CORVUS:

A COGNITIVE RADIO APPROACH FOR USAGE OF VIRTUAL UNLICENSED SPECTRUM

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Abstract:

While the vast majority of the frequency spectrum is licensed to different organizations, observations provide evidence that usage of the licensed spectrum is by far not complete neither in the time domain nor the spatial domain. In this paper we present ***CORVUS****, a vision of a* ***Cognitive Radio (CR)*** *based approach to create and use virtual unlicensed spectrum in a way not restricting the privileges of the original license holders. We discuss the basic notions of such an approach, as well as the general architecture and basic functions of* ***CORVUS****. Two companion papers will provide an outline of a possible specification of the individual functions, as well as assumptions for a first case study.*

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1. 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 has arisen from the intense competition for use of spectra at frequencies below 3 GHz. At higher frequencies, as seen by the snapshot of spectrum usage in an urban area shown in Figure 1, there is actually very little usage at the time, place and direction that this measurement was taken. Analysis of the snapshot in Figure 1 reveals that the actual utilization in the 3-4 GHz frequency band is 0.5% and drops to 0.3% in the 4-5 GHz band. This seems totally in contradiction to the concern of spectrum shortage, since in fact we have spectrum abundance, and the spectrum shortage is in part an artificial result of the regulatory and licensing process.

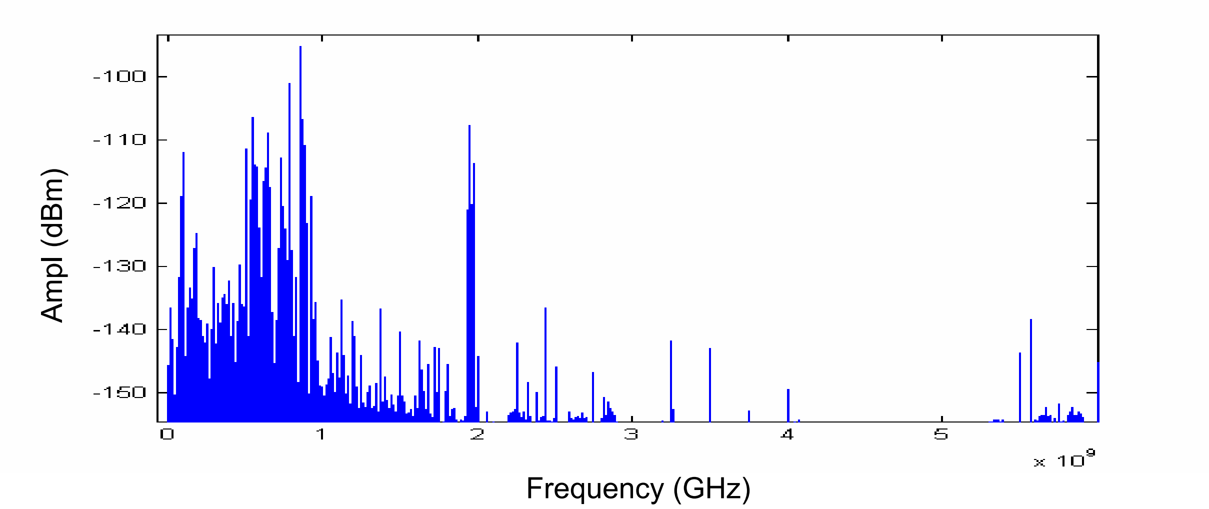

Figure 1 A snapshot of the spectrum utilization up to 6 GHz in an urban area: taken at mid-day with 20 kHz resolution taken over a time span of 50 microseconds with a 30 degree directional antenna.

What is remarkable is that this low level of usage seems inconsistent with the FCC frequency chart from 3-6 GHz shown in Figure 2, that indicates that there are multiple allocations over all of the frequency bands. 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 by observing in Figure 1, that there is considerable usage in the upper 5 GHz band in this location. This corresponds to the unlicensed UNII spectra, which has only minimal constraints from the regulatory standpoint. What is clearly needed is an extension of the unlicensed usage to other spectral bands, while accommodating the present users who have legacy rights and also to insure that future requirements can be met.

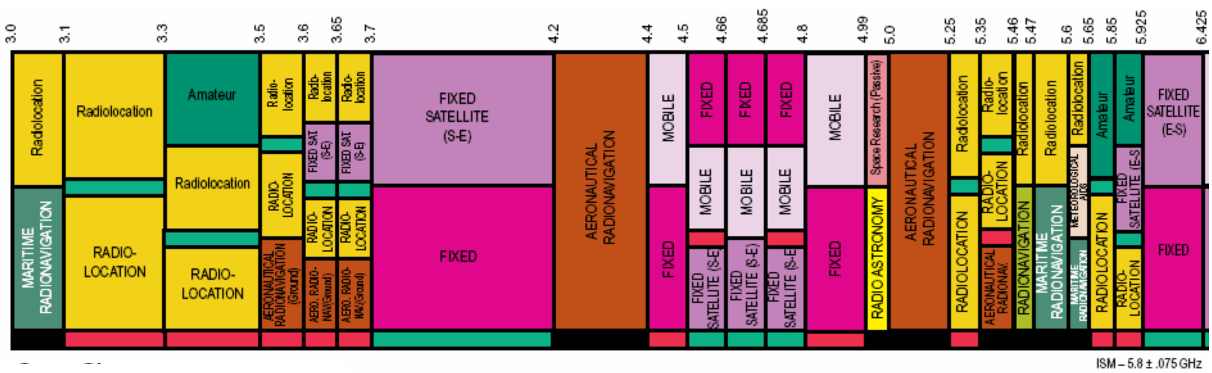

Figure 2 The FCC frequency allocation from 3-6 GHz.

An approach, which can meet these goals, is to develop a radio that is able to sense the spectral environment over a wide available band and use the spectrum only if communication does not interfere with licensed user. These un-licensed low priority **Secondary Users (SU)** would thus be using **Cognitive Radio (CR)** techniques, to ensure non-interfering co-existence with higher priority users and thus reduce concerns of a general allocation to unlicensed use [**FCC_03322**]. The sensing should involve more than just determining the power in a frequency band as presented in Figure 1, since a wireless channel actually is built on multiple *signal dimensions* that include time, frequency, physical space, and user networks [**POON_03**]**.** The optimal CR operation will allow sensing of the environment and transmission optimized across all of the dimensions and thus allows a truly revolutionary increase in the ability to support new wireless applications. In a sense our cognitive radio discovers unused capacity and creates out of this unused capacity a “virtual unlicensed spectrum” to be used in a way not constraining the licensed owners.

The primary goal of this white paper is to present a general concept for such Cognitive Radio, and discuss research challenges to make it a reality. It is our intention to follow-up with two additional white papers that would further address concepts developed in this first vision. The second white paper will analyze potential solutions and algorithms for realization of system functions, and define interfaces between the physical and link layer. In the third white paper we will specifically target one specific implementation of a Cognitive Radio system based on the approach and developed framework presented in the first two white papers. This system with specific parameters and architecture will be targeted for the implementation and demonstration of our cognitive ideas, and also serve as a feasibility study.

2. PREVIOUS WORK

The terms *Cognitive Radio* and *Spectrum Pooling* were both defined by Joseph Mitola III within his Dissertation *"Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio"* [**MITOLA_00**]. He suggests the following definition for Cognitive Radio:

“The term cognitive radio identifies 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 Cognitive Radio 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 and supposably soon available resources. Much of the work in [**MITOLA_00**] deals with learning and reasoning capabilities of Cognitive Radios used to fulfill this goal. Interestingly enough, the idea of a system supporting selection of the best possible modus operandi over multiple technical variants, using different frequency spectrum has been already presented in [**FETT_96**], [**BRONZ_97**] under the name IBMS (Integrated Broadband Mobile System) where also the concept of a universal signaling channel supporting the organization of such system has been introduced.

Although the term Cognitive Radio has been defined originally as an extension to software radios ([**MAGUIRE_99**] introduced originally in [**MITOLA_92**]), which is able to reason about external factors, recently the term Cognitive Radio is mostly used in a narrower sense. FCC [**FCC_03322**] suggests that any radio having the 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 is 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 anyway a high degree of flexibility since the radio environment is highly variable, both because of channel variation and interference.

The notion of **Spectrum Pooling** was first introduced in [**MITOLA_99**]. Spectrum for mobile networks is limited but at the same time many frequencies are only sporadically used. Most of today’s spectrum is owned by license owners (GPRS, UMTS, emergency services, broadcast TV...) who could provide their unused spectrum to so called Secondary Users (SU). *"In this resource sharing strategy called Spectrum Pooling the license owner would get the highest priority*" [**CAPAR_02**]. Once a Primary User (= license owner) appears in a frequency band all secondary users would have to clear this band giving priority to the license owner.

There are two principle possibilities for a license owner to access spectrum [**CAPAR_02**]:

1. It searches for free frequencies within the licensed frequency range. The license owner has the right to reclaim frequencies from secondary users who are operating within that band. This approach requires the license owner to be able to detect secondary users and probably even to communicate with them. There is an underlying assumption that the license owner does not necessarily need the use of the entire controlled spectrum and is willing to share it under certain constraints.

2. In the second approach the license owner has no knowledge about secondary users. Consequently it just claims some frequency within its frequency band forcing a secondary user to change to other unoccupied frequencies.

In both approaches Secondary Users have to sense the spectrum in order to detect unused frequencies before they acquire spectral resources. They also have to continuously sense the frequencies they use in order to detect (re)appearing Primary Users. For the first approach the primary user might possibly inform the secondary user about his intended reappearance before acquiring its spectrum thus eliminating the need for continuous sensing.

Depending on physical characteristics of the spectrum Mitola III defined four spectrum pools that allow to realize the idea of spectrum pooling [**MITOLA_99**]: very low band (26.9 - 399.9 MHz), low band (404 - 960 MHz), mid band (1390 - 2483 MHz) and high band (2483 - 5900 MHz). Depending on bandwidth requirement, propagation distance and other traffic characteristics one of these pools can be used. Capar et al. [**CAPAR_02**] defined a pool as *"a contiguous spectrum, which can be used by renter processes"*. They organized pools supporting the same kind of applications (i.e. bandwidth, QoS, propagation requirements etc.) into pool groups.

Mitola III envisioned an approach of renting unused spectrum to secondary users. Management authorities would have to be introduced in order to manage the unused spectrum and the price depending on bandwidth, location, interference level etc. Secondary users could then get cost-effective spectrum access using cognitive radio. They would schedule their transmissions dependent on urgency, available resources, or price. An email, which is written during a taxi ride to the company for example would not be sent using expensive GPRS technology but would rather be delayed and sent using the companies, wireless LAN.

A cognitive radio / spectrum pooling architecture has been developed at the University of Karlsruhe. Weiss and Jondral [**WEISS_04**] have defined a centralized spectrum pooling architecture based on OFDM. They envision an 802.11 like access-point based 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. Using OFDM has the advantage to be able to feed certain sub-carriers with zeros resulting in no emission of radio power on these carriers (occupied by licensed users). The use of OFDM also enables the analysis of the spectral activity of licensed users at no extra cost, as an FFT is required anyway.

In this solution in order to detect primary users the base station periodically broadcasts so called *detection frames* which are frames containing no data at all. During that period all mobile users perform sensing of the spectrum. All the sensing data has to be gathered at the base station, which would take considerable time using traditional medium access techniques. Thus a *boosting* protocol is used omitting the MAC layer and using only the physical layer for signaling. All mobile terminals (but the base station) modulate a complex symbol at maximum power in those sub-carriers where a licensed user appeared, i.e. only those sub-carriers that were not occupied by a licensed user before. If all mobile terminals do this simultaneously the base station would receive an amplified signal on all sub-carriers with new licensed users resulting in a high reliability for the detection. Although this causes extra interference to the licensed users the *boosting* period is short enough to neglect it. Additionally this is only done for sub-carriers with newly detected licensed users. In a second period of the *boosting* protocol all disappeared licensed users are determined. Weiss and Jondral [**WEISS_04**] also investigated the problem of mutual interference. Both systems put additional interference on each other as spectral resolution and FFT operations are not perfect. A remedy to limit this interference is to disable adjacent sub-carriers next to the active license owners – resulting in a decrease of available bandwidth to the rental system on the other hand.

DARPA followed a much more general approach and tries to define an architectural framework based on a “vision” paper within the neXt Generation (XG) program to implement policy based intelligent radios [**XG_VISION**]. DARPA’s XG aims to address the problem of having radios with regulable kernels, which can be controlled via policy rules. This allows radios to transcend regulatory borders with simple policy changes. XG radios are capable of sensing the environment to determine unused spectrum (opportunity awareness), use policy constraints to allocate these channels (opportunity allocation) among a group of radios that together form an XG-domain and to determine mechanisms for using those channels (opportunity use) [**XG_ARCH**]. As with any multi-user network, centralized and distributed variants of the three functions (awareness, allocation and use) are possible.

Regulatory domains are realizing the need for new technologies in order to efficiently using available spectral resources as well. Recent studies by the Federal Communications Commission's (FCC) Spectrum Policy Task Force (SPTF) have reported vast temporal and geographic variations in the usage of allocated spectrum with utilization ranging from 15% to 85% [**FCC_DB**]. In order to utilize these 'white spaces', the FCC has issued a Notice of Proposed Rule Making [**FCC_03322**] advancing Cognitive Radio (CR) technology as a candidate to implement negotiated or opportunistic spectrum sharing.

The FCC would like to use the sensing and self-modification capability of the cognitive radio to address the following applications:

- Increasing Transmitter Power by 8 dB in areas with low population density and low spectrum usage (defined as rural areas). CRs should be capable of sensing 'low spectrum usage' and increasing transmit power accordingly.

- Interruptible Spectrum leasing by a primary user to a secondary user. The secondary user must have sensing capability to determine unused spectrum and to recognize spectrum assignment/revocation 'beacons' from the primary user. This method is well suited for public safety channels.

- Dynamically coordinated spectrum sharing using knowledge of temporal and spatial characteristics of users.

- Facilitating interoperatibility between systems by using CRs to receive and transmit using different modulation/coding/error correction formats.

- Multi-hop RF networks using Transmit Power Control (TPC) and environment determination properties of CRs.

3. SYSTEM OVERVIEW

In this section we explain the principles of CORVUS. 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 legally owns some **frequency band (F-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 F-Band. On the other hand, a Secondary User (SU) is an entity that wants to acquire unused spectrum of license owners (Primary Users) for its own communication. 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, SUs have constrained access to a Primary User F-Band. SUs can use an F-Band (or parts of it) as long as the corresponding Primary User is not using it. A Secondary User cannot use any F-Band currently used by a PU. Concurrent use of Primary and Secondary Users for specific PU systems is subject to further studies. A Primary User PU_x can tolerate a maximal interference of 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 the PU must have a free F-Band in order to communicate which means that all SUs have to clear the frequencies belonging to the F-Band within this time period. Even if a Secondary User is currently using parts of a F-Band, the PU assumes that his/her F-Band is empty and starts the transmission without informing the SU. For PU systems using carrier sensing protocols a SU operating in that F-Band hence 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 reliably monitor the presence of Primary Users (at least every Δt_x). Detection of Primary Users is based on **Primary User Footprints (PUF)** assumed to be available in the SU System a priori. PUF include but are not limited to the information from FCC's spectrum inventory table [**FCC_DB**]. Additional information could be local characteristics of PUs such as average communication times or peak hours, etc.

Firstly, before start of any activity the SU has to sense for PUs to ensure that it does not disturb PU communication. Furthermore, a SU has to periodically sense for PUs on the frequencies that it is currently using and back off as soon as a PU tries to access that frequency band (F-Band). SUs should, however be able to organize (or re-organize) the usage of the spectrum so, as to compensate the possible re-claim of frequencies by Primary Users with minimum loss of service quality and service reliability for the Secondary User.

In our system model, SUs form **Secondary User Groups (SUG)** to coordinate their communication. Members of a SUG might communicate with each other in an ad-hoc modus or, alternatively access a fixed infrastructure via a dedicated access point, being part of an existing networking infrastructure, most frequently the Internet. Communication between Secondary Users from different SUGs is not possible.

In either mode we assume only a unicast communication, either between a pair of SUs or between a SU and the access point (broadcast is not supported by our SU system). In both cases organization of the communication might be either distributed, or centralized, with a specific station acting as leader. The traffic pattern for the Secondary Users is wireless-LAN-like and comes mostly in two flavors:

1) Web traffic where Secondary Users are primarily interested in Internet access. Web traffic implies that there has to be some kind of a base station / access point providing connection to the Internet. Consequently this kind of traffic would most likely use an infrastructure based (centralized) approach.

2) Ad hoc networking covers all kinds of ad-hoc traffic that does not assume any infrastructure where the main purpose is to communicate with each other and exchange information within a SUG. This traffic pattern obviously suggests an ad-hoc (distributed) approach.

CORVUS operates in a large **Spectrum Pool** covering a broad frequency range from tens of MHz to several GHz creating a “virtual unlicensed band” with usage capabilities comparable to the ISM/UNII frequency bands. A Spectrum Pool is defined as a (not necessarily contiguous) frequency range used by a Secondary User Group (SUG). Spectrum Pools of different SUGs may overlap and different SUGs will compete for the available resources.

Each Spectrum Pool will be divided into n **Sub-Channels** (where n computes to: “size of the spectrum pool” divided by “size of a sub-channel”). The size of a Sub-Channel should be selected such, that a single Sub-Channel is a (rather small) part of any F-band defined in the Spectrum Pool.

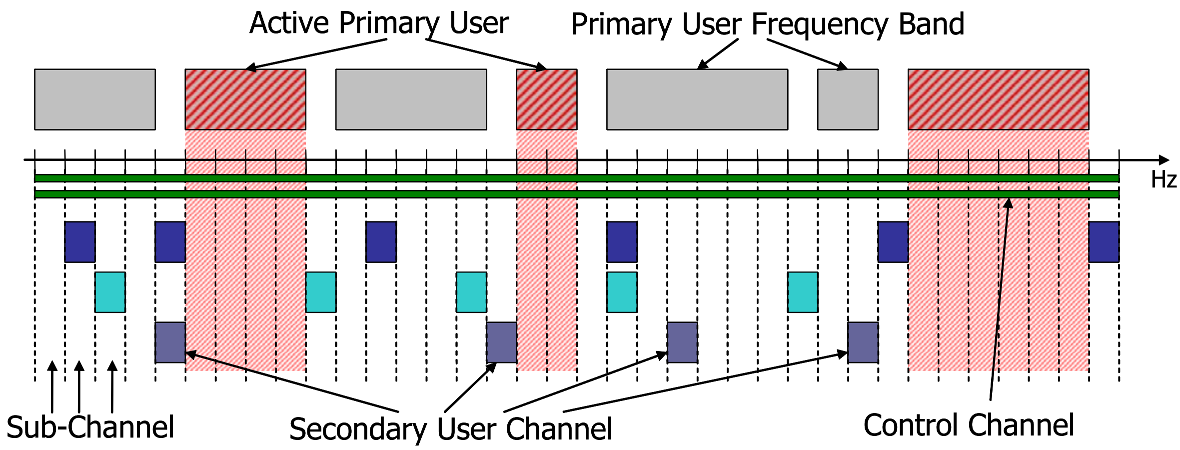

Figure 3 Spectrum Pooling Idea

Figure 3 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 certain time. The (red-)shaded F-Bands indicate that the PU is currently using its spectrum and consequently this F-Band cannot be used by any SU. The figure 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 (SUL)**. The number of Sub-Channels may vary depending on the quality of the Sub-Channels, the bandwidth of a single Sub-Channel and QoS requirement for that connection.

As basic principle of CORVUS the Sub-Channels selected to create a Secondary User Link should be scattered over multiple F-Bands, ideally only one Sub-Channel should be taken out of any F-band. This principle has a double significance. On one hand it limits the impact of the secondary user on the re-appearing primary user (for example the carrier sensing function of the Primary User might ignore the existence of the Secondary User). On the other hand if a Primary User appears during the lifetime of a SUL it would impact very few (preferable one) of the Sub-Channels used by the SUL. The communication peers using that link would have to immediately clear the affected Sub-Channel and would start to find a new free Sub-Channel instead. In fact in order to keep a continuous QoS Secondary Users should always have a redundant amount of Sub-Channels for their SUL.

Within CORVUS, Secondary Users 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 (UCC)** and **Group Control Channels (GCCs)**. The UCC is globally unique and has to be known to every SU a priori. Without the knowledge of that control channel a SU has no communication possibilities. The main purpose of the UCC is to announce existing groups and enable newly arriving users to join a group. Additionally SUs, which want to create a new group, can request the local PUF on that channel. Although globally unique the communication range should be locally limited as SUGs are as well limited to a local area. In addition to the UCC each group has one logical GCC for the exchange of group control and sensing information. Control channels will carry a limited load of low-bit rate signaling. These control channels might be:

a. located in some spectrum licensed specifically for this purpose

b. located in one of the ISM bands

c. UWB (Ultra Wide Band).

We identify the option c as especially attractive (although do not preclude usage of options a or b). Unlicensed character, low impact on other types of communication, the limited distance covered, and the possibility to operate independently with different codes makes out the attractiveness of this option.

Note that the Universal Control Channel and the Group Control Channels are logical concepts, which might even be mapped to a single physical channel!

Figure 3 illustrates the idea of the control channel used by Secondary Users. In this example we used UWB (Ultra-Wide-Band) for the control channel.

4. METRICS FOR SYSTEM EVALUATION

For system design purposes we will need to define metrics that will guide our development. These metrics need to be sufficiently broad, that a realistic system can be designed through an optimization of all the metrics that we define. This would therefore need to include metrics to measure the performance of the CR network, the effectiveness of the design to achieve the CR requirements of non-interference and spectrum reuse and the cost in hardware to implement such a system. There are therefore 3 basic dimensions that we need to optimize (always should be 3!), Performance, CR specific metrics, and hardware costs.

1) Performance metrics:

Performance metrics will be based on a traditional WLAN scenario. This, however, could be expanded to other use models (e.g. point-to-point links, streaming data, etc.) in the future.

a) Saturation Throughput (link level)

Every station in the CR network transmits as much data as possible and the throughput, T (bytes/sec), is calculated for each of them. Both the total throughput as well as the fairness (differences in the throughput achieved by individual stations) are of interest. The following parameters must be set to have useful comparisons (maybe more need to be defined):

Packet length distribution

Channel model

Station distribution (distance to base station or network topology for ad hoc)

b) Delay vs. system load (link level)

There are N stations each of which has a packet of P bytes available for transmission every X seconds. The load in bytes/second is defined as L= N*P/X. A relative load can be defined which is the fraction of the nominal station data rate, B [bits/second], as S= 8L/B. The Delay, D, mean and variance is then calculated as a function of S. The nominal rate could be one value if the radios are not adaptive, or could be the peak value for adaptive radios. This clearly will depend on the inter-packet arrival time distribution and on parameters of metric 1 a) as well.

2) CR Interference and Efficiency metrics:

The CR specific metrics relate to how well the CR is able to avoid Primary Users and the efficiency in using available spectrum. This will require a model for Primary User dynamics, such as disappearance and reappearance time intervals, the amount of spectrum being used and the strength and location of the PUs.

a) Interference metric: The fraction of time that a CR interferes with a Primary User. Normalized to the amount of spectra being used by PUs and the size of the Spectrum Pool.

b) Spectrum efficiency: How efficiently the CR is able to recapture the Primary User spectra.

This can be expressed as a fraction of time in which spectrum not claimed by Primary User cannot be used by the Secondary User in spite of existing demands of SUs. This again should be normalized as above.

This metric is basically the complement to metric 2a). As a permitted interference decreases, the efficiency will likely degrade.

3) Hardware metrics:

Employing an expensive solution, which may dissipate excess power, can make an improvement in the above metrics. Hence it is important to quantify the overall cost of the implementation platform in terms of area, power and per-unit cost.

a) Power (PHY level)

This metric captures the total amount of power required as a function of throughput, interference and efficiency. Critical design parameters will be the power required for the A/D, which we can get as a function of the number of bits, speed and bandwidth. Similarly we can define power levels for varying levels of the ability to resolve signals in the presence of interference (more power is required as linearity is increased). The use of active cancellation will reduce some of the analog power costs (such as the A/D) but will add new costs. We can use power estimates such as MOPS/Watt to estimate the power dissipation due to the digital processing.

b) Area on the chip for a given technology (PHY Level)

Rough estimates for the critical radio functions are available. Some things are relatively easy to estimate, for example the cost of multiple antenna solutions have a multiplicative cost as a function of the number of independent channels resolved. For the digital processing we can use MOPS/mm^2 estimates from available evaluations of the technologies.

5. 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 not of interest in this paper.

Figure 4 shows the main building blocks for the deployment of our Cognitive Radio system. We identify six systems functions and two control channels that will implement the core functionality of our baseline Cognitive Radio design. This section gives an overview and brief description of the system functions. Details of these functions and possible implementations will be discussed in a follow up paper.

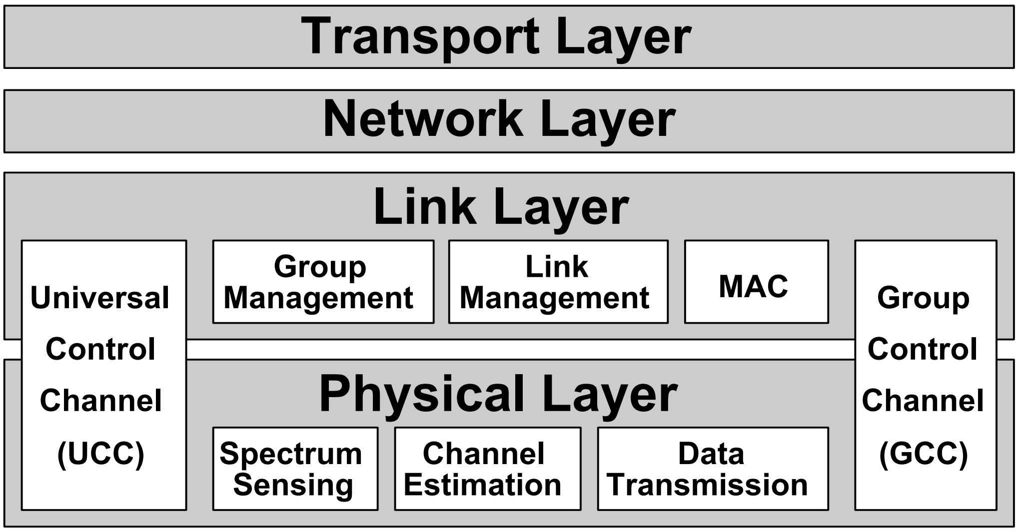

Figure 4 General ISO/OSI Stack for a Cognitive Radio

The six system functions can be split between the physical and the link layer. Whereas the physical layer is responsible for sensing the spectrum, detecting active Primary Users and estimating the quality of the Sub-Channels, the link layer has to deal with group management, link setup and maintenance and handle the medium access of the Sub-Channels.

Physical Layer Functions

1. Spectrum Sensing

The main function of the physical layer is to sense the spectrum over all the available degrees of freedom (time, frequency and space) in order to identify Sub-Channels currently available for transmission. From this information, Secondary User Links (SUL) 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 Secondary Users 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 Secondary Users to exchange and merge their local sensing information in order to optimally detect interfering Primary Users. This cooperation between SUs within a communicating group will be important to realize adequate accuracy of interference activity. Merging of interference information form different SUs becomes especially interesting considering an optimal utilization of the available spectral resources using directed antennas.

2. Channel Quality Estimation

On link setup channel sounding is used to determine the quality of Sub-Channels between Secondary Users that want to communicate. The transmission parameters (sending power, bit rate…) are determined based on the sounding results. The physical layer also continuously estimates the quality of Sub-Channels analyzing the data packets received during an ongoing communication.

3. Data Transmission

A flexible radio is required to optimally use the environment as determined by the spectrum sensing and channel estimation functions described above. This radio will 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). The most likely basic strategy will be based on OFDM-like modulation across the entire bandwidth in order to most easily resolve the frequency dimension with subsequent spatial and temporal processing.

<u>Link Layer Functions</u>

4. Group Management

We assume that any secondary station will belong to a Secondary User Group (SUG). A newly arriving user can either join one of the existing groups or create a new one. The Universal Control Channel (UCC) is used for group management. New arriving users will be able to get all information necessary to join a specific group. Additionally a Secondary User who wants to create a new group will be able to get all necessary information using the UCC.

5. Link Management

Link management covers the setup of a link in order to enable the communication between two Secondary Users and afterwards the maintenance of this Secondary User Link (SUL) for the duration of the communication. The link layer will choose a pattern of Sub-Channels in order to create a Secondary User Link (SUL). Which Sub-Channels to choose depends on various factors such as information from the sensing function (Sub-Channels with Primary User Interference cannot be used), channel estimation (quality of specific Sub-Channels) as well as user-defined and/or regulatory policies (e.g. distribute Sub-Channels used over different Primary User F-Bands). Once the SUL is established the link layer has to maintain the link. The physical layer may sense Primary Users trying to access their Frequency Band requiring the link layer to vacate the corresponding Sub-Channels and acquiring new Sub-Channels. Packet losses on certain Sub-Channels may cause the link layer to vacate these Sub-Channels as well and switch to others with better quality.

6. Medium Access Control

The Medium Access Control (MAC) is probably one of the most challenging tasks for our Cognitive Radio system. As long as it can be assured that all Sub-Channels are used exclusively, i.e. all Sub-Channels used by one Secondary User Link (SUL) cannot be used by any other SUL this problem comes down to a simple token-passing algorithm ensuring that only one of the two communication peers is talking at a time. 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 very realistic. So the MAC has to provide means to concurrently access a SUL by Secondary Users or – worst case – even to manage the concurrent access of individual Sub-Channels by different connections of different Secondary Users.

6. CONCLUSION

In this white paper we present the CORVUS system concepts to harness unused frequency bands for the creation of virtual unlicensed spectrum. The motivation for this approach comes from the popularity of WiFi operating in the unlicensed ISM bands and the realization that licensed spectra is highly underutilized.

Cognitive Radios (CR) 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.

Previous work in this area can be categorized as: (1) development of agile radios (2) definition of radio etiquette to allow disparate radio systems to work with each other and (3) spectrum leasing policies. CORVUS on the other hand, is focused on opportunistic spectrum use, using temporal and spatially available degrees of freedom.

In the CORVUS architecture, a group of Cognitive Radios forms a Secondary User Group (SUG) to coordinate their communication. Each member of the SUG senses the Spectrum Pool, which is divided into Sub-Channels. A pair of SUs pick a set of Sub-Channels spread over multiple Primary Users F-Bands to form a Secondary User Link (SUL). Sub-Channels are picked based on estimated channel gain of a Sub-Channel and a user's QoS requirements. Furthermore, chosen Sub-Channels are scattered over frequency bands (F-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 (UCC) is used by all groups to announce themselves. Members of a group use separate Group Control Channels (GCC) to exchange sensing information and establish SULs.

Further analysis of CR system functions at the physical and link layer with specifications and parameters for a first implementation will be addressed in two white papers to follow.

7. ACRONYMS

Cognitive Radio (CR) – A radio having cognitive radio capabilities

Primary User (PU) – Entity, which owns a frequency band (F-Band) or several and thus has primary access rights to it.

Secondary User (SU) – Cognitive Radios that compete for unused spectrum.

Secondary User Group (SUG) – A group of SU that communicate with each other.

Spectrum Pool – The (not necessarily contiguous) spectrum used by a SUG.

Frequency Band (F-Band) – A channel of a PU. There are usually several F-Bands within a Spectrum Pool.

Sub-Channel – Segment of the Spectrum Pool. The Spectrum Pool is divided into a number of Sub-Channels. An F-Band may span a set of consecutive Sub-Channels.

Secondary User Link (SUL) – A set of Sub-Channels allocated to a pair of SU. The SU users use these Sub-Channels to transmit the data.

Spatial Sub-Channel – An angular fraction of a Sub-Channel in case directional antennas are used.

Maximal interference time (Δt_x) – Time within which all SUs must vacate all Sub-Channels belonging to a specific F-Band once the PU appears in that F-Band. This time is PU specific.

Primary User Footprint (PUF) – Information about a PU covering the FCC's spectrum inventory table plus additional local information on that PU

Primary User Interference (PUI) – Interference caused by a PU

Secondary User Interference (SUI) – Interference caused by a SU

8. REFERENCES

[**BRONZ_97**] M. Bronzel, D. Hunold, G. Fettweis, T. Konschak, T. Doelle, V. Brankovic, H. Alikhani, J.-P. Ebert, A. Festag, F. Fitzek, and A. Wolisz, "Integrated Broadband Mobile System (IBMS) featuring Wireless ATM", In *Proc. of ACTS Mobile Communication Summit 97*, pp. 641-646, Aalborg, Denmark, October 1997

[**CAPAR_02**] 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.

[**FCC_DB**] URL http://www.fcc.gov/oet/info/database/spectrum/

[**FCC_02155**] FCC. Et docket no. 02-155. Order, May 2002.

[**FCC_03322**] FCC. Et docket no. 03-322. Notice of Proposed Rule Making and Order, December 2003.

[**FETT_96**] G.-P. Fettweis, K. Iversen, M. Bronzel, H. Schubert, V. Aue, D. Maempel, J. Voigt, A. Wolisz, G. Walf, and J.-P. Ebert, "A Closed Solution for an Integrated Broadband Mobile System (IBMS)", In *Proc. of Intl. Conf. on Universal Personal Communications (ICUPC'96)*, pp. 707-711, Cambridge, Massachusetts, USA, October 1996.

[**MITOLA_99**] Joseph Mitola III. Cognitive radio for flexible mobile multimedia communications. In *Sixth International Workshop on Mobile Multimedia Communications (MoMuC'99)*, San Diego, CA, 1999.

[**MITOLA_00**] Joseph Mitola III. *Cognitive Radio An Integrated Agent Architecture for Software Defined Radio*. PhD thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2000.

[**MAGUIRE_99**] Joseph Mitola III and Gerald Maguire Jr. Cognitive radio: Making software radio more personal. *IEEE Personal Communications*, 6:13–18, august 1999.

[**MITOLA_92**] Jospeh Mitola III. Software radios-survey, critical evaluation and future directions. In *IEEE National Telesystems Conference*, pages 13/15–13/23, New York, 1992.

[**WEISS_04**] Timo Weiss and Friedrich Jondral. Spectrum pooling: An innovative strategy for the enhancement of spectrum efficiency. *IEEE Communications Magazine*, 42:S8–S14, march 2004.

[**XG_ARCH**] Darpa XG working group. The xg architectural framework rfc v1.0, 2003. URL http://www.darpa.mil/ato/programs/XG/rfc_af.pdf.

[**XG_VISION**] Darpa XG working group. The xg vision rfc v1.0, 2003. URL http://www.darpa.mil/ato/programs/XG/rfc_vision.pdf.

[**DOAN_04**] C. Doan, S. Emami, A. Niknejad and R. Brodersen. Design of CMOS for 60 GHz Applications. *IEEE International Solid-State Circuits Conference Digest of Technical Papers,* 2004.

[**TSE_03**] S. Y. Poon, D. N. C. Tse, and R. W. Brodersen. An adaptive multiple-antenna transceiver for slowly flat-fading channels. *IEEE Trans. on Communications*, vol. 51, pp. 182Õ1827, Nov. 2003.

[**POON_03**] 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 2003.