fig. 21 are implemented as soft-core 32 bit RISC processors in both modem and networking modules.

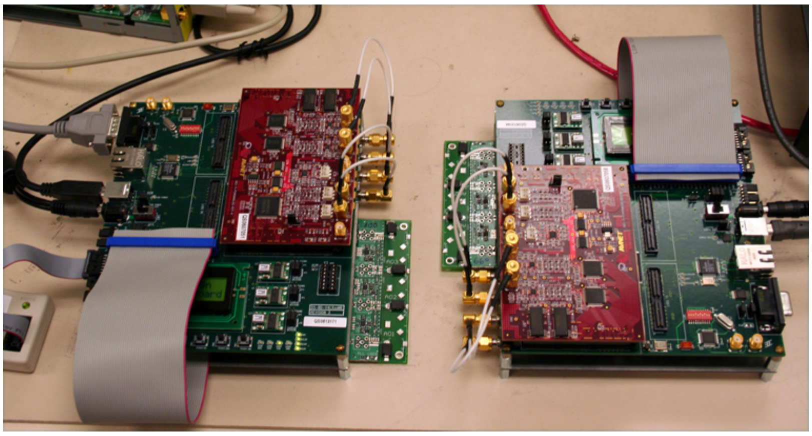


Fig. 24. WiNC2R board in a two-node experimental setup.

In order to experimentally validate the hardware architecture introduced in this paper, we established the test setup shown in Fig. 24 consisting of two prototype WiNC2R boards connected to two ORBIT [68] nodes used as host processors. These boards are currently being used for hardware debugging via basic PHY and MAC connectivity tests, and will next be used for validation of the *CogNet* protocols and algorithms described in Section 3. Once prototyping and proof-of-concept experiments on this back-to-back evaluation setup are completed, larger scale experiments with more complex topologies are planned on the ORBIT testbed, with radio nodes upgraded to support programmable PHY and MAC.

5. Conclusions and future work

Cognitive radio technology has the potential to dramatically improve spectral efficiency and performance in the next generation of wireless networks. We have identified the design space for cognitive radios as ranging from simple reactive algorithms to proactive spectrum etiquettes and finally to collaborative adaptive wireless networks. A "common spectrum coordination channel (CSCC)" approach is proposed as a mechanism to enable efficient spectrum etiquettes, and we have shown that CSCC-based schemes can provide significant performance advantages in dense or clustered radio environments. We believe that collaborative networks of cognitive radios will be required to achieve the next level of performance, and have proposed a specific *CogNet* protocol architecture to enable the formation and operation of these adaptive wireless networks. Some results from ongoing prototyping work on cognitive radio platforms (the WiNC2R board) have also been presented in order to provide an idea of hardware architecture issues. Future work includes proof-of-concept development of small scale adaptive wireless networks using the GNU/USRP and WiNC2R platforms as building blocks. Controlled experiments on the ORBIT testbed [68] eventually leading to larger scale outdoor trials are also planned in the future.

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