The Smart Radio Channel Change Protocol
A Primary User Avoidance Technique for Dynamic Spectrum Sharing Cognitive Radios
to Facilitate Co-Existence in Wireless Communication Networks

Mark D. Silvius, Rohit Rangnekar, Allen B. MacKenzie, Charles W. Bostian
Center for Wireless Telecommunications (CWT), Wireless@Virginia Tech
302 Whittemore Hall – MC0111, Blacksburg, VA, USA, 24061
[msilvius, rangnek, mackenab, bostian]@vt.edu

Abstract—This paper details the design, implementation, simulation, and testing of the Smart Radio Channel Change Protocol (CCP), a primary user avoidance technique for dynamic spectrum sharing cognitive radios in wireless communication networks. The CCP enables a digital cognitive radio to detect the presence of legacy analog or digital radios, and to facilitate channel-change procedures to use an alternate, vacant block of spectrum. This allows primary and secondary users to co-exist in the same band with minimal interference and reductions in quality of service (QoS). The CCP also provides an advantage to other systems’ frequency management schemes in terms of simplicity of design and execution. We evaluate the CCP’s performance through OMNeT++ simulations and experiments in a five node laboratory network testbed. We present our results in terms of the CCP’s ability to detect and avoid the primary user and record its improvement to user QoS.

Keywords—Primary User Avoidance; Dynamic Spectrum Sharing; Cognitive Radio; Wireless Network Co-Existence; OMNeT++; GNU Radio

I. INTRODUCTION

White space studies highlight the underutilization of the frequency spectrum and emphasize the utility of dynamic spectrum sharing communication systems [1]. Here, secondary users operating in this scenario would need to detect the presence of an actively transmitting analog or digital radio, and immediately vacate the channel, resuming channel on a different unoccupied channel. An existing, fixed wireless data communications system, such as 802.11 WiFi, would be a poor choice for a secondary user system. Currently, this system does not fulfill the sensing and adaptability requirements needed to be used as a secondary user scenario. This traditional wireless LAN technology has little provision to continually sense the channel for primary users, or to adapt and reconfigure itself to use an alternate channel when the primary user appears. As a result, its data communications would be corrupted from the interference from the primary user, in same way it would corrupt the voice/data communications of other primary users with its interference.

In an experiment, we demonstrated that 802.11 WiFi could easily be degraded by other wireless communications waveforms. In this mock scenario, WiFi had a noticeable decrease in QoS even with a single burst of data from primary user transmitting a GMSK waveform, as shown in Figure 1. The reverse would be true for the primary user as well.

II. PROPOSED SOLUTION

To address this deficiency, we present a straightforward and flexible primary user avoidance technique—the Smart Radio Channel Change Protocol (CCP). This protocol could be retrofitted in an existing wireless LAN technology like 802.11 WiFi, or be readily implemented in a software defined radio (SDR) based cognitive radio. This radio access protocol allows a secondary user to avoid the interference generated by competing legacy analog and digital primary user radios in the environment, so as to improve overall user QoS. We apply our initial prototype to the problem of co-existence between digital cognitive radios and analog and digital radios in a wireless communication network. This paper builds on CWT’s recent efforts in cognitive radio and dynamic spectrum access systems [2-5].

A. Conceptual Operation

The first task of the CCP is primary user detection. We exploit the frame length to distinguish between the primary and secondary waveforms. We use a timer, coupled to the PHY and MAC layers of the base system to measure the lengths of
the incoming transmissions. The system starts the timer when the PHY and MAC layers detect the presence of the carrier of an incoming frame. If a complete digital frame is received and demodulated within the predicted signal duration, the CCP resets the timer. If the signal persists longer than the expected frame duration, the CCP warns the radio resource manager that a primary user has been detected. At this point, the resource manager—such as a master control module or cognitive engine—can pause the current communication session, and direct the PHY and MAC layers to change to a different operating frequency.

Although the proceeding discussion explained how the CCP incorporated into a digital radio could detect and avoid an analog radio, the same principles could be used to distinguish between two different digital radios. The technique is equally applicable to digital waveforms such as BPSK, QPSK, 8PSK, and GMSK. The primary user would need to have a well-known digital signal structure, and its standard frame length would need to be longer than that used by the secondary user system.

![Figure 2. Modifications to GNU Radio protocol stack to support the CCP. In particular, this diagram highlights the operation of carrier sense (CS) module and transmission (TX) and receive (RX) modules.](image)

**III. Evaluation**

To evaluate the performance of the CCP, we relied on simulations using OMNeT++ and lab experiments using a five node network testbed.

**A. Simulations**

OMNeT++ is open-source, discrete-event simulation tool used to model the performance of network protocols [8]. For this simulation, we wrote a simplified protocol stack based on the IEEE 802.11 standard. As in the GNU Radio case, we enhanced the typical CSMA implementation, by adding an additional carrier sensing timer required by the CCP. Our simulation scenario involved six secondary users and one primary user, as shown in Figure 3. Secondary users used a digital waveform with a fixed frame length, and the primary user used an analog waveform with a longer frame length, with sufficient signal strength so as to be in range of all secondary users.

![Figure 3. Our OMNeT++ simulation scenario with six secondary users and one primary user.](image)

Figures 4-7 summarize the results of our simulations where a primary user began transmitting at t=2.22 and t=4.62. First, Figures 4-5 record the measured in-channel interference strength (i.e. signal + noise + interference power) received by each of the secondary user radios nodes in the network. In the CCP case, the technique reduced the total duration of the received in-channel interference from 1.4s to 0.26s—an interference reduction of approximately 81.4% from the non-CCP case. Second, Figures 6-7 depict the time plot of the MAC layer, i.e more specifically the dots indicate when Nodes 1 and Node 4 transmitted and received frames. The large horizontal gaps between the points indicate delays (i.e. latencies) resulting from outgoing frames being queued, rather than transmitted as result of primary user interference. Mirroring the previous results, these timing plots show that the overall average system interference decreased by approximately 81.4% in the CCP-enabled case. Third, we measured average goodput and packet loss incurred during the simulation, as a function of the secondary user’s frame length, for the both the CCP and non-CCP case. For the CCP-enabled case, received goodput increased by 21% to 40Kbit/s and packet loss decreased by 25% to an average loss rate of 22%.
**B. Laboratory Experiments**

In addition to software simulations using the OMNeT++, we also evaluated the performance of the CCP by using CWT’s five node network testbed. Our physical laboratory setup matched the simulation setup in Figure 7, except that we used four secondary user nodes and one primary user node. The first four nodes were cognitive radio nodes, built using the GNU Radio and the USRP, housed on Linux-based laptop computers, and running the CCP. The fifth node acted as a primary user and source of interference. In all our experiments, the primary user transmitted twice, first at $t=10-20s$ using analog FM, and then at $t=30-40s$ using GMSK. All secondary users used GMSK at 500Kbit/s using a maximum frame length of 2200 bytes. The primary user, when in digital mode, also transmitted GMSK at 500Kbits/s, but with a minimum frame length of 2500 bytes.

First, to measure the QoS of the network formed by the secondary users, we used the IPERF open source software tool [9]. IPERF allowed us to measure the UDP goodput, packet loss, and jitter of the three-hop path from Node 1 to Node 4. When configuring IPERF, we used a stream of 1 Kbyte sized UDP segments at an offered rate of approximately 100 Kbit/s. By transmitting our test stream at less than our link rate of 500 Kbit/s, we ensured that there was space between the outbound transmitted frames, and therefore, our IPERF generated plots were generally smoother and more reproducible. We also used the standard PING command, available in Linux, to measure the round-trip-time along this path.

Figure 8 shows the UDP goodput response of the four node cognitive radio network. In the non-CCP case, the effective goodput of the secondary user network essentially dropped to zero during the two 10s intervals where the primary user is transmitting. Note that at $t=32s$ and $t=36s$, the secondary user network was able to successfully transmit and receive a handful of packets, slipping them past the primary user, during the inter-packet quiet periods of the primary user’s transmission cycle. In the CCP case, the technique was able to successfully detect the presence of the primary user and then switch to an alternate operating channel. The periods of network outage due...
to interference dropped by over 50%, from 10s to 5s, resulting in a 33% increase in goodput. Moreover, the width of the trough in the CCP-case represents a maximum of 4-5s of “switching time,” specific to our SDR platform’s implementation. In additional measurements, we also recorded the jitter, packet loss, and latency response in the UDP stream from Node 1 to Node 4. The CCP technique, with its ability to avoid the primary user, reduced the periods of instability from 10s to approximately 4-5s, and reflected 65%, 55%, and 42% decreases in these metrics respectively.

Second, we evaluated the precision of the CCP’s threshold in detecting the primary user. In this experiment, we designated that the maximum secondary user packet size to be 2200 bytes. We set our goal CCP threshold to be slightly higher than this value, at 2300 bytes. Then we had the primary user send a stream of digital frames with frame lengths varying between 100 bytes and 4096 bytes, with step sizes of 100 bytes. We recorded the results for three network conditions: first, when the network was idle; second, when Node 1 streamed packets to Node 3 at an offered rate of 50 Kbit/s; and third, when the network was idle; second, when Node 1 streamed packets to Node 3 at an offered rate of 50 Kbit/s; and third, when Node 1 streamed packets to Node 3 at an offered rate of 50 Kbit/s. The resulting curve in Figure 9, shows that the detection break-point occurred sharply at 2350 bytes, as desired. Detection reliability was also the highest for the idle condition and gradually decreased as the offered rate increased.

IV. DISCUSSION

Although we first introduced the conceptual operation of the CCP in [4], at that time, our evaluation consisted of a simple scenario consisting of two digital cognitive radio secondary users and one analog FM primary user. Initial observations established that the CCP-enabled cognitive radios did successfully detect the FM radio and switch to a vacant channel, when its user keyed the audio microphone. However, this paper quantified to what degree the CCP improved the network QoS of a multi-hop configuration of cognitive radios, and it evaluated the reliability of the detection scheme under varying offered network loads. It also verified that the CCP performed as initially conceived in [4], through the use of OMNeT++ simulations and five node laboratory experiments.

Table I summarizes the results of both the OMNeT++ simulations and the five node experiments. Both sets confirmed that the CCP did indeed improve the network QoS metrics. Although, implementation differences in the protocol stacks of OMNeT++ and GNU Radio prevent us from doing an exact comparison, the performance trends coincide and verify that the CCP does operate as conceived, enabling wireless co-existence between primary and secondary users.

### Table I. QoS Improvements with CCP Technique Over Baseline

<table>
<thead>
<tr>
<th>QoS Metric</th>
<th>Simulation Result</th>
<th>Experimental Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interference Duration</td>
<td>-1.14s (-81%)</td>
<td>≤-5s (≤-50%)</td>
</tr>
<tr>
<td>Goodput</td>
<td>+40Kbit/s (+21%)</td>
<td>+24Kbit/s (+37%)</td>
</tr>
<tr>
<td>Jitter</td>
<td>n/a</td>
<td>-25ms (-67%)</td>
</tr>
<tr>
<td>Packet Loss</td>
<td>-22% loss (-25%)</td>
<td>-25% loss (-64%)</td>
</tr>
<tr>
<td>Latency</td>
<td>-1.14s (-81%)</td>
<td>-59ms (-29%)</td>
</tr>
</tbody>
</table>

B. Reliability: Offered Rate versus Probability of Detection

The threshold results in Figure 9 highlight a noteworthy trade-off between available network bandwidth and primary user detection reliability. As the system’s maximum offered rate was reduced, the spectral awareness of the radio increased and the probability of cross-network interference decreased. In terms of spectrum sharing protocol design, the offered rate determines the spacing between transmitted packets, known as the “quiet period,” in which the node conducts carrier sensing and primary user detection. For the CCP, the quiet period had to be at least as long as the secondary user’s frame length, but longer quiet periods, further improved the CCP’s primary user detection reliability.

V. CONCLUSION

The CCP offers secondary users a straightforward technique for the detection and avoidance of primary users in its band. This technique allows for reduced interference and improved co-existence between competing communications networks. It can be applied to existing wireless LAN technologies or readily implemented in SDR-based cognitive radios.
Our work was supported by the National Institute of Justice, Office of Justice Programs, US Department of Justice under Award No. 2005-IJ-CX-K017, and by the National Science Foundation under Grant No. CNS-0519959. In addition, we would like to thank the Air Force Institute of Technology (AFIT) for its continued support of this work. The views, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of these sponsors or the official policy or position of the Air Force, Department of Defense or the U.S. Government.

REFERENCES


VI. APPENDIX

This section contains additional figures detailing the results of our QoS experiments.

Fig. A1. A 802.11 WiFi secondary user’ UDP jitter is degraded during the transmission of a primary user with a GMSK waveform, between t=30s to t=40s.

Fig. A2. A 802.11 WiFi secondary user’ packet loss rate is degraded during the transmission of a primary user with a GMSK waveform, between t=30s to t=40s.

Fig. A3. A 802.11 WiFi secondary user’ UDP latency is degraded during the transmission of a primary user with a GMSK waveform, between t=30s to t=40s.

Fig. A4. UDP Jitter during GNU Radio Experiment.
Fig. A5. UDP Packet Loss Rate during GNU Radio Experiment.

Fig. A6. Latency during GNU Radio Experiment.

Fig. A7. Time plot showing the conceptual operation of the CCP. Adapted from [4].

Fig. A8. In our OMNeT++ simulation, the CCP increased goodput (left). Fig. A9. Conversely, the CCP decreased packet loss (right).