CAPACITY ENHANCEMENT IN AERONAUTICAL CHANNELS WITH MIMO TECHNOLOGY

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ABSTRACT

This paper shows how the application of MIMO (multiple-input multiple-output) communication methods can enhance telemetry systems. The main contribution of MIMO to the communication system is improving spectral efficiency by exploiting spatial diversity of multiple antennas. For communications using high order QAM modulated signals, a blind MIMO equalizer is proposed in earlier works. In this work possibilities of adapting blind MIMO equalizer to iNET problems is explored. In addition, MIMO equalization is adapted to operate as a successive interference cancellation (SIC) scheme to improve the quality of received signal in a high interference environment by capturing and cancelling the interferer.

1. INTRODUCTION

With increasing demand for data rate and limited spectrum, high efficiency systems are highly desired. Telemetry is one of the areas in wireless communications that needs higher data rates for faster and higher quality communication. MIMO offers several fold increase of data rate over the same bandwidth with no additional cost. Just three decades ago, simultaneous transmission of multiple data streams over the entire available bandwidth, would have been an impossible. Starting from the 80’s remarkable research toward that very promising but unusual idea has resulted in the development of MIMO technology. The MIMO technique refers to the use of multiple antennas at both the transmitter and receiver. Each pair of transmit and receive antennas provides a single path from the transmitter to the receiver. MIMO transmission exploits the spatial dimension in a rich scattering environment by using multiple transmit and receive antennas. Shannon capacity calculation for a MIMO channel states that the channel capacity increases proportional to the number of transmit and receive antennas. Following the fundamental capacity research into MIMO system in [1]- [2], it received significant attention in recent years because of its ability to enhance overall performance of communication links. In traditional single-input single-output (SISO) communication link, a dedicated channel frequency is used for a single pair of transmit and receive antennas, which can only transmit and receive a single signal at any given time. By increasing the number of antennas at the transmitter and receiver, it is now possible to communicate several signals instantaneously on the same frequency. In this work, higher spectral efficiency and a method for interference mitigation over aeronautical channel with MIMO technology is investigated. This matter requires an equalizer to combat inter-symbol interference (ISI). A blind MIMO adaptive equalizer is introduced and discussed in detail. A method for
interference rejection (cancellation) with the proposed MIMO equalizer to achieve higher efficiency performance in the interference limited environments is also presented.

2. MIMO SYSTEMS

In this chapter, a brief introduction to MIMO communication system models is provided. Next, the capacity in MIMO systems is discussed and the improvement in the channel capacity in multi-antenna systems is shown by comparing a SISO (single-input single-output) system to a MIMO communications system.

Wireless communication has become the fastest growing field of electrical engineering in recent years. Its growth is primarily due to rapidly increasing demand for high data rates on wireless devices (such as droid phones and ipads). In this data extravaganza, the battle over the precious spectrum seems to be never-ending. However, it does have limitations, due in part to the proportionality of data rate to the bandwidth as well as the restricted range of usable spectrum. This fact is significant to the signal processing community, who often try to augment the limited bandwidth with higher efficiency to push the limits of traditional communications and expand it in dimensions that are greater than just frequency. By increasing the number of antennas at the transmitter and receiver, it is now possible to communicate several signals instantaneously on the same frequency. In this case, several MIMO techniques are required to receive and separate the multiple sources [3], but if this goal is reached, the links are richer, and each carrier frequency is utilized to communicate with several fold higher throughput. Originally MIMO was applied to narrow-band systems [4], but in the past few years, broad-band systems have also started to employ MIMO for applications such as the 4G mobile communication standards. The purpose of MIMO can be also described as a technique to enhance the performance of communication links by combating and exploiting multipath fading. Spatial diversity, spatial multiplexing, adaptive beamforming, and null-steering in smart antennas are some of the different techniques that take advantage of MIMO communication setup. Benefits of using MIMO include increased data rate, increased reliability, array gain, and interference rejection. With the emerging technologies, such as LTE-4G standard [5], which employs a MIMO configuration in the RF link, MIMO equalization is a rising star.

2.1. SYSTEM MODEL

In this work, we consider a coherent and synchronous environment with single tone signaling, where carrier timing and waveform recovery have been achieved. Both the channel and the equalizer are modeled as linear FIR filters. For a MIMO system with M transmit antennas and P receive antennas, we consider M sources $s_1, \ldots, s_M$ transmitted in data blocks of length, $N$ over a broadband channel with $K$ taps. Figure 1 show a simple block diagram of the MIMO systems:
The received data vector is the input to a multiple-input multiple-output (MIMO) equalizer. Independent data signal blocks can be given as

$$s_j(n) = [s_j(n) \ s_j(n-1) \ \ldots \ s_j(n-N+1)]^T \in \mathbb{C}^{N\times1}$$

where $j$ is the $j^{th}$ transmission antenna index.

The MIMO channel is modeled as:

$$H(k,n) = \begin{bmatrix} h_{11}(k,n) & \ldots & h_{1M}(k,n) \\ \vdots & \ddots & \vdots \\ h_{P1}(k,n) & \ldots & h_{PM}(k,n) \end{bmatrix} \in \mathbb{C}^{P\times M}$$

(1)

where $h_{ij}(k,n)$ represents the $k^{th}$ path between the $j^{th}$ transmit and $i^{th}$ receive antenna at a time instance of $n$. For example, in time invariant independent and identically distributed (i.i.d.) channel modeling, one can choose $h_{ij}(k,n) = \mathcal{C}N(0,\sigma_k^2)$, where the $\sigma_k^2$ is computed w.r.t. the power delay profile (pdp) of the channel for $k=1, 2, \ldots K$ taps. With the given definitions, the received signal at time $n$, after transmission over the channel can be shown as

$$x(n) = \sum_{k=1}^{K} H(k,n)S(k) + v(n)$$

(2)

where $v(n)$ is the vector of additive white Gaussian noise signal of the channel. $x_i(n) = [x_i(n) \ x_i(n-1) \ \ldots \ x_i(1)]^T \in \mathbb{C}^{N\times1}$ is the $i^{th}$ received signal block. $S(k)$ is the input signals stacked in a matrix format.

### 2.2. CAPACITY IN MIMO SYSTEMS

MIMO promises to increase spectrum efficiency by separating data streams on the same bandwidth in the multipath environment. This can only be achieved if the channel paths are independent and have flat Rayleigh fading profiles and the total power is constrained. With these assumptions, Foschini [1] presented clear analytical basis for the capacity of MIMO systems where expressions for the capacity of SISO, SIMO and MIMO systems are derived. The capacity of a MIMO system can be calculated by (3), if the channel is assumed to be stationary Rayleigh fading during transmission of a data block and the total transmitted power remain the same with any number of transmit antennas:

$$C = \log_2 \left( \det \left( [I_M + (\frac{\rho}{r}) \cdot HH^H] \right) \right) \frac{\text{bits}}{s/\text{Hz}}$$

(3)

where $\rho$ is the signal to noise ratio at each receiver, $H$ is the channel matrix, and $r$ is the rank of the channel matrix. If the channel matrix consist of i.i.d. Rayleigh fading coefficients, it is shown [6] that at 25 dB SNR, the capacity increases to approximately 52 bits/s/Hz for an 8x8 MIMO setup, compared to 7 bits/s/Hz for SISO system. Detailed discussion on MIMO capacity also can be found in [1], [2]. To clearly demonstrate the effectiveness of MIMO structure in increasing the capacity of the communication link, random complex i.i.d. channels are generated and results are averaged over 1000 Monte Carlo realization for different SNR and different number of transmit/receive antennas and shown in figure 2. In these experiments, the number of transmit and receive antennas are assumed to be equal (i.e. $N_t = N_r$), and channels are generated independently,
so that the system has full rank \((r)\), and the capacity gain is maximized i.e. \((N_t = N_r = r)\). In figure 2, linear increase of capacity by number of antennas is observed.

![Figure 2: Capacity of wideband (4 time-taps) MIMO system vs. (left) \(r\) and (right) SNR](image)

Now that the major advantage of MIMO in increasing the capacity of system has been theoretically illustrated, the next section introduces the equalization and the need for this step in communications to take a step forward toward implementation of a MIMO communication link.

### 3. EQUALIZATION

Wireless communication systems — specifically MIMO links — are prone to inter-symbol interference due to multipath. The goal of MIMO equalization is to design an optimum filter such that reverses the effect of the unknown channel on the signal and provides the best approximation of the input signals. Multipath fading and Doppler spread are two of the main reasons that make the radio channel dynamic and results in degradation of signal quality at the receiver end. Note that the \(j\)th output of the equalizer is given by:

\[
y_j(n) = X(n) * w_j(n) \quad \text{for each } j = 1, 2, \ldots, M
\]

where \(^T\) denotes the transpose operator and the filter weight vector is given by:

\[
w_j(n) = [w_{11}(n) \ w_{12}(n) \ \ldots \ w_{1L}(n) \ |w_{21}(n) \ \ldots \ w_{2L}(n)| \ \ldots \ w_{PL}(n)]^T
\]

where the weight vector \(w_j(n)\) and its updates are determined by the type of equalization algorithm. The next section introduces the CMA+AMA equalization algorithm, which is the desired equalization method for the proposed MIMO equalization.

#### 3.1. BLIND CMA+AMA EQUALIZATION

Godard in [7] has proposed so called Godard-p constant modulus (CM) algorithm for design of a blind equalizer, which is independent of the symbol constellation and carrier phase. Treichler and Agee [8], independently proposed an equalization algorithm which is a special case of Godard-p CMA. The cost function is defined and the weight vector of the equalizer is updated using steepest descent to find an optimal set of weights that minimizes the specified cost function. This algorithm is blind and does not use a training sequence. CMA equalizer is well known and commonly used equalizer for constant modulus signals, but for non-constant modulus signals such
as 16-QAM, CMA is unable to fully recover the signal and suffers from high residual error. In later efforts a linear combination of CMA and AMA (alphabet matched algorithm) by [9] has shown to be effective in equalization of higher order non-constant modulus QAM signals [10]. The cost function for CMA+AMA equalizer is given by:

\[ J_{CMA+AMA} (y(n)) = J_{CMA} (y(n)) + J_{AMA} (y(n)) \]    (6)

where the CMA cost function is

\[ J_{CMA} (y(n)) = E \left\{ \left( |y(n)|^2 - R_2 \right)^2 \right\} \]    (7)

where \( R_2 = \frac{E[|c(i)|^4]}{E[|c(i)|^2]} \) and \( c(i), i=1,2,\ldots,M \) are the known constellation points. The notation \( E\{.\} \) denotes the expected value taken over an entire block of transmitted data symbols. The AMA cost function from [9] is given by:

\[ J_{AMA} (y(n)) = E \left\{ 1 - \sum_{i=1}^{MQ} e^{-\frac{|y(n) - c(i)|^2}{2\sigma^2}} \right\} \]    (8)

\( \sigma \) is a parameter used to control the width of the nulls around each constellation point, \( c(i) \) and is chosen such that those nulls do not overlap.

The update for the equalizer weight vector \( w_j(n) \), is given by the stochastic block gradient descent rule:

\[ w(n+1) = w(n) - \mu_n \nabla_w J_{CMA+AMA} (y(n)) \]    (9)

where each equalizer vector \( w_j(n) \) is updated independently for \( j=1,2,\ldots,M \). Detailed discussion on the CMA+AMA equalizer can be found in [10].

### 3.2. MULTISTAGE MIMO EQUALIZATION

In MIMO environment where more than one signal is transmitted, by nature CMA equalizer converges to the most powerful signal while nulling the others [11]. In order to recover the other signals, a multistage blind source separation technique is proposed for MIMO communication links.
Figure 3: Multistage MIMO equalization and source separation

Figure 3 shows the block diagram of the proposed multistage source separation method, for a two input and three output MIMO system. In this method, after equalization of the first signal at MISO equalizer, the contribution of the signal is cancelled from the received signals. The modified signal set is fed to another MISO equalizer, which will recover the next most powerful signal. This process can be repeated up to the number of transmitted sources to recover all of the source signals. It is observed that, the MIMO equalizer captures both the transmitted sources.

As it is seen from the figure, after the first stage of MISO equalization, a channel estimator and signal canceller is needed to make MIMO equalization possible by removing the captured source. The next section describes the theory behind these processes.

4. BLIND SOURCE SEPARATION

Blind source separation in the MIMO systems is achieved based on the following theorem from [12]:

**Theorem:** By modifying the input signal of the MISO equalizer with

\[
\tilde{X}(n) = X(n) - \tilde{h}_j y_j^T(n)
\]

where \( y_j(n) \) is the equalized signal and \( \tilde{h} = \frac{1}{\sigma_{\hat{y}_j}^2} R_{xx} (K - 1) w_j^0 \), the contribution of the captured source is cancelled in \( \tilde{X}(n) \).

This theorem proves that using second order statistics of the received signal (autocorrelation of \( X(n) \)) and the final weights of the CMA+AMA equalizer, channel is estimated without any prior knowledge about its statistics. MSE for the proposed blind channel estimator is computed and compared to well-known MMSE and ML channel estimation methods. Figure 4 shows the result of this comparison in which at higher SNR values acceptable performance of the blind channel estimator is observed. Note that ML and MMSE estimators require training signals.

![Figure 4: MSE for blind, ML, and MMSE channel estimators](image-url)
5. INTERFERENCE CANCELLATION

In this section multistage MIMO equalization and source separation method is adapted to operate as a successive interference cancellation (SIC) scheme to improve the quality of received signal in a high interference environment. In a 3-stage setup, after capturing the signal of interest (SOI), interference is estimated and cancelled at second stage. After cancellation of the interference, the last stage of equalization recaptures the SOI with better quality due to higher SINR at its input signals.

Figure 5: Three-stage interference cancellation

The proposed model consists of three identical stages of equalization and cancellation. The model is shown in figure 5 and has two input signals; i) data signal, \( S(n) \) and ii) interferer, \( I(n) \). At the first stage the MISO CMA+AMA equalizer converges to the most powerful signal. For this system, the interferer is assumed to have less power compared to the data signal. With this assumption, the output of the first stage, \( \hat{S}(n) \) is an estimated version of the data signal, \( S(n) \). This signal and the steady state value of the equalizer filter weights are used at the second stage for estimating the channel vector effective on \( S(n) \). The signal canceller at stage 2, cancels the captured signal and produces the modified signal se of \( \tilde{x}_j(n) \) for \( j=1, 2, \ldots P \). This modified signal set does not contain the data signal \( S(n) \) since it is cancelled at this stage. The MISO equalizer in this stage captures the only signal present in \( \tilde{x}_j(n) \) set which is the interferer. The output of this stage \( \tilde{I}(n) \) is estimated interference signal.

In the third stage, the channel vector corresponding to the interferer is estimated and the interference is cancelled from the received signals to produce \( \tilde{x}_j(n) \) for \( j=1, 2, \ldots P \). In this signal set the interference is cancelled and the only remaining signal is the data signal, \( S(n) \). The MISO equalizer at third stage recaptures the \( S(n) \) shown as \( \hat{S}(n) \). Since the input for third stage of MISO
equalizer has higher SIR compared to stage 1 and this enables the CMA+AMA equalizer to capture the data signal in interference free environment so the \( \tilde{S}(n) \) has better quality compared to \( \hat{S}(n) \).

To evaluate the performance of the proposed signal cancellation scheme, a data block with 1400 symbols with 16-QAM modulation is transmitted and the signals are received with 3 receiver antennas. The CMA+AMA equalizer filter length is 12 and the equalizer weights are iterated 1000 times. Results are averaged over 1500 Monte Carlo realizations. The channel is 4 time-taps (\( K = 4 \)), Rayleigh fading iid channel with \( CN(0, \sigma_k^2) \), \( \sigma_k^2 = (1/2)^{K-1} \) entries. To quantify the improvement is the quality of the data signal in this 3-stage scheme, interference cancellation gain (ICG) is defined as:

\[
ICG = SIR_3 - SIR_i
\]

where \( SIR_i = \frac{Power(S)}{Power(I_i)} \)

and \( I_i \) refers to interference at stage i. ICG for the experiment above is measured and shown in figure 6.

![Figure 6: Interference cancellation gain for iid channel](image)

In figure 6 at higher SNR values more than 10dB interference cancellation is an impressive gain for fully blind SIC method which is a combination of a blind equalizer, channel estimator and signal canceller. It is also observed that by increasing the SNR value, the cancellation gain increases drastically. Analysis have shown that with no noise (SNR=\( \infty \)), the interference is completely removed and SIR at stage 3 approaches infinity.

We have shown that using this method with successful equalization at the first stage, we are able to achieve approximately 10 dB cancellation gain when interferer is as strong as signal(SIR=0) and SNR is 35 dB.

6. CONCLUSION

In this work we have achieved blind source separation with multiple stages of MISO CMA+AMA equalizer dispersed with blind channel estimator and signal cancellers. The resulting MIMO equalizer can be implemented in telemetry systems to increase the capacity of the system.
The proposed equalizer has been successfully tested with high order QAM signals, which means by upgrading the telemetry modulation to M-QAM from BPSK, data rate can be multiplied by $\log_2 M$. For instance 64-QAM modulation will increase data rate by factor of 6 in comparison to 1 bit/symbol for BPSK modulation.

Also it is demonstrated that the multistage MIMO equalization can be used as interference cancellation mechanism. This can lead to significant link improvement in telemetry communications.

These methods show great promise for expanding the available spectrum efficiencies for telemetry application by a factor of 2-10 depending on the configuration.

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7. REFERENCES


