A COGNITIVE RADIO WITH MULTIANTENNA INTERFERENCE MITIGATION

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ABSTRACT

Traditional cognitive radios have typically relied on sensing and dynamic spectrum access (DSA) to move away from channels with interference. However, as wireless systems proliferate and base station and user terminal density increase, the availability of "white spaces" (frequencies with low interference levels) will be difficult to come by. In some cases an opponent may be actively trying to deny access to white spaces. Therefore increasing network performance in cognitive networks will require an adaptive cognitive engine designed to work in "gray spaces" (frequencies with high levels of interference) and in some cases "black spaces" (frequencies undergoing intentional jamming).

In this paper, we propose a method for leveraging a 2X4 MIMO array to create a subspace projection that leads to significant increase in cognitive system performance. This paper also shows how the concept can be further enhanced by using the mobility of the end user terminals to increase the effective size of the antenna matrix – leading to increased improvements in interference mitigation, bit error rate and link budgets. Simulation results for both methods are presented that quantify the performance improvements of these approaches.

1. INTRODUCTION

Interference is a major impediment to reliable and efficient wireless transmissions, and can negatively impact performance and coverage in mobile systems. As more people (and their wireless smart phones, tablets, laptops, etc.) share the scarce airwaves used by today's data networks, they not only use more bandwidth, but they also increase the overall interference level in the network. New heterogeneous network architectures that reuse spectrum in an effort to increase capacity with a mix of macro, pico- and femtocells present additional challenges as self-limiting interference is introduced into the network. Thus, dealing with increasing levels of interference is a critical issue for wireless systems designers and service providers alike. Cognitive, or "smart radio" technologies combined with flexible Software Defined Radios (SDR) and Multiple input Multiple Output (MIMO) architectures offer the potential to combat interference.

By definition, a cognitive radio "provides radio resources and services most appropriate" to the user's needs [1]. However, with an expanding Digital Signal Processor (DSP) and SDR capabilities, the cognitive operation can be expanded within and beyond the original definition, and can include the use of RF and antenna systems in different modes depending upon environment and operational requirements. For example, a MIMO capable antenna system can be simultaneously used for Maximal Ratio Combining (MRC) and interference mitigating array configurations so long as the signal processing system can deliver adequate computing performance within the available size, power and thermal budgets.

This paper discusses a cognitive interference mitigating SDR MIMO radio that is initially designed to operate in the ITU Region 2 900MHz ISM band.

2. OVERVIEW OF INTERFERENCE IN 900MHZ ISM BAND

The unlicensed 900MHZ band is extensively used by various devices from telemetry and video links to cordless phones and wireless baby monitors. To comply with FCC part15 rules in the USA the minimum bandwidth, power spectral density and transmit power are strictly limited. The minimum bandwidth is 500 kHz and maximum radiated output power is 36dBm EIRP. Large numbers of uncoordinated devices on the band also increase the noise floor to the point that traditional radio systems may not work or they deliver reduced range and data rates. Common interferers in the band include cordless phones that use frequency hopping spread spectrum modulation. Another common type of transmission used by fixed broadband systems is wide band Frequency Shift Keying (FSK) or Orthogonal Frequency Division Multiplexing (OFDM). These types of systems often occupy the entire 902-928MHz band.

To operate a mobile broadband data network in the presence of these systems, multiple methods to mitigate the interference are required.

3. A COGNITIVE APPROACH FOR OPERATING WITH INTERFERENCE

While a large amount of research is devoted to interference free secondary sharing, Preston Marshall introduces a term of Interference-Tolerant Sharing in his book of "Quantitative analysis of Cognitive Radio and Network Performance" [2]. The concept of interference tolerant sharing offers a potential for a large increase of network density. The cognitive radio described in this paper not only attempts to avoid interference; it also incorporates techniques that increase its interference tolerance while maximizing system capacity within Part 15 FCC rules.

Faced with ever increasing density of unlicensed use of ISM bands, xG Technology's xMax cognitive radio uses a multifaceted strategy for dealing with interference. The system incorporates a Dynamic Spectrum Access (DSA) concept including the ability to automatically identify and dynamically access better spectrum in response to the presence of potentially harmful interference. The system can locate another portion of spectrum with less interference in 40ms, move the communications to the new, clearer portion of the spectrum, and monitor interference levels in these new frequencies. In short, the cognitive system performs real-time sensing of interference on a channel and then rapidly changes channels when interference exceeds preset thresholds.

One of the challenges for real-time sensing is to create sensing opportunities for both the base station and user terminals. Additionally, the system has to avoid self-interference from co-located devices, specifically from base stations and access points that are collocated to serve multiple channels. The xMax system uses Time Division Duplexing (TDD) and Time Division Multiple Access (TDMA) as a channel access method. Unlike CSMA/CA, the TDMA approach allows terminals to use DSP and RF resources for scanning other frequencies during time periods when they are not communicating with their associated base station.

4. THE XMAX COGNITIVE RADIO PLATFORM

The xMax platform is targeted for commercial service, initially using the 900MHz ISM band. Delivering high system capacity while meeting low power requirements from both FCC Part 15 rules and battery powered operation presents implementation challenges when balancing functionality, range and signal processing with maximum operating time and low-cost. Additionally the size of the radio has to be within an envelope that allows for portable operation.

To allow efficient MIMO and smart antenna operation the system uses 4x2 antenna configuration, i.e. four receive antennas and two transmit antennas together with a parallel DSP processor that can dynamically execute multiple receiver algorithms under the control of a cognitive control system. xMax cognitive radio block diagram (Figure 1) shows the main parts of the system and illustrates the number of receiver algorithms available to the cognitive engine.

Figure 2 shows the first hardware implementation of this radio. In this image the DSP subsystem is visible on a stack, where the RF subsystem is on a separate board mounted below the main digital board.

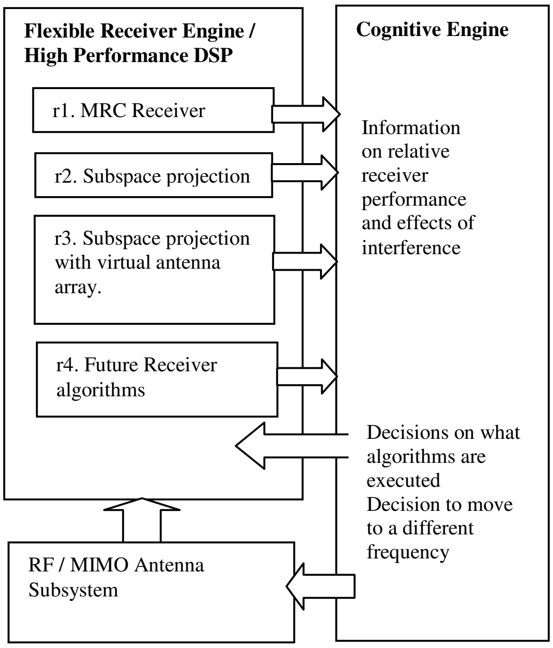

Figure 1. xMax Cognitive Radio Block Diagram

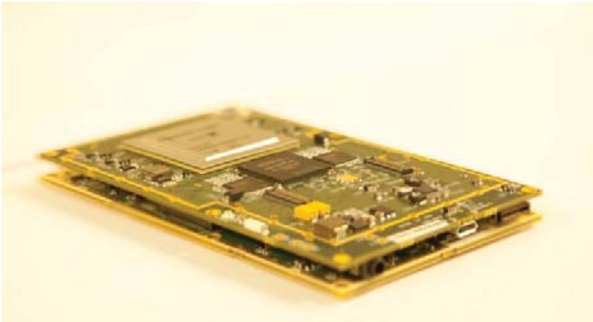

Figure 2. xMax Cognitive Radio Platform

4.1. Antenna System

Antenna system for a cognitive MIMO radio with an interference mitigation system present contradicting requirements. Small size, high performance and different modes of operation requiring four antenna elements are difficult to include into a portable, compact design.

A low envelope correlation coefficient is a key metric for good diversity performance in a fading radio channel. Typically a value of less than 0.5 is required [1]. The final antenna system used was designed to achieve 10dB diversity gain in a Rayleigh fading channel. As a result of testing multiple approaches and designs, a patch antenna solution using high permittivity low loss printed circuit board material was implemented.

Measurements confirmed that the design exceeded the goal of diversity gain by 2 dB (12dB actual). The xMax MIMO antenna (Figure 3) shows the patch antenna design. The antenna operates by exciting a patch structure through multiple ports. The volume of the antenna is extremely small and it is designed to stack on top of the cognitive radio platform. The cuts on the antenna board improve efficiency by stopping surface wave propagation.

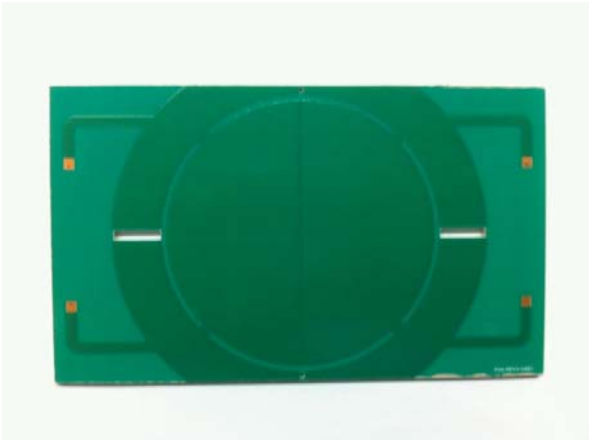

Figure 3. xMax MIMO antenna

4.2. RF Subsystem

Due to the cognitive nature of the system, the 4x2 MIMO RF subsystem design is flexible in nature. The front end is capable of 400MHz-3GHz of operation. However, to save cost in the first implementation, the power amplifiers are designed only for 900MHz band operation. The base band signals are digitized using 14-bit converters. The xMax system allows programmable channel bandwidth up to 20MHz - where a second stage of selectivity filtering uses the DSP subsystem. Additionally, the front end band filtering can be bypassed in cases where there are no strong interfering signals present to improve performance and reduce power consumption.

4.3. Digital Signal Processing Subsystem

The DSP subsystem is able to dynamically execute multiple receiver algorithms depending on decisions from the cognitive engine. To deliver the required signal processing performance in a battery operated device a C-programmable 100 core parallel signal processor is used. The processor delivers 50GOPS and 25GFLOPS of processing performance in a single chip, and can execute 100 parallel threads while integrated Direct Memory Access (DMA) engines transfer data between the processing elements. Digitized baseband signals are fed into the DSP and routed to processor cores that execute receiver algorithms. Processed signals are compared for cyclic redundancy check (CRC) matches and if the packet is received error free the decoded data bits are delivered to the Logical Link Control (LLC) and Media Access Control (MAC) layers being executed on a Texas Instruments OMAP that contains traditional DSP and ARM processors in a single package.

4.4. The Cognitive Engine

The goal of the xMax cognitive system operating in an unlicensed band is not to protect incumbent operations, but to share spectrum fairly with other systems and to use the spectrum efficiently. However, a DSA-only system might not be able to find and operate in a low-interference channel if one is not available. For this reason the cognitive engine in xMax includes a capability to select among multiple receiver algorithms and waveforms to mitigate interference. There are several practical ways to do this; spread spectrum, adaptive antenna arrays, polarization and space diversity are few examples. The cognitive approach chosen includes the use of a flexible antenna system and signal processing system that allows the cognitive engine to dynamically decide what approach is most beneficial for mitigating encountered interference. The cognitive engine can optimize operations by instructing the physical layer to execute different algorithms, and based on real-time measurements, can choose what parameters are beneficial to implement.

It is anticipated that it will be possible to add a learning cognitive engine into the design by using a classifier in the future. For example, received signal strength, measured SNR and achieved data rate can be used to select a subset of operational modes using nearest neighbor or k-nearest neighbor clustering algorithms.

5. ADAPTIVE RECEIVER ALGORITMS

If the measurements indicate that a better channel is available, the system tunes to a new frequency within 40ms. However, if there is no better frequency available the system will use adaptive receiver algorithms to combat interference. Multiple receiver algorithms are executed under control of the cognitive engine and statistics of the interference measured by the user terminal devices and the base stations and are used to choose what receiver algorithms are most beneficial.

For example, if the receiver signal strength (RSSI) is low, MRC is effective in improving link budget and to combat fading. If RSSI is high, but packet error rate is higher than expected for the conditions, the results from multiple receiver algorithms are compared to gather information on what transmit waveform and receiver algorithm combination will be most effective.

In the case of severe interference and when there is no better frequency to move on to, the system uses the multi antenna system to orthogonalise the interference to the desired signal. Additionally the cognitive system can use the physical motion of the user terminal to create a virtual antenna array.

The selection criteria for these modes are complex and can be tuned over time as field experience with the system is gained. For example, there may be instances where the same link performance can be reached with multiple algorithm combinations. This creates a danger of possibly selecting a local minima at a terminal where the performance goal is reached, but the solution also greatly reduces the overall system capacity. An example of this is operation in the presence of burst interference where increasing a modulation rate may improve operation by reducing the probability of data bursts being "hit" by an interferer (at high data rate bursts are shorter in time). A typical approach for non-cognitive radios in this scenario is to reduce modulation rate in an effort to improve the link budget.

5.1. Cognitive Subspace Projection Receiver

One of the adaptive antenna technologies available to the xMax cognitive engine is a subspace projection receiver. The receiver algorithm uses multiple dimensions of a receive signals from a MIMO antenna to orthogonalize the interference to the desired signal. The performance of the algorithm depends on many factors, including the number of antenna elements, element spacing and correlation to mention a few. The idea of the algorithm is to compute a projection from multi-dimensional signal space into a lower dimension so that Signal to Noise Ratio (SNR) is maximized.

Subspace projection in Figure 4 shows the idea by illustrating a 3-dimensional vector "a" projected on the 2-dimensional signal subspace "S". The point "P" is chosen so that "v" and "e" are orthogonal, where "e" is error signal, i.e. interference.

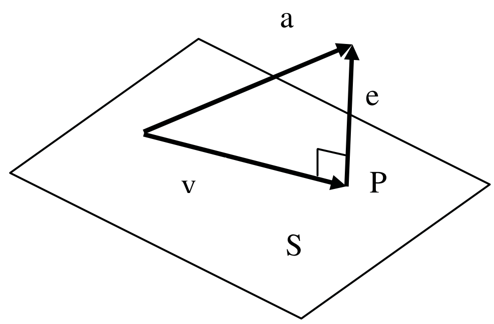

Figure 4. Subspace projection principle

For efficiency, the real-time computation of the projection can be done in the frequency domain. OFDM systems are beneficial in this case because the information in the receiver is already in the frequency domain after initial Fast Fourier Transform (FFT). However, the system performs well only when the projection is computed using carriers that are within a radio channel's coherence bandwidth.

Due to the FCC rules for ISM bands, a transmit beam forming approach is not beneficial. The FCC rules require power reduction by factor of $10*\log_{10}(N)$ where N is the number of transmit antennas. The reduction is required irrespective of the signal processing system, which in theory could reduce interference by projecting transmission into the estimated null space of a non-cognitive radio receiver [4].

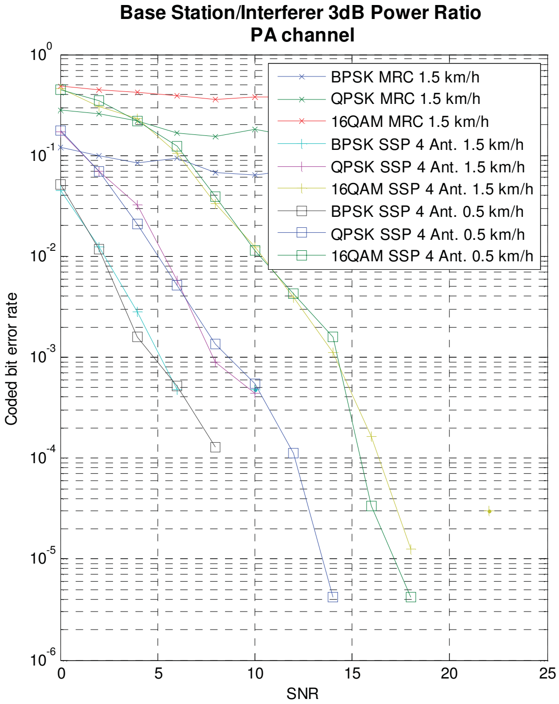

Figure 5. Simulation results of MRC and subspace projection in an interference

In a 1.4MHz 128 carrier system the simulation shows that the number of subcarriers per projection has to be in the range of 10-15 to perform in mobile radio channels. To compute the projection, a known reference signal is transmitted. For example, a Least Squares (LS) solution W can be computed as $W = (A^T A)^{-1} * A^T * d$, where the d is a known signal (local stored reference) and A contains measured complex subcarrier values. The solution is reasonably straightforward because the signal vector d is known, unlike in signal parameter estimation cases where both A and d have to be estimated [5]. In a four antenna xMax system, computations have to be done 8 times, i.e. once per each group of 13 subcarriers in a received frame.

Simulation results of MRC and subspace projection in an interference rich environment quantified in Figure 5 show the performance of a MRC receiver compared to xMax's four antenna subspace projection processing. In these scenarios, a user terminal is communicating with a picocell that is on a same channel as a nearby macro base station, resulting in 3dB higher power for macro cell signal at the receiver. In the scenario shown, the MRC receiver fails to maintain adequate link performance, while the subspace projection based receiver delivers an adequate bit error performance.

5.2. Virtual antenna system using platform motion

A cognitive radio receiver can automatically change transmission parameters and even signal formatting. In severe interference cases the motion of the end user terminal can be used to increase performance by using it to create a "virtual antenna array". When the cognitive engine decides that changing the frequency is not an optimal solution, and that MRC or subspace projection receivers are not delivering adequate performance, it is able to switch to a mode where Hybrid Automatic Repeat Request (HARQ) retransmissions are used to increase receiver signal dimensionality.

This method is an extension of the subspace projection method, except that the size of matrix A is doubled using a retransmission to a moving end user terminal. When a received packet fails, the subcarrier information is stored and HARQ retransmission is used to fill the 8x8 MIMO matrix A. The computational complexity of the solution increases roughly as the third order of the matrix A size. However, with parallel DSP processing the solution can be computed in real-time. Simulation results show that the motion and resulting increase in the size of matrix A outperforms the original four antenna projection method by more than 5dB, depending on the terminal speed. Generally, increased speed improves link performance due to the dimensions of the virtual antenna array increasing as the result of terminal motion between retransmissions.

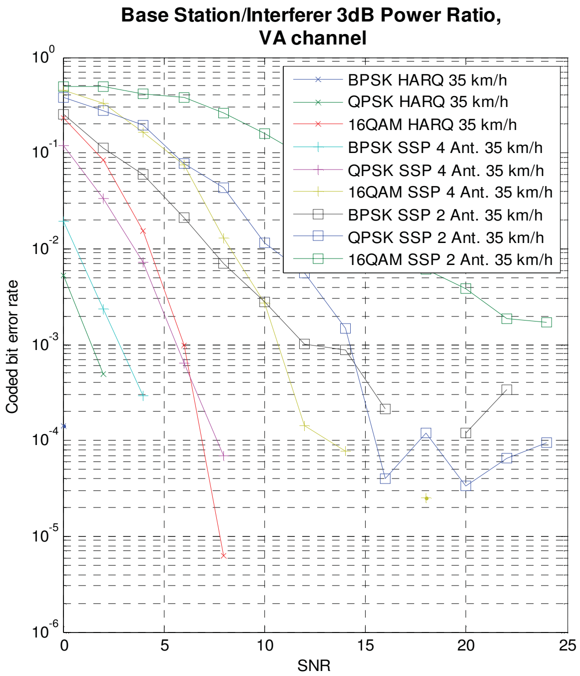

Figure 6. Coded BER of subspace projection method using platform motion to increase antenna matrix size.

Coded BER of subspace projection method using platform motion shown in Figure 6 illustrates the performance improvement using HARQ with the increase of matrix A size. It is important to note that the bit error rate improvement using HARQ comes at a cost of transmitting the data burst twice.

6. CONCLUSIONS

This paper has presented a cognitive MIMO radio with advanced interference mitigation capabilities that allows for increased network density or base stations and or user terminals. The radio system incorporates a cognitive engine that receives information on the relative performance of different receiver algorithms. This information is used to decide how best to use the antenna system and available DSP resources to maximize capacity, throughput or other network performance measures. The radio can change transmission protocols and use a virtual antenna array created by the physical motion of user terminals as a way to maintain the data link under exceptionally harsh RF conditions. Although the presented system is designed for commercial operation on unlicensed bands and does not require incumbent protection, the cognitive engine tries to share the band fairly.

The goal of this paper is to introduce an expanded view of the conventional cognitive radio concept to include a cognitive engine that can dynamically apply one or more receiver algorithms while also using multiple modes of its MIMO antenna system. This ability allows the radio to dynamically transform from a simple MRC based receiver to a relatively complex radio that uses retransmissions and terminal motion of its MIMO matrix array to increase signal dimensionality. Simulation results confirm that the concept of a cognitive radio where receiver algorithms are C-programmable applications that execute on a high performance parallel DSP under control of a cognitive engine can produce significant increases in the link budget.

7. REFERENCES

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