Novel Diversity Combining in OFDM-Based MIMO Systems

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Abstract: - In this paper, we investigate the performance of a novel diversity combining technique, termed root-mean-square diversity combining (RMSGC), for OFDM transmission over flat Rayleigh fading channels in MIMO systems in the presence of co-channel interference (CCI). Prior published results on BPSK transmission over SIMO channels using ML-detected RMSGC diversity signal showed superior bit error rate performance to classical EGC, SC, SLC diversity combining schemes. In addition, the performance of RMSGC was previously shown to be near-optimal in the sense that it was very close to that of the optimal, but complicated and in many cases non-practical, MRC. While this proved to be a very promising technique for fading channels, it suffered from CCI and its performance deteriorated for more than 8 antennas. In this work, we overcame this drawback and showed that CCI can be resolved using RMSGC-combined and ML-detected OFDM-driven MIMO systems. The performance was further improved using SVM detection, which was also successfully tested in previous work.

Key-Words: - Co-channel interference, equal gain combining, maximum ratio combining, multiple-input multiple-output channels, OFDM, root-mean-square gain combining, support vector machine

1 Introduction

The rapid growth of video, voice, and data communication over the internet, as well as the equally spectacular pervasion of mobile telephony, have triggered a new era of mobile multimedia technology. Research and development have exponentially grown worldwide to develop standards for the next generation of wireless broadband multimedia communications systems (WBMCs). Next generation broadband radio systems must deliver unprecedented performance and higher data rates. To achieve these goals, it is imperative that transceivers are optimally designed to account for the fading and reduced signal-to-noise-ratio (SNR) from which wireless systems notoriously suffer.

An emerging modern technique for multipath capacity gain is the multi-input multi-output (MIMO) scheme. MIMO systems use multiple antennas at both transmitter and receiver ends for communication [1-4]. Independent channel fading caused by multipath between different transmitting and receiving antenna pairs provides a significant capacity gain and link reliability over conventional single antenna systems. Independence of channels also means that the receiver will have more than one independent replica of the transmitted signal. MIMO systems can also be applied to provide a higher data rate and reliable communication. These have led to MIMO being regarded as one of the most promising emerging wireless DSP technologies [5]. Numerous MIMO systems using advanced DSP have been proposed in [2-5].

In fact, there exists standardization of MIMO in W-CDMA (Wideband Code Division Multiple Access systems), such as HSDPA (currently underway). W-CDMA is the higher speed transmission protocol (up to 11 Mbps) used in the Japanese FOMA system and in the advanced UMTS 3G system. Many researchers are optimistic that MIMO will be the “key to Gigabit wireless communication system” and believe that the challenge has already been set for wireless researchers to break the Gigabit barrier [5].

The rest of this paper is organized as follows. In section 2, we describe our previously published novel RMSGC diversity combining technique whose performance was investigated for BPSK transmission over Rayleigh fading channels in single-input multiple-output (SIMO) systems (a sub-component of MIMO). In section 3, we survey schemes for modeling CCI and study the performance of transmitted OFDM signals in MIMO systems over flat Rayleigh fading channels with CCI. The demodulation process consists of SVM-
and ML-based detection. Section 4 concludes this paper with a summary of the results, their significance, and suggested extensions.

2 RMSGC in MIMO Systems

In this section, we start by presenting a brief survey of common receiver diversity combining techniques. Then, we present a detailed description of our novel receiver combiner technique.

2.1 Basic Diversity Combining Schemes

Diversity techniques are generally used to generate multiple signal branches between transmitter and receiver and have been shown to improve mean signal strength [6] and reduce signal level fluctuations in the fading channel. There are four basic pure diversity combining schemes, depending on the complexity restrictions placed on the communication system and the amount of channel state information available at the receiver: Maximum ratio combining (MRC), equal gain combining (EGC), maximum gain combining (MGC) or selective combining (SC), and post-detection square-law combining (SLC). The term “pure” is used as a distinction from recently proposed “hybrid” switched techniques [6]. Diversity combining uses the multiple signal branches in the wireless channel advantageously by improving the antenna diversity and system performance, resulting in lower bit error rate (BER) and higher channel capacity.

MRC provides optimal performance but suffers from high implementation complexity and is not practical in systems using differentially coherent (e.g., DPSK, DQPSK) and non-coherent modulation (e.g., BFSK) since it requires estimation of fading channel coefficients. On the other hand, MRC can be used in conjunction with unequal energy systems such as M-QAM where estimation of the diversity paths amplitudes is needed for automatic gain control purposes.

EGC is widespread because of its practicality. In fact, it can be simply implemented by equally weighing each branch before combining (summing) them. Although sub-optimal, EGC with coherent detection is often an attractive solution since it does not require estimation of the fading amplitudes and hence, it is often limited in practice to coherent modulations with equal energy symbols (e.g., MPSK).

Other alternative combining techniques such as MGC (or SC) and post-detection square-law combining (SLC) are also used because of their reduced complexity relative to the optimum MRC scheme. In MGC, the receiver simply selects the signal path with the highest gain. Although conceptually simple, MGC is not as popular as EGC since it requires continual monitoring of the diversity channels and its performance is very sub-optimal. SLC was initially introduced by Proakis [7] and later analysed by a number of researchers to non-coherent and differentially modulated signals. The main distinctive feature of SLC is that it is a post-detection combining technique and requires simultaneous detection of the received diversity signals. SLC is therefore not suitable for more complicated detection schemes such as SVM.

For SIMO systems (sub-components of MIMO) with \( L \) antennas at the receiver, diversity receivers extract multiple signal branches or copies of the same signal received from different channels and apply gain combining schemes to enhance the signal-to-fading-noise ratio and improve the system’s performance.

2.2 New Root-Mean-Square Gain Combiner

In this section, we introduce our receiver diversity gain combining scheme, termed root-mean-square gain combining (RMSGC) and illustrated in Fig. 1. In the RMSGC scheme, diversity signal paths arrive at the \( L \) receiver antennas, where each signal is squared using a square law device. Depending on the polarity of the original arriving signal, the squared signal is inverted (if originally negative), which is achieved by a signum filter. Then all the signals are summed and the composite diversity signal is processed using a square-root (of the absolute value) device before being sent to a detector. If the polarity of the composite signal is negative, the square-rooted signal is inverted using a signum gain.

In previous work [8, 9], we considered \((1 \times L)\) SIMO systems and suggested that the results be extended to \((M \times L)\) MIMO systems using simple spatial cycling techniques [7].

![Fig. 1 Novel RMSGC diversity combining scheme](image-url)
Under such techniques, MIMO systems are implemented by using only one transmitter at a time and by cycling over the $M$ transmitters periodically, effectively employing a SIMO structure at every transmission period (this simple method is a subject of another work, not this one). For comparative analysis, we studied the practical and widely used EGC scheme and the theoretically optimal MRC for BPSK signalling over flat Rayleigh fading channels with AWGN. RMSGC proved to be near optimal in the sense that the ML-based BER results were lower than EGC, very similar to MRC and almost identical to it for SNR over 16 dB. In addition, we found that the BER of RMSGC decreased as the number of antennas increased, but the improvement was gradually diminished and negligible after 8 antennas. We proposed RMSGC as a promising relatively simple new technique which, unlike MRC, does not require SINR estimation and can be implemented using FPGA.

In the following sections, we extended previous work to SVM-based detection and we analyse both SVM-based and ML-based detection for an OFDM-driven CCI-limited MIMO system.

3 OFDM-Based MIMO Systems

In this section, we present a brief survey of commonly used models for co-channel interference and later implement an OFDM-driven MIMO system with CCI.

3.1 Co-Channel Interference Models

Wireless systems present a uniquely different challenge in the sense that, in addition to the hostile fading environment (multiplicative noise), they are also noise- and interference-limited (additive white or colour noise), unlike wire-line systems which are only noise-limited. As a mobile receiver moves in a multipath channel, fading causes the signal power to fluctuate in space along with interfering noise, resulting in a random SINR.

Performance of diversity systems is affected by various operating conditions and channel characteristics and parameters as indicated below:

1. Fading parameters: The combined paths are assumed to come from the same family of fading distribution with identical parameter (average fading power), which is consistent with a uniform power delay profile. This was the basic assumption in our previous work [8, 9]. BER performance of dual MRC diversity with different Rayleigh and Nakagami-m average fading powers is treated in [7, Eq. (14-5-26)] and [10], respectively.

2. Severity of fading: Multipath fading in macro-cellular environment typically obeys a Rayleigh distribution (as we assumed in [8, 9]), while fading in micro-cellular type of environment tends to follow a Rician or Nakagami-m or more complicated statistics [11].

3. Fading correlation: The performance of diversity systems operating over the same fading, background, and AWGN receiver thermal noise conditions is also affected by CCI characteristics such as fading correlation. This is caused by insufficient antenna spacing in small size mobile units equipped with space antenna diversity. With CCI present in the channel characteristic parameters, the maximum theoretical diversity gain cannot be achieved.

CCI are generally based on 3 models:

(i) Non uniform decaying power profile: In interference- limited environment, the combined paths do not come from the same family of fading distribution with identical parameter because the average fading power no longer follows a uniform power delay profile. In fact, the average fading power typically follows an exponentially decaying power delay profile with equispaced delays modeled as $\bar{\Gamma}_l = \Gamma_0 e^{-l(l-1)/l}$ (for $l = 1, \ldots, L$ antennas), where $\delta \geq 0$ is the average fading power decay factor, and $\Gamma_0$ is the mean reference-SNR of the 1st signal path [7]. In dB scale, $\bar{\Gamma}_l[\text{dB}] = \Gamma_0[\text{dB}] - \chi^{(\text{CCI})}_l$, where $\chi^{(\text{CCI})}_l = \delta(l-1)/\ln 10$ is the extra dB noise figure which is effectively added to the underlying additive noise (due to CCI) for every $l$-th added diversity path.

(ii) Uniform decaying power delay profile: Another simpler model is the uniformly decaying power delay profile $\bar{\Gamma}_l = \Gamma_0 / \delta \forall l$. In dB scale, $\bar{\Gamma}_l[\text{dB}] = \Gamma_0[\text{dB}] - 10 \log(\delta)$, so that if $\delta = 0.01$, every extra interfering diversity path introduces an extra 10 dBm to the underlying additive noise.

(iii) Compounded fading: In this model (proposed in Matlab forum), the 1st reference diversity signal is transmitted over a fading channel with AWGN. Then the noisy signal is recursively fed back $L - 1$ times through the same channel where the noise will get compounded.

In Figure 2, the simulated mean BER curves are plotted versus the average SNR $\bar{\Gamma}_0 = E_s/N_0$ (per signal path) for different number of antennas using RMSGC diversity of BPSK signals in SIMO systems. CCI is assumed to follow the “exponential decaying power” model. In the absence of CCI, the BER is expected to decrease with an increase in the
number of antennas. However, this improvement is diminished because the compounded CCI effect causes “more harm than good” as the number of antennas is increased beyond a critical level (8 antennas). Fig. 2 clearly demonstrates this by showing performance degradation for 16 antennas.

3.2 OFDM in CCI-limited MIMO Systems

MIMO technology is best compatible with non-frequency selective fading channels to ensure low complexity and power consumption in the receiver. Therefore, the channel in this work is considered to be flat Rayleigh fading with noise and interference (CCI) present, in which the code word encompasses \( N \) (TX + RX antennas) fading blocks. CCI is modeled as a Markov modulated white Gaussian process whose variance across one block obeys a 2-state Markov chain and changes independently from block to block. While this model may not be perfect, it is proposed in [12, 13] since it maintains desirable properties of constructed codes when used in realistic wireless channels.

Fig. 2 CCI effect on BPSK-driven RMSGC in SIMO

MIMO is mostly used in conjunction with OFDM, a modulation technology that is part of the IEEE 802.16 and IEEE 802.11n “High-Throughput” standards. OFDM’s high spectral efficiency and resistance to multipath make it an extremely suitable technology to meet the demands of wireless data traffic. OFDM inherently provides frequency diversity over sub-channels (or tones), which offers an opportunity for both interference averaging and interference avoidance in the frequency domain [14]. In fact, multi-carrier signals in OFDM enable the antenna arrays to operate independently, thus combating CCI. Consequently, OFDM is introduced to our system with the ultimate goal of resolving CCI and its performance is compared to the previously simulated non-OFDM (BPSK) based system.

OFDM is widely implemented in the literature according to the scheme illustrated in Fig. 3. The user signals are passed through IFFT, parallel-to-serial (P/S) conversion, and cyclic prefix insertion (+CP) at the transmitter side, and corresponding inverse processing is applied at the receiver. The operations of CP insertion and removal turns the effective channel responses into circulant matrices, which can be diagonalized by unitary normalized IFFT and FFT matrices.

Fig. 3 OFDM-driven MIMO system

The outcome of this implementation is presented in Fig. 4, where the mean BER is plotted vs. the mean SNR per signal path for 2x4 and 2x8 MIMO systems using SVM and ML detectors. We note that OFDM successfully overcame the deterioration effect of the compounded CCI noise. In contrast to the results of Fig. 2 that showed an increase in the BER after a certain critical number of antennas, the 2x8 system outperformed the 2x4 system. With ML detection, the CCI effect was also combated, but the performance was expectedly inferior to SVM [8].

Fig. 4 Performance of SVM-detected OFDM-MIMO system

Since the critical number of antennas in CCI-limited systems was found to be 8, we simulated 1x8
SIMO and 2x4 OFDM-MIMO systems in Fig. 5. As expected, MIMO outperformed SIMO for the same number of total antennas between TX and RX. In addition, the superiority of the SVM-based detector over the classical ML detector was once again evident [8]. SVM performance was nearly identical for 1 x 8 SIMO and 2 x 4 MIMO.

4 Conclusions and Future Work

In this paper, we successfully implemented an OFDM-driven MIMO system with flat Rayleigh fading channels in a CCI environment. OFDM was able to resolve the compounding effect of CCI noise in contrast to prior work [9] where BER degradation was observed after a critical number of 8 antennas. In addition, the MIMO system outperformed SIMO for the same number of total antennas between TX and RX. The superiority of the SVM-based to the ML-based detection was another result consistent with previous research [8].

It is hoped that such work could be implemented in future MIMO-based technologies in WLAN, WPAN, 4G cellular, broadband wireless networks, and DTV, where BER reduction will allow for increased transmission rate and higher speed, longer transmission range, and more reliable wireless links.

As future work, we suggest incorporating adaptive modulation to MIMO systems in order to further improve their performance. Adaptive modulation allows the communication system to adjust the signal modulation scheme depending on the channel conditions. When the link SNR is high, the highest modulation scheme is used, giving the system more capacity and increased throughput. When the signal fades, the system shifts to a lower modulation scheme to maintain the connection quality and link stability. Further extensions of this work may also include analysis of other QoS metrics such as outage probability and AOD in the presence of other CCI models.

References: