A Cognitive Radio Approach for Usage of Virtual Unlicensed Spectrum

Danijela Čabrić[1], Shridhar Mubaraq Mishra[1], Daniel Willkomm[2], Robert Brodersen[1], Adam Wolisz[2]

[1]Berkeley Wireless Research Center, University of California at Berkeley, USA

[2]Telecommunication Networks Group, Technical University of Berlin, Germany

Email: danijela@eecs.berkeley.edu

Abstract— While essentially all of the frequency spectrum is allocated to different applications, observations provide evidence that usage of the spectrum is actually quite limited, particularly in bands above 3 GHz. In this paper we present a *C*ognitive *R*adio approach for usage of *V*irtual *U*nlicensed *S*pectrum (CORVUS), a vision of a Cognitive Radio (CR) based approach that uses allocated spectrum in a opportunistic manner to create "virtual unlicensed bands" i.e. bands that are shared with the primary (often licensed) users on a non-interfering basis. Dynamic spectrum management techniques are used to adapt to immediate local spectrum availability. We define the system requirements for this approach, as well as the general architecture and basic physical and link layer functions of CORVUS.

I. INTRODUCTION

It is commonly believed that there is a crisis of spectrum availability at frequencies that can be economically used for wireless communications. This misconception is strengthened by a look at the FCC frequency chart [1], which shows multiple allocations over all of the frequency bands; which is a situation essentially also true worldwide. This has resulted in fierce competition for use of spectra, especially in the bands below 3 GHz. On the other hand, actual measurements taken in downtown Berkeley (Figure 1) reveal a typical utilization of 0.5% in the 3-4 GHz frequency band. This utilization drops to 0.3% in the 4-5 GHz band. This seems in contradiction to the concern of spectrum shortage, since in fact we have spectrum abundance, and the spectrum shortage is partially an artifact of the regulatory and licensing process.

It is this discrepancy between FCC allocations and actual usage, which indicates that a new approach to spectrum licensing is needed. Part of the solution can be found in Figure 1, which shows considerable usage in the upper 5 GHz band at this location. This spectrum corresponds to the unlicensed UNII bands, which have only minimal constraints from the regulatory standpoint. What is clearly needed is an approach, which provides the incentives and efficiency of unlicensed usage to other spectral bands, while accommodating the present users who have higher priority or legacy rights (***primary users***) and enabling future systems a more flexible spectrum access.

An approach, which can meet these goals, is to develop a radio that is able to reliably sense the spectral environment over a wide bandwidth, detect the presence/absence of legacy users and use the spectrum only if communication does not interfere with any primary user. These radios are lower priority ***secondary users,*** which exploit cognitive radio (CR) techniques, to ensure non-interfering co-existence with the primary users**.** The sensing function is one of the most important attributes of cognitive radios - as it ensures non-interference to licensed users - and should involve more sophisticated techniques than simple determination of power in a frequency band . A CR must sense across the multiple *signal dimensions* of time, frequency and physical space, of a wireless channel and user networks [7]**.** Optimal CR operation will allow sensing of the environment and transmission optimized across all of these dimensions and thus allows a truly revolutionary increase in the capacity of spectra to support new wireless applications.

Regulatory domains are also realizing the need for new technologies in order to efficiently use available spectral resources. Recent studies by the FCC Spectrum Policy Task Force have reported vast temporal and geographic variations in the usage of allocated spectrum [2]. In order to utilize these 'white spaces', the FCC has issued a Notice of Proposed Rule Making [3] advancing CR technology as a candidate to implement negotiated or opportunistic spectrum sharing.

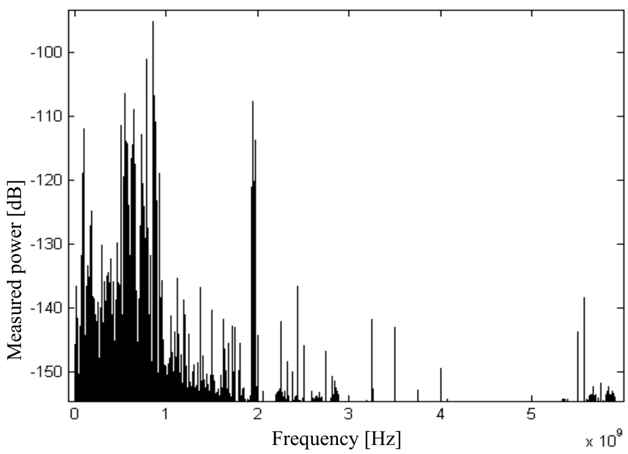

Figure 1. Spectrum utilization measurement at BWRC

II. PREVIOUS WORK

The term *Cognitive Radio* was first defined by Mitola [5] as "the point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to: (a) detect user communications needs as a function of use context, and (b) to provide radio resources and wireless services most appropriate to those needs." Thus a CR is able to automatically select the best and cheapest service for a radio transmission and is even able to delay or bring forward certain transmissions depending on the currently or soon to be available resources. The learning and reasoning capabilities of CRs needed to fulfill this goal which would be implemented in software as a high layer functionality have been investigated [4][5]. However, this work lacks a specific radio architecture for physical and link layer that would enable the advanced cognitive techniques.

Recently the term Cognitive Radio has been used in a narrower sense: The FCC suggests [3] that any radio having adaptive spectrum awareness should be referred to as "Cognitive Radio". More precisely: *"A cognitive radio (CR) is a radio that can change its transmitter parameters based on interaction with the environment in which it operates. The majority of cognitive radios will probably be SDRs (Software Defined Radios), but neither having software nor being field programmable are requirements of a cognitive radio."* Implicit in the realization of this type of radio is a high degree of flexibility needed to overcome high variation in channel quality and interference.

Spectrum Pooling is a resource sharing strategy that organizes the available spectrum into a spectrum pool which is then optimized for a given application [6][7]. Once a primary user appears, secondary users need to cease transmission if they will cause interference. A cognitive radio / spectrum pooling architecture based on OFDM has been developed by Weiss and Jondral [6]. They envision an 802.11 like access-point scenario for the cognitive radio system consisting of a cognitive radio base-station and cognitive radio mobile users and do not assume any changes to licensed user systems. In order to detect primary users, sensing data of the mobile clients is gathered at the base station. This would take considerable time using traditional medium access techniques, so a *boosting* protocol is used omitting the MAC layer and using only the physical layer for signaling [6].

Our approach on the other hand focuses on a system architecture with separation of signaling and data transmission functionalities as will be shown.

III. SYSTEM REQUIREMENTS

The basic premises of the CORVUS system are as follows:

1) Abundance of spectra, which is available and used for spectrum sharing by *Secondary Users* (SU).

2) SUs use cognitive radio techniques to avoid interfering with *Primary Users* (PU) when they are present.

We define a PU as an entity that has a high priority in a given frequency band (e.g. cell phone provider, TV station, emergency services, etc). PUs are not cognitive radio aware, i.e. there are no means to exchange information between primary and secondary users provided by a primary system. Specifically, PUs do not provide special signaling in order to access their frequency band. We assume all SUs having cognitive radio capability, i.e. the system only consists of Primary Users and Cognitive Radio capable SUs. Cognitive unaware Secondary Users are treated as noise by our system.

In this heterogeneous network, it is assumed that a PU can tolerate interference for no more than Δt_x time units. Note that this interference time is dependent on the primary system and may be different for different PUs. After this interference time all SUs have to clear the frequencies belonging to the frequency band of the respective PU. Also, even if a SU is currently using parts of a primary user frequency band, the PU of that band may start the transmission at any time. In case the PU is using a carrier sense access scheme, an SU operating in that band thus has to operate below the carrier sense sensitivity of the PU.

From the above, it is clear that a fundamental requirement for the Secondary User is to continually monitor the presence of Primary Users (or at least every Δt_x). In order to reliably detect primary users, SUs use information based on the *Primary User Footprint,* which is assumed to be available to the SU System. The primary user footprint includes - but is not limited to - the information from FCC's spectrum inventory table [1]. Additional information could be maximum interference time Δt_x, and local characteristics of PUs such as minimum communication times or time of use.

IV. SYSTEM ARCHITECTURE

In our system model, SUs form *Secondary User Groups* (SU Groups) to coordinate their communication. Members of a SU Group use a common control channel for signaling and might communicate with each other in a distributed ad-hoc mode or through a centralized access point. In either mode we assume only a unicast communication, either between a pair of SUs or between a SU and the access point. Direct point-to-point communication between Secondary Users from different SU Group's or broadcast is not supported.

The traffic pattern for the SUs will be initially assumed to have the following characteristics:

1. <u>Centralized, infrastructure based</u> where there has to be a base station or access point providing connection to a backbone connection, as typically found in Internet access networks.
2. <u>Ad hoc networking</u> covers all kinds of ad-hoc traffic that does not assume any infrastructure. Main purpose is to communicate with each other and exchange information within a SU Group.

To support this traffic CORVUS operates over a Spectrum

Pool, which could cover from tens of MHz to several GHz creating a "virtual unlicensed band". It is not necessarily a contiguous frequency range and Spectrum Pools of different SU Groups may overlap which implies that SU Groups will compete for the available resources. Each Spectrum Pool will be further divided into N Sub-Channels, which will be the basic resolution used for sensing and transmission.

Figure 2 shows the principle idea of a Spectrum Pooling system in CORVUS. Primary Users own different parts of the spectrum but may not be active at a particular time. The shaded frequency bands indicate that the PU is currently using its spectrum and consequently this frequency band cannot be used by any SU. The figure also shows three different active Secondary User communications. For each communication a pair of SUs picked a pattern of sub-channels to form a *Secondary User Link* (SU Link). The number of sub-channels in a SU link may vary depending on the quality of the sub-channels, the bandwidth of a single sub-channel and QoS requirement for that connection.

Sub-channels selected to create a SU Link should be scattered over multiple PU frequency. This principle has a double significance. On one hand it limits the interference impact of a SU on a re-appearance of a PU, while on the other hand if a PU appears during the lifetime of a SU Link it would impact very few (preferable one) of the Sub-Channels used by the SU Link. The communication peers using that link would have to immediately clear the affected sub-channel and find a new free sub-channel. In order to maintain QoS, SUs should always have a redundant number of sub-channels for their SU Link.

Within CORVUS, SUs use dedicated logical channels for the exchange of control and sensing information. We envision two different kinds of logical control channels, a *Universal Control Channel* and *Group Control Channels*. The Universal Control Channel is globally unique and has to be known to every SU operating in the relevant frequency bands, since access to that channel is pre-requisite for initiating communications. The main purpose of the Universal Control Channel is to announce existing groups and to give the relevant transmission parameters to enable newly arriving users to join a group. Additionally SUs, which want to create a new group can request the local primary user footprints on that channel. Although globally unique the communication range should be locally limited as SU Groups are limited to a local area. In addition to the Universal Control Channel each group has one logical Group Control Channel for the exchange of group control and sensing information.

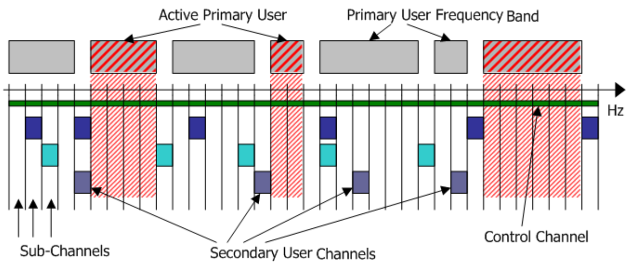

Figure 2. Spectrum pooling idea

Control channels will carry a limited load of low-bit rate signaling which could be located in:

a) dedicated spectrum for this purpose
b) an unlicensed band such as the ISM/UNII bands
c) unlicensed UWB (Ultra Wide Band)

We believe the UWB option is especially attractive if we are considering use of the 3-10GH band. UWB control channels would be unlicensed but with low impact on other types of communication and with the possibility to operate independently using different spreading codes. There are severe limitations on the power of UWB emissions limiting its range, but the control channel requires very low data rates, so spreading gain will increase the range to be adequate for most applications (more than 10,000 times lower datarate than the commercial UWB systems being envisaged in this band). Note that the Universal Control Channel and the Group Control Channels are logical concepts, which might even be mapped to a single physical channel.

V. System Functions

Our system design only covers the ISO/OSI layers one (physical layer) and two (link layer). Higher layers will implement standard protocols not specific to cognitive radios and thus are not relevant to our discussion. Figure 3 shows the main building blocks for the deployment of a Cognitive Radio system. We identify six systems functions and two control channels that will implement the core functionality.

A. Physical Layer Functions

1) *Spectrum Sensing:* The main function of the physical layer is to sense the spectrum over all available degrees of freedom (time, frequency and space) in order to identify sub-channels currently available for transmission. From this information, SU Links can be formed from a composition of multiple sub-channels. This will require the ability to process a wide bandwidth of spectrum and then perform a wideband spectral, spatial and temporal analysis. Sub-Channels currently used for transmission by SUs have to be surveyed at regular intervals – at least every Δt_x – to detect Primary Users activity on those Sub-Channels ("reclaiming the usage of their Sub-Channels") and if there is activity then those Sub-Channels must be given up.

It will be necessary for the SUs to exchange and merge their local sensing information in order to optimally detect presence of PUs and avoid the *hidden terminal problem*. This cooperation between SUs within a communicating group will be important to realize adequate accuracy of interference activity. Spectrum sensing is best addressed as a cross-layer design problem since sensitivity can be improved by enhancing radio RF front-end sensitivity, exploiting digital signal processing gain for specific primary user signal, and network cooperation where users share their spectrum sensing measurements [9].

2) *Channel Estimation:* In order to set up the link, channel sounding is used to estimate the quality of sub-channels between SUs that want to communicate. The transmission parameters (transmit power, bit rate, coding, etc.) are determined based on the channel sounding results. After the setup, the physical layer continuously estimates the quality of sub-channels analyzing the data packets received during ongoing communication.

3) *Data Transmission:* CR's optimally uses the available spectrum as determined by the spectrum sensing and channel estimation functions. Therefore it should have the ability to operate at variable symbol rates, modulation formats (e.g. low to high order QAM), different channel coding schemes, power levels and be able to use multiple antennas for interference nulling, capacity increase (MIMO) or range extension (beam forming). One possible strategy would be based on an OFDM-like modulation across the entire bandwidth in order to most easily resolve the frequency dimension with subsequent spatial and temporal processing.

B. Link Layer Functions

1) *Group Management:* We assume that any secondary station will belong to a SU Group. A newly arriving user can either join one of the existing groups or create a new one through the Universal Control Channel.

2) *Link Management:* covers the setup of a link in order to enable the communication between two SUs and afterwards the maintenance of this SU Link for the duration of the communication. The link layer will initially choose a set of Sub-Channels in order to create a complete SU link subject to the considerations described previously.

3) *Medium Access Control (MAC):* As long as it can be assured that all Sub-Channels are used exclusively, i.e. all Sub-Channels used by one SU Link cannot be used by any other SU Link this problem comes down to a simple token-passing algorithm ensuring that only one of the two communication peers is using the link. However, when considering a multi-group, multi-user system, which may not be centrally organized, making the assumption of exclusively used Sub-Channels is not realistic. So the MAC has to provide means to concurrently access a SU Link by SUs or even to manage the concurrent access of individual Sub-Channels by different connections of different SUs.

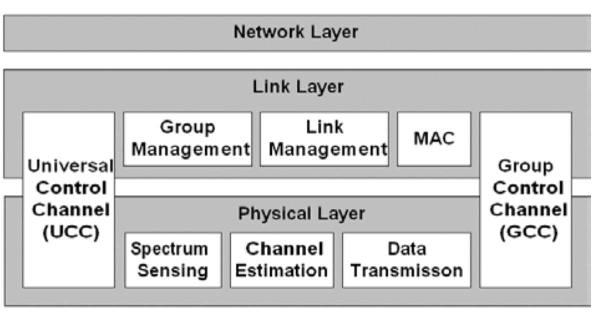

Figure 3. General ISO/OSI Stack for a Cognitive Radio

VI. Conclusion

In this paper we present the CORVUS system concepts to harness unoccupied frequency bands for the creation of virtual unlicensed spectrum. The motivation for this approach comes from the enormous success of unlicensed bands and the realization that the present strategy of allocation has resulted in much under-utilized spectra.

Cognitive Radios are capable of sensing their spectral environment and locating free spectrum resources. In CORVUS, these radios perform local spectrum sensing but Primary User detection and channel allocation is performed in a coordinated manner. This collaborative (either centralized or distributed) effort greatly increases the system's ability in identifying and avoiding Primary Users.

In the CORVUS architecture, a group of Cognitive Radios forms a Secondary User Group to coordinate their communication. Each member of this group senses the Spectrum Pool, which is divided into sub-channels. A pair of Secondary Users picks a set of sub-channels spread over multiple Primary User frequency bands to form a Secondary User Link. Sub-channels are picked based on estimated channel gain of a sub-channel and the user's QoS requirements. Furthermore, chosen sub-channels are scattered over the frequency bands of multiple Primary Users to reduce disruption when a Primary User reappears. For group management a number of underlay control channels exists. A Universal Control Channel is used by all groups for coordination and separate Group Control Channels are used by members of a group to exchange sensing information and establish Secondary User Links.

References

[1] http://www.fcc.gov/oet/info/database/spectrum/
[2] FCC. Et docket no. 02-155. Order, May 2002.
[3] FCC. Et docket no. 03-322. Notice of Proposed Rule Making and Order, December 2003.
[4] Joseph Mitola III. Cognitive radio for flexible mobile multimedia communications. In *Sixth International Workshop on Mobile Multimedia Communications (MoMuC'99)*, San Diego, CA, 1999.
[5] Joseph Mitola III. *Cognitive Radio An Integrated Agent Architecture for Software Defined Radio*. PhD thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2000.
[6] Timo Weiss and Friedrich Jondral. Spectrum pooling: An innovative strategy for the enhancement of spectrum efficiency. *IEEE Communications Magazine*, 42:S8–S14, March 2004.
[7] Fatih Capar, Ihan Martoyo, Timo Weiss, and Friedrich Jondral. Comparison of bandwidth utilization for controlled and uncontrolled channel assignment in a spectrum pooling system. In *Proceedings of the IEEE 55th Vehicular Technology Conference VTC Spring 2002*, pages 1069–1073, Birmingham (AL), 2002.
[8] Ada S. Y. Poon, Robert W. Brodersen and David N. C. Tse. Degrees of Freedom in Spatial Channels: A Signal Space Approach. submitted to *IEEE Trans. on Information Theory*, August 2004.
[9] D.Cabric, S. M. Mishra, R.B. Brodersen, "Implementation Issues in Spectrum Sensing for Cognitive Radios", *38th Annual Asilomar Conference on Signals,Systems and Computers*, November 2004.