DESIGN OF MODULAR SDR ARCHITECTURE FOR RESOURCE CONSTRAINED MANET

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ABSTRACT

This paper presents the design & implementation of Software Defined Radio (SDR) to support dynamically variable modulation schemes, data processing under multi-path fading with dynamically changeable data rate based on real time knowledge of channel conditions when using KV transform and Cognitive Radio functions. The algorithms are executed with minimal processing time in order to support maintaining a sustained Quality of Service (QoS) for end user multi-service applications. There was minimal change in the processing times, power efficiency and bandwidth efficiency compared to the performance measures established for each function independently. In this paper, we focused on the architecture of SDR that allowed different functions to be placed modularly and a cluster of SDRs were used to demonstrate the performance.

1. OVERVIEW

Traditional radio units that are typically used in different network centric theaters have been implemented in hardware and tend to be less flexible in terms of dynamical changes to control data rates, frequencies and transparent use in different theaters. They are also inflexible to incorporate new features. The concept of Cognitive Radio that effectively allows built in intelligence to seek unused spectrum slots by learning and upgrading autonomously cannot be implemented in legacy hardware radios easily.

Software Defined Radios (SDRs) use minimal hardware component and allows flexible modular functional components in software or firmware allowing dynamic configuration of each of these functional components based on the real time needs of multi-service applications. It has the ability to allow the design of network management function in each radio in software allowing it to be efficiently designed both in terms of processing time and use of cross-layer functions in the management plane to achieve desired performances such as Quality of Service (QoS), bandwidth and power efficiencies. Thus, design of SDR is expected to provide the desired flexibility for supporting channel and terrain conditions.

In this paper, we are focusing on the design and implementation of SDR with specific focus on seamless support of multi-dimensional tactical operations in the theater.

1.1 Tactical Requirements of the Theater

Tactical requirements that are critical to be considered in the design of SDR for Mobile Ad Hoc Network (MANET) include [1]:

- Security and Trust: Trust verification of software for end user confidence level; enabling of end user to port own proprietary waveforms and replace existing waveforms for security; and a place holder for encryption and security management.
- Power and Resource Efficiency: Critical for MANET as software algorithms are flexibly changed for different operational scenarios.
- Management Function for Efficient operation: Minimal configuration with a set of Managed Objects and associated attributes as part of the Management Information Base (MIB) for different layers achieving both processing time and bandwidth efficiency for management protocol.
- Quality of Service Assurance for Multi-Service Applications: The design must encompass the need for processing efficient cross-layer functions in management to achieve QoS for multi-service applications with high probability of success.
- Flexible and Dynamically Configurable Algorithms for Different Tactical Environment with Different RF: Automatic selection of desired frequencies and modulation schemes, and handling of communications in impaired channels for different tactical environment needs to be achieved.
- IP Based Information Transport Allow Interfacing Fixed Networks.

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1.2 SDR to Increase the Life Cycle of Existing Network Architectures

Software Defined Radio is a novel implementation that allows different radio functions to be configured flexibly with a set of programmable elements and can be used for tactical operations [2]. It extends the life cycle of the network architecture (10 or More Years) by allowing new and evolving algorithms to be incorporated in SDR for network centric operation and interoperate with existing conventional radios. The modularity of the components in different layers of OSI reference model allows dynamical changes of functions with cross-layer functional control within the network management. The software modules allow easier way to replace the hardware, thus increasing the life cycle of the network architecture [3].

A unique aspect of the implemented SDR is its ability to handle multi-path interference and provide data transport continuously. Provisioning of dynamic changes to modulations, constellations allows maintaining high integrity communications across the theater by handling different types of channel impairments (Jamming, Multi-path interference) [4]. This paper presents an initial implementation of the SDR design in terms of dynamical changes to the modulation methods, cognitive radio function and dynamical changes to the effective data rate to sustain bounded performance in terms of sustained data rate, response time and data error rate which are the basic performance measures to support QoS.

2. DESIGN OF SDR

The design of SDR needs to consider power efficiency, and resource efficiency for multi-band and multimode, multi-role tactical environment that requires flexible configuration of SDR. The implementation must also facilitate trusted software and system for the end user. SDR design needs distributed embedded network management for reducing the time and processing delay. Finally, the use of dynamic reconfiguration capability allows flexible usage in different theater environment under all terrain conditions.

The architecture of the proposed SDR design is shown in Fig. 1. Specifically, the following functions were implemented in the proposed SDR:

- Dynamically changeable modulations and demodulations, cognitive radio spectrum sensing and transmit power setting functions are modules within the Physical Medium Dependent (PMD) sub-layer.
- Frequency synchronization, modulation and demodulation control functions, Koay-Vaman transform coding and real time channel condition measurement to support dynamically changeable data rate are modules within the Physical Services (PS) Sub-layer.
- The MAC sub-layer and higher layers are consistent with ISO standards for any radio operation.
- Cognitive Radio management, power control and cross-layer QoS management are part of Management Plane.

The hardware components of the SDR implementation are shown in Fig. 2. All functions described above are implemented at the baseband. The hardware consists of a transceiver with an antenna. The RF is converted to an IF frequency before the incoming signal is processed. It passes through an A/D converter and uses an FPGA for specific functions and the software is processed using a processor. On the outgoing side, the digital information is passed through a D/A converter and the IF to RF conversion is done prior to transmission.

The proposed SDR design that supports dynamically variable modulation, KV transform for real channel condition measurement and error correction to handle fading channels, and cognitive radio function has been implemented using GNU radio platform [5, 6].

3. SPECIFIC IMPLEMENTED FUNCTIONS

There are three functional components that were implemented as part of the SDR design:

3.1 Modulators

The proposed SDR implemented three types of modulations and allowed dynamic changes to the modulation schemes: Gaussian Minimum Shift Keying (GMSK); Differential Binary Shift Keying (DBPSK) and Differential Quadrature Phase Shift Keying (DQPSK) as examples. The transceiver pair decides on the type of modulation during the time of frequency synchronization. The default modulation is chosen to be GMSK and is used to initially send a control message. Control messages are exchanged between the peer PS sub-layers when requesting change in the modulator type. The request is included in the acknowledgement packet. The design allows porting any other modulation type through a user control. This also allows the ability to port secure waveforms after the design has been validated to protect the end user network architecture. Figures 3a, 3b and 3c illustrate the spectrum of GMSK modulation, DBPSK modulation and DQPSK modulation methods.

3.2 Handling of Multi-path Fading with Real Time Channel Condition

We implemented Koay-Vaman (KV) transform coding technique to correct errors. KV transform is implemented in software at the Physical Services Layer. The transform uses a set of discrete samples with each sample constructed using n bits of data from MAC frames received. The KV transform block uses four samples per KV block and produces four discrete coefficient samples and two error correction samples. At the receiving side, the discrete coefficient samples are corrected using the error correction samples. Current implementation corrects one out of four discrete samples exactly and the data is recovered. The number of bits, n per sample can be dynamically varied based on the channel conditions between peer radios. The implementation uses "discrete sample interleaving" with one retransmission of selected KV blocks in error in each ensemble to derive very low BER (10^{-7}) at very low Eb/N0 (<<10 dB) which is typically observed in the case for multi-path fading (Rayleigh) [4]. Error correction in this manner achieves significantly improved BER performance and is preferred over the equalization techniques used typically to handle multi-path fading. The processing and response times are maintained constant using this transform coding.

Real time channel condition is measured for each ensemble of blocks using the ratio of number of blocks in error and the total number of blocks transmitted. Dynamic reconfiguration of KV transform based on real time channel condition estimation is demonstrated based on a desired target BER of $2*(10^{-3})$ without using the single selected retransmission or interleaving of KV blocks. Therefore, the Eb/N0 for demonstration is much higher than when using single selected retransmission and interleaving of KV blocks. As Eb/N0 decreases BER increases and the target BER is maintained by lowering the value of n per sample. n is varied between 2 bits to 4 bits in the demonstration.

The implemented SDR has used DBPSK (1 bit/sample), DQPSK (2 bits/sample) and M-ary PSK (3 bits, 4 bits, 5 bits/sample) for validating the dynamic change of n at different Eb/N0. The switching of n between 4, 3 and 2 bits is achieved at Eb/No of 16 dB, 14 dB and 12 dB respectively while maintaining a target BER of 10^{-3} as shown in Fig. 4.

Figure 5 shows achievable BER for different Eb/N0 and the values of n per discrete sample. It should be noted that to achieve optimum data transmission with a BER < 10^{-7} at Eb/N0 of << 10 dB, both selective retransmission and interleaving of samples are required to be implemented in addition to error correction of one out of four samples [5].

3.3 Implementation of Cognitive Radio Function

Cognitive Radio framework was originally proposed by Mitola [7]. The Cognitive Radio (CR) function is managed at the physical layer within the SDR architecture. For improving the spectral efficiency, CR function includes dynamic spectrum management and configure multi-mode operation.

We have implemented the energy detection for spectrum sensing and use distributed listening channels for frequency synchronization at the Physical layer [8]. It is based on reactive sensing and uses wideband sensing where the spectrum is divided into smaller sub-channels (programmable bandwidth). The antenna is iteratively tuned to the center frequency of each sub-channel. The power spectral density (PSD) is obtained using N point (512, 1024) FFT. The average PSD (Pc) is computed and compared to the threshold, P0. If Pc > P0, then the channel is declared busy and if PC < P0, the channel is declared available. Thus, spectrum holes are identified at each CR. The following functions are specifically implemented as part of each CR: Radio Spectrum sensing; Dynamic Channel Allocation (PMD); Transceiver Frequency Synchronization (PS); Transmission/Reception of data (PMD/PS); and Reconfiguration of the CR (Management). Each CR is equipped with two radios: one for data transmission and one for listening channel. CR radios are characterized at instances of time in terms "primary user", "secondary user", and "priority user" based on the status of the network [9, 10]. The Primary user is a CR who has already entered the network, the secondary user is a CR who has to be accommodated in the network; and the priority user is a CR that has priority over a radio channel that needs to be relinquished by others upon request. Channel allocation amongst different users was controlled in the management using the cross-layer information at each CR.

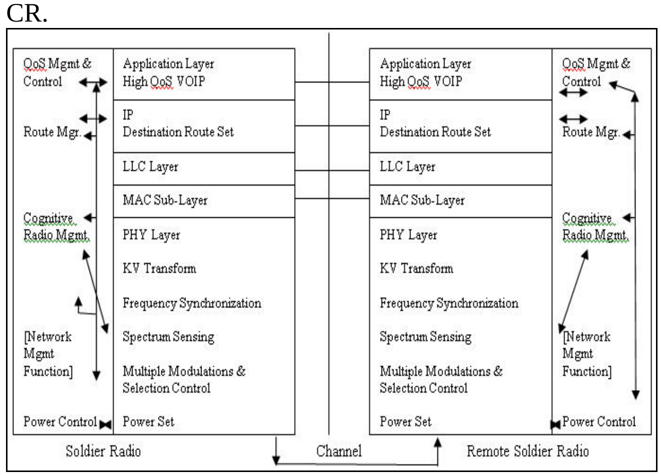

Fig. 1: Proposed Architecture of SDR

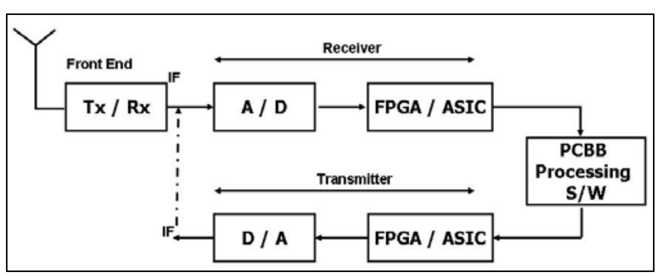

Fig. 2: Hardware Components of the implemented SDR

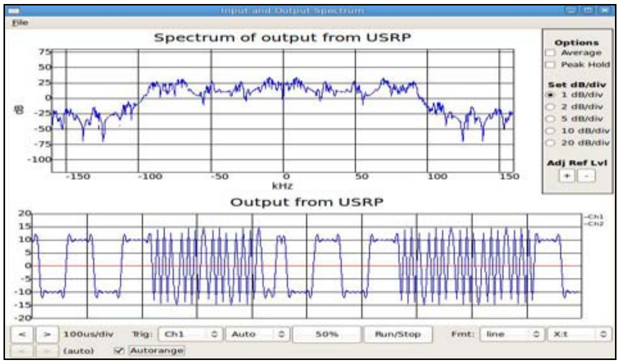

Fig. 3a: Spectrum of GMSK Modulation

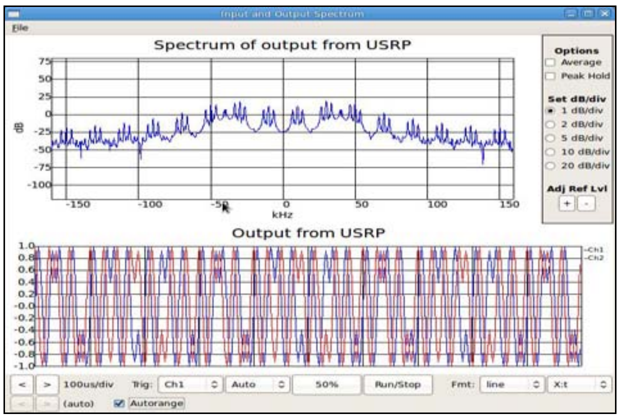

Fig. 3b: Spectrum of DBPSK Modulation

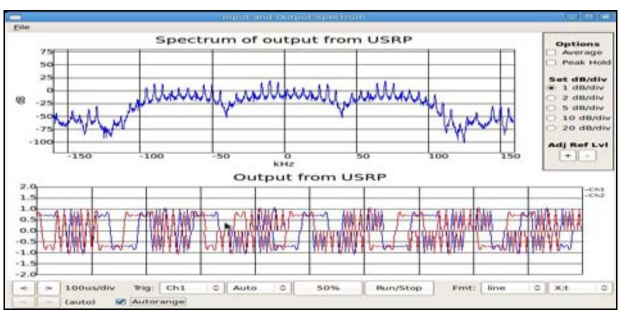

Fig. 3c: Spectrum of DQPSK Modulation

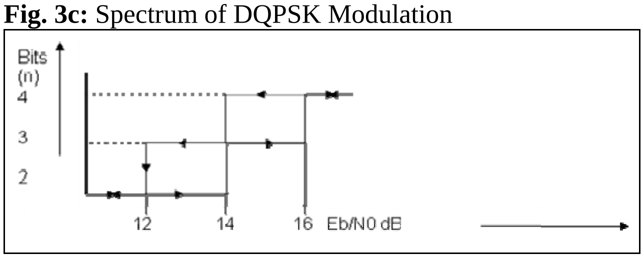

Fig. 4: Value of n (bits/KV sample) transmitted at different Eb/N0

In order to determine the sensing threshold, P0, the CR is tuned to the center frequency of each channel; it performs FFT on the observed signal, and determines the PSD and compute the average (μ) & the standard deviation (σ). The threshold P0 is set at μ + 3 σ.

For initial handshake, each CR is pre-assigned listening channels (LC). In MANET, where Cognitive Radios are associated with clusters with a cluster head, during the initialization, each cluster will assign LCs to each CR. Also, each transmit CR has knowledge of LCs of other CRs. The CR transmitter senses the entire spectrum and identifies the free or available channels. It will send a control signal in free LCs of intended receiver iteratively. The transmitter remains on each LC for a fixed amount of time, Tc. The CR receiver is in idle state listens to its LCs for a duration of N*Tc where N is the total number of LCs. Once the listening is complete, the transmitter of a CR configures with a receiver of another CR the data channel for transmission.

Eb/N0 dB	Value of n - Bits/discrete sample			
9.8	4	3	2	1
10	.05	.03	.0098	.001
12	.01	.009	.002	10^{-4}
14	$5x10^{-3}$	$2x10^{-3}$	$2x10^{-4}$	10^{-8}
16	$9.8x10^{-4}$	$5x10^{-4}$	$9x10^{-6}$	$<10^{-8}$
18	$9x10^{-6}$	10^{-8}	$<10^{-8}$	$<10^{-8}$

Fig. 5 Configured values of n as a function of Eb/N0 of the Channel for a simple KV transform (no interleaving and no selective single retransmission of KV blocks

Figure 6 illustrates the spectrum sensing and assigning of the data channel. In Fig. 7, channel 4 is available and is synchronized for data transmission between the transmitter, Tx and the receiver Rx.

In the proposed CR implementation, there are two cases of dynamic spectrum switching: 1. Detection of a Priority User where a CR recognizes priority users using RF ID; and 2. Unfavorable Channel Condition where mobility and unsustainable data transmission in a channel due to fading or other impairments require dynamic switching. Figure 7 illustrates dynamic spectrum switching. A CR user chooses channel 2 which was available, but needs to relinquish since a priority CR user has access to it. Thus, channel 4 is chosen. Figure 8 illustrates the overall system implementation.

4. SUMMARY AND CONCLUSION

This paper presents an initial SDR implementation on GNU radio platform that demonstrates use of multiple modulators; data recovery under multi-path fading with dynamically changeable data rate based on real time channel condition using KV transform while maintaining a target BER; and Cognitive Radio function has been implemented to ensure spectrum efficiency and dynamic switching of channels for different conditions. As part of the future work, the SDR will be integrated with sensor network fabric.

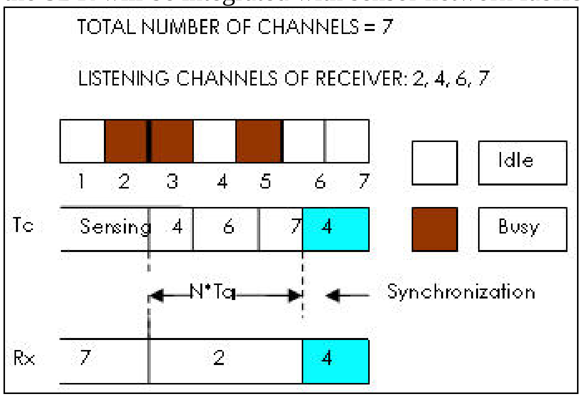

Fig. 6: Illustration of Spectrum Sensing and Spectrum Synchronizing the Channels

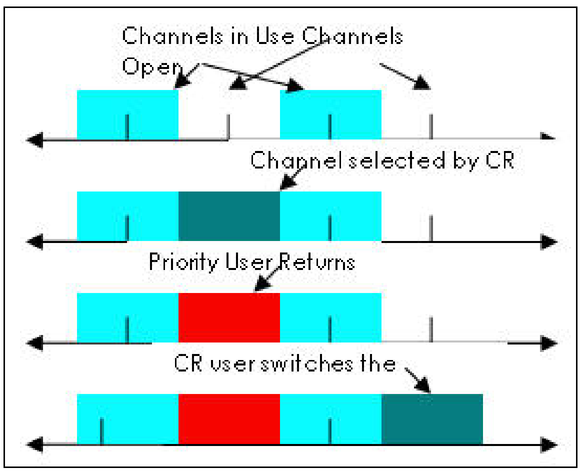

Fig. 7: Illustration of Dynamic Switching

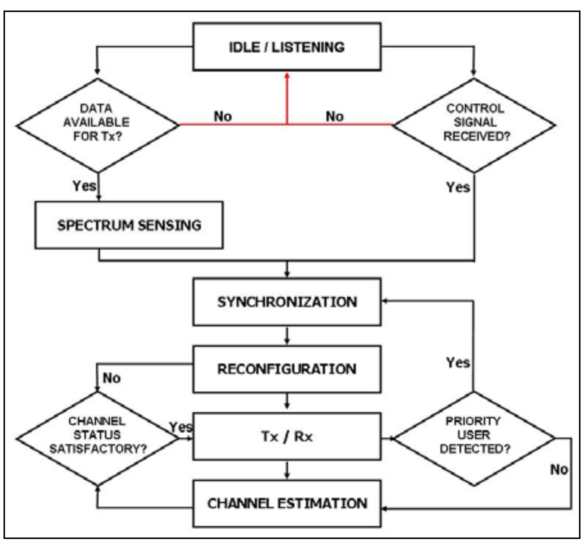

Fig. 8: Flow Diagram of CR Operation

5. ACKNOWLEDGEMENTS

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