SPECTRUM ACCESS FOR FIRST RESPONDERS USING COGNITIVELY INTREPID RADIO EMERGENCY NETWORK

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ABSTRACT

This paper describes the proposed solution provided by Virginia Tech's Team MPRG in the SDR Forum's 2007 "Smart Radio Challenge" design competition to address the problem of spectrum accessing for first responders. It also discusses what changes have been made after the competition and what projects have been emerged depending on the research performed for this competition. Traditionally, communication between first response teams following major disasters such as earthquakes or floods is hampered due to the limitation of fixed--frequency legacy radios. These limitations include the protocols assuming static channels which may leave airways gridlocked and useless, interoperability issues among the radios of various public safety agencies, and lack of simultaneous support of voice and data. A novel system named the cognitively intrepid radio emergency network (CIREN) is proposed for deploying software-defined radio handsets that contain voice and multimedia data communications between mobile nodes to mitigate the mentioned limitations. This paper briefly presents the testing and validation of the developed CIREN protocol. It also summarizes the accomplishments from this project and introduces our preliminary research with Lyrtech SFF-SDR board.

1. INTRODUCTION

First response teams following major disasters such as earthquakes or floods require accurate and reliable radio links to provide voice and data communications between team members. Information such as high resolution area maps, streaming audio, building floor plans, and other pertinent data are imperative to the safety of both rescue personnel and the people they are trying to help. Traditionally, radios use static channels that can only be adjusted by their users, however in such situations there generally exist more radios than available channels. Fixed-frequency radio systems may leave the airways gridlocked and useless, leaving personnel at risk of being without communication when it is needed most. Furthermore, radios from each response team (e.g. the police and fire departments) often cannot communicate with one another, leaving personnel at further risk. Spectrum in licensed bands is particularly underutilized, especially in the UHF television bands. Cognitive networks that employ dynamic spectrum access techniques are capable of sensing unused licensed bands can use them with greater efficiency by creating ad-hoc wireless links between radios.

The CIREN radios developed in this project are capable of supporting voice and data transmission using a channelized frequency allocation. The legacy users are conventional narrow-band FM users. The radios use the family radio service (FRS) spectrum consisting of fourteen 25 kHz wide channels distributed across a range of frequencies between 462MHz to 467MHz in the UHF television band. The CIREN radios establish communication channels by transmitting a beacon signal to rendezvous with the desired user. By continuously scanning the channels when not connected, the intended destination nodes are able to find this beacon quickly. Furthermore, by employing simple cognition algorithms, the CIREN radios are able to manage spectrum resources, gauge link quality, and share their information among other users.

A key issue for these radios is minimizing interference to primary incumbent legacy users. As a secondary user, the radios must constantly sense the spectrum to detect occupants and share the spectrum accordingly. Avoiding incumbent occupants is of particular importance as such radios are the primary users of the spectrum and have superiority over secondary users. When a primary user becomes active on a channel, the radio system adapts by changing frequency without causing a loss of service to either user.

The CIREN radios support two operational modes. The first mode is a 16kbps CVSD-encoded audio link employing QPSK modulation with Reed Solomon channel encoding The second supports a 19.2kbps computer link using half-rate convolution codes and 8-PSK. Additional data formats may be used as required and can be used to support higher data rates and advanced services (such as real-time video streaming) when the channel quality is good. However, even with the two operational modes mandated by the problem statement, the radio can supply voice and data services (such as high resolution maps, floor plans, or images) to first responders. Ultimately, the hand-held units support still-image transmissions to other users and provide a means for displaying this information to the user.

The remainder of this paper comprises eight additional sections. Section 2 describes the CIREN protocol. Section 3 describes the testing and validation of this protocol. Section 4 and 5 discusses FPGA up/down converter and project risks respectively. Summary of accomplishments and improvements are discussed in Section 6 and 7 respectively. Finally, Section 8 concludes this paper and Section 9 presents some references.

2. CIREN PROTOCOL

This section describes the basic functionality of how CIREN radios operating in the FRS band establish and maintain data links. The radios can operate in a master/slave mode with either a point-to-point (PTP) connection, or in a voice broadcast (VB) mode. The protocol specifications are flexible enough to support most basic digital services over voice or data channels. One of the most difficult tasks for this problem has been developing a reliable protocol for rendezvousing with the intended receiver to establish a connection, maintaining link quality, and avoiding incumbent FRS users.

Ad-hoc rendezvous is a difficult problem in wireless communications, particularly when no base station or reliable control channel exist. This is exacerbated by the necessity to share the precious spectrum with incumbent/primary users entering and leaving the FRS channels in a stochastic manner, making this quite possibly the most critical development for this problem.

The link is first established when the user of one CIREN radio invokes the push-to-talk button. This radio, the master node, transmits a beacon on one of the free FRS channels.

While not connected, each receiver scans the 14 FRS channels looking for a beacon signal and gathering information about channel availability. Detected CIREN signals are decoded by the slave node and correlated with its own UID m-sequence (and a special m-sequence for VB mode). The slave node sends a reply when the correlator output is high. Otherwise, after a short time, the receiver will move on to the next channel. This scanning process also allows for the radios to determine which channels are available or, if occupied, what type of user in which the channel currently resides. A graphical depiction of the link establishment can be seen in Figure 1. While in scanning mode, the receiver keeps a database of available channels.
A flowchart of the operational mode in the CIREN radios can be found in Figure 2. This protocol allows for great flexibility in radio networks and can be extended to incorporate ad hoc network packet routing for scenarios where more bandwidth is available.

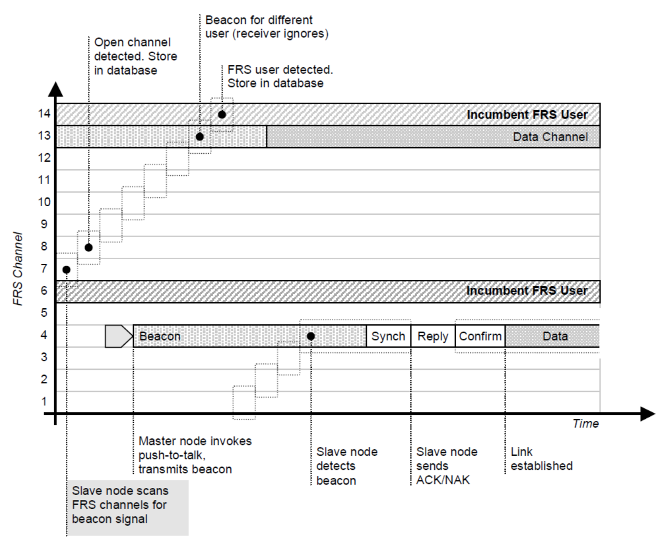

Fig.1: Spectrum access behavior of CIREN system.

3. TESTING AND VALIDATION

Testing and validation is perhaps the most critical stage in system, and it can be, in many ways, the most difficult to execute. Validation of the CIREN system was integrated within development in several major steps: algorithm level, component level, waveform level, and system level. In the following subsections we briefly describe each independent testable feature identified as well as the test case selection process and the infrastructure required to execute them. The detailed procedure and description of these testing and validation can be found in [1].

3.1. Algorithm DSP Prototyping in MATLAB

The majority of the signal processing blocks were prototyped using MATLAB before implementing in C/C++. MATLAB allows for rapid prototyping of source code and an incredibly flexible debugging environment for validating signal processing algorithms. This was particularly critical for the successful implementation of the physical layer synchronizers for symbol timing and carrier phase recovery.

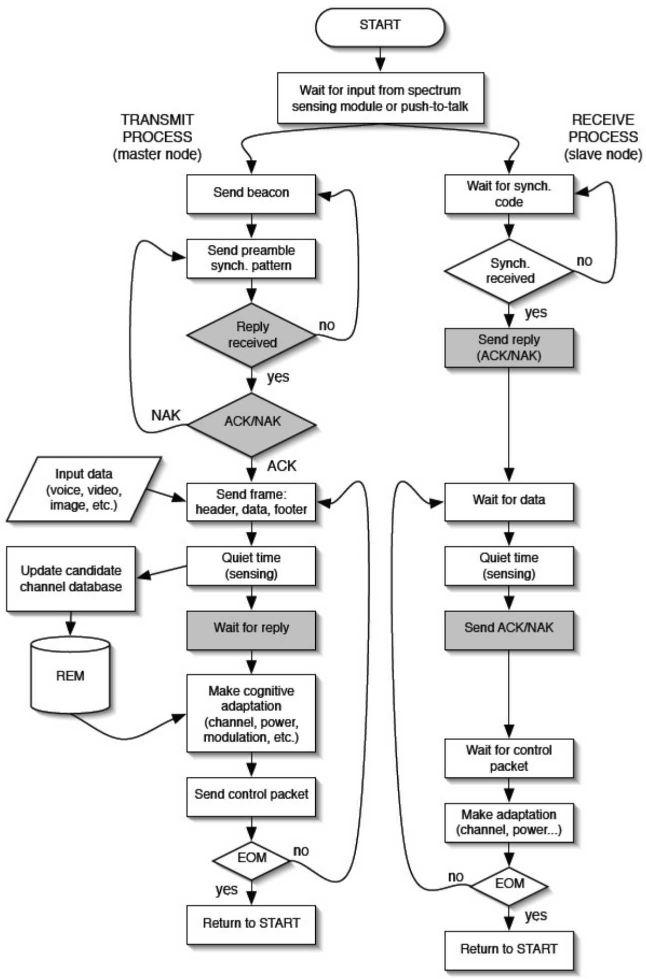

Fig.2: Flow chart of the CIREN protocol. Highlighted blocks are used in PTP mode only (ignored in VB mode).

3.2. Dynamic Spectrum Access Assessment

The dynamic spectrum access ability of the CIREN system sets it apart from traditional radios. Being a novel feature, there are no standard procedures for validating the correct DSA operation of the system. Therefore, we devised a procedure to define system test cases based on functional (black- box) [2] analysis, mixing traditional software testing techniques and traditional radio measurement. This test case analysis is performed independently of the implementation, thus avoiding any bias.

3.3. Scanner Sensitivity

The goal of this test is to identify the minimum signal level in a channel that is labeled as occupied. Because there is no actual sensitivity requirement, the output of this test is just a characterization. It is important to note, however, that if this level is higher than the minimum signal level demodulated by an FRS radio, then there is great potential for interference to the primary users.

3.4. Channel Occupancy Detection

The purpose of this test is to evaluate the ability of the system to reliably detect if an FRS channel is occupied or not. Because signal classification (incumbent user or CIREN transmission) is not scheduled to be completed in the first version of CIREN we omitted the test case analysis for it.

3.5. Link establishment: Rendezvous

The correct establishment of an ad-hoc link between the master and slave nodes, is one of the most critical aspects of the CIREN system. Link establishment occurs at the beginning of a transmission when a master is trying to locate a slave. It also happens after a primary user of the FRS band reclaims the channel where a CIREN connection was initially established. The purpose of this test is to verify the correct implementation of the protocol and report the probability of link establishment success as a function of channel properties. Due to the experimental nature of the CIREN project, its specifications are written in natural language. Therefore, the analysis performed to define the test cases provided valuable feedback identifying gaps and inconsistencies in the specification.

3.6. Link Termination

Although there are many link termination scenarios to be tested, in this report we only consider the termination of the link due to a primary FRS user occupying the transmission channel. This is the initial step towards switching the CIREN link to a secondary channel. The purpose of this test is to verify the correctness of the system in implementing the CIREN protocol and to measure the peak and average vacancy time. The evacuation time is defined as the time elapsed between the beginning of the primary user's transmission and the CIREN transmission stopping.

4. FPGA DOWN/UP CONVERTER SOLUTION

Even though most of the functions such as cognition/adaptation and modulation/demodulation are performed during the baseband digital processing, front end processing is crucial due to the limitation of the processor's speed. The RF signal processing module converts an RF frequency to an IF frequency for further processing during the reception and vice versa for the transmission. On the other hand, all the quadrature down/up-conversion, decimation and interpolation are implemented in the digital intermediate frequency (DIF) module. Currently, the DIF design for RX-path, down-conversion and decimation, is completed. For flexibility to various types of received signals and to requirement from the processor, our design supports a programmable frequency for direct digital synthesis (DDS) and programmable rates for the decimator and the interpolator which are implemented by Cascade Integrator Comb (CIC) filter with Hogenauer filter structure. We also implemented a fast channel sensing through Fast Fourier Transform (FFT). The interfacing and baseband signal processing is done using video processing subsystem (VPSS) technique. The Small Form Factor SFF-SDR board [3] from Lyrtech Inc. is used as a hardware platform to implement all of the described functions. The detailed description of this implementation can be found in [4]

4.1. Hardware Platform

The overall structure of a SFF-SDR board from Lyrtech is shown in Figure 3, which is composed of an RF module, a data conversion module, and a digital processing module. The RF module covers 20 to 928 MHz in receiving and 200 to 930 MHz in transmitting. For receiving, intermediate frequency (IF) is located at 30 MHz and there are two selectable bandwidths: 5 or 20 MHz. The data conversion module includes two ADCs and one DAC. ADC output bit-width is 14-bit and its speed is up to 125 Msps. DAC has a 16-bit dual- channel with 500 Msps. For interfacing to the digital processing module, a Virtex-4 LX25 is used. The baseband module features Virtex-4 SX35 and TI TMS320DM6446 DSP chip. Virtex-4 SX35 FPGA is configurable according to the specific application, and the TI chip contains a TMS320CC64x+ digital signal processor (DSP) core and an ARM9 general-purpose processor (GPP).

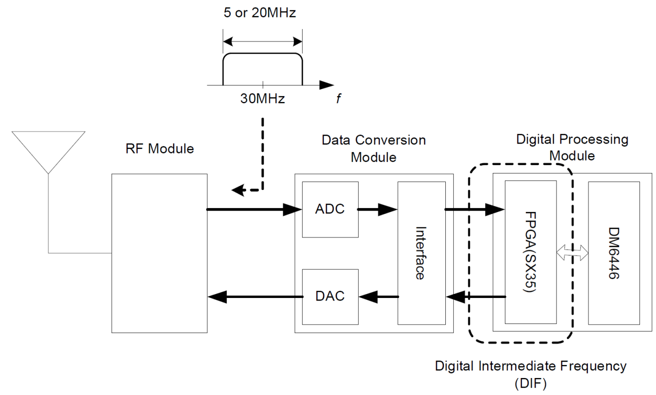

Fig.3: Lyrtech SFF-SDR hardware platform.

4.2. Flexible DIF Module Design

The main functions of a DIF are the quadrature down/up-conversion, decimation, and interpolation. Additionally, an FFT is implemented in RX-path, which is exploited for fast channel sensing. The configuration of the DIF is shown in Figure 4 and 5. This design is implemented on Virtex-4 SX35. For the flexible DIF, the design supports (1) a programmable frequency for down/up conversion and (2) programmable rates of decimation and interpolation. In the DIF, there are four components: a CIC filter for decimation and interpolation [5], Direct Digital Synthesis (DDS), a multiplier, and an FFT. The impulse response of the CIC filter is a box car or a sliding average filter. But the CIC filter has a multiply-free structure, a cascade of integrator and comb filter. This significantly reduces hardware complexity.

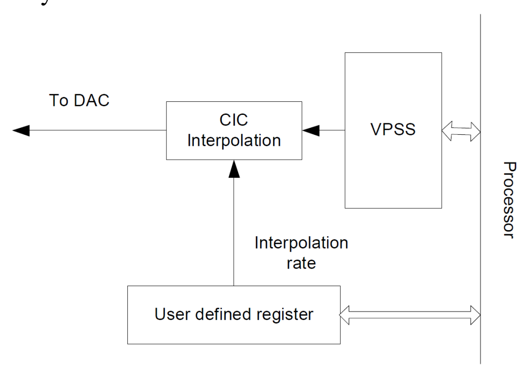

Fig.4: Transmit path configuration of the DIF

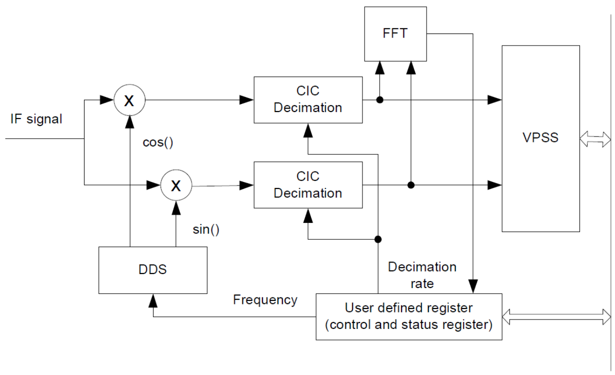

Fig.5: Receive path configuration of the DIF

5. PROJECT RISKS

While the team encountered numerous challenges in building the CIREN system, several major hurdles caused serious delays in its development. This section describes two key problems that significantly hindered progress of the project.

5.1. Lyrtech Small Form Factor SDR Board

In our proposal, the final system targeted the Lyrtech SFF SDR board. The SFF SDR contains all the elements needed to complete the project. The board is based on the Texas Instrument (TI) DaVinci processor, which contains and ARM926 general purpose processor and a TI C64 DSP on the same chip. Lyrtech combined this part with two Xilinx FPGA's and a custom RF interface, containing data convertors and the circuitry to interface the data convertors to antennas.Unfortunately, our proposal included porting the OSSIE software from Virginia tech to the SFF SDR board. This process required we port Linux to the SFFSDR. Lyrtech supplies the board with the Integrity operating system but since our long term project goals do not include supporting Integrity, we chose to try porting Linux to the SFFSDR board. This was identified as a project risk factor in the proposal.

5.2. Control & Automatic Component Configuration

Data communication within SCA waveforms is executed by passing CORBA sequences as packets between components. Depending upon the interface, these data can represent anything from hardware ADC samples to decoded source data bits. Initially, data packets do not carry any identifying information about their properties, or how components should be configured to process them. This imposes several limitations on a flexible radio that must be able to handle a variety modulation schemes, coding operations, and other configurable modes.

6. SUMMARY OF ACCOMPLISHMENTS

This section summarizes the many accomplishments the team has achieved while working on this project.

6.1. Development of open-source processing blocks

The following open source signal processing blocks have been developed during the project: continuously variable slope delta (CVSD) encoder/decoder, convolutional encoder/decoder, PHY synchronization, MAC synchronization, digital modulator/demodulator library.

6.2. FPGA verification

While not used in the radio challenge itself due to time limitations, the physical layer FPGA work was originally crucial to the successful operation of the CIREN radios. During the competition the RTL design for the RX-path was completed in verilog-HDL. We simulate the design in MATLAB and verilog compiler to verify the RTL design by comparing the results.

6.3. Tools Development

In order to interface the OSSIE debugging environment with MATLAB, two tools are developed: an arbitrary waveform generator and a write-to-file tool.

6.4. Application Layer Components

Three components are developed for the application layer of the system. One component provides a graphical user interface (GUI) allowing the user to send and receive basic text messages. This component also provides a push-to-talk button that is capable of forwarding CVSD voice data that is being sent to one of the component's provides ports. The next two application layer components developed are the image capture component and the image display component.

7. IMPROVEMENTS AFTER THE COMPETITION

Several improvements have been developed based on CIREN platform including GUI improvement, broadcast networking capability, and clustering capability. The previous CIREN code uses debug information to show the status of network connection and channel status. A new GUI is added to show the channel status and the ID numbers of nodes within a network. The channel score is shown with a bar figure which makes it much easier to demonstrate operation of the system.

In previous version of CIREN platform, each node will dwell on the vacancy channel once it received a beacon reply message from the other CIREN node. A peer-to-peer communications network is formed through this process. In the disaster environment, the capability to form a broadcast network to share information is critical. This requires the CIREN nodes negotiate with each other and make agreement on the channel that all of them will dwell on. This functionality has been added to CIREN code by defining a master node which is also the only node that can make a decision about the channel to use for the whole network. The differentiation between Master Node and other node is implemented using the node identification (Node ID). The node with ID = 0 will send out beacon reply message while the nodes with other IDs cannot send out this "Stop" signal. In such a way, only Node 0 can make other nodes dwell on a particular channel and the whole network will converge to that channel.

The other developing effort of CIREN platform is to form a Cognitive Network (CORNET) Testbed. This CORNET developed in Virginia Tech is one of the kind research platforms to test and validate the concepts of cognitive radio and cognitive networks. To perform the networking functions, such as routing and forwarding, a clustering functionality has been integrated into the CIREN code. The CIREN nodes are divided to two kinds of nodes, leader nodes and slave nodes. Several CIREN nodes are selected as the leader nodes which has similar functionality of previous Node 0. Each of these leader nodes can form a cluster around them and these clusters will use different channels. Moreover, these leader nodes have a thread to sensing all the channels periodically to locate other CIREN clusters. Once it found the existence of the other clusters, it will record the number of channels that used by them in a channel list, which will be developed as a routing table in the future. The second functionality of clustering is forwarding. Each leader node can receive a message from the slave nodes inside its cluster and forward it to the adjacent cluster with different channel. Since the leader nodes know all the channels that the adjacent cluster is using as well as the channel for its own cluster, the forwarding function can be achieved by receive one message from nodes inner the cluster, buffer it for a while and retransmission it through a different frequency channel. This clustering functionality laid a foundation for the implementation of routing algorithm design in the future.

8. CONCLUSION

To complete the system proposed for the radio challenge, OSSIE needs to be ported to the SFFSDR board. In order to move the software developed for the radio challenge to the SFF SDR board three tasks need completion; port u-boot to the SFF SDR, modify Linux for the SFFSDR and develop software to interface with the DSP and FPGA on the SFF SDR board. Our experience building OSSIE for similar ARM based systems strongly suggests that porting OSSIE the ARM processor on the SFF SDR will go smoothly so this is not considered a separate task. Designing a radio to seek spectrum holes and dynamically switch frequencies while operating under a number of parametric constraints presented many challenges. Software-defined radio is an interdisciplinary field requiring expertise in RF engineering, communication engineering, software engineering and project management. Development of such a system requires sufficient understanding of each.

9. REFERENCES

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