GEOMETRICAL SPACE DIVERSITY AND DISTRIBUTED SPACE DIVERSITY TECHNIQUES FOR WIRELESS COMMUNICATION SYSTEMS

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GEOMETRICAL SPACE DIVERSITY AND DISTRIBUTED SPACE DIVERSITY TECHNIQUES FOR WIRELESS COMMUNICATION SYSTEMS

by

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LIST OF ABBREVIATIONS

ADC	Analogue to Digital Converter
AF	Amplify-and-Forward
AGC	Automatic Gain Control
CDMA	Code division Multiple Access
CF	Compress-Forward
CSI	Channel State Information
DAC	Digital to Analogue Converter
DF	Decode-and-Forward
DFT	Discrete Fourier Transform
DQE Codeboooks	Distributed QE Codebooks
DQE2-1	Distributed Quantized Equal-Gain BPSK Codebooks with 1 Bit of Feedback Per Phase Angle
DQE2-2	Distributed Quantized Equal-Gain BPSK Codebooks with 2 Bits of Feedback Per Phase Angle
DQE4-2	Distributed Quantized Equal-Gain QPSK Codebooks with 2 Bits of Feedback Per Phase Angle
DQE8-3	Distributed Quantized Equal-Gain 8PSK Codebooks with 3 Bits of Feedback Per Phase Angle
DQE16	Distributed Quantized Equal-Gain 16QAM Codebooks with 4 Bits of Feedback Per Phase Angle

EG	Equal Gain
EGC	Equal Gain Combining
EGT	Equal Gain Transmission
FDD	Frequency Division Duplexing
GLA	Generalized Lloyd Algorithm
GMRC	Generalized Maximum Ratio Combining
i. i. d	Independent and Identically Distributed
LOS	Line Of Sight
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
ML Detector	Maximum Likelihood Detector
MMSE	Minimum Mean Square Error
MR	Maximum Ratio
MRC	Maximum Ratio Combining
MRT	Maximum Ratio Transmission
MU-MISO	Multi-User MISO
MU-MIMO	Multi-User MIMO
ODF	Opportunistic Decode-Forward Protocol
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection

OMRS	Orthogonal Multiple-Relay Selection
PDF	Probability Density Function
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QE Codebook	Quantized Equal-Gain Codebooks
QE2-1	Quantized Equal-Gain BPSK With 1 Bit of Feedback Per Each Phase Angle
QE2-2	Quantized Equal-Gain BPSK With 2 Bits of Feedback Per Each Phase Angle
QE4-2	Quantized Equal-Gain QPSK With 2 Bits of Feedback Per Each Phase Angle
QE8-3	Quantized Equal-Gain 8PSK With 3 Bits of Feedback Per Each Phase Angle
QE16	Quantized Equal-Gain 16QAM With 4 Bits of Feedback Per Each Phase Angle
QEGT	Quantized Equal Gain Transmission
QOS	Quality of Service
RF	Radio Frequency
RRDF	Relay-Reuse Decode-Forward
RSS	Received Signal Strength
RVQ	Random Vector Quantization
SDT	Selection Diversity Transmission
SDC	Selection Diversity Combining
SEGT	Scalar Equal Gain Transmission

SISO	Single Input Single Output
SIMO	Single Input Multiple Output
SMRT	Scalar Maximum Ratio Transmission
SNR	Signal to Noise Ratio
SRS	Single Relay Selection
STBC	Space-Time Block Codes
SVD	Singular Value Decomposition
TDD	Time Division Duplexing
VQ	Vector Quantization
WARP	Wireless Open-Access Research Platform
WZ	Wyner-Ziv

LIST OF SYMBOLS

N_t Number of Transmit Antennas

N_r Number of Receive Antennas

$h_{j,i}$ Channel from the ith transmit antenna to the jth receive antenna

$\mathbf{H}$ Channel Matrix

s Transmit Symbol

$\mathbf{w}$ Beamforming Vector

$\mathbf{c}$ Basic Combining Vector

$\mathbf{c}_u$ The Set of Possible Combining Vectors

u The Set of Constellation Symbols

n Noise Component

N_0 Variance of the Noise

$d^2(a,b)$ Squared Euclidean Distance Between a and b

γ Instantaneous SNR

$\overline{\gamma_0}$ Minimum Average SNR

ref The Reference Antenna at The Receiver

$\overline{\gamma_{ref}}$ The Average SNR of The Reference Antenna

φ The Equal-Gain Beamforming Vectors Phase Angles In Radian

ε_s Average Energy of the Symbols

B Number of Feedback Bits Per Each Phase Angle

$card$ Cardinality

L Quantization Level of a Phase Angle

O complexity Order

$argmax_z(f)$ The Argument of the Set z, Which Maximizes f

β_{N_t,N_r} The Scale Factor Which Maps the Minimum Average SNR to The Exact Average SNR

σ_j The Standard Deviation Of The Noise At the j Receive Antenna

$M(.)$ Moment Generating Function

R_k The kth phase Region

Δ_i The Deviation Angle of the Noise-Free Signal Transmuted by the ith Transmit Antenna From the Angle Of The Symbol

ω Phase Angle in Radian

$\angle$ Angle

$e\angle$ Error of Phase

$e|.|$ Error of Magnitude

E_s Energy of Symbol

E_b Energy of Bit

M Number of Constellation Symbols

R Number Of Relay Nodes

N Number of Antennas at Each Relay Node

L_1 Location of The Transmitting Node in a Relay Network

L_2 Location of The Receiving Node in a Relay Network

α Magnitudes of the SMRT

π Pi

P Probability Density Function

TEKNIK-TEKNIK GEOMETRI RUANG KEPELBAGAIAN DAN TERAGIH KEPELBAGAIAN UNTUK SISTEM PERHUBUNGAN TANPA WAYAR

ABSTRAK

Kajian ini menghasilkan satu skima kepelbagaian ruang yang tulin berdasarkan konsep geometri yang mengoptimakan Isyarat kepada Nisbah Bunyi (SNR) untuk sistem komunikasi sama-keuntungan Pelbagai Kemasukkan dan Satu Keluaran (MISO). Pada peringkat kedua, kaedah ini diperluaskan kepada sistem Pelbagai Kemasukkan dan Pelbagai Keluaran (MIMO). Kaedah-kaedah dicadangkan untuk menyelesaikan masalah utama dalam sistem konvensional gelung tertutup MISO dan sistem MIMO seperti kerumitan yang tinggi, kelewatan maklum balas, purata SNRs yang tidak diketahui, pergantungan terhadap penghantar antena, tiada penyesuaian terhadap saluran, dan kekaburan fasa. Pada peringkat ketiga, struktur yang dicadangkan untuk skima Skalar Sama Penghantaran Keuntungan dan Nisbah Maksima Penggabungan Umum (SEGT / GMRC) di ikuti untuk mencipta bentuk kod buku maklum balas terhad untuk MISO dan MIMO sistem yang menyediakan satu kaedah yang berbeza berbanding dengan kod buku yang terkenal sebelumnya. Cadangan kod buku terkuantum gandaan sama (QE), memerlukan bilangan bit maklum balas yang minima untuk menghasilkan bentuk alur vektor. Pada peringkat ke empat, kod buku QE dicadangkan untuk menyediakan kepelbagaian ruang teragih dalam rangkaian geganti tanpa wayar. Memandangkan antena penghantar adalah bebas dengan sendirinya, lanjutan kepada rangkaian geganti adalah mudah. Reka bentuk baharu dinamakan kod buku yang teragih QE (DQE), di mana setiap nod geganti menyimpan kod buku QE. Didalam penyelidikan ini, peralatan memasuki tanpa wayar terbuka penyelidikan platform (WARP) telah digunakan untuk prototaip kod buku QE yang dicadangkan. Skim baharu geometri kepel-

bagaian sistem yang dicadangkan menghapuskan proses mencari dan berfungsi sebagai sistem yang optima untuk penghantaran sistem MISO gandaan sama. Dengan melanjutkan kaedah ini untuk kepelbagaian ruang teragih (DQE), masalah utama yang berkaitan dengan kaedah konvensional seperti kerumitan, maklumat keadaan saluran (CSI) sejagat, maklum balas kelewatan, geganti nod bergantung dan tidak diketahui purata SNR telah dapat diselesaikan. Keputusan yang memberangsangkan untuk QE dan codebooks DQE adalah seperti yang terdapat didalam tesis. Kod buku yang dicadangkan menunjukkan bahawa QE dapat menghasilkan prestasi yang hampir optima. Tesis ini juga telah membuktikan bahawa sistem yang mempunyai hanya satu bit maklum balas setiap sudut setiap fasa tidak boleh menghasilkan prestasi yang optima. Jurang prestasi isyarat kod buku yang dicadangkan menggunakan QPSK dan BPSK skima pemudalatan dengan 90 darjah kebebasan adalah kurang daripada 0.25-0.75 dB pada kadar kesilapan simbol 10^{-5}. Jurang ini dikurangkan untuk isyarat kod buku menggunakan 8PSK dan 16QAM skima pemudalatan dengan 45 dan 30 darjah kebebasan masing-masing. Platform WARP mengesahkan reka bentuk geometri kod buku QE. Ia menunjukkan bahawa kod buku QE yang dicadangkan adalah lebih mudah untuk dilaksanakan dan kod buku QE yang lebih rendah tahapnya adalah lebih sesuai untuk saluran yang mempunyai garis laluan penglihatan. Rangkaian sistem komunikasi menggunakan DQE juga boleh dilaksanakan dengan kerumitan yang minima. Sistem komunikasi yang menggunakan Kod buku DQE telah ditunjukkan mempunyai prestasi lebih baik daripada sistem komunikasi penghantaran terus bebas daripada lokasi mereka dalam rangkaian mengagihkan. Bilangan nod relay memainkan peranan yang penting terhadap prestasi rangkaian. Sebagai contoh, prestasi kesilapan untuk 3 nod relay yang terletak berhampiran dengan sumber dan setiap daripada mereka menggunakan QPSK atau 8PSK kod buku teredar, adalah bertambah baik dengan 14 dB pada kadar kesilapan sebanyak 10^{-5} apabila bilangan nod relay teredar meningkat kepada 8. Ia juga menunjukkan bahawa kod buku DQE mengatasi kod buku QE apabila nod geganti adalah dekat ke nod sumber. Jumlah peningkatan adalah sekitar 1 dB untuk QPSK kod buku teredar dan sekitar 2 dB untuk 8PSK kod buku teredar. Kelebihan skima geometri yang dicadangkan berbanding dengan kerja-kerja yang terkenal adalah seperti berikut: kaedah pencarian terhapad kecapaian yang optima bagi bentuk alur vector yang sama dan teredar adalah dihapuskan, oleh itu kerumitan dan kelewatan sistem menjadi rendah sementara prestasi masih optima; masalah kekaburan fasa diselesaikan; purata SNR pada penerima antena boleh didapati; penghantar antena dan nod relay adalah bebas yang membolehkan penggunaan lebih daripada satu pautan maklum balas; maklum balas yang terhad bagi bentuk alur vektor bergantung kepada skima pemodulatan, yang menggalakkan reka bentuk untuk kod buku yang mudah dengan menggunakan tingkat konstilasi yang lebih rendah; sistem baru boleh menyesuaikan diri dengan perubahan kelakuan saluran tanpa melakukan operasi matriks.

GEOMETRICAL SPACE DIVERSITY AND DISTRIBUTED SPACE DIVERSITY TECHNIQUES FOR WIRELESS COMMUNICATION SYSTEMS

ABSTRACT

This research produces a novel space diversity scheme based on geometrical concept for optimizing the Signal to Noise Ratio (SNR) of the equal-gain Multiple Input and Single Output (MISO) communication system. In the second stage, this method is extended to Multiple Input and Multiple Output (MIMO) systems. These methods are proposed to solve the main problems of the conventional closed-loop MISO and MIMO systems such as high Complexity, feedback delay, the unknown average SNRs, dependant on transmit antennas, non-adaptivity to channels, and phase ambiguity. In the third stage, the structure of the proposed Scalar Equal Gain Transmission and Generalized Maximum Ratio Combining (SEGT/GMRC) scheme is followed to design the limited-feedback codebooks for MISO and MIMO systems which provide a different methodology as compared to the previous well-known codebooks. The proposed quantized equal-gain (QE) codebooks, requires the minimum number of feedback bits to form the beamforming vector. In the fourth stage, the proposed QE codebooks are employed to provide the distributed spatial diversity in a wireless relay network. Since transmit antennas are independent, the extension to relay network is straightforward. The new design is named Distributed QE (DQE) codebooks, in which each relay node stores a QE codebook. In this research, the wireless open-access research platform (WARP) is employed for prototyping the proposed QE codebooks. The proposed new geometrical space diversity system eliminates the searching process and serves as the optimal system for equal-gain MISO transmission systems. By extending this method to the distributed space diversity (DQE), the main problem related to the

conventional methods such as complexity, global Channel state Information (CSI), feedback delay, dependent relay nodes, and unknown average SNR are solved. Many encouraging results are obtained for QE and DQE codebooks, where some of them are as follows. It is shown that the proposed QE codebooks perform near optimal, and also it is proven that a system with one bit of feedback per each phase angle cannot perform near optimal. The performance gap of the proposed codebooks signals using QPSK and BPSK modulation schemes with 90 degrees of freedom are less than .25-.75 dB at the symbol error rate of 10^{-5}. This gap is reduced for the codebooks signals using 8PSK and 16QAM modulation schemes with 45 and 30 degrees of freedom, respectively. The Warp platform validates the geometrical design of the QE codebooks and it is shown that the proposed QE codebooks are easier to implement and the lower order QE codebooks are more suitable for the channels with the line of sight path. The DQE network can also be implemented easily with minimum complexity. It is shown that the proposed DQE codebooks perform better than direct transmission independent of their location in the distributed network. Number of relay nodes plays an important role on the performance of the network. For example, the error performances of 3 relay nodes located near to the source and each of them employing distributed QPSK or 8PSK codebook, is improved by 14 dB at the error rate of 10^5 when the number of distributed relay nodes is increased to 8. It is also shown that the DQE codebooks outperform its QE counterpart when the relay nodes are close to the source node. The amount of improvement is around 1 dB for distributed QPSK codebook and around 2 dB for distributed 8PSK codebook. This significance of the proposed geometrical scheme as compared to the well-known works are as follows: the searching methods to find the optimal equal gain beamforming and distributed beamforming vectors are eliminated, therefore the complexity and the system delay become lower while the performances are still optimal; the phase ambiguity problem is fixed; the average SNR of the receive antennas are available; transmit antennas and the relay nodes are independent which enable the system to employ more than one feedback link; the limited feedback beamforming vectors depend on the modulation scheme, which facilitates the design for more simpler codebooks using lower constellation orders; the new system can adapt itself for any change in channel behaviour without performing any matrix operations.

CHAPTER 1

INTRODUCTION

1.1 Preface

During the past decade, many schemes have been proposed to increase the reliability of the point-to-point digital communication systems to fulfil the quality of the data, which is required to be increased day-by-day by the advent of new emerging applications over the internet such as on-line voice, video, and radio/TV streams. In a wireless communication, since a wave reaches the receiver by several paths, the combination of these replicas may result in a very weak signal, which is not detectable at the receiver. This process is known as multipath fading. The most exciting method to increase the reliability of the link is to employ diversity; to transmit several replicas of the signal over independent channels. The most well-known diversity schemes employ independent communication channels over time, frequency, or space. The time diversity introduces a delay to the final detected symbol, which must be considered when a time-sensitive applications such as on-line voice/video is streaming. The frequency diversity requires more bandwidth resource and the Doppler effect must be considered to adjust the independent frequency channels when the end-user is mobile. The space diversity requires the uncorrelated antennas, whose distance from each other must be several times greater than the signal's half wavelength. Installing more than one antenna over the end-user devices such as smart phones or personal laptops highly depends on the antennas' design technology. There are also diversity schemes formed by combining these three such as space-time, space-frequency, and time-frequency diversities.

Space diversity can provide a reliable physical layer for a point-to-point communication system to support data applications, which require the high quality of service (QoS). The space diversity can be formed by installing multi transmit and/or receive antennas over the small scale utilities (hand phones) as well as large scale utilities (base stations). Although many advances have been in the area of frequency and space-time diversity, less attention paid to the space diversity, where most of the proposed schemes cannot be practically installed. One of the major drawbacks of space diversity is the time delay imposed by the conventional methods. Naturally, the space diversity must be faster than space-time diversity in order to make it more competitive.

Space diversity can be utilized by introducing a transmission/reception scheme when there are multiple transmit and/or receive antennas. In general, the space diversity can be divided into Single Input Multiple Output (SIMO) system (i.e. there is only one transmit antenna, but there are multiple receive antennas), Multiple Input Single Output (MISO) system (i.e. there is only one receive antenna, but there are multiple transmit antennas), and Multiple Input Multiple Output (MIMO) system (i.e. there are multiple transmit and receive antennas). The space diversity schemes for a SIMO system are well studied by many researchers during the past decades. Although there have been some theoretical works available in the literature, the practical aspects of space diversity schemes for MISO and MIMO systems are not yet considered in depth. One of the main hindrances that make the realization of MISO and MIMO systems complicated is the existence of a feedback link (Love and Heath, 2003a).

A transmit symbol's phase and magnitude are adjusted by a weight for each transmit antenna prior to transmission. These weights form a vector known as beamforming vector (Lo, 1999), (Anderson, 2000), (Love and Heath, 2003a). The received signal's phase and magnitude must be adjusted by another weight prior to detection as well. These weights form a vector known as the combining vector at the receiver. To be specific, designing a MISO or a MIMO system is referred to a beamforming/combining vector design. The combining vector depends on the available information about the channels after performing channel estimation, and designing the beamforming vector depends on the information obtained from the feedback link. The feedback link can include information about the phase and/or gains of the beamforming vector. According to this information, the power must be distributed among the beamforming vector components. When the feedback link only conveys the phase information, the power is shared between the beamforming vector components equally. This beamforming vector is known as Equal-Gain (EG) beamforming vector. If the receiver has a full access to the channels (gains and phases of all channels), the corresponding combining vector is known as Maximum Ratio (MR) combining (Lo, 1999),(Anderson, 2000). The conventional methods to design the EG/MR (beamforming/combining) systems is based on matrix operations, non-linear-optimizations, or other complicated searching processes. These vector-based systems are called Equal-Gain Transmission and Maximum Ratio Combining (EGT/MRC). The output beamforming vector has not been known prior to applying these searching processes. These systems are not fast and accurate enough to provide the requirements of the communication systems. The implementation of the conventional EGT/MRC system (Love and Heath, 2003a) is impractical, since it is impossible to obtain the complete precision for the beamforming vector. Therefore, the feedback bits must be limited. Consequently, a set of possible beamforming vectors are quantized into a codebook and the index of the desired beamforming vector is sent to the transmitter. This is known as quantized EGT/MRC in general (Love and Heath, 2003a). In general, there are two ways to indicate which vector of the quantized codebook is the nearest one to the optimal beamforming vector. In the first method, the optimal beamforming vector must be found by the employed searching scheme such as non-linear optimization. Afterwards, the label of the vector of the quantized codebook with the minimum squared Euclidean distance from the optimal beamforming vector is sent to the transmitter. The second scheme selects a vector of the quantized codebook by examining all the vectors. In this scheme, each vector of the codebook is multiplied by the channel matrix, and the label of a vector of the codebook that provides the maximum squared Euclidean distance is sent to the transmitter.

In the distributed space diversity (or a wireless relay network), some relays are located between the source and the destination to assist the source by forwarding its message to the destination, or assist the destination to forward its message to the source. The proposed schemes for distributed diversity systems in a cellular network must be as simple as possible in order to prevent battery drain. Since the distributed space diversity systems make a virtual SIMO, MISO, and MIMO systems, their design's complexity depend on the design complexity of space diversity schemes. Similarly, in the conventional methods as will be reviewed in the next chapter in detail, the possible distributed beamforming vectors are quantized into a codebook and the index of the desired distributed beamforming vector is sent to the relays. This process is highly complicated and the searching scheme is required at the destination node.

In this thesis, the new way of designing EG beamforming and MR combining vectors based on geometrical concepts are proposed. Unlike the conventional methods, the new method provides the fast and accurate feedback link. This method is very fast since no searching process (matrix operations, non-linear optimization or other searching processes) is engaged, and it is accurate since there is no phase ambiguity. The new scheme is called Scalar Equal-Gain Transmission and Generalized Maximum Ratio Combing (SEGT/GMRC). Similarly, implementing SEGT/GMRC is impractical since it requires ultimate precision. However, instead of sending the index of the beamforming vector, the index of each of the phase regions is sent to the transmitter. This has become possible, since the optimal equal-gain beamforming vector is known at the receiver. These codebooks are called Quantized Equal-Gain (QE) codebooks.

Since the transmit antennas are independent, the new scheme (SEGT/GMRC) can be easily upgraded from point-to-point communications to point-to-relay-to-point communications, which are known as distributed spatial diversity or wireless relay network. Therefore, the QE codebooks are extended to be employed in distributed spatial diversity systems, which again do not need for any searching scheme. These codebooks are called as Distributed QE (DQE) codebooks, which in turn reduces the complexity of the network along with providing the near-optimal performances.

The proposed system for an optimal feedback link (SEGT/GMRC) and the limited-feedback codebooks (QE and DQE) are examined precisely considering the exact average SNRs of the receive antennas, which are only available by the proposed methods. The exact error performances are achieved by the simulations along with implementing a hardware (WARP platform). The examinations validate the optimality (performance, complexity) of the proposed systems for space and distributed space diversity systems.

1.2 Problem Statement

The fundamental methods to introduce diversity are space, time, and frequency diversity schemes. The time and frequency diversity schemes are fully investigated during the past decade and many practical methods are proposed. Specifically, the combination of space and time diversity, which is known as space-time diversity, is well studied during the past decade. However, the space diversity design, especially the design of EG beamforming and MR combining vectors in MISO and MIMO systems, still remain in an active research area (Love et al., 2008). Although the EG has the simple power sharing policy, finding the phase angles of the beamforming vector components is not an easy task. The methods proposed to find these phase angles are usually time-lasting, complicated, and infeasible. The EG beamforming vector is the fundamental form of MR bemaforming vector, where receiver applies more advanced power sharing policy to find the most optimal beamforming vector. Therefore, introducing an optimal and practical EG beamforming vector is a first step to define the empirical MR beamforming vector. This study, concentrates on a novel design of the EG beamforming vector and the design of corresponding MR combining vector. The new system can be easily installed on a real-time hardware since there is no need for exhaustive searching at the receiver. Moreover, the new design will try to solve some common problems in this area such as complexity of searching the beamforming vector, the phase ambiguity of the beamforming vector, non-adaptability to the channels, feedback delay, and the unknown receive Signal to Noise Ratio (SNR) of the receiver antennas.

The information conveyed by the feedback link must be ready as fast as possible, since most of the channels are not remaining constant for a long time. The main problem concerning the conventional methods is the complexity of finding the information to be transmitted by the feedback link. These schemes utilize matrix optimizers and non-linear searching schemes, whose order of the complexity grows with the number of transmit antennas in an exponential way. This computational complexity increases the feedback delay substantially.

Phase ambiguity (as will be discussed in the following chapter) is the other main problem related to the feedback information. The phase ambiguity prevents the output of the conventional optimizers to reach the transmitter. This problem is serious enough to make a practical system's performance very weak.

A system is said to be non-adaptive when it cannot adapt for a certain variable. In this study, the channels are the systems' variables. Therefore, an adaptive system must easily change the process when channels have a certain behavior. The conventional methods are not adaptive and cannot reduce the complexity of the operation.

The complexity of finding the beamforming vector, introduces delay for the feedback link. This delay plays an important role in the practical communications, since the feedback information is valid until the channel changes.

One of the most important parameters in the communication is the average Signal to Noise Ratio (SNR). This parameter is crucial to find the average error performance of the system. The conventional methods have access the minimum, maximum, and the instantaneous SNR, but the precise amount of average SNR is not known.

Moreover, a practical way of EG beamforming vector design will have a great effect on the distributed space diversity schemes. The way of introducing the phase angles of a beamforming vector components can be employed by independent relay nodes with equal transmit power. The schemes proposed for distributed space diversity are usually suffering from the same problems as space diversity schemes and their implementations are not feasible (Mudumbai et al., 2009). The other contribution of this thesis is to design a practical scheme of the distributed network and also to solve the problems in this area such as complexity, non-adaptivity, full feedback, the unknown receive SNR, and dependent relays.

1.3 Research Objective

This study introduces a novel transmission scheme with EG and distributed EG beamforming vectors, and the corresponding reception scheme with MR combining vector. The new methods are based on geometrical concepts and can solve the relevant problems in the area of space diversity and distributed space diversity. The process of this investigation is described by the following steps chronologically as follows:

1. To introduce a novel optimal transmission/reception scheme to provide maximum SNR with minimum computational complexity as compared with the existing methods. This system, which is based on geometrical concepts, is called SEGT/GMRC system and its performance is analysed in MISO and MIMO communications.

2. To introduce the limited-feedback codebooks for MISO and MIMO communications,

which are called as QE codebooks, and examine their performances.

3. To employ the proposed QE codebooks in the single-hop distributed space diversity network with single-antenna relay nodes, which are called as DQE codebooks, and examine their performances.

1.4 Scope of The Research

The proposed schemes for the space diversity spans over vast research areas. These works are classified into three main areas according to the content of the feedback link. This study only concentrates on the equal-gain transmission, which means that the feedback link only conveys the phase information (Love and Heath, 2003a). The reason to choose this topic is due to the fact that equal gain transmission is more important for practical space diversity systems (Tsai et al., 2009).

There are also many schemes proposed for the distributed space diversity systems with diverse configurations. This study will concentrate on the single-hop relay network with single-antenna equal-gain relay nodes.

1.5 Outline of The Thesis

The background information about the diversity schemes, and the most important parameters that will be required throughout this study are introduced in Section 1.1. Furthermore, the main theory of space and distributed space diversity schemes are presented in Section 1.2, the problem is stated in Section 1.3, and the objectives are defined in Section 1.4. The remaining of this study and the structure of the thesis is as follows.

The second Chapter will focus on the review of the related literature, the well-known works, and the most cited works about the space and distributed space diversity scheme, especially those concentrating on EGT and distributed EGT schemes.

The third Chapter includes the new design of EG beamforming for MISO and MIMO schemes. This chapter introduces a novel geometric transmitter (SEGT), introduces the corresponding MR combing vector receiver, which must be employed as a receiver (GMRC), presents the new geometrical limited-feedback codebooks (QE codebooks), and illustrates the theoretical results.

The fourth Chapter contains a new design for distributed space diversity based on the new geometrical scheme (SEGT/GMRC). This chapter explains the relay network; signal processing and detection scheme for distributed SEGT/GMRC (optimal feedback) as well as Distributed QE codebooks (suboptimal feedback). The new theoretical results are illustrated and discussed in this section.

The fifth Chapter is describing the implementation aspects of the QE codebooks. These codebooks are empirically installed by employing a WARP platform and the results are presented in detail.

The last Chapter concludes the study and highlights the main results and also provides the future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The space diversity is an appealing method to increase the reliability of the wireless communication system since it doesn't need to increase the bandwidth as in frequency diversity, or time as in time diversity. The first work recorded in the IEEE database backs to 1931 (Beverage and Peterson, 1931), when the space diversity was employed in the radiotelegraphy wireless system. The goal was to mitigate the effects of noise and fading in the wireless communication by installing more than one receive antenna. This scheme is named receive diversity or Single-input and Multiple-Output (SIMO) wireless system. Following this method, several techniques are proposed for different combining schemes in the work presented by the authors in (Brennan, 1959). The SIMO communication is applicable in the uplink of the wireless communications, where the base station can implement several receiving antennas. The well-known works about the methods proposed for the receive diversity are collected and presented in book (Jakes, 1974).

By the advent of new technologies, where the end-user is enabled to employ more than one receiving antenna, the transmission/reception schemes for Multiple Input Multiple Output (MIMO) systems are proposed by many researchers. One of the first studies about a MIMO system is the work presented by the author of (Winters, 1987), where the fundamental limits on the data rate of multiple antenna systems in a Rayleigh fading environment are studied. In this work, the capacity of the MIMO system (without considering any specific MIMO transmission scheme) is analysed to find the maximum data rate that can be provided. The early MIMO works such as (van Etten, 1976) and (Winters, 1987) are further organized and developed by the most recent papers that will be presented and discussed in this chapter. The researchers also tried to find practical schemes to implement Multiple Input Single Output (MISO) in the downlink of a wireless communication. MISO is also considered as a degenerated form of MIMO, which means that receiver has access to more than one antenna, but only utilizes one of them. The studied schemes for MISO and MIMO are classified into two main groups. The studies included in the first group propose the optimal transmission, which cannot be implemented practically due to the requisition of an infinite number of feedback bits (Love et al., 2008). The other group includes detailed schemes for practical implementation. These schemes are usually known as limited-feedback MIMO or MISO codebooks (Love et al., 2008). In this chapter, the well-known conventional methods for optimal and limited-feedback MIMO and MISO transmission/reception will be presented, the difference among them will be highlighted, and the main problems will be addressed.

Implementing a direct wireless link between two points (point-to-point communications) are not mostly practical or the connection is too weak to be utilized (Laneman and G.W.Wornell, 2000), (Laneman et al., 2004a). In these situations, some intermediate relay nodes are needed to make a wireless communication between two nodes. These communications refer to point-to-relay-to-point communications or distributed space diversity in general. This branch of telecommunication is still in the open research area and many schemes are proposed, which are mostly based on the newly developed schemes for MISO and MIMO communications (Love et al., 2008). There are many applications that can employ the distributed space diversity transmission/reception schemes. These schemes can also be divided into two groups as well. The first group includes optimal implementations, which is impossible to implement practically. The other group includes the works of researchers, which proposed to implement the distributed space diversity practically by employing limited-number of feedback bits. In the following, the main methods for optimal and limited-feedback distributed MIMO and MISO networks will be compared, the difference among them will be highlighted, and the main problems will be addressed.

The concentration of this study is on the equal-gain beamforming vector design scheme for MISO and MIMO as well as equal-gain distributed beamforming vector design for distributed MISO and MIMO system in a single-hop relay network with single-antenna relay nodes. Searching the history, there are a few works related to the equal-gain beamforming and distributed beamforming vector design. However, since the basic design structure of the equal-gain and maximum ratio beamforming vectors are similar (Love et al., 2008), the main design schemes will be highlighted in the literature review chapter.

2.1.1 System Parameters

Analyzing a new theoretically proposed algorithm for wireless communication system is a complicated process, which requires consideration of all the employed resources (such as delay in time, the amount of transmit power or occupied bandwidth) and practical imperfections (such as error in estimation of channels or the effect of noise). There are many parameters that are used to define the efficiency of any new systems. These parameters are utilized to compare the performance with the performances of the existing wireless systems. As stated in the first chapter, there are many schemes that have been proposed for the space diversity and the distributed space diversity systems. The well-known parameters that are employed in these studies in order to compare different systems are capacity, outage, bit/symbol error rates and finally the complexity. The first three parameters depend on SNR; thus a system with higher SNR is expected to have the more better capacity, outage, and bit/symbol error rate (Proakis and Salehi, 2005). There is another parameter known as ‘”diversity order” that is common in space diversity (Love and Heath, 2003a). In general, the diversity order calculates the branch of independent data channels employed by a system. For example, the diversity order of a communication system with five transmit and one receive antennas is less than a system with three transmit and two receive antennas, since the latter system implements six diversity branches. However, it is not guaranteed that the latter one has the better bit/symbol error performance, since the average SNR of the former can be better in some systems. The error performance has a steady relationship with the employed resources such as the number of antennas, the amount of power, the amount of bandwidth, and the consumed time. Since counting the error performance considering all the resources is a complicated task, most researches perform optimization over one or two of the resources (Proakis and Salehi, 2005).

2.1.2 System Simulation

The samples of the channel and noise are derived from their distribution for analyzing the system. Therefore, the transmission scheme only considers the instantaneous values. The error performances are achieved by assuming the noise as a complex Gaussian random variable with zero mean and $N_0/2$ variance per real dimension, which are affected by the amount of average Signal to Noise Ratio (SNR), which is assumed as a variable in dB. In order to mitigate the influence of the noise and obtain the more efficient error performances, one can simply increase the power, or any other employed resources to achieve the required SNR at the receiver. The beamforming vector design considering the instantaneous values of the channels such as Maximum Ratio Transmission (MRT), the Equal Gain Transmission (EGT), the Selection Diversity Transmission (SDT), and the multi-user beamforming vector can be simulated in a similar manner. The Maximum Likelihood (ML) detectors, the Maximum Ratio Combining (MRC), the Equal Gain Combining (EGC), the Selection Diversity Combining (SDC) receivers can be simulated as the receiver of the mentioned transmitters. These transceivers are employable when the channels are slowly fading. For fast fading channels, the transceivers include the distribution of the noise and/or channels in order to design the signals. In this case the optimal signals may differ from the signals designed by the deterministic transceivers. These transiences depend on the channel matrix's mean and covariance feedback. The details about how to simulate a wireless communication system and analyze the different parts is well documented and presented in (Tranter et al., 2003).

2.2 Space Diversity

The space diversity model can be divided into three configurations as MISO, SIMO, and MIMO. In SIMO, there is no need to employ a feedback link to convey either the channel state information or the beamforming weight back to the transmitter (Jakes, 1974) . But, the information about the beamforming vector must be conveyed in MISO and MIMO systems. A feedback link can convey different types of information (Love and Heath, 2003a) as follows

1. Information about the magnitudes of the beamforming vector.

2. Information about the phase angles of the beamforming vector.

3. Information about the magnitudes and phases of the beamforming vector.

The type of feedback link determines the structure of the beamforming vector (transmission scheme), which is a unit-norm vector. When the feedback link of type one is employed, the magnitudes of beamforming vector components are available at the transmitter, where one or some components can have zero magnitudes (some antennas may not transmit). A special form of this feedback link which only selects one or a subset of antennas to transmit a symbol is known as a Selection Diversity Transmission (SDT) or transmit antenna selection in general. One of the earliest works of transmit antenna selection backs to 1959 in the work represented in (Smith, 1959). This scheme only considers the electronic equipments of the transmit side without employing a feedback link from the receiver. The new transmit antenna selection schemes in the MIMO jargon is followed in some papers such as (Saleh and Hamouda, 2009), in which transmitter squires a limited-feedback link.

The second type of feedback link provides the phase angles of the beamforming vector; therefore, there is no knowledge about how to share power among the beamforming vector components. It requires that the unit power to be equally shared between the beamforming vector components. This transmission is known as Equal Gain Transmission (EGT). The well-known and accepted reference for this scheme is presented in (Love and Heath, 2003a).

The third feedback link can introduce a transmission scheme known as Maximum Ratio Transmission (MRT), which includes EGT and SDT as well. The MRT scheme have access to the magnitudes and phases of the beamforming vector; therefore, can form an optimal beamforming vector according to the current Channel State Information (CSI). The unique and well-known work for this scheme is the work presented in (Lo, 1999). When the channels are fast fading, transmitting the components of the instantaneous beamforming vector is not a good solution. This is usually occurring in mobile communications, where the Doppler spread is relatively large. In this case, the feedback link may convey some information about the statistical behavior of the channels such as mean and covariance.

A combining vector, can also be designed by three reception schemes (Love and Heath, 2003a). The first reception scheme is the Maximum Ratio Combining (MRC), which employs the all channels' phases and magnitudes to perform the optimal detection. The Equal Gain Combining (EGC) is the second reception scheme, where the receiver has only access to the phases of the channels. The third reception scheme is the Selection Diversity Combining (SDC), by which receiver selects a single or a subset of antennas to capture the signals. The earliest work about the combining schemes go back to 1959 in the work presented by (Brennan, 1959). In this work three combining techniques mentioned above are examined and it is

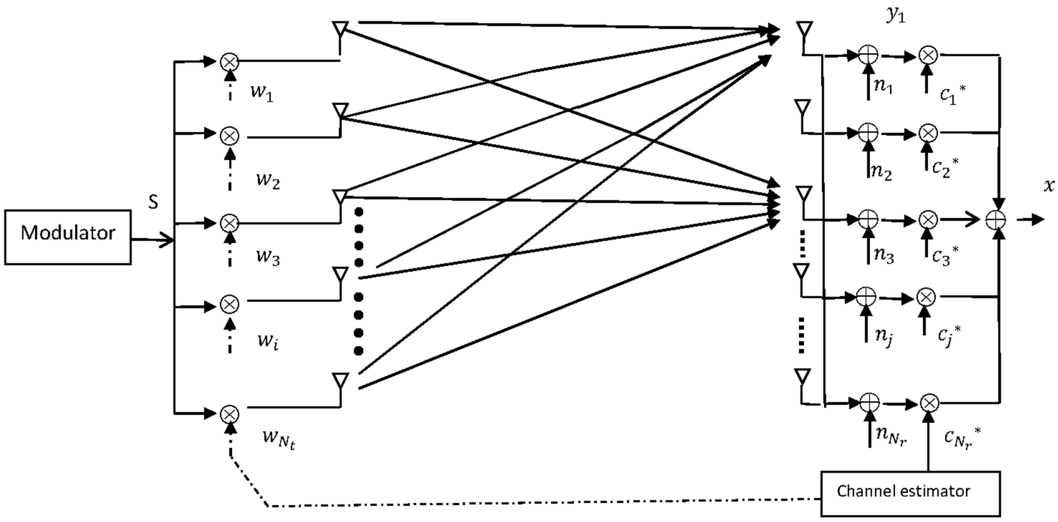

Figure 2.1: A Space Diversity System Model

shown that the simplest form of combining (SDC) has approximately the same performance as an optimal combining scheme such as the MRC.

The concentration of this study is on the equal-gain transmission (As stated in (Tsai, 2010), The equal gain transmitters have more practical importance since there is no need for complicated power amplifier) and maximum ratio combining systems which requires the phase feedback.

2.2.1 MIMO

The beamforming vector in Figure 2.1 can achieve a considerable gain if a fast feedback link is employed. For Maximum Ratio Transmission (MRT), the feedback link conveys the information about the magnitudes and phase angles of the optimal beamforming vector. However, for Equal-Gain transmission (EGT), the feedback link only conveys the information about the phase angles of the optimal beamforming vector. This scheme provides rate-1 transmission (one symbol is transmitted in one time slot) for any number of transmit and receive antennas, and can rapidly adapt to the channel, and change the number of transmit and receive antennas when necessary. The MIMO and MISO systems with optimal phase and gain feedback were studied in (Lo, 1999),(Anderson, 2000). It has been shown that the optimal MIMO beamforming vector is the dominant right singular vector of the channel matrix. To determine the right singular vector corresponding to the largest singular value, the receiver has to employ the singular value decomposition (SVD) process (Appendix A.2.1). This vector is sent to the transmitter by the optimal feedback link, which means that the gains and the phase angles of the right singular vector components are available at the transmitter without any distortion.

A MIMO system with optimal phase feedback was studied in (Love and Heath, 2003a). In that study, which presents equal gain transmission/maximum ratio combing (EGT/MRC), the receiver employs a nonlinear optimizer to determine the optimal beamforming vector. An optimal feedback link conveys this vector to the transmitter without any distortion. It is claimed that the optimal equal gain beamforming vector obtained by the nonlinear optimizer is not unique. Consequently, this scheme has difficulty in finding the exact symbol error rates. The presented symbol error rates in (Love and Heath, 2003a) are based on the lower bound of the overall average signal to noise ratio (SNR). However, to compare EGT/MRC with the corresponding prototype system, the exact error rates must be available. The following summarizes the work in (Love and Heath, 2003a) and mentions the problems.

A MIMO system with N_t transmit antennas and N_r receive antennas is illustrated in Figure 2.1. The transmit symbol,s, is multiplied by the beamforming vector, $\mathbf{w} = [w_1 \ldots w_{N_t}]^T$, and the data received by the antennas, $\mathbf{y} = [y_1 \ldots y_{N_r}]^T$, is multiplied (inner product) by $\mathbf{c}^* = [c_1^* \ldots c_{N_r}^*]^T$ to obtain the data x, where vector $\mathbf{c}$ is the basic combining vector, $(.)^T$ denotes transposition, and $(.)^*$ denotes conjugation. A precise time synchronization between the transmit and receive antennas must be obtained before applying the combining vectors. The noise term, n_j, is an independent complex Gaussian random variable with zero mean and N_0 variance per complex dimension. This process is represented as

$$x = (\mathbf{c}^H \mathbf{H}\mathbf{w})s + \mathbf{c}^H \mathbf{n} \tag{2.1}$$

where $(.)^H$ denotes conjugate transposition. The transmit symbol, s, is the final form of data to be transmitted to the receiver. This symbol may experience source coding (compression, cryptography, or etc.), channel coding (repetitive coding with interleaving, Reed-Solomon coding, Trellis coding, or etc.), or multi-carrier processing (OFDM, CDMA, or etc.) prior to transmission.

The channels must be estimated at the receiver prior to define the beamforming and combing vectors. Conveying the all channel matrix back to transmitter in order to analyse the channel matrix and find the optimal beamforming vector, is almost impractical (Love et al., 2008), (Love et al., 2004), (Love and Heath, 2003a). The most practical way is to let receiver analyse the channel matrix and inform transmitter about the beamforming vector.

The data x goes to the maximum likelihood (ML) detector. The ML detector selects symbol s_I if and only if

$$d^2(\mathbf{c}^H \mathbf{y}, s_I) = d^2(x, s_I) \leq d^2(x, s_u) \quad \forall I \neq u \tag{2.2}$$

where $d^2(a,b)$ is the squared Euclidean distance between the signals a and b. In other words, $\mathbf{c}s_I$ has the least squared Euclidean distance from the signal $\mathbf{y} = (\mathbf{H}\mathbf{w})s + \mathbf{n}$. Therefore, there are M possible combining vectors that are given as

$$\mathbf{c}_u = \mathbf{c}s_u \tag{2.3}$$

where M is the number of constellation points, $u \in \{1, 2, \ldots, M\}$. and $\mathbf{c}_u$ refers to the set of possible combining vectors. The overall instantaneous receive SNR can be represented as follows:

$$\gamma = \frac{\varepsilon_s |\mathbf{c}^H \mathbf{H}\mathbf{w}|^2}{||\mathbf{c}^H||_2^2 N_0} \tag{2.4}$$

where $||(.)||_2$ is the two-norm, $|.|$ is the absolute value, and ε_s is the transmitted symbol's energy. It must be mentioned that this term cannot distinguish the average SNR of each of the receive antennas separately. That is because the term $|\mathbf{c}^H\mathbf{H}\mathbf{w}|^2$ is an instantaneous value.

2.2.2 Equal-Gain MIMO

In the equal gain transmission scheme that was presented in (Love and Heath, 2003a), which is known as EGT/MRC scheme, the equal gain beamforming vector is found as follows. The beamforming and basic combining vectors are unit-norm vectors and the total SNR is upper bounded by

$$|\mathbf{c}^H\mathbf{H}\mathbf{w}|^2 \leq ||\mathbf{H}\mathbf{w}||_2^2 \tag{2.5}$$

This upper bound can be achieved if $\mathbf{c} = \mathbf{H}\mathbf{w}/||\mathbf{H}\mathbf{w}||_2$. Therefore, the optimal equal gain beamforming vector $\mathbf{w} = [w_1 \ldots w_{N_t}]^T = 1/\sqrt{N_t}[e^{j\varphi_1} \ldots e^{j\varphi_{N_t}}]^T = 1/\sqrt{N_t}\varphi$ can be found through a nonlinear optimization as follows:

$$\varphi \in argmax\ ||\mathbf{H}\varphi||_{2_{\varphi \in [0,2\pi)^{N_t}}} \tag{2.6}$$

where it is claimed that φ is not a unique beamforming vector. This nonlinear optimization must be repeated when the channel matrix is changed. As mentioned in (Lo, 1999), the average SNR is bounded by

$$N_t\overline{|h_{j,i}|^2}\,\overline{\gamma_0} \leq \overline{\gamma} \leq N_t N_r \overline{|h_{j,i}|^2}\,\overline{\gamma_0} \tag{2.7}$$

where$\overline{(.)}$ denotes the statistical expectation. The term γ_0 is chi-square distributed and $\overline{\gamma_0} = \varepsilon_s/\sigma_n^2$ is the average SNR in the case of the single transmission antenna. The lower bound of the overall average SNR is accepted as a metric to assess the error performance of the

EGT/MRC and similar schemes.

In some well-known works such as Love and Heath (2003a), (Tsai, 2010), (Tsai, 2011), (Tsai, 2009a), (Ryan et al., 2009), (Heat and Paulraj, 1998), and (Love and Heath, 2003b), the term $e^{j\varphi_1}$ is also factored out to reduce the feedback bits from BN_t to $B(N_t - 1)$, where B is the number of feedback bits assigned for each phase angle. However, this scheme distorts the optimal beamforming vector by reducing the number of feedback bits.

Proof: This scheme factors out $e^{j\varphi_1}$ from $\varphi = e^{j\varphi_1}\tilde{\varphi} = e^{j\varphi_1}[1e^{j\varphi_2-\varphi_1}\dots e^{j\varphi_{N_t}-\varphi_1}]^T$, and sends $\tilde{\varphi}$ to the transmitter. However, $\varphi_i - \varphi_1 (2 \leq i \leq N_t)$ are only phase differences and the transmitter requires the phase angle φ_1 to reform the original beamforming vector φ. Therefore, this process deletes the valuable data φ_1 since it is not discoverable at the transmitter. Let us assume that $\varphi = e^{j\pi/4}[1e^{j(\pi-\pi/4)}]^T$ and the vector $\tilde{\varphi} = [1e^{j3\pi/4}]^T$ is sent to the transmitter. However, there are infinite conditions that result $\varphi_2 - \varphi_1 = 3\pi/4$, thus $\varphi_1 = \pi/4$ and $\varphi_2 = \pi$ are not known at the transmitter.

Beside this crucial problem which we will refer as phase ambiguity, the conventional design schemes, which are based on vector calculations, introduces some other serious problems, especially when this system is empirically installed in a real-time communications as follows:

1. Computational complexity: due to the exhaustive searching in Eq (2.6). This process is very complex as compared to the other processes such as co-phasing. Moreover, it consumes a lot of time at the receiver to find the optimal phase angles of the beamforming vector. The comprehensive study about the complexity of the beamforming systems are presented in (Leung et al., 2010). The systems based on exhaustive searching are the most complicated systems according to the computational complexity

2. Feedback Delay: Since finding the beamforming vector angles are time-lasting, the feed-

back reaches the transmitter after a long delay. In a slow fading channels, where the symbol duration is comparable with the coherence time of the channel, this results in receiving an irrelevant feedback information. In other words, the feedback delay plus the symbol duration must not exceed the coherence time of the channel.

3. Non-adaptability: The nonlinear optimization, Eq. (2.6), performs on the channel matrix. The complexity of this operation increases when the size of the channel matrix increases. The receiver must perform this operation once the channel matrix has been changed. However, there could be other occasions where only some components of the channel matrix experience change and others remain constant. The vector based schemes do not have any solution for this case and the whole searching process must be done again for the new channels.

4. The average SNR is not known at the receiver. In order to assess the performance of the system, the average SNR of the receive antennas must be available. However, the conventional schemes have only access to the instantaneous, minimum, and maximum average SNR.

There are some other works that propose a new design for optimal equal gain MIMO systems (Tsai, 2010), (Tsai, 2011), (Choi, 2008), (Jafar and Goldsmith, 2004), and (Love and Heath, 2005) but again these suffer from the above mentioned problems.

The work in (Tsai, 2010), offers that the phase components of the right singular vector corresponding to the maximum singular value of $\mathbf{H}$ for the MIMO/EGT design. However, this scheme requires the information about the gains of the beamforming vector along with the phase angles of the beamforming vector. This means that the transmitter must be informed about the transmit antennas' selection. Moreover, this scheme suffers the same problems as mentioned for (Love and Heath, 2003a) specially the problem of phase ambiguity.

The work in Tsai (2011), provides transmit antenna selection scheme for EGT/MIMO design and suffers from the phase ambiguity problem.

The other works that are mentioned in Choi (2008), Jafar and Goldsmith (2004), and-Love and Heath (2005) studied MIMO beamforming systems employing the statistical transceivers by conveying the mean or covariance of the channel matrix back to the transmitter via the feedback link.

2.2.3 MISO

In a MISO system with perfect channel information at the transmitter, the optimal beamforming vector is $\mathbf{w} = \mathbf{h}^* / ||\mathbf{h}||_2$, where $\mathbf{h}$ is the C^{N_t} dimensional channel vector (Roh and Rao, 2006) and (Zheng et al., 2007a). This transmission requires a feedback link to send the phase and the magnitudes of the beamforming vector. However, as mentioned in the equal-gain MIMO the first phase component of the beamforming vector is factored out, which causes the beamforming vector to be distorted.

From another point of view, MISO was known as a special form of MIMO, where receiver only utilizes one of the multiple receive antennas and neglects the other receive antennas in detection. Therefore several works are conducted to examine the receive antenna selection in the context of MIMO system such as the works presented in (Sanayei and Nosratinia, 2004), Shen and Ghrayeb (2006), Sun et al. (2012), and (Gorokhov et al., 2003).

In the work presented in (Shen and Ghrayeb, 2006), it is assumed that 1) for a given N_r receive antennas, the receiver selects the best antennas that maximize the capacity, 2) the channel state information is perfectly known at the receiver, but not at the transmitter, 3) the subchannels fade independently, and 4) the fading coefficients change very slowly such that averaging with respect to these coefficients is not possible. This work shows that the proposed scheme preserves diversity order. The authors of (Sun et al., 2012) implemented a MIMO system in the frequency band of 2.4 GHz and showed that receive antenna selection can increase the capacity of the system. The authors in (Gorokhov et al., 2003) developed selection algorithms for maximizing the channel capacity. One algorithm in particular allows tractable statistical analysis of performance. The authors illustrated that the capacity of the system through receive antenna selection is statistically lower bounded by the capacity of a set of parallel independent single input multiple output (SIMO) channels, each with selection diversity. This provides the crucial step in proving the next main result: The diversity order that is achievable through the antenna selection is the same as that of the full system. In general, receive antenna selection does not need any feedback, since this process is done independently at the receiver. Although the receive antenna selection does not need to employ feedback, the beamforming vector design at the transmitter still requires some sort of feedback from the receiver.

The authors in (Blum et al., 2009), presented the joint transmit and receive antenna selection. In this study a MISO system is generated by selecting a subset of transmit antennas along with an antenna at the receive side. The authors of (Blum et al., 2009) have followed the selection since antenna selection is a low-complexity low-cost alternative for implementing MIMO systems. It was proposed to trade off system hardware cost and system performance by keeping the same number of antennas and using a fewer RF chain. In this paper (Blum et al., 2009), the authors considered the joint transmit and receive antenna selection capacity-maximization problem in MIMO systems. The optimal joint transmit and receive antenna selection should be achieved by exhaustively searching all the transmit and receive antenna subsets, its applicability is limited due to the high computational complexity. The authors proposed suboptimal algorithms decoupled the selection into transmit antenna selection and receive antenna selection, and exhibit a performance loss compared to the optimal method. They demonstrated that their selection scheme performs very close to the optimal exhaustive search method.

Up to now, there is no study about the transmission scheme where the feedback link only conveys the phase angles of $\mathbf{w}$. The nearest work is the work mentioned in (Tsai, 2009a) which compares the performance of the MRT and EGT, but again follows the phase ambiguity as mentioned in the previous subsection. Moreover, the MRT (Maximum Ratio Transmission) presented in (Brennan, 1959) suffers from the same problems pointed out for equal-gain MIMO scheme in the previous subsection. For example the amount of the average SNR of the receive antenna is not known in this work, or the same searching process must be performed to find the MRT vector.

There are some other works (Zheng et al., 2007a), (Vagenas et al., 2011), Vu (2011), (Vazquez et al., 2012), (Slim et al., 2011), (Baik et al., 2012), and (Jung et al., 2011) about interference MISO, mutlti-user MISO (MU-MISO), or broadcast MISO which will be described in brief.

The paper (Zheng et al., 2007a) has developed a general framework for the analysis of multiple-antenna systems with finite-rate feedback from a source coding perspective. The problem was formulated as a general fixed-rate vector quantization problem with side information available at the encoder but unavailable at the decoder. The tight lower and upper bounds of the average asymptotic distortion and sufficient conditions for the achievability of the distortion bounds were provided. The utility of the framework was demonstrated by using the proposed asymptotic distortion analysis to analyze a finite-rate feedback MISO beamforming system over i.i.d. Rayleigh flat-fading channels. Numerical and simulation results were presented and further confirmed the accuracy of the proposed asymptotic distortion bounds. In summary, this study tries to find the optimal MISO beamforming vector employing high resolution vector quantization codebooks, but there is no idea about the optimal and limited-feedback equal-gain MISO beamforming vector. Moreover, the phase ambiguity problem is also prevailed in this paper.