Interference Avoidance via Adaptive Wavelet Packet Modulation in Wireless Communication Systems

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Abstract—**This paper addresses the problem of adaptive modulation/demodulation scheme in the presence of interferences for wireless communication systems. We developed an adaptive modulation/demodulation scheme which modifies users' signature waveforms by maximizing the signal to interference ratio based on wavelet packet analysis and the state-of-art interference avoidance algorithms.**

Keywords-Interference Avoidance; Adaptive Modulation; Wavelet Packet Analysis; Software Defined Radio; Orthogonal Communication

I. Introduction

Wireless communication has experienced rapid growth in recent years. As of June 2009, there were an estimated 4.3 billion cell-phone users worldwide. Despite of the rapid growth, current wireless communication system is confronting two major problems: scarcity of the spectrum usage and the coordination difficulty between different systems [1]. According to the Defense Advanced Research Projects Agency's (DARPA) assessment, on average, only 13 percent of the spectrum is actually in use in the United States at any given moment, even though all the spectrums have been allocated [2]. Current communication systems allocate each service with a fixed-block of spectrum whether the service is in use or not. This often results in under utilization of the spectrum and hence a waste of resources. In addition, different communication systems require proper coordination of the resources. It is harder and harder to deploy a new system based on the existing fixed-block allocation methodology due to the globalization. Therefore, *adaptability* is an important concept for the development of future communication systems.

With the recent technology advancing in software-defined radios (SDR) [3] [4], cognitive radio [5] emerges as a promising concept for achieving adaptive utilization of spectrum efficiently. Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment and is capable of adapting to statistical variations of the incoming RF stimuli by making corresponding changes in certain operating parameters such as transmit-power, carrier frequency, and modulation strategies in real-time. The goal of the cognitive radio is to achieve reliable communication and efficient utilization of the radio spectrum.

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In fact, several recent programs are related to the concept of cognitive radio. DARPA next Generation (XG) Communications program [1] developed the technology to allow multiple users to share the spectrum more efficiently through adaptive spectrum management through the sensing of available spectrum holes. NSF Programmable Wireless Networking (NeTS-ProWiN) program [6] developed a wireless programmable frequency-agile radio platform which offers the opportunity to use dynamic spectrum management techniques to help lower interference, adapt to time-varying local situations, and provide greater quality of service. The IEEE 802.22 working group is creating a standard for physical and MAC layers, and the air interface, for unlicensed devices that would operate in the UHF/VHF spectrum and would avoid interfering with television services [7]. All of the existing approaches are focusing on advancing the capacity of communication via utilizing the frequency diversity efficiently.

As an extension to frequency diversity, we propose a novel adaptive wavelet packet modulation design which exploits both time and frequency diversity for enhancing the capacity of the wireless communication system. By integrating with the state-of-the-art interference avoidance algorithms [8] [9], the adaptive wavelet packet modulation design is capable of achieving orthogonal communications for wireless communication systems. The orthogonal communication concept adapts the communication space to be orthogonal to the sensed RF interferences, and aligns with the basic framework of cognitive radio.

II. Overview of the System Architecture

The basic concept of cognitive radio focuses on three fundamental cognitive tasks: radio-scene analysis, channel identification, and transmit-power control for dynamic spectrum management. Following the concept of cognitive radio [5], Figure 1 depicts our proposed adaptive wavelet packet modulation method.

We are focusing on designing an adaptive wavelet modulation scheme for achieving orthogonal communications under the symbol-synchronous single-cell multi-user communication system. We use wavelet packet analysis for radio scene analysis in view of the superior spectrum estimation capability of wavelet packet analysis. Based on the generic interference avoidance adaptive signature waveform design scheme by Rose [8] and Popescu [9], a transmitting radio is instructed to vary its waveform so as to maximize the signal-to-interference plus noise-ratio (SINR). Through a general CDMA scheme in which distinct waveforms are assigned to distinct symbol or users, the codewords rather than waveform are optimized via this interference avoidance algorithm. This new adaptive modulation scheme will not only improve the robustness of the communication system when confronting interferences, but also has great potential to increase the system capacity. Figure 2 illustrates the implementation diagram of the proposed adaptive interference avoidance wavelet packet transceiver.

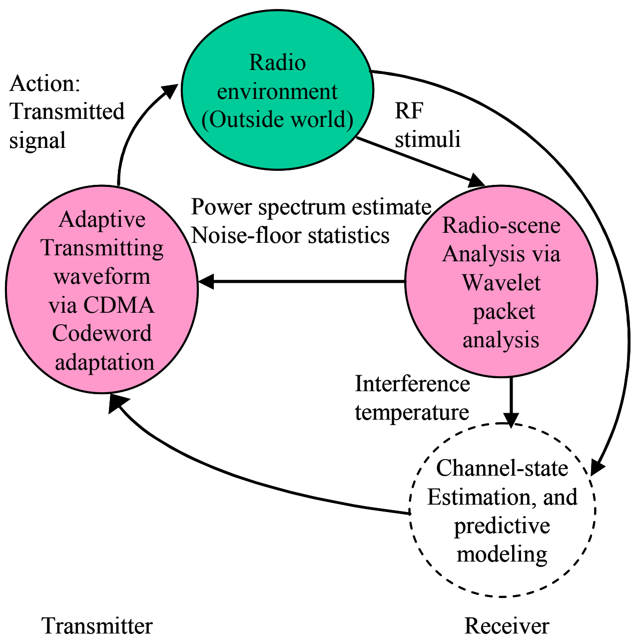

Figure 1. Adaptive Wavelet Packet Modulation Method

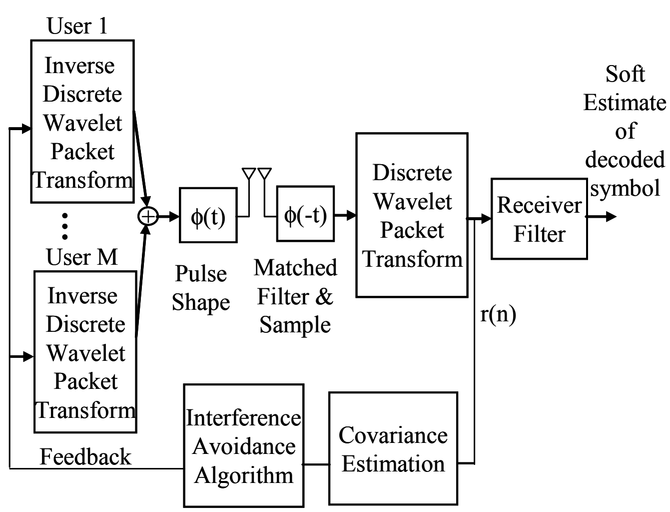

Figure 2. Adaptive Interference Avoidance Transceiver

The interference avoidance algorithm serves as part of the channel coding of the communication system, whereas the wavelet packets are used as shaping pulses. The basis function of the signature waveform is adapted to the interferences seen at the receiver. Assuming that the interference is stationary for a certain time interval, the characteristics of the interference can be captured by its power spectrum obtained by projecting the interference onto the unknown Karhunen-Loève basis. Here, we use wavelet packet analysis to estimate the power spectrum of the interferences. The codeword at the transmitters are then adapted via the interference algorithm to minimize the effect of interferences using the selected wavelet packet basis fed-back from the receiver. In order to track the time-varying spectral property of the interference, the signal-to-interference ratio (SIR) is continuously monitored. Once the SIR falls below some certain threshold value; the interference covariance and the corresponding best-basis of wavelet packet transform are re-estimated.

III. EVALUATION RESULTS

Performance of the adaptive modulation scheme has been demonstrated in the MATLAB® environment as well as on a software-defined radio under the scenario of synchronous single-cell multi-user wireless communications. The performance metric is the inverse signal-to-interference (SIR) ratio at the receiver. A smaller inverse SIR indicates a better reception at the receiver. To illustrate the benefits of integrating wavelet packet modulation with the interference avoidance algorithm, we compare its performance with DS-CDMA modulation and with wavelet modulation, in which the IDWPT/DWPT blocks in Figure 2 were replaced with IDWT/DWT. The conventional DS-CDMA scheme modulates the digital symbols via the quadrature amplitude modulation (QAM) with the raised-cosine shaping filter. For both wavelet and wavelet packet modulation experiments demonstrated here, the Daubechies wavelet of order 3 was applied unless stated otherwise.

Several types of interferences including single tone, multiple tone, impulse train noise, Gaussian white noise, chirp, autoregressive filtered noise, and sum of impulse train and sinusoidal tones were simulated to assess their effects on the system. Figure 3 shows the average inverse SIR history for the impulse train interference with 33 agile users and codeword dimension of 32. The interference avoidance adaptation occurs once at 7th symbol index. In general, we observe 5 to 10 times improvement on SIR after applying the adaptation for different simulated interferences.

Several factors would impact the performance of the proposed adaptive modulation scheme: time-variation of the interferences, codeword quantization, and inaccurate covariance estimation of the interferences. Figure 4 shows the average inverse SIR history for the chirp interference under the same scenario as in the previous impulse train example. Due to the time-varying characteristic of the chirp interference, the average SIR decreases gradually when the covariance estimate is not valid anymore. The remedy is to monitor the SIR and re-run the IA algorithm whenever SIR is below some predefined threshold.

Imperfect codeword feedback from the receiver would impact the performance of the adaptive wavelet packet modulation. In our study, we also examined the impact of the codeword quantization on the average SIR. Figure 5 shows the histogram of the average converged inverse SIR for 1000 interference algorithm trials. The average SIR decreases with coarser quantization. The variance of the converged SIR increases with coarser quantization.

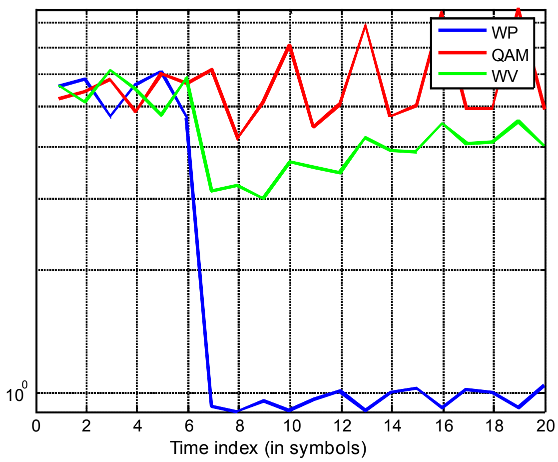

Figure 3. Inverse SIR for Impulse Train Interference

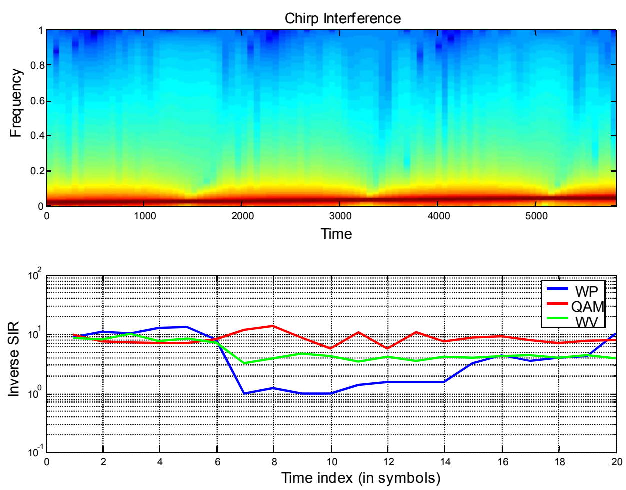

Figure 4. Inverse SIR for Chirp Interference

To study the impact of covariance estimation inaccuracy on the interference avoidance capability, a quantitative relationship between the compact energy index and the SIR improvement ratio was derived. The compact energy index is defined as the ratio between the number of wavelet packet coefficients which capture 90% of the signal energy and the codeword dimension. The SIR improvement ratio is defined as the ratio between the SIR before and after the IA adaptation. We propose to assess the accuracy of the wavelet packet covariance estimation by measuring the degree of compactness of the wavelet packet representation. The smaller the compact energy index, the more compact the wavelet packet representation. Intuitively, the proposed adaptive modulation scheme has a better performance when the compact energy index is smaller. Figure 6 shows the scatter plot between the improved SIR ratio and the compact energy index for 700 random runs. For each run, the interference was simulated using the first order autoregressive Gaussian noise with varying autoregressive filter coefficient. In Figure 6, improved SIR ratio 1 (red line) indicates no improvement after IA adaptation. From Figure 6, we observe that the compact energy index is inversely proportional to the improved SIR ratio. Moreover, the IA adaptation is only effective when the compact energy index is below some threshold value.

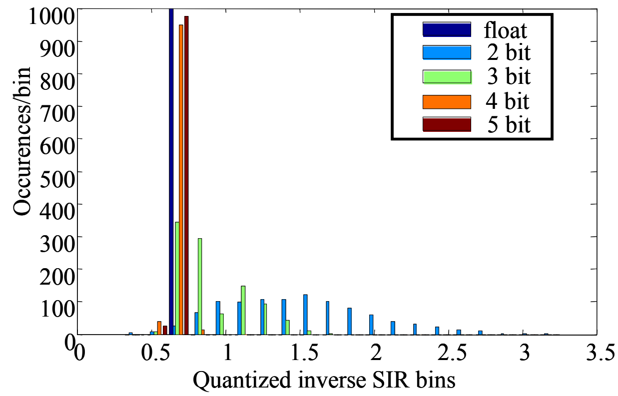

Figure 5. Inverse SIR with Uniform Quantization

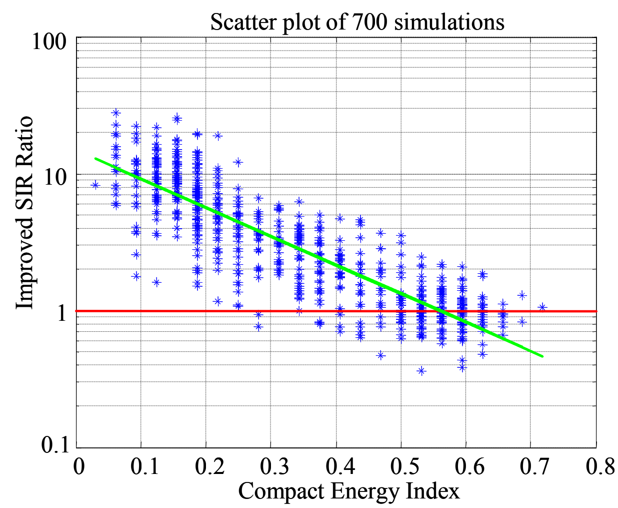

Figure 6. Compact Energy Index

In addition to MATLAB® simulations, a software-defined radio prototyping platform was built based on the WaveRunner Plus PCI (Model 253 [10]). The PCI card which is a poly-channel programmable digital transceiver can provide up to 8 transmit and receive channels with maximum base-band bandwidth of 8.6 MHz. The tests show that the performance under the SDR platform is similar to the MATLAB® simulation even under real noise and delay. Figure 7 shows one example of comparing the SIR performances under the MATLAB® simulation and the SDR platform. The code dimension (or the number of wavelet packet coefficients) is set to be 64 in this example. At the 11th symbol index, the optimal codeword derived from the IA algorithm was applied. The sudden decline on the inverse SIR for both implementation platforms after the 11th symbol time due to the adaptation of the codeword can be observed.

As a follow-on work, we are building another software-defined radio platform based on the open-source GNU Radio software [11] and the newly released Universal Software Radio Peripheral (USRP2) transceiver hardware [12]. The new platform will provide additional flexibility in evaluating the new modulation design.

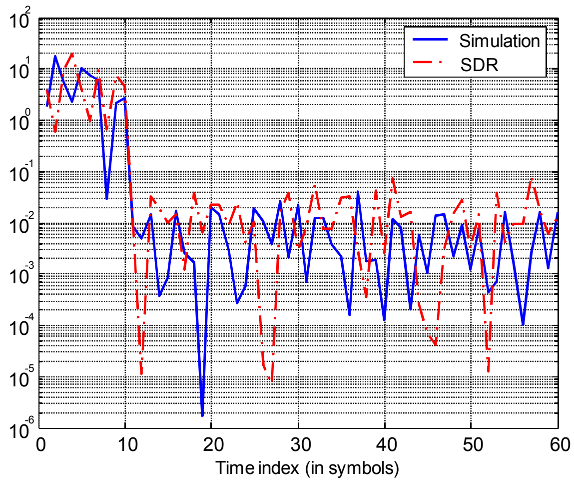

Figure 7. Performance Comparison between Simulation and SDR

IV. CONCLUSION

We have developed a complete system design of the adaptive wavelet packet modulation scheme for single-cell multi-user communication systems. We have shown that the performance of the interference avoidance algorithm has been significantly enhanced by the proposed wavelet packet modulation scheme. The proposed adaptive modulation scheme is capable of avoiding several different types of locally stationary interferences. Future work will extend the baseline design to multi-base wireless systems and ad-hoc communication networks. Realistic communication issues such as synchronization, mobility and non-ideal channels will also be addressed to evaluate the possibility of physically implementing this orthogonal communication concept. In addition to wireless communication applications, we are presently extending the proposed orthogonal communication framework to radar applications.

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