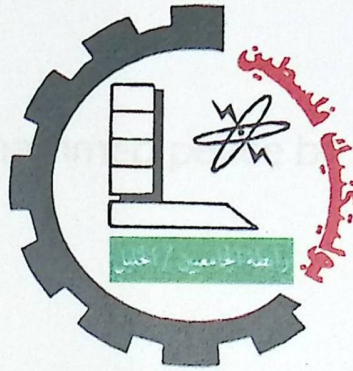


Palestine Polytechnic University



College of Engineering & Technology

Electrical and Computer Engineering Department

Spatial Multiplexing in 4G Systems

Project Team

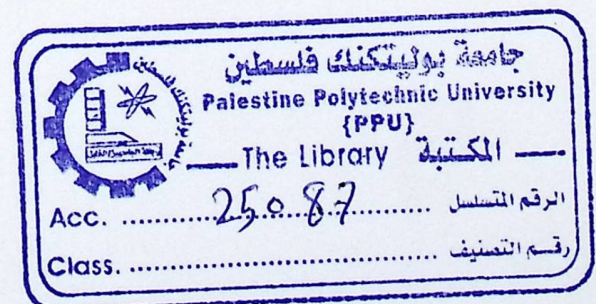
Mohammad Talal Mutasem Fanasheh Ayman Al_dasht

Project Supervisor

Dr.khaled Hijeh

Hebron-Palestine

2011



Dedication

To our prophet Mohammed peace be upon him ...

To our families

To our parents ... for their extraordinary sacrifices which made it possible for us to come this far ...

To the man who learned us what is the research ... who learned us how to make a thing but something ...who let us gain from his experience and discover for no pain
Our big brother and guider *Dr. Khalid Hijjah*

To N... R... F...

To our friends for their support ...

Acknowledgment

All praise be to Allah the ultimate guide and the cherisher who gave us the courage and ability to complete this study with a satisfying degree of perfection.

The most deserving of our Acknowledgment is to our respected supervisor Dr. Khalid Hijeh for his extraordinary support throughout the research time .

Thanks are also to all those who by way of encouragement, prayer or advice might have contributed directly or indirectly towards the actualization of this work.

Mutasem Fanasheh

Ayman Aldasht

Mohammed Outtaineh

June 15-2011

Abstract

Wireless access technologies has followed different evolutionary paths aimed at unified target which is to increase the *performance* and *efficiency* of the wireless systems, and now as the evolution of wireless access technologies is about to reach its fourth generation the newly rising systems should support many applications like real time video, high definition TV, virtual reality programs, online video games and many other greedy applications which consumes most of the available bandwidth, this put an additional pressure on wireless systems designers to keep the offered capacity and quality of the new systems. Therefore 4G systems adopted the multiple input multiple output (MIMO) technique to enhance the performance of the wireless systems while maintaining the same bandwidth and with no additional transmitting power.

This research studied the main concept of spatial multiplexing using MIMO antennas as a viable solution to increase the efficiency of the future systems.

Also the effect of many real life cases (cross-polarization discrimination, keyhole phenomena, line of sight and spatial fading correlation) on the capacity offered by the spatially multiplexed MIMO system has been studied using the Matlab simulator considering the near realistic cases, and with changing many parameters and for many antennas configurations to investigate the effect of the number of the antennas on the offered ergodic capacity. The results showed that the spatial fading correlation severely degrade the ergodic capacity of MIMO. The keyhole has severely degraded the ergodic capacity of the MIMO producing capacities similar MISO case. the LOS degraded the capacity of MIMO systems, The degradation in capacity can be reduced by using more transmitters. Regarding the XPD the simulations shows that it enhances the MIMO capacity at high SNR.

Abstract

Wireless access technologies has followed different evolutionary paths aimed at unified target which is to increase the performance and efficiency of the wireless systems, and now as the evolution of wireless access technologies is about to reach its fourth generation the newly rising systems should support many applications like real time video, high definition TV, virtual reality programs, online video games and many other greedy applications which consumes most of the available bandwidth, this put an additional pressure on wireless systems designers to keep the offered capacity and quality of the new systems. Therefore 4G systems adopted the multiple input multiple output (MIMO) technique to enhance the performance of the wireless systems while maintaining the same bandwidth and with no additional transmitting power.

This research studied the main concept of spatial multiplexing using MIMO antennas as a viable solution to increase the efficiency of future systems.

Also the effect of many real life cases (cross-polarization discrimination, keyhole phenomena, line of sight and spatial fading correlation) on capacity offered by the spatially multiplexed MIMO system has been studied using the Matlab simulator considering the near realistic cases and with changing many parameters and for many configurations to investigate the effect of the number of the antennas on the offered ergodic capacity. The results showed that the spatial fading correlation severely degrade the ergodic capacity of MIMO. The keyhole has severely degraded the ergodic capacity of the MIMO system. The capacities similar MISO case. the LOS degraded the capacity of MIMO systems, The degradation in capacity can be on XPD and degeneracy on transmitters. Regarding the XPD the simulations shows that the MIMO capacity at high SNR.

Table of Contents

Dedication

Acknowledgments

Abstract

Table of Content

List of Abbreviations

List of Mathematical Expressions

List of Figures

List of Tables

Chapter one: Introduction

1.1 Overview.....	2
1.2 General idea about the project.	2
1.3 Objective.	2
1.4 Need for high data rates..	2
1.5 Introduction for 4G systems.	3
1.6 4G systems requirements according to ITU.	3
1.7 The problems in wireless communication.....	3
1.8 Capacity limits of communication systems.....	4
1.9 Shannon's theory for capacity.....	4
1.10 Multiple antenna system basic concepts.....	4
1.11 Spatial Multiplexing.....	6
1.12 conclusion.....	7

Chapter 2: literature review.

2.1 Cellular communication.....	9
2.2 3GPP Family	9
2.2.1 Status and highlights of release 8.....	10
2.2.2 Status of release 9.....	10
2.2.2.1 HSPA enhancements	10
2.2.2.2 MIMO + DC-HSDPA	11

2.2.2.3 Contiguous dual-cell HSUPA (DC-HSUPA).....	11
2.2.2.4 IMT-ADVANCED.....	11
2.3 The wireless channel	12
2.3.1 Path loss.....	12
2.3.2 Fading	13
2.3.2.1 Macroscopic fading	13
2.3.2.2 Microscopic fading	13
2.3.2.2.1 Doppler spread - Time selective fading.....	14
2.3.2.2.2 Delay spread - frequency selective fading	14
2.3.2.2.3 Angle spread - space selective fading.....	15
2.4 Space time channel.....	15
2.4.1 SISO channel.....	15
2.4.2 SIMO channel.....	15
2.4.3 MISO channel.....	16
2.4.4 MIMO channel.....	16
2.5 Spatial Multiplexing.....	17
2.6 Capacity of the frequency flat deterministic MIMO channel.....	18
2.6.1 Channel unknown to the transmitter.....	18
2.6.2 Channel known to the transmitter.....	19
2.6.3 Capacities of SIMO and MISO channels.....	21
2.7 Capacity of random MIMO channels.....	21
2.7.1 Ergodic capacity.....	21
2.7.2 Outage capacity	22
2.8 Influence of the Ricean, fading, fading correlation, XPD and degeneracy on MIMO capacity.....	22
2.8.1 Influence of the spatial fading correlation.....	22
2.8.2 Influence of the LOS component.....	23
2.8.3 Influence of XPD.....	24
2.8.4 Influence of degeneracy.....	24

2.9 Spatial multiplexing processing techniques.....	25
2.9.1 A spatial Domain Link Adaptation Technique.....	25
2.9.2 Hybrid Spatial Division Multiplexing/Space –Time Coding Schemes.....	26
2.9.3 Linear Preorders for STBC by Exploiting Long term Knowledge.....	28
2.9.4 Limited CSI Spatial Multiplexing; Per Antenna Rate Control and per Stream Rate Control.....	28

Chapter three: Simulation results

3.1 Overview.....	30
3.2 The flow chart of the Matlab code.....	31
3.3 Ideal cases simulation results.....	35
3.4 Results tables for the ideal cases.....	44
3.5 Effect of spatial fading correlation on MIMO efficiency.....	47
3.5.1 Relation between the ergodic capacity and fading correlation factor at SNR=20 dB.....	47
3.5.2 Relation between the ergodic capacity and SNR for no correlation.....	55
3.5.3 Relation between the ergodic capacity and SNR for 0.7 correlation.....	63
3.5.4 Relation between the ergodic capacity and SNR for 0.9 correlation.....	71
3.6 Effect of line of sight component on MIMO efficiency.....	77
3.6.1 Relation between the K-factor and the ergodic capacity at SNR=15 dB.....	77
3.6.2 Relation between the ergodic capacity and the SNR.....	80
3.7 The effect of the keyhole phenomena on the ergodic capacity	93
3.8 Effect of the cross-polarization discrimination.....	105
3.9 Summary.....	114

References

Appendix A

Appendix B

Appendix c

List of Abbreviations

ADD	Antenna Division Duplexing
CDMA	Code Division Multiple Access
CQI	Channel Quality Indicator
CSI	Channel State Information
DLDC	Downlink Dual Carrier
EDGE	Enhanced Data rates for GSM Evolution
ETSI	European Telecommunications Standards Institute
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
GPRS	Third-Generation Partnership Project
GSM	Global Systems for Mobile Communications
HSDPA	High Speed Downlink Packet Access
LTE	Long Term Evolution
MMSE	Minimum Mean Square Error
MIMO	Multiple Input Multiple
MISO	Multiple Input Single Output
OFDM	Orthogonal Frequency Division Multiplexing
PARC	per Antenna Rate Control
PDF	Probability density function
SIC	Successive Interference Cancellation
SINR	Signal to Interference Noise Ratio
SISO	Single Input Single Output
SIMO	Single Input Multiple Input
SMUX	Spatial Multiplexing
SON	Self Organizing Network
S-PARC	Selective PARC
STBC	Space-Time block Coding
TDD	Time Division Duplex
TDMA	Time division multiple access
TTA	Telecommunication technology association
TTC	The telecommunication technology committee
UTRA	UMTS Terrestrial Radio Access
WCDMA	Wideband Code Division Multiple Access

XPD	Cross-Polarization Discrimination
ZF	Zero Force
ZMCSCG	Zero Mean Circularly Symmetric Complex Gaussian noise

List of Mathematical Expressions

(K_D)	Demmel condition number where:
$\lambda_{\min}$	The smallest eigenvalues
$\ h\ _F^2$	Forbenius norm of the channel
$f(A)$	The probability distribution of vector A.
$\text{Tr}(A)$	The trace of A
I_m	$M \times M$ identity matrix
HH	The conjugate transpose
ε	Expectation operation
$r(A)$	Rank of the matrix A

Chapter Three:

Figure 3.3.1: SNR Vs. Efficiency in SISO scheme.....	35
Figure 3.3.2: SNR Vs. Efficiency in 1x2 SIMO.....	36
Figure 3.3.3: SNR Vs. Efficiency in 2x1 MISO.....	36
Figure 3.3.4: SNR Vs. Efficiency in MISO 3x1 scheme.....	37
Figure 3.3.5: SNR Vs. Efficiency in MISO 4x1 scheme.....	37
Figure 3.3.6: SNR Vs. Efficiency in MIMO 1x2 scheme.....	38
Figure 3.3.7: SNR Vs. Efficiency in MIMO 3x2 scheme.....	38
Figure 3.3.8: SNR Vs. Efficiency in MIMO 4x2 scheme.....	39
Figure 3.3.9: SNR Vs. Efficiency in MISO scheme.....	40
Figure 3.3.10: SNR Vs. Efficiency in SIMO 1x2 scheme.....	41
Figure 3.3.11: SNR Vs. Efficiency in MISO 2x1 scheme.....	41
Figure 3.3.12: SNR Vs. Efficiency in MIMO 2x2 scheme.....	42
Figure 3.3.13: SNR Vs. Efficiency in MIMO 4x2 scheme.....	42

List of Figures

Chapter one:

Figure 1.1: show multiple antenna technique which can be categorizes to four type. .5

Chapter two:

Figure 2.1: Spatial division multiplexing scheme.....	17
Figure 2.2: Schematic of modal decomposition of H when the channel is known to the transmitter and receiver.....	20
Figure 2.3: Spatial multiplexing processing techniques.....	25
Figure 2.4: a block diagram of the Alamouti space-time encoder.....	27
Figure 2.5 (A): Transmission of 2 spatial streams on 3 antennas (SMUX/STBC).....	27
Figure 2.5 (B): Transmission of 3 spatial streams on 4 antennas (SMUX/STBC).....	27

Chapter Three:

Figure 3.3.1: SNR Vs. Efficiency in SISO scheme.....	35
Figure 3.3.2: SNR Vs. Efficiency in 1X 2 SIMO.....	36
Figure 3.3.3: SNR Vs. Efficiency in 2X1 MISO.....	36
Figure 3.3.4 : SNR Vs. Efficiency in MISO 3×1 scheme.....	37
Figure 3.3.5 : SNR Vs. Efficiency in MISO 4×1 scheme.	37
Figure 3.3.6: SNR Vs. Efficiency in MIMO 2×2 scheme.....	38
Figure 3.3.7 : SNR Vs. Efficiency in MIMO 3×2 scheme.....	38
Figure 3.3.8 : SNR Vs. Efficiency in MIMO 4×2 scheme.....	39
Figure 3.3.9: SNR Vs. Efficiency in SISO scheme.....	40
Figure 3.3.10: SNR Vs. Efficiency in SIMO 1×2scheme.....	41
Figure 3.3.11: SNR Vs. Efficiency in MISO 2×1 scheme.....	41
Figure 3.3.12: SNR Vs. Efficiency in MIMO 2×2 scheme.....	42
Figure 3.3.13: SNR Vs. Efficiency in MIMO 4×2 scheme.....	42

3.5 Effect of spatial fading correlation on MIMO efficiency.

3.5.1 Relation between the ergodic capacity and fading correlation factor at 20 SNR.

Fig 3.5.1:capacity Vs. correlation factor for 2x2 and 2x4.....	47
Fig 3.5.2:capacity Vs. correlation factor for 4x2 and 4x4.....	47
Fig 3.5.3:capacity Vs. correlation factor for 6x2 and 6x4.....	47
Fig 3.5.4:capacity Vs. correlation factor for 8x2 and 8x4.....	47
Fig 3.5.5:capacity Vs. correlation factor for 10x2 and 10x4.....	48
Fig 3.5.6:capacity Vs. correlation factor for 12x2 and 12x4.....	48
Fig 3.5.7:capacity Vs. correlation factor for 14x2 and 14x4.....	48
Fig 3.5.8:capacity Vs. correlation factor for 16x2 and 16x4.....	48
Fig 3.5.9: capacity Vs. correlation factor for 2x6 and 2x8.....	49
Fig 3.5.10:capacity Vs. correlation factor for 4x6 and 4x8.....	49
Fig 3.5.11:capacity Vs. correlation factor for 6x6 and 6x8.....	49
Fig 3.5.12:capacity Vs. correlation factor for 8x6 and 8x8.....	49
Fig 3.5.13:capacity Vs. correlation factor for 10x6 and 10x8.....	49
Fig 3.5.14:capacity Vs. correlation factor for 12x6 and 12x8.....	49
Fig 3.5.15:capacity Vs. correlation factor for 14x6 and 14x8.....	50
Fig 3.5.16:capacity Vs. correlation factor for 16x6 and 16x8.....	50
Fig 3.5.17:capacity Vs. correlation factor for 2x10 and 2x12.....	51
Fig 3.5.18:capacity Vs. correlation factor for 4x10 and 4x12.....	51
Fig 3.5.19:capacity Vs. correlation factor for 6x10 and 6x12.....	51
Fig 3.5.20:capacity Vs. correlation factor for 8x10 and 8x12.....	51
Fig 3.5.21:capacity Vs. correlation factor for 10x10 and 10x12.....	51
Fig 3.5.22:capacity Vs. correlation factor for 12x10 and 12x12.....	51
Fig 3.5.23:capacity Vs. correlation factor for 14x10 and 14x12.....	52
Fig 3.5.24:capacity Vs. correlation factor for 16x10 and 16x12.....	52
Fig 3.5.25:capacity Vs. correlation factor for 2x14 and 2x16.....	53
Fig 3.5.26:capacity Vs. correlation factor for 4x14 and 4x16.....	53
Fig 3.5.28:capacity Vs. correlation factor for 8x14 and 8x16.....	53
Fig 3.5.27:capacity Vs. correlation factor for 6x14 and 6x16.....	53
Fig 3.5.29:capacity Vs. correlation factor for 10x14 and 10x16.....	53
Fig 3.5.30:capacity Vs. correlation factor for 12x14 and 12x16.....	53
Fig 3.5.31:capacity Vs. correlation factor for 14x14 and 14x16.....	54
Fig 3.5.32:capacity Vs. correlation factor for 16x14 and 16x16.....	54

3.5.2 Relation between the ergodic capacity and SNR for no correlation.

Fig3.5.33: capacity Vs. SNR for 2x2 and 2x4.....	55
Fig 3.5.34:capacity Vs. SNR for 4x2 and 4x4.....	55
Fig 3.5.35:capacity Vs. SNR for 6x2 and 6x4.....	55
Fig3.5.36:capacity Vs. SNR for 8x2 and 8x4.....	55
Fig3.5.37:capacity Vs. SNR for 10x2 and 10x4.....	55
Fig3.5.38:capacity Vs. SNR for 12x2 and 12x4.....	55
Fig3.5.39:capacity Vs. SNR for 14x2 and 14x4.....	56
Fig3.5.40:capacity Vs. SNR for 16x2 and 16x4.....	56

3.5 Effect of spatial fading correlation on MIMO efficiency.

3.5.1 Relation between the ergodic capacity and fading correlation factor at 20 SNR.

Fig 3.5.1:capacity Vs. correlation factor for 2x2 and 2x4.....	47
Fig 3.5.2:capacity Vs. correlation factor for 4x2 and 4x4.....	47
Fig 3.5.3:capacity Vs. correlation factor for 6x2 and 6x4.....	47
Fig 3.5.4:capacity Vs. correlation factor for 8x2 and 8x4.....	47
Fig 3.5.5:capacity Vs. correlation factor for 10x2 and 10x4.....	48
Fig 3.5.6:capacity Vs. correlation factor for 12x2 and 12x4.....	48
Fig 3.5.7:capacity Vs. correlation factor for 14x2 and 14x4.....	48
Fig 3.5.8:capacity Vs. correlation factor for 16x2 and 16x4.....	48
Fig 3.5.9: capacity Vs. correlation factor for 2x6 and 2x8.....	49
Fig 3.5.10:capacity Vs. correlation factor for 4x6 and 4x8.....	49
Fig 3.5.11:capacity Vs. correlation factor for 6x6 and 6x8.....	49
Fig 3.5.12:capacity Vs. correlation factor for 8x6 and 8x8.....	49
Fig 3.5.13:capacity Vs. correlation factor for 10x6 and 10x8.....	49
Fig 3.5.14:capacity Vs. correlation factor for 12x6 and 12x8.....	49
Fig 3.5.15:capacity Vs. correlation factor for 14x6 and 14x8.....	50
Fig 3.5.16:capacity Vs. correlation factor for 16x6 and 16x8.....	50
Fig 3.5.17:capacity Vs. correlation factor for 2x10 and 2x12.....	51
Fig 3.5.18:capacity Vs. correlation factor for 4x10 and 4x12.....	51
Fig 3.5.19:capacity Vs. correlation factor for 6x10 and 6x12.....	51
Fig 3.5.20:capacity Vs. correlation factor for 8x10 and 8x12.....	51
Fig 3.5.21:capacity Vs. correlation factor for 10x10 and 10x12.....	51
Fig 3.5.22:capacity Vs. correlation factor for 12x10 and 12x12.....	51
Fig 3.5.23:capacity Vs. correlation factor for 14x10 and 14x12.....	52
Fig 3.5.24:capacity Vs. correlation factor for 16x10 and 16x12.....	52
Fig 3.5.25:capacity Vs. correlation factor for 2x14 and 2x16.....	53
Fig 3.5.26:capacity Vs. correlation factor for 4x14 and 4x16.....	53
Fig 3.5.28:capacity Vs. correlation factor for 8x14 and 8x16.....	53
Fig 3.5.27:capacity Vs. correlation factor for 6x14 and 6x16.....	53
Fig 3.5.29:capacity Vs. correlation factor for 10x14 and 10x16.....	53
Fig 3.5.30:capacity Vs. correlation factor for 12x14 and 12x16.....	53
Fig 3.5.31:capacity Vs. correlation factor for 14x14 and 14x16.....	54
Fig 3.5.32:capacity Vs. correlation factor for 16x14 and 16x16.....	54

3.5.2 Relation between the ergodic capacity and SNR for no correlation.

Fig3.5.33: capacity Vs. SNR for 2x2 and 2x4.....	55
Fig 3.5.34:capacity Vs. SNR for 4x2 and 4x4.....	55
Fig 3.5.35:capacity Vs. SNR for 6x2 and 6x4.....	55
Fig3.5.36:capacity Vs. SNR for 8x2 and 8x4.....	55
Fig3.5.37:capacity Vs. SNR for 10x2 and 10x4.....	55
Fig3.5.38:capacity Vs. SNR for 12x2 and 12x4.....	55
Fig3.5.39:capacity Vs. SNR for 14x2 and 14x4.....	56
Fig3.5.40:capacity Vs. SNR for 16x2 and 16x4.....	56

Fig3.5.41:capacity Vs. SNR for 2x6 and 2x8.....	57
Fig3.5.42:capacity Vs. SNR for 4x6 and 4x8.....	57
Fig3.5.43:capacity Vs. SNR for 6x6 and 6x8.....	57
Fig3.5.44:capacity Vs. SNR for 8x6 and 8x8.....	57
Fig3.5.45:capacity Vs. SNR for 10x6 and 10x8.....	57
Fig3.5.46:capacity Vs. SNR for 12x6 and 12x8.....	57
Fig3.5.47:capacity Vs. SNR for 14x6 and 14x8.....	58
Fig3.5.48:capacity Vs. SNR for 16x6 and 16x8.....	58
Fig3.5.49:capacity Vs. SNR for 2x10 and 2x12.....	59
Fig3.5.50:capacity Vs. SNR for 4x10 and 4x12.....	59
Fig3.5.51:capacity Vs. SNR for 6x10 and 6x12.....	59
Fig3.5.52:capacity Vs. SNR for 8x10 and 8x12.....	59
Fig3.5.53:capacity Vs. SNR for 10x10 and 10x12.....	59
Fig3.5.54:capacity Vs. SNR for 12x10 and 12x12.....	59
Fig3.5.55:capacity Vs. SNR for 14x10 and 14x12.....	60
Fig3.5.56:capacity Vs. SNR for 16x10 and 16x12.....	60
Fig3.5.57:capacity Vs. SNR for 2x14 and 2x16.....	61
Fig3.5.58:capacity Vs. SNR for 4x14 and 4x16.....	61
Fig3.5.59:capacity Vs. SNR for 6x14 and 6x16.....	61
Fig3.5.60:capacity Vs. SNR for 8x14 and 8x16.....	61
Fig3.5.61:capacity Vs. SNR for 10x14 and 10x16.....	61
Fig3.5.62:capacity Vs. SNR for 12x14 and 12x16.....	61
Fig3.5.63:capacity Vs. SNR for 14x14 and 14x16.....	62
Fig3.5.64:capacity Vs. SNR for 16x14 and 16x16.....	62

3.5.3 Relation between the ergodic capacity and SNR for 0.7 correlation

Fig4.1.65:capacity Vs. SNR for 2x2 and 2x4.....	63
Fig4.1.66:capacity Vs. SNR for 4x2 and 4x4.....	63
Fig3.5.68:capacity Vs. SNR for 8x2 and 8x4.....	63
Fig3.5.67:capacity Vs. SNR for 6x2 and 6x4.....	63
Fig3.5.69:capacity Vs. SNR for 10x2 and 10x4.....	63
Fig3.5.70:capacity Vs. SNR for 12x2 and 12x4.....	63
Fig3.5.71:capacity Vs. SNR for 14x2 and 14x4.....	64
Fig3.5.72:capacity Vs. SNR for 16x2 and 16x4.....	64
Fig3.5.73:capacity Vs. SNR for 2x6 and 2x8.....	65
Fig3.5.74:capacity Vs. SNR for 4x6 and 4x8.....	65
Fig3.5.75:capacity Vs. SNR for 6x6 and 6x8.....	65
Fig3.5.76:capacity Vs. SNR for 8x6 and 8x8.....	65
Fig3.5.77:capacity Vs. SNR for 10x6 and 10x8.....	65
Fig3.5.78:capacity Vs. SNR for 12x6 and 12x8.....	65
Fig3.5.79:capacity Vs. SNR for 14x6 and 14x8.....	66
Fig3.5.80:capacity Vs. SNR for 16x6 and 16x8.....	66

Fig3.5.41:capacity Vs. SNR for 2x6 and 2x8.....	57
Fig3.5.42:capacity Vs. SNR for 4x6 and 4x8.....	57
Fig3.5.43:capacity Vs. SNR for 6x6 and 6x8.....	57
Fig3.5.44:capacity Vs. SNR for 8x6 and 8x8.....	57
Fig3.5.45:capacity Vs. SNR for 10x6 and 10x8.....	57
Fig3.5.46:capacity Vs. SNR for 12x6 and 12x8.....	57
Fig3.5.47:capacity Vs. SNR for 14x6 and 14x8.....	58
Fig3.5.48:capacity Vs. SNR for 16x6 and 16x8.....	58
Fig3.5.49:capacity Vs. SNR for 2x10 and 2x12.....	59
Fig3.5.50:capacity Vs. SNR for 4x10 and 4x12.....	59
Fig3.5.51:capacity Vs. SNR for 6x10 and 6x12.....	59
Fig3.5.52:capacity Vs. SNR for 8x10 and 8x12.....	59
Fig3.5.53:capacity Vs. SNR for 10x10 and 10x12.....	59
Fig3.5.54:capacity Vs. SNR for 12x10 and 12x12.....	59
Fig3.5.55:capacity Vs. SNR for 14x10 and 14x12.....	60
Fig3.5.56:capacity Vs. SNR for 16x10 and 16x12.....	60
Fig3.5.57:capacity Vs. SNR for 2x14 and 2x16.....	61
Fig3.5.58:capacity Vs. SNR for 4x14 and 4x16.....	61
Fig3.5.59:capacity Vs. SNR for 6x14 and 6x16.....	61
Fig3.5.60:capacity Vs. SNR for 8x14 and 8x16.....	61
Fig3.5.61:capacity Vs. SNR for 10x14 and 10x16.....	61
Fig3.5.62:capacity Vs. SNR for 12x14 and 12x16.....	61
Fig3.5.63:capacity Vs. SNR for 14x14 and 14x16.....	62
Fig3.5.64:capacity Vs. SNR for 16x14 and 16x16.....	62

3.5.3 Relation between the ergodic capacity and SNR for 0.7 correlation

Fig4.1.65:capacity Vs. SNR for 2x2 and 2x4.....	63
Fig4.1.66:capacity Vs. SNR for 4x2 and 4x4.....	63
Fig3.5.68:capacity Vs. SNR for 8x2 and 8x4.....	63
Fig3.5.67:capacity Vs. SNR for 6x2 and 6x4.....	63
Fig3.5.69:capacity Vs. SNR for 10x2 and 10x4.....	63
Fig3.5.70:capacity Vs. SNR for 12x2 and 12x4.....	63
Fig3.5.71:capacity Vs. SNR for 14x2 and 14x4.....	64
Fig3.5.72:capacity Vs. SNR for 16x2 and 16x4.....	64
Fig3.5.73:capacity Vs. SNR for 2x6 and 2x8.....	65
Fig3.5.74:capacity Vs. SNR for 4x6 and 4x8.....	65
Fig3.5.75:capacity Vs. SNR for 6x6 and 6x8.....	65
Fig3.5.76:capacity Vs. SNR for 8x6 and 8x8.....	65
Fig3.5.77:capacity Vs. SNR for 10x6 and 10x8.....	65
Fig3.5.78:capacity Vs. SNR for 12x6 and 12x8.....	65
Fig3.5.79:capacity Vs. SNR for 14x6 and 14x8.....	66
Fig3.5.80:capacity Vs. SNR for 16x6 and 16x8.....	66

Fig3.5.81:capacity Vs. SNR for 2x10 and 2x12.....	67
Fig3.5.82:capacity Vs. SNR for 4x10 and 4x12.....	67
Fig3.5.83:capacity Vs. SNR for 6x10 and 6x12.....	67
Fig3.5.84:capacity Vs. SNR for 8x10 and 8x12.....	67
Fig3.5.85:capacity Vs. SNR for 10x10 and 10x12.....	67
Fig3.5.86:capacity Vs. SNR for 12x10 and 12x12.....	67
Fig3.5.87:capacity Vs. SNR for 14x10 and 14x12.....	68
Fig3.5.88:capacity Vs. SNR for 16x10 and 16x12.....	68
Fig3.5.89:capacity Vs. SNR for 2x14 and 2x16.....	68
Fig3.5.90:capacity Vs. SNR for 4x14 and 4x16.....	68
Fig3.5.91:capacity Vs. SNR for 6x14 and 6x16.....	69
Fig3.5.92:capacity Vs. SNR for 8x14 and 8x16.....	69
Fig3.5.93:capacity Vs. SNR for 10x14 and 10x16.....	69
Fig3.5.94:capacity Vs. SNR for 12x14 and 12x16.....	69
Fig3.5.95:capacity Vs. SNR for 14x14 and 14x16.....	70
Fig3.5.96:capacity Vs. SNR for 16x14 and 16x16.....	70

3.5.4 Relation between the ergodic capacity and SNR for 0.9 correlation

Fig4.1.97:capacity Vs. SNR for 2x2 and 2x4.....	71
Fig4.1.98:capacity Vs. SNR for 4x2 and 4x4.....	71
Fig3.5.99:capacity Vs. SNR for 6x2 and 6x4.....	71
Fig3.5.100:capacity Vs. SNR for 8x2 and 8x4.....	71
Fig3.5.101:capacity Vs. SNR for 10x2 and 10x4.....	71
Fig3.5.102:capacity Vs. SNR for 12x2 and 12x4.....	71
Fig3.5.103:capacity Vs. SNR for 14x2 and 14x4.....	72
Fig3.5.104:capacity Vs. SNR for 16x2 and 16x4.....	72
Fig3.5.105:capacity Vs. SNR for 2x6 and 2x8.....	72
Fig3.5.106:capacity Vs. SNR for 4x6 and 4x8.....	72
Fig3.5.107:capacity Vs. SNR for 6x6 and 6x8.....	72
Fig3.5.108:capacity Vs. SNR for 8x6 and 8x8.....	72
Fig3.5.109:capacity Vs. SNR for 10x6 and 10x8.....	73
Fig3.5.110:capacity Vs. SNR for 12x6 and 12x8.....	73
Fig3.5.111:capacity Vs. SNR for 14x6 and 14x8.....	73
Fig3.5.112:capacity Vs. SNR for 16x6 and 16x8.....	73
Fig3.5.113:capacity Vs. SNR for 2x10 and 2x12.....	74
Fig3.5.114:capacity Vs. SNR for 4x10 and 4x12.....	74
Fig3.5.115:capacity Vs. SNR for 6x10 and 6x12.....	74
Fig3.5.116:capacity Vs. SNR for 8x10 and 8x12.....	74
Fig3.5.117:capacity Vs. SNR for 10x10 and 10x12.....	74
Fig 3.5.118:capacity Vs. SNR for 12x10 and 12x12.....	74
Fig3.5.119:capacity Vs. SNR for 14x10 and 14x12.....	75
Fig3.5.120:capacity Vs. SNR for 14x10 and 14x12.....	75

Fig3.5.121:capacity Vs. SNR for 2x14 and 2x16.....	75
Fig3.5.122:capacity Vs. SNR for 4x14 and 4x16.....	75
Fig3.5.123:capacity Vs. SNR for 6x14 and 6x16.....	75
Fig3.5.124:capacity Vs. SNR for 8x14 and 8x16.....	75
Fig3.5.125:capacity Vs. SNR for 10x14 and 10x16.....	76
Fig3.5.126:capacity Vs. SNR for 12x14 and 12x16.....	76
Fig3.5.127:capacity Vs. SNR for 14x14 and 14x16.....	76
Fig3.5.128:capacity Vs. SNR for 16x14 and 16x16.....	76

3.6 Effect of line of sight component on MIMO efficiency.

3.6.1 Relation between the K-factor and the ergodic capacity at SNR=20 dB

Fig 3.6.1:capacity Vs. K factor for 2,4,6,8 x2.....	77
Fig 3.6.2:capacity Vs. K factor for 10,12,14,16 x2.....	77
Fig 3.6.3:capacity Vs. K factor for 2,4,6,8 x4.....	77
Fig 3.6.4:capacity Vs. K factor for 10,12,14,16 x4.....	77
Fig 3.6.5:capacity Vs. K factor for 2,4,6,8 x6.....	77
Fig 3.6.6:capacity Vs. K factor for 10,12,14,16 x6.....	77
Fig 3.6.7:capacity Vs. K factor for 2,4,6,8 x8.....	78
Fig 3.6.8:capacity Vs. K factor for 10,12,14,16 x8.....	78
Fig 3.6.9:capacity Vs. K factor for 2,4,6,8 x10.....	78
Fig 3.6.10:capacity Vs. K factor for 10,12,14,16 x10.....	78
Fig 3.6.11:capacity Vs. K factor for 2,4,6,8 x12.....	78
Fig 3.6.12:capacity Vs. K factor for 10,12,14,16 x12.....	78
Fig 3.6.13:capacity Vs. K factor for 2,4,6,8 x14.....	79
Fig 3.6.14:capacity Vs. K factor for 10,12,14,16 x14.....	79
Fig 3.6.15:capacity Vs. K factor for 2,4,6,8 x16.....	79
Fig 3.6.16:capacity Vs. K factor for 10,12,14,16 x16.....	79

3.6.2 Relation between the ergodic capacity and the SNR.

Fig 3.6.17:capacity Vs. SNR for 2x2.....	80
Fig 3.6.18:capacity Vs. SNR for 4x2.....	80
Fig 3.6.19:capacity Vs. SNR for 6x2.....	80
Fig 3.6.20:capacity Vs. SNR for 8x2.....	80
Fig 3.6.21:capacity Vs. SNR for 10x2.....	80
Fig 3.6.22:capacity Vs. SNR for 12x2.....	80
Fig 3.6.23:capacity Vs. SNR for 14x2.....	81
Fig 3.6.24:capacity Vs. SNR for 16x2.....	81
Fig 3.6.25:capacity Vs. SNR for 2x4.....	81
Fig 3.6.26:capacity Vs. SNR for 4x4.....	81
Fig 3.6.27:capacity Vs. SNR for 6x4.....	81
Fig 3.6.28:capacity Vs. SNR for 8x4.....	81
Fig 3.6.29:capacity Vs. SNR for 10x4.....	82
Fig 3.6.30:capacity Vs. SNR for 12x4.....	82
Fig 3.6.31:capacity Vs. SNR for 14x4.....	82
Fig 3.6.32:capacity Vs. SNR for 16x4.....	82

Fig 3.6.33:capacity Vs. SNR for 2x6.....	82
Fig 3.6.34:capacity Vs. SNR for 4x6.....	82
Fig 3.6.35:capacity Vs. SNR for 6x6.....	83
Fig 3.6.36:capacity Vs. SNR for 8x6.....	83
Fig 3.6.37:capacity Vs. SNR for 10x6.....	83
Fig 3.6.38:capacity Vs. SNR for 12x6.....	83
Fig 3.6.39:capacity Vs. SNR for 14x6.....	84
Fig 3.6.40:capacity Vs. SNR for 16x6.....	84
Fig 3.6.41:capacity Vs. SNR for 2x8.....	85
Fig 3.6.42:capacity Vs. SNR for 4x8.....	85
Fig 3.6.43:capacity Vs. SNR for 6x8.....	85
Fig 3.6.44:capacity Vs. SNR for 8x8.....	85
Fig 3.6.45:capacity Vs. SNR for 10x8.....	86
Fig 3.6.46:capacity Vs. SNR for 12x8.....	86
Fig 3.6.47:capacity Vs. SNR for 14x8.....	86
Fig 3.6.48:capacity Vs. SNR for 16x8.....	86
Fig 3.6.49:capacity Vs. SNR for 2x10.....	86
Fig 3.6.50:capacity Vs. SNR for 4x10.....	86
Fig 3.6.51:capacity Vs. SNR for 6x10.....	87
Fig 3.6.52:capacity Vs. SNR for 8x10.....	87
Fig 3.6.53:capacity Vs. SNR for 10x10.....	87
Fig 3.6.54:capacity Vs. SNR for 12x10.....	87
Fig 3.6.55:capacity Vs. SNR for 14x10.....	87
Fig 3.6.56:capacity Vs. SNR for 16x10.....	87
Fig 3.6.57:capacity Vs. SNR for 2x12.....	88
Fig 3.6.58:capacity Vs. SNR for 4x12.....	88
Fig 3.6.59:capacity Vs. SNR for 6x12.....	88
Fig 3.6.60:capacity Vs. SNR for 8x12.....	88
Fig 3.6.61:capacity Vs. SNR for 10x12.....	88
Fig 3.6.62:capacity Vs. SNR for 12x12.....	88
Fig 3.6.63:capacity Vs. SNR for 14x12.....	89
Fig 3.6.64:capacity Vs. SNR for 16x12.....	89
Fig 3.6.65:capacity Vs. SNR for 2x14.....	90
Fig 3.6.66:capacity Vs. SNR for 4x14.....	90
Fig 3.6.67:capacity Vs. SNR for 6x14.....	90
Fig 3.6.68:capacity Vs. SNR for 8x14.....	90
Fig 3.6.69:capacity Vs. SNR for 10x14.....	90
Fig 3.6.70:capacity Vs. SNR for 12x14.....	90
Fig 3.6.71:capacity Vs. SNR for 14x14.....	91
Fig 3.6.72:capacity Vs. SNR for 16x14.....	91
Fig 3.6.73:capacity Vs. SNR for 2x16.....	91
Fig 3.6.74:capacity Vs. SNR for 4x16.....	91
Fig 3.6.75:capacity Vs. SNR for 6x16.....	91
Fig 3.6.76:capacity Vs. SNR for 8x16.....	91
Fig 3.6.77:capacity Vs. SNR for 10x16.....	92

Fig 3.6.78:capacity Vs. SNR for 12x16.....	92
Fig 3.6.79:capacity Vs. SNR for 14x16.....	92
Fig 3.6.80:capacity Vs. SNR for 16x16.....	92

3.7 The effect of the keyhole phenomena on the ergodic capacity .

Fig 3.7.1:capacity Vs. SNR for 2x2.....	93
Fig 3.7.2:capacity Vs. SNR for 4x2.....	93
Fig 3.7.3:capacity Vs. SNR for 6x2.....	93
Fig 3.7.4:capacity Vs. SNR for 8x2.....	93
Fig 3.7.5:capacity Vs. SNR for 10x2.....	93
Fig 3.7.6:capacity Vs. SNR for 12x2.....	93
Fig 3.7.7:capacity Vs. SNR for 14x2.....	94
Fig 3.7.8:capacity Vs. SNR for 16x2.....	94
Fig 3.7.9:capacity Vs. SNR for 2x4.....	94
Fig 3.7.10:capacity Vs. SNR for 4x4.....	94
Fig 3.7.11:capacity Vs. SNR for 6x4.....	94
Fig 3.7.12:capacity Vs. SNR for 8x4.....	94
Fig 3.7.13:capacity Vs. SNR for 10x4.....	95
Fig 3.7.14:capacity Vs. SNR for 12x4.....	95
Fig 3.7.15:capacity Vs. SNR for 14x4.....	95
Fig 3.7.16:capacity Vs. SNR for 16x4.....	95
Fig 3.7.17:capacity Vs. SNR for 2x4.....	95
Fig 3.7.18:capacity Vs. SNR for 4x4.....	95
Fig 3.7.19:capacity Vs. SNR for 6x4.....	96
Fig 3.7.20:capacity Vs. SNR for 8x4.....	96
Fig 3.7.21:capacity Vs. SNR for 10x4.....	96
Fig 3.7.22:capacity Vs. SNR for 12x4.....	96
Fig 3.7.23:capacity Vs. SNR for 14x4.....	97
Fig 3.7.24:capacity Vs. SNR for 16x4.....	97
Fig 3.7.25:capacity Vs. SNR for 2x8.....	97
Fig 3.7.26:capacity Vs. SNR for 4x8.....	97
Fig 3.7.27:capacity Vs. SNR for 6x8.....	97
Fig 3.7.28:capacity Vs. SNR for 8x8.....	97
Fig 3.7.29:capacity Vs. SNR for 10x8.....	98
Fig 3.7.30:capacity Vs. SNR for 12x8.....	98
Fig 3.7.31:capacity Vs. SNR for 14x8.....	98
Fig 3.7.32:capacity Vs. SNR for 16x8.....	98
Fig 3.7.33:capacity Vs. SNR for 2x10.....	98
Fig 3.7.34:capacity Vs. SNR for 4x10.....	98
Fig 3.7.35:capacity Vs. SNR for 6x10.....	99
Fig 3.7.36:capacity Vs. SNR for 8x10.....	99
Fig 3.7.38:capacity Vs. SNR for 12x10.....	99
Fig 3.7.37:capacity Vs. SNR for 10x10.....	99
Fig 3.7.39:capacity Vs. SNR for 14x10.....	99

Fig 3.7.40:capacity Vs. SNR for 16x10.....	99
Fig 3.7.41:capacity Vs. SNR for 2x12.....	100
Fig 3.7.42:capacity Vs. SNR for 4x12.....	100
Fig 3.7.43:capacity Vs. SNR for 6x12.....	100
Fig 3.7.44:capacity Vs. SNR for 8x12.....	100
Fig 3.7.45:capacity Vs. SNR for 10x12.....	100
Fig 3.7.46:capacity Vs. SNR for 12x12.....	100
Fig 3.7.47:capacity Vs. SNR for 14x12.....	101
Fig 3.7.48:capacity Vs. SNR for 16x12.....	101
Fig 3.7.49:capacity Vs. SNR for 2x14.....	102
Fig 3.7.50:capacity Vs. SNR for 4x14.....	102
Fig 3.7.51:capacity Vs. SNR for 6x14.....	102
Fig 3.7.52:capacity Vs. SNR for 8x14.....	102
Fig 3.7.53:capacity Vs. SNR for 10x14.....	102
Fig 3.7.54:capacity Vs. SNR for 12 x14.....	102
Fig 3.7.55:capacity Vs. SNR for 14x14.....	103
Fig 3.7.56:capacity Vs. SNR for 16x14.....	103
Fig 3.7.57:capacity Vs. SNR for 2x16.....	103
Fig 3.7.58:capacity Vs. SNR for 4x16.....	103
Fig 3.7.59:capacity Vs. SNR for 6x16.....	103
Fig 3.7.60:capacity Vs. SNR for 8x16.....	103
Fig 3.7.61:capacity Vs. SNR for 10x16.....	104
Fig 3.7.62:capacity Vs. SNR for 12x16.....	104
Fig 3.7.63:capacity Vs. SNR for 14x16.....	104
Fig 3.7.64:capacity Vs. SNR for 16x16.....	104

3.8 The effect of the cross-polarization discrimination on the ergodic capacity

Fig 3.8.1 capacity Vs. SNR for 2x2 XPD 1V 1H at transmitter and 1V1H at receiver.....	105
Fig 3.8.2 capacity Vs. SNR for 4x2 XPD VHVH at transmitter and 1V1H at receiver.....	105
Fig 3.8.3 capacity Vs. SNR for 4x2 XPD VVHH at transmitter and 1V1H at receiver.....	105
Fig 3.8.4 capacity Vs. SNR for 4x2 XPD VVVH at transmitter and 1V1H at receiver.....	105
Fig 3.8.5 capacity Vs. SNR for 6x2 XPD VH..VH at transmitter and 1V1H at receiver.....	106
Fig 3.8.6 capacity Vs. SNR for 6x2 XPD 3V3H at transmitter and 1V1H at receiver.....	106
Fig 3.8.7 capacity Vs. SNR for 6x2 XPD V..VHH at transmitter and 1V1H at receiver... ..	106
Fig 3.8.8 capacity Vs. SNR for 6x2 XPD V...VH at transmitter and 1V1H at receiver.....	106
Fig 3.8.9 capacity Vs. SNR for 8x2 VH....VH at transmitter and 1V1H at receiver.....	107

Fig 3.7.40:capacity Vs. SNR for 16x10.....	99
Fig 3.7.41:capacity Vs. SNR for 2x12.....	100
Fig 3.7.42:capacity Vs. SNR for 4x12.....	100
Fig 3.7.43:capacity Vs. SNR for 6x12.....	100
Fig 3.7.44:capacity Vs. SNR for 8x12.....	100
Fig 3.7.45:capacity Vs. SNR for 10x12.....	100
Fig 3.7.46:capacity Vs. SNR for 12x12.....	100
Fig 3.7.47:capacity Vs. SNR for 14x12.....	101
Fig 3.7.48:capacity Vs. SNR for 16x12.....	101
Fig 3.7.49:capacity Vs. SNR for 2x14.....	102
Fig 3.7.50:capacity Vs. SNR for 4x14.....	102
Fig 3.7.51:capacity Vs. SNR for 6x14.....	102
Fig 3.7.52:capacity Vs. SNR for 8x14.....	102
Fig 3.7.53:capacity Vs. SNR for 10x14.....	102
Fig 3.7.54:capacity Vs. SNR for 12 x14.....	102
Fig 3.7.55:capacity Vs. SNR for 14x14.....	103
Fig 3.7.56:capacity Vs. SNR for 16x14.....	103
Fig 3.7.57:capacity Vs. SNR for 2x16.....	103
Fig 3.7.58:capacity Vs. SNR for 4x16.....	103
Fig 3.7.59:capacity Vs. SNR for 6x16.....	103
Fig 3.7.60:capacity Vs. SNR for 8x16.....	103
Fig 3.7.61:capacity Vs. SNR for 10x16.....	104
Fig 3.7.62:capacity Vs. SNR for 12x16.....	104
Fig 3.7.63:capacity Vs. SNR for 14x16.....	104
Fig 3.7.64:capacity Vs. SNR for 16x16.....	104

3.8 The effect of the cross-polarization discrimination on the ergodic capacity

Fig 3.8.1 capacity Vs. SNR for 2x2 XPD 1V 1H at transmitter and 1V1H at receiver.....	105
Fig 3.8.2 capacity Vs. SNR for 4x2 XPD VHVH at transmitter and 1V1H at receiver.....	105
Fig 3.8.3 capacity Vs. SNR for 4x2 XPD VVHH at transmitter and 1V1H at receiver.....	105
Fig 3.8.4 capacity Vs. SNR for 4x2 XPD VVVH at transmitter and 1V1H at receiver.....	105
Fig 3.8.5 capacity Vs. SNR for 6x2 XPD VH..VH at transmitter and 1V1H at receiver.....	106
Fig 3.8.6 capacity Vs. SNR for 6x2 XPD 3V3H at transmitter and 1V1H at receiver.....	106
Fig 3.8.7 capacity Vs. SNR for 6x2 XPD V..VHH at transmitter and 1V1H at receiver... ..	106
Fig 3.8.8 capacity Vs. SNR for 6x2 XPD V...VH at transmitter and 1V1H at receiver.....	106
Fig 3.8.9 capacity Vs. SNR for 8x2 VH....VH at transmitter and 1V1H at receiver.....	107

Fig 3.8.10 capacity Vs. SNR for 8x2 XPD 4V4H at transmitter and 1V1H at receiver.....	107
Fig 3.8.11 capacity Vs. SNR for 8x2 XPD 5V3H at transmitter and 1V1H at receiver.....	107
Fig 3.8.12 capacity Vs. SNR for 8x2 XPD 7V 1H at transmitter and 1V1H at receiver.....	107
Fig 3.8.13 capacity Vs. SNR for 10x2 VH...VH at transmitter and 1V1H at receiver.....	108
Fig 3.8.14 capacity Vs. SNR for 10x2 XPD 5V5H at transmitter and 1V1H at receiver.....	108
Fig 3.8.15 capacity Vs. SNR for 10x2 XPD 8V2H at transmitter and 1V1H at receiver.....	108
Fig 3.8.16 capacity Vs. SNR for 10x2 XPD 9V1H at transmitter and 1V1H at receiver.....	108
Fig 3.8.17 capacity Vs. SNR for 12x2 VH...VH at transmitter and 1V1H at receiver.....	109
Fig 3.8.18 capacity Vs. SNR for 12x2 6V 6H at transmitter and 1V1H at receiver.....	109
Fig 3.8.19 capacity Vs. SNR for 12x2 8V 4H at transmitter and 1V1H at receiver.....	109
Fig 3.8.20 capacity Vs. SNR for 12x2 11V 1H at transmitter and 1V1H at receiver.....	109
Fig 3.8.21 capacity Vs. SNR for 14x2 VHVH... at transmitter and 1V1H at receiver.....	110
Fig 3.8.22 capacity Vs. SNR for 14x2 7V 7H at transmitter and 1V1H at receiver.....	110
Fig 3.8.23 capacity Vs. SNR for 14x2 11V 3H at transmitter and 1V1H at receiver.....	110
Fig 3.8.24 capacity Vs. SNR for 14x2 13V 1H at transmitter and 1V1H at receiver.....	110
Fig 3.8.25 capacity Vs. SNR for 16x2 VHVH... at transmitter and 1V1H at receiver.....	111
Fig 3.8.26 capacity Vs. SNR for 16x2 8V 8H at transmitter and 1V1H at receiver.....	111
Fig 3.8.27 capacity Vs. SNR for 16x2 12V 4H at transmitter and 1V1H at receiver.....	111
Fig 3.8.28 capacity Vs. SNR for 16x2 15V 1H at transmitter and 1V1H at receiver.....	111
Fig 3.8.29 capacity Vs. SNR for 2x4 1V 1H at transmitter and 2V2H at receiver.....	112
Fig 3.8.30 capacity Vs. SNR for 4x4 2V 2H at transmitter and 2V2H at receiver.....	112
Fig 3.8.31 capacity Vs. SNR for 6x4 3V 3H at transmitter and 2V2H at receiver.....	112
Fig 3.8.32 capacity Vs. SNR for 8x4 4V 4H at transmitter and 2V2H at receiver.....	112
Fig 3.8.33 capacity Vs. SNR for 10x4 5V 5H at transmitter and 2V2H at receiver.....	113

Fig 3.8.10 capacity Vs. SNR for 8x2 XPD 4V4H at transmitter and 1V1H at receiver.....	107
Fig 3.8.11 capacity Vs. SNR for 8x2 XPD 5V3H at transmitter and 1V1H at receiver.....	107
Fig 3.8.12 capacity Vs. SNR for 8x2 XPD 7V 1H at transmitter and 1V1H at receiver.....	107
Fig 3.8.13 capacity Vs. SNR for 10x2 VH...VH at transmitter and 1V1H at receiver.....	108
Fig 3.8.14 capacity Vs. SNR for 10x2 XPD 5V5H at transmitter and 1V1H at receiver.....	108
Fig 3.8.15 capacity Vs. SNR for 10x2 XPD 8V2H at transmitter and 1V1H at receiver.....	108
Fig 3.8.16 capacity Vs. SNR for 10x2 XPD 9V1H at transmitter and 1V1H at receiver.....	108
Fig 3.8.17 capacity Vs. SNR for 12x2 VH...VH at transmitter and 1V1H at receiver.....	109
Fig 3.8.18 capacity Vs. SNR for 12x2 6V 6H at transmitter and 1V1H at receiver.....	109
Fig 3.8.19 capacity Vs. SNR for 12x2 8V 4H at transmitter and 1V1H at receiver.....	109
Fig 3.8.20 capacity Vs. SNR for 12x2 11V 1H at transmitter and 1V1H at receiver.....	109
Fig 3.8.21 capacity Vs. SNR for 14x2 VHVH... at transmitter and 1V1H at receiver.....	110
Fig 3.8.22 capacity Vs. SNR for 14x2 7V 7H at transmitter and 1V1H at receiver.....	110
Fig 3.8.23 capacity Vs. SNR for 14x2 11V 3H at transmitter and 1V1H at receiver.....	110
Fig 3.8.24 capacity Vs. SNR for 14x2 13V 1H at transmitter and 1V1H at receiver.....	110
Fig 3.8.25 capacity Vs. SNR for 16x2 VHVH... at transmitter and 1V1H at receiver.....	111
Fig 3.8.26 capacity Vs. SNR for 16x2 8V 8H at transmitter and 1V1H at receiver.....	111
Fig 3.8.27 capacity Vs. SNR for 16x2 12V 4H at transmitter and 1V1H at receiver.....	111
Fig 3.8.28 capacity Vs. SNR for 16x2 15V 1H at transmitter and 1V1H at receiver.....	111
Fig 3.8.29 capacity Vs. SNR for 2x4 1V 1H at transmitter and 2V2H at receiver.....	112
Fig 3.8.30 capacity Vs. SNR for 4x4 2V 2H at transmitter and 2V2H at receiver.....	112
Fig 3.8.31 capacity Vs. SNR for 6x4 3V 3H at transmitter and 2V2H at receiver.....	112
Fig 3.8.32 capacity Vs. SNR for 8x4 4V 4H at transmitter and 2V2H at receiver.....	112
Fig 3.8.33 capacity Vs. SNR for 10x4 5V 5H at transmitter and 2V2H at receiver.....	113

Fig 3.8.34 capacity Vs. SNR for 12x4 6V 6H at transmitter and 2V2H at receiver.....	113
Fig 3.8.35 capacity Vs. SNR for 14x4 7V 7H at transmitter and 2V2H at receiver.....	113
Fig 3.8.36 capacity Vs. SNR for 16x4 8V 8H at transmitter and 2V2H at receiver.....	113

List of Tables

Table (3.1) Summary of the results for the capacity versus SNR.....	45
Table(3.2) Summary of the simulation of the efficiency versus noise.....	46
Table (3.3) capacity for line of sight case for different k factor at constant SNR=15 dB.....	114
Table (3.4) capacity in fading correlation case for different correlation factor at constant SNR=20 dB.....	115
Table (3.5) capacity for line of sight case for different k factor at constant SNR=20dB.....	116
Table (3.6) capacity for line of sight case for different k factor at constant SNR=20dB.....	117
Table (3.7) capacity in degeneracy case at constant SNR=20dB.....	118
Table (3.8) capacity in degeneracy case at constant SNR=20dB.....	119

Chapter one

Introduction

Contents

- 1.1 Overview.
- 1.2 General idea about the project.
- 1.3 Objectives.
- 1.4 Need for high data rates.
- 1.5 Introduction for 4G systems.
- 1.6 4G systems requirements according to ITU.
- 1.7 The problems in wireless communication.
- 1.8 Capacity limits of communication systems.
- 1.9 Shannon's theory for capacity
- 1.10 Multiple antenna system basic concepts.
- 1.11 Spatial Multiplexing.
- 1.12 Conclusion.

1.1 Overview

This chapter explains the motivation behind the project and its objectives, and an overview of the fourth generation systems and finally the conclusion of the study.

1.2 General idea about the project

Today's life seems to be impossible without wireless communication. However, wireless systems suffer from many problems, but the main ones are the crowded spectrum problem, and capacity. Since the demand on the spectral availability is endless; the main area of the previous year's researches is how to find a way to improve the spectrum efficiency, capacity, and link reliability to increase the data rate for the users of the coming generation systems, which should support greedy applications.⁽¹⁾

MIMO antennas were introduced in 4G systems to overcome the wireless communication system's problems. Therefore, this project will study the main concepts of the spatial multiplexing using MIMO antennas in 4G systems as a solution to increase the offered capacity and data rate. Our study depends on making a simulation tool to simulate spatial multiplexing in MIMO by the MATLAB program, which is applied in 4G systems.

1.3 Objective

1. To better understand the main concepts of spatial multiplexing using MIMO antennas in 4G systems.
2. To investigate the effect of the degeneracy, line of sight component, cross-polarization discrimination and spatial fading correlation on the ergodic capacity of the MIMO system for different antenna configuration up to 16×16 .

1.4 Need for high data rates

Because millions of users started actively to use smart phones, tablets, and laptops that support thousands of mobile applications, the need of wireless communications with very high data rates has increased. 4G systems should provide very high data rates to support the future applications, while in fact no available technology meets the requirements of the 4G systems. New technologies should rise to build the future generation.⁽²⁾

1.5 Introduction for 4G systems

Because of the high rate of technological innovations, we are seeing another major transition in broadband wireless, from 3G to 4G Systems. Where 4G is promises a higher data rates and throughput, also better QoS. ⁽³⁾

LTE-Advanced and mobile WIMAX represents some of the 4G technologies, with peak theoretical speeds up to 1 Gbps, are expected to be completed by March 2011 making LTE-Advanced one of the first technologies defined to meet ITU's IMT-Advanced requirements. ⁽⁴⁾

1.6 4G systems requirements according to ITU

4G systems also known as beyond 3G mobile communications, the term 4G will apply to networks that comply with the requirements of IMT-Advanced, some of the key requirements or statements include:

1. High data rate transmission: DL: 100Mbps/ UL: 20Mbps. ⁽⁵⁾
2. Larger system capacity: 6-12Mbps/1MHz. ⁽⁵⁾
3. Lower cost/bit. ⁽⁵⁾
4. Downlink peak spectral efficiency is 15 bit/s/Hz (assumes 4X4 MIMO). ⁽⁶⁾
5. Uplink peak spectral efficiency is 6.75 bit/s/Hz. (assumes 2X4 MIMO). ⁽⁶⁾
6. Scalable bandwidth up to and including 40 MHz, the researches targets to get 100MHz. ⁽⁶⁾
7. Less than 100 ms latency shall be achievable from idle state to an active state in such a way that the user plane is established. ⁽⁶⁾

1.7 The problems in wireless communication

Wireless communications are facing many problems that reduce its performance. The main source of wireless channel problem is the propagation channel's environment. Since the signal may reach the destination from multipath at the receiver side producing many copies of the signal with different attenuations and with different delays. The multipath environment causes the **fading problem** in the channel resulted from scattering, reflections, refractions and diffractions. ⁽⁸⁾

Beside the fading problem the wireless channels face the **path loss** problem where the signal power drops due to the propagation loss which depends on the range; many mathematical models describe the power loss in the signal due to the pass it propagates across. Another major problem which rises in the previous years is the crowded spectrum because it's a scare resource the dependence on it is very limited. ⁽⁸⁾

Wireless faces also the noise problem where the channel in the wireless communication is the free space and its shared between thousands of users so the space is full of other waves that act as a noise power on any signal propagates across the space. ⁽⁸⁾

The major limiting factor in performance of the wireless system is the interference, it's happens when there are more than one device uses the same frequency band in the same area, such as two base stations work in the same frequency band, or maybe other devices operate in the frequency band allocated for the cellular system .The interference may occur on voice channels to produce crosstalk, or on control channel to produce call blocking since the interference increase the bit error rate in the control signal. ⁽⁸⁾

1.8 Capacity limits of communication systems

The capacity for wireless channel defined as “the maximum quantity of information that can be transmitted with the least error rate”. And the mathematical equation which determines the maximum capacity can be achieved in a certain channel was introduced by Claudy Shannon, and we state this equation in section 9 of this chapter. The capacity of the channel will increase as long as we use wider bandwidth and larger signal to noise ratio (SNR). ⁽¹⁾

1.9 Shannon's theory for capacity

According to Shannon's capacity equation, it's clear that to increase the capacity for the channels in wireless system we have to increase the bandwidth of the channel and/or signal power in order to increase the SNR. The relation between these two parameters and the capacity is given by Shannon's theorem for noisy channel (channel with AWGN) according to this equation:

$$C=W \text{Log}_2 (1+\text{SNR}) \text{ bit /s} \quad (1.1)$$

Where

C: the capacity of the channel.

W: the bandwidth of the channel.

SNR: signal to noise ratio.

And as we can see, the capacity is limited by bandwidth of the channel and the power of the transmitted signal. Therefore, other alternative methodologies are needed to increase the capacity, and MIMO technologies are one of them. ⁽⁹⁾

1.10 Multiple antenna system basic concepts

MIMO technology (multiple input multiple output antenna) with appropriate space time coding, modulation, demodulation and decoding were found to offer number of benefits to face the wireless challenges. The MIMO technology depends on using many antennas at the transmitter and many antennas at the receiver to transmit and receive different data streams simultaneously, thus higher data rates are achieved by using MIMO system. ⁽⁷⁾

1. **Single Input Single Output (SISO):**

Uses one antenna for transmitting and one antenna for the receiving.

2. **Single Input Multiple Output (SIMO):**

Use one antenna in the transmitter and multiple antennas in the receiver.

3. **Multiple Input Signal Output (MISO):**

Many antennas at the transmitter and one antenna at the receiver.

4. **Multiple Inputs Multiple Outputs (MIMO):**

Many antennas at the receiver and many antennas at the receiver.

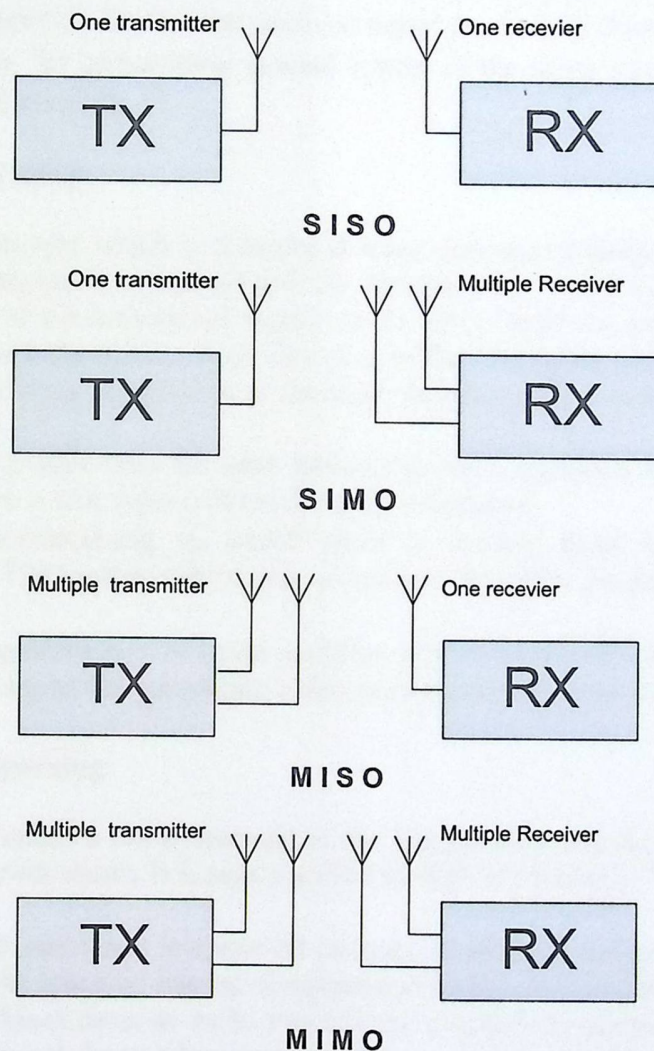


Figure (1.1) show multiple antenna technique which can be categorize to four types.

Benefits of multiple antenna systems:

1. Array gain:

The receiver of the multiple antennas receives different copies of transmitted signal with different amplitudes and phases. It will combine them coherently using one of the combining techniques so that the resultant signal will have higher SNR. The average increase in SNR ratio due to this coherent aggregation of the received copies at the multiple antenna system is called array gain and this increase is proportional to the number of antenna.⁽⁷⁾

2. Diversity gain:

The transmitted signals arrive at the receiver through multipath channels having different propagation characteristics. So that the received signal power will fluctuate and fade. According to this issue the idea for transmitting several copies of the same signal was adopted by MIMO systems and is called diversity.⁽⁷⁾

3. Beamforming:

In beamforming technique which is considered smart antenna technique, the array of antenna is used to create a directional beam toward the direction of arrival of the desired signal thus increasing the SNR of the transmitted signal, on the other hand the antenna array can form the nulls (destructively add the phases in the direction of the interfering signal) toward the direction of arrival of the interfering signal so as to decrease its effect, this technique is used mainly in the military applications.

In today's cellular systems only the base station has been equipped with multiple antennas in such MISO case there is two types of beamforming techniques

- Switched Beamforming in which there is several fixed beams that are selected accordingly, The system selects one or more of the prior programmed beams at a given time.
- Adaptive Beamforming the beam could be steered at any direction to track the user with an individual beam thus providing better performance than the switched beamforming.

1.11 Spatial Multiplexing

Spatial multiplexing offers a linear increase in the transmission rate for the same bandwidth and with no additional power waste. It is only possible in MIMO Channels.⁽¹⁰⁾

The bit stream is split into many low-rate bit streams, modulated and transmitted simultaneously from the antennas. The receiver, having complete knowledge of the channel, could recover these bit streams and combines them so as to recover the original bit stream. Since the receiver has knowledge of the channel it provides receive diversity, but the system has no transmit diversity since the bit streams are completely different from each other in that they carry totally different data. Thus spatial multiplexing increases the transmission rates proportionally with the number of transmit-receive antenna pairs.⁽⁷⁾

This concept can be extended to MIMO-MU (MIMO multiuser) .In such a case; two users transmit their respective information simultaneously to the base station equipped with two antennas. The base station can separate the two signals and can likewise transmit two signals with spatial filtering so that each user can decode his or her own signal correctly. This allows capacity to increase proportionally to the number of antennas at the base station and the number of users ⁽⁷⁾

1.12 Conclusion:

The simulations showed that the effect of degeneracy is a limiting factor on the ergodic capacities of these MIMOs, since the channel is reduced to behave similar to a MISO channel. The reductions in the in the ergodic capacities is shown dramatic regardless of deploying more transmitters and receivers. Main conclusion is that care has to be taken when deploying MIMO arrays in reality nearby windows or outside tunnels.

The study showed that the ergodic capacity of the system will be affected by the LOS and it will degrade as the power from the line of sight component increases. At high SNR high capacity will be obtained, as the number of transmit antennas increases.

The XPD has positive effect on the capacity and the effect will be better if the number of vertical antennas is close to the number of horizontal antennas. At high SNR high XPD will provide better performance than low XPD.

The simulation showed that the capacity of the system will be affected by the spatial fading correlation and it will degrade as the correlation between the signals increases, the degradation in the capacity will be higher if the number of transmit and receive antennas is higher

Chapter 2

Literature review

Contents

- 2.1 Cellular communication.
- 2.2 3GPP Family.
- 2.3 The wireless channel.
- 2.4 Space time channel.
- 2.5 Spatial Multiplexing.
- 2.6 Capacity of the frequency flat deterministic MIMO channel.
- 2.7 Capacity of random MIMO channels.
- 2.8 Influence of the fading correlation, LOS, XPD, and degeneracy on MIMO capacity.
- 2.9 Spatial multiplexing processing techniques

2.1 Cellular communication

In a relatively short time of cellular evolution we are close to see the fourth generation of cellular networks. Basic mobile voice were introduced in The first generation, which is an analog FDMA based system communicates through 30KHz FM modulated channels, but lacked uniform standardization, with total bandwidth 50 MHz.⁽¹¹⁾

Standardization is the noticeable feature of the second generation; Global Systems for Mobile communications (GSM) standard introduced digital communication with a combination of TDMA and slow frequency hopping.⁽¹¹⁾

In the United States, Interim Standard-136 considered TDMA and FDMA with phase shift keyed modulation, where IS-95 considered CDMA with the same modulation scheme. Also packet-based data services introduced in 2G like GPRS and EDGE, GPRS reached peak data rates up to 140 Kbps, and EDGE has increased data rates up to 384 Kbps.⁽¹¹⁾

2.2 3GPP Family:

The Third-Generation Partnership Project (3GPP) is the standards developing body that specifies the 3G UTRA and GSM systems. 3GPP is a partnership project formed by the standards bodies ETSI, ARIB, TTC, TTA, CCSA and ATIS.⁽¹³⁾

The needs of data at higher speeds leads to 3G technologies, the 3GPP has introduced the 3G technologies, UMTS and WCDMA technologies introduced in Rel-99 were the next step after GPRS and EDGE, and with a 5MHz bandwidth they offer improved data and voice services.⁽¹¹⁾

Rel-4 introduced call and bearer separation in the Core Network, and Rel-5 introduced some enhancements to UMTS, including High Speed Downlink Packet Access (HSDPA), IP Multimedia Subsystem IMS which is an architecture to assist internet protocol (IP) to provide multimedia services, and IP UMTS Terrestrial Radio Access Network (UTRAN) To offer flexibility to operator to provide such hosted services for greater user experience.⁽¹¹⁾⁽¹²⁾⁽¹³⁾

Rel-6 introduced further enhancements to UMTS including High Speed Uplink packet Access (HSUPA), Multimedia Broadcast and Multicast Services (MBMS) which is a broadcasting service aims to provide mainly the mobile TV service, The combination of HSDPA and HSUPA is called HSPA.⁽¹¹⁾⁽¹²⁾⁽¹³⁾

Rel-7 enhancements were introduced as HSPA+, the advantage of HSPA+ is that it's cost-efficient for rapidly growing data traffic volumes, the ability to work with all HSPA devices, and improved end-user experience by reducing latency, Rel-7 HSPA+ networks sometimes also deployed with MIMO antenna systems providing high performance benefits.⁽¹¹⁾⁽¹²⁾⁽¹³⁾

Rel-7 developed EDGE as GERAN Evolution or EDGE Evolution with the following features: Downlink Dual Carrier (DLDC), EGPRS2, Latency Reductions and MS Receive Diversity. The next update, called EGPRS 2B, will double peak theoretical downlink speeds up to 1.2 Mbps and

uplink speeds of up to 473 kbps. These evolutionary enhancements are essential to provide service continuity with HSPA and LTE, since 68 percent of HSPA networks are deployed with EDGE and 83 percent of HSPA devices also support EDGE. ⁽¹¹⁾⁽¹²⁾⁽¹³⁾

2.2.1. Status and highlights of release 8

3GPP Rel-8 provided significant new capabilities, not only through enhancements to the W-CDMA technology but also the addition of OFDM technology through the introduction of LTE, Rel-8 also provided the capability to perform 64QAM modulation with 2x2 MIMO on HSPA+ as well as the capability to perform dual carrier operation for HSPA+. ⁽¹²⁾

Rel-8 also introduced Evolved Packet System (EPS) consisting of a new flat-IP core network called the Evolved Packet Core (EPC) coupled with a new air interface based on OFDM called Long Term Evolution (LTE) or Evolved UTRAN (E-UTRAN). The EPS consists of only two nodes in the user plane: a base station and a core network GW. The node that performs control-plane functionality (MME) is separated from the node that performs bearer-plane functionality ⁽¹²⁾

In Rel-8, LTE defined new physical layer specifications consisting of an OFDMA based downlink and SC-FDMA. Rel-8 defined options for both FDD and TDD LTE carriers, FDD provides two channels one for uplink and the other for the downlink, so simultaneously transmit and receive data. TDD provides one channel for both uplink and downlink and its divided by time between the transmitter and the receiver. ⁽⁸⁾

Rel-8 also defined MIMO capabilities supporting open and closed loop techniques, Spatial Multiplexing, Multi-User MIMO schemes and Beamforming. Because OFDMA/SC-FDMA are narrowband based technologies, LTE supports various forms of interference avoidance or coordination techniques called Inter-Cell Interference Coordination (ICIC). ⁽¹²⁾

Rel-8 provided other enhancements to IMS, Multi-Media Priority Service, IMS centralized services (ICS).

2.2.2. Status of release 9:

2.2.2.1. HSPA enhancements:

Rel-9 enhanced dual-band HSDPA operation; where in the downlink of the primary serving cell takes a carrier in one frequency band and the secondary serving cell on a carrier in another frequency band. The uplink takes only on one carrier, which can be configured by the network on any of the two frequency bands. ⁽¹²⁾

Dual-band HSDPA operation re-uses the L1/L2 solutions that were specified for Rel-8 dual-carrier HSDPA operation on adjacent carriers.

This technique allow the user to be scheduled in the primary serving cell as well as in a secondary serving cell over two parallel HS-DSCH transport channels, this feature facilitates efficient load balancing between carriers in one base station sector. ⁽¹²⁾

2.2.2.2. MIMO + DC-HSDPA

Rel-9 combines dual-carrier HSDPA with MIMO technique. The peak downlink rate is thus doubled to 84 Mbps and the spectral efficiency is clearly increased compared to dual-carrier HSDPA operation without MIMO. In order to provide maximum flexible operation, the MIMO configuration is carrier-specific, meaning that, one carrier can be operated in non-MIMO mode and the other carrier in MIMO mode. ⁽¹²⁾

2.2.2.3. Contiguous dual-cell HSUPA (DC-HSUPA):

The user has two serving cells corresponding to two carriers in the same sector of the base station which has the ability to activate and deactivate the secondary carrier dynamically using so-called HS-SCCH orders. When two uplink carriers are active, they are to a large extent operating independently from each other in a way that is very similar to the single-carrier HSUPA operation specified in earlier releases. ⁽¹²⁾

2.2.2.4. IMT-ADVANCED

The progress now is beyond the LTE with the next generation of technologies in Rel-10 after ITU-R M.2134 stated many Requirements Related to Technical Performance for IMT-Advanced. IMT advanced is a mobile systems that include the new capabilities of IMT which provides access to many telecommunication services including advanced mobile services, supported by mobile and fixed networks, IMT-ADVANCED considered a major enhancement for the 4G.

Some of the key features of IMT-Advanced will be:

- Worldwide functionality & roaming.
- Compatibility of services.
- Interworking with other radio access systems.
- Enhanced peak data rates to support advanced services and applications (100 Mbps for high and 1 Gbps for low mobility) ⁽¹²⁾

2.3 The wireless channel

The signal propagating across the wireless channel reaches its destination along different paths due to scattering, reflection and diffraction. Diffraction occurs when the signal is obstructed by a surface with sharp irregular edges and hits the edge of an obstacle which is large relative to the wavelength. Reflection occurs when the signal goes through two different mediums, thus part of it is transmitted and the other is reflected. Reflection may cause a phase shift on the original signal. Scattering occurs when the signal hits a body of small size relative to its wavelength.⁽¹⁴⁾

These propagation mechanisms influence path loss and fading models differently. We refer to all previous mechanisms as "scattering".⁽¹⁴⁾

The power of the transmitted signal drops off due to path loss and the two fading types, macroscopic fading and microscopic fading.⁽¹⁴⁾

2.3.1. Path loss:

Path loss is a measure of attenuation and is range dependent, it comes from inverse square law in power loss in ideal free space.

The free space model (also known as Friis model):

$$P_r = P_t \frac{G_t G_r \lambda^2}{4\pi d^2} \quad (2.1)$$

Where:

P_r : The received power.

P_t : The transmitted power.

G_t : The gain of the transmitter.

G_r : The gain of the receiver.

λ : The wavelength of the propagating signal.

d : The distance between transmitter and receiver.

In real environment the main path is accompanied with a surface reflected path which destructively interferes with the main path and causes more reduction in power, thus the received power can be described as follows:⁽¹⁴⁾

$$P_r = P_t \frac{G_t G_r}{d^2} (h_t h_r)^2 \quad (2.2)$$

Where h_t, h_r are the effective heights of the transmit and receive antennas respectively. Here we notice that the path loss follows inverse fourth power law.⁽¹⁴⁾

2.3.2. Fading:

In addition to the power drop on the signal through propagation, the signal also faces fluctuations in its level due to fading. Fluctuation in signal level is composed of two components macroscopic and microscopic fading.⁽¹⁴⁾

2.3.2.1. Macroscopic fading:

It represents the long term variation of the received signal power level, so it's called long term fading or slow fading. It's caused by the effect of building or natural features. Slow fading is determined by the local mean of the fast fading signal, the probability density function of long term signal power fluctuation⁽¹⁴⁾

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (2.3)$$

Where:

σ : The standard deviation

μ : The mean

2.3.2.2. Microscopic fading:

It represents the rapid fluctuations of the received signal in space, time and frequency. It occurs due to the objects between transmitter and receiver which cause multipath propagation. The main effects of the small-scale fading are rapid changes in signal strength over a small distance, random frequency modulation due to varying Doppler shifts on different multipath signals and time dispersion caused by multipath propagation delays.⁽¹⁴⁾

The envelope of the received signal follow the Rayleigh density function if there is no direct line of sight between the transmitter and receiver.

The Rayleigh function is given by:

$$f(x) = \frac{2x}{\Omega} e^{-\frac{x^2}{\Omega}} u(x) \quad (2.4)$$

Where:

Ω : The average received signal power.

$u(x)$: The unit step function.

If there is a line of sight component between the transmitter and receiver the envelope of the signal will follow the Ricean, the Ricean distribution is defined by the factor K, the Ricean (PDF) is given by: (14)

$$f(x) = \frac{2x(2K+1)}{\Omega} e^{\left(-k - \frac{(K+1)x^2}{\Omega}\right)} I_0\left(2x\sqrt{\frac{K(K+1)}{\Omega}}\right) u(x) \quad (2.5)$$

Where:

I_0 : The zero order modified Bessel function.

We notice that when there is no (LOS) i.e. $K=0$ the Ricean PDF reduces to Rayleigh ⁽¹⁴⁾

There are three types of microscopic fading

2.3.2.2.1 Doppler spread - Time selective fading:

Doppler spread is a measure of the spectral broadening caused by the mobility of the transmitter. When a signal is transmitted with a frequency f_c the received signal spectrum (also called Doppler spectrum) will have components in the range $f_c - f_d$ to $f_c + f_d$ where f_d is the Doppler shift which is a function of the velocity of the mobile. ⁽¹⁴⁾

Time selective fading is characterized by the coherence time T_c which is a measure of how fast the channel changes in time and it defines the time duration over which the channel impulse response is invariant. ⁽¹⁴⁾

$$T_c = \frac{0.423}{f_m} \quad (2.6)$$

$$f_m \text{ is the maximum Doppler shift, } f_m = \frac{v}{\lambda}. \quad (2.7)$$

Where:

λ : is the wave length of the transmitted signal

v : is the velocity of the mobile transmitter.

2.3.2.2.2 Delay spread - frequency selective fading:

Due to multipath environment, several copies of the signal will reach the transmitter with different delays. The delay spread τ_{RMS} increases with distance from the transmitter and it causes frequency selective fading. Frequency selective fading is characterized by the channel coherent bandwidth which is a measure of the frequencies over which the channel considered to be flat (passes all frequencies with equal gain). If the frequency of the transmitted signal is larger than the coherent bandwidth then the channel creates **frequency selective fading** on the received signal. Thus the channel induces inter symbol interference (ISI), ISI occurs when $\tau_{RMS} > T_s$ ⁽¹⁴⁾

2.3.2.2.3 Angle spread – space selective fading:

The multipath components will reach the receiver antenna array with different angles, this causes space selective fading which means that the signal amplitude depends on the spatial location of the antenna. Space selective fading is characterized by the coherence distance D_C (defines the needed spatial separation between the transmitters) which is inversely proportional to the angle spread $D_C \propto \frac{1}{\theta_{RMS}}$ Where θ_{RMS} is the angle of arrival of the transmitted signal. ⁽¹⁴⁾

2.4 Space time channel

We will define SISO, SIMO, MISO and MIMO channels and their input output model, additive noise assumed to be negligible. ⁽¹⁴⁾

2.4.1. SISO channel

In SISO there is a single transmitter and single receiver, so there is one channel $h(\tau, t)$ between them where $h(\tau, t)$ is the time-varying channel impulse response from the input of the pulse shaping $g(\tau)$. ⁽¹⁴⁾

If the transmitter sends the signal $s(t)$ then the received signal will be:

$$y(t) = \int_0^{\tau_{total}} h(\tau, t) s(t - \tau) d\tau = h(\tau, t) * s(t) \quad (2.8)$$

Where: τ_{total} , duration of the impulse response.

2.4.2. SIMO channel

In SIMO channel there are M_R receiver antennas and one transmitter antenna, SIMO channel can be decomposed into M_R SISO channels, the impulse response between the transmitter and i th receiver antenna is $h_i(\tau, t)$, where $i = (1, 2, 3, \dots, M_R)$, so the $M_R \times 1$ channel vector can be represented as. ⁽¹⁴⁾

$$\mathbf{h}(\tau, t) = [h_1(\tau, t) h_2(\tau, t) \dots h_{M_R}(\tau, t)]^T \quad (2.9)$$

The received signal at the i th receive antenna is given by:

$$y_i(t) = h_i(\tau, t) * s(t) \quad (2.10)$$

Denoting the received signals by the $M_R \times 1$ vector the previous relation can be expressed as

$$\mathbf{y}(t) = \mathbf{h}(\tau, t) * s(t) \quad (2.11)$$

Where:

$s(t)$: is the transmitted signal.

$$\mathbf{y}(t) = [y_1(t) y_2(t) \dots y_{M_R}(t)]^T \text{ Is } M_R \times 1 \text{ vector}$$

2.4.3. MISO channel

In MISO channel there are M_T transmit antennas and one receiver antenna, MISO channel can be decomposed into M_T SISO channels, the impulse response between the receiver and j th transmit antenna is $h_j(\tau, t)$, where $j = (1, 2, 3, \dots, M_T)$, so the $M_T \times 1$ channel vector can be represented as: ⁽¹⁴⁾

$$\mathbf{h}(\tau, t) = [h_1(\tau, t) h_2(\tau, t) \dots h_{M_T}(\tau, t)] \quad (2.12)$$

The received signal at the j th receive antenna is given by

$$y(t) = \sum_{j=1}^{M_T} h_j(\tau, t) * s_j(t) \quad (2.13)$$

Denoting the received signals by the $1 \times M_T$ vector the previous relation can be expressed as

$$\mathbf{y}(t) = \mathbf{h}(\tau, t) * \mathbf{s}(t) \quad (2.14)$$

$$\text{Where: } \mathbf{s}(t) = [s_1(t) s_2(t) \dots s_{M_T}(t)]^T \text{ Is } M_T \times 1 \text{ vector}$$

2.4.4. MIMO channel

In MIMO channel there are M_T transmit antennas and M_R receive antennas, the impulse response between the j th transmit antenna, and the i th receiver is given by $h_{i,j}(\tau, t)$, the MIMO channel can be describes by the $M_T \times M_R$ matrix $\mathbf{H}(\tau, t)$ with: ⁽¹⁴⁾

$$\mathbf{H}(\tau, t) = \begin{bmatrix} h_{1,1}(\tau, t) & h_{1,2}(\tau, t) & \dots & h_{1,M_T}(\tau, t) \\ h_{2,1}(\tau, t) & h_{2,2}(\tau, t) & \dots & h_{2,M_T}(\tau, t) \\ \vdots & \vdots & \ddots & \vdots \\ h_{M_R,1}(\tau, t) & h_{M_R,2}(\tau, t) & \dots & h_{M_R,M_T}(\tau, t) \end{bmatrix} \quad (2.15)$$

The received signal at the i th receive antenna is given by

$$y_i(t) = \sum_{j=1}^{M_T} h_{i,j}(\tau, t) * s_j(t) \quad (2.16)$$

Denoting the received signals by the vector $M_R \times 1$, the previous relation can be expressed as

$$\mathbf{y}(t) = \mathbf{H}(\tau, t) * \mathbf{s}(t) \quad (2.17)$$

Where:

$$s(t) = [s_1(t) s_2(t) \dots s_{M_T}(t)]^T \text{ Is } M_T \times 1 \text{ vector}$$

$$y(t) = [y_1(t) y_2(t) \dots y_{M_R}(t)]^T \text{ Is } M_R \times 1 \text{ vector}$$

2.5 Spatial Multiplexing:

As we have seen in the first chapter, the transmitter in Spatial Multiplexing transmits simultaneously independent data sub-streams from different antenna; in order to have a linear increase in the transmission rate for the same bandwidth and with no additional power. Figure 2.1 illustrate spatial division multiplexing technique for M transmitters and N receivers' antenna. (15)

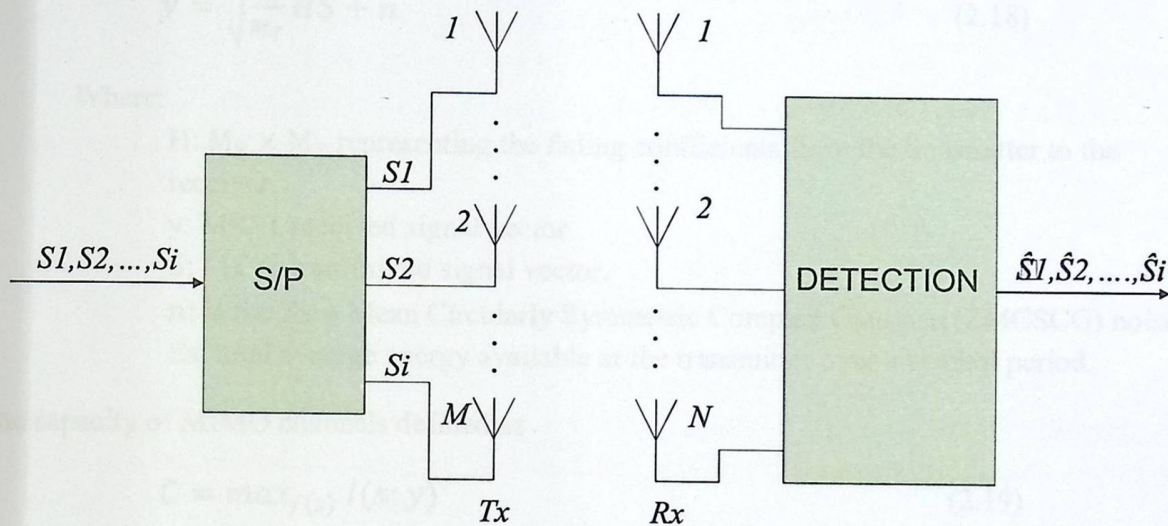


Figure 2.1 Spatial division multiplexing scheme

From the last figure, spatial multiplexing increases the transmission rates proportionally with the number of transmit-receive antenna pairs.

According to [15], there are three types of spatial multiplexing, they differs from each other according to the availability the channel state information CSI (channel knowledge for the interest link and other interfering links) at the transmitter, as explain below.

1. **Open loop SMUX** (Channel unknown to the transmitter): the transmitter doesn't have CSI, so all transmitter antennas have equal power and data rat, we'll study the capacity channel of this case in section 2.6.1. (15)
2. **Close loop SMUX** (Channel known to the transmitter): the transmitter has CSI which can be achieved by different ways as shown in section 2.7.2, so the transmitted power will distributed unequally amongst the sub-channel, also the transmitter can apply different coding and modulation method on each data sub stream to improve the capacity, we'll study the capacity channel in this case In section 2.7.2. (15)

3. **Partial CSI SMUX:** the transmitter has only limited CSI which allow simple improvement in capacity over open loop SMUX case.

2.6 Capacity of deterministic MIMO channel:

Although the channel H is random or stochastic, firstly the deterministic one will be studied, then introduce the capacity of random H . for a frequency flat channel, which is a narrowband channel where every input in this band faces the same effect by this channel, the input-output relationship for MIMO channel can be introduced in the following equation: ^{(10) (14)}

$$y = \sqrt{\frac{E_s}{M_T}} H S + n. \quad (2.18)$$

Where:

H : $M_R \times M_T$ representing the fading coefficients from the transmitter to the receiver.

y : $M_R \times 1$ received signal vector.

S : $M_T \times 1$ transmitted signal vector.

n : is the Zero Mean Circularly Symmetric Complex Gaussian (ZMCSCG) noise.

E_s : total average energy available at the transmitter over a symbol period.

The capacity of MIMO channels defined as

$$C = \max_{f(s)} I(s; y) \quad (2.19)$$

Where:

$f(s)$ is the probability distribution of vector s .

$I(s; y)$ Is the mutual information between s and y .

It follows that the capacity of the MIMO channel is given by

$$c = \max_{Tr(R_{ss})=M_T} \log_2 \det \left(I_{M_R} + \frac{E_s}{M_T N_0} H R_{ss} H^H \right) \quad (2.20)$$

Where $T_r(R_{ss})$ is the trace of the covariance matrix of s , and its must equal to M_T in order to constrain the total average energy transmitted over a symbol period, and H^H is the conjugate transpose of H . ^{(10) (14)}

We can note that the capacity of the MIMO channel depends on the channel matrix, SNR, number of transmitter; this capacity is also referred to the data rate per unit bandwidth.

2.6.1. Channel unknown to the transmitter:

In this case the transmitter does not know the nature of the channel, so it will transmit equal power at each antenna, this implies that $R_{ss} = I_{M_T}$. Then the equation 2.20 becomes

$$C = \log_2 \det(\mathbf{I}_{M_R} + \frac{E_s}{M_T N_0} \mathbf{H} \mathbf{H}^H) \quad (2.21)$$

The MIMO channel capacity simplifies to

$$C = \sum_{i=1}^r \log_2(1 + \frac{E_s}{M_T N_0} \lambda_i) \quad (2.22)$$

This equation implies that the MIMO channel capacity is the sum of the capacities of r SISO channels, where r is the rank of the $\mathbf{H} \mathbf{H}^H$, with a power gain equals to the eigenvalues λ_i of those channels, and each antenna transmits power equals E_s/M_T .⁽¹⁰⁾⁽¹⁴⁾

For a full rank orthogonal MIMO channel with $M_T = M_R = M$ and $\mathbf{H} \mathbf{H}^H = \mathbf{H}^H \mathbf{H} = (\zeta/M) \mathbf{I}_M$, with a fixed total power transfer $\|\mathbf{H}\|_F^2 = \zeta = \sum_{i=1}^M \lambda_i$ and the length of each element of $\mathbf{H}$ is equal to one so $\|\mathbf{H}\|_F^2 = M^2$, the capacity of such channel will be the maximum channel capacity achieved with no channel knowledge at the transmitter, which is equal to⁽¹⁰⁾⁽¹⁴⁾

$$C = M \log_2(1 + \frac{E_s}{N_0}) \quad (2.23)$$

2.6.2. Channel known to the transmitter:

We have discussed the capacity of the MIMO channels when the channel is unknown to the transmitter, in that case we allocated equal power signals to the transmitter antennas, now consider that the channel is known to the transmitter, and see the advantage of this knowledge at the transmitter.⁽¹⁰⁾⁽¹⁴⁾

The channel knowledge at the transmitter can be achieved by two different techniques, via feedback or reciprocity principle in duplex system.

Feed-back: In the first technique the receiver estimate the forward channel, and send the feedback to the transmitter via the reverse link, in order to reduce the overhead caused by this feedback we can send a slow changing statistic of the channel such as the correlation matrices, or a partial channel information.⁽¹⁴⁾

Reciprocity: Let $h_f(t_f, f_f, i_f)$ and $h_r(t_r, f_r, i_r)$ be the forward and reverse channels respectively where t, f, i are the time, frequency, and antenna index respectively, the reciprocity principle says that if all those parameters are equated then the reverse and forward channels are identical, and this will give the transmitter a sufficient information's to estimate the channel.⁽¹⁴⁾

In order to realize the duplexing schemes we need to hold a separation in time, or frequency or spatial parameters, so we can prevent interference.

In time division duplexing (TDD) we use the same frequency and antenna index with different time slots in the forward and reverse channels, for the channels to be equated, the time delay must be much less than the coherence time of the channel.⁽¹⁴⁾

In frequency division duplexing (FDD) we use the same time and antenna index with different frequencies, for the channels to be equated, the frequency difference must be much less than the coherence bandwidth of the channel, but a physical limits of the of duplexing filters force the frequency difference to be large, so FDD is not a choice for the reciprocity principle.⁽¹⁴⁾

In antenna division duplexing (ADD) we use the same frequency and time with different antennas, for the channels to be equated, the separation between the antennas must be much less than the coherence distance, cause the coherence distance between the antennas is relatively small, such separation can't be realized.⁽¹⁴⁾

So in real life communication systems use a combination of time, antenna, and frequency separations in the duplexing links, making the reciprocity principle not feasible.⁽¹⁴⁾

Now when the channel is known to the transmitter we can maximize the capacity by allocating different power levels to the antennas, depending on the basis that the better channel, gets better power and vice versa.⁽¹⁴⁾

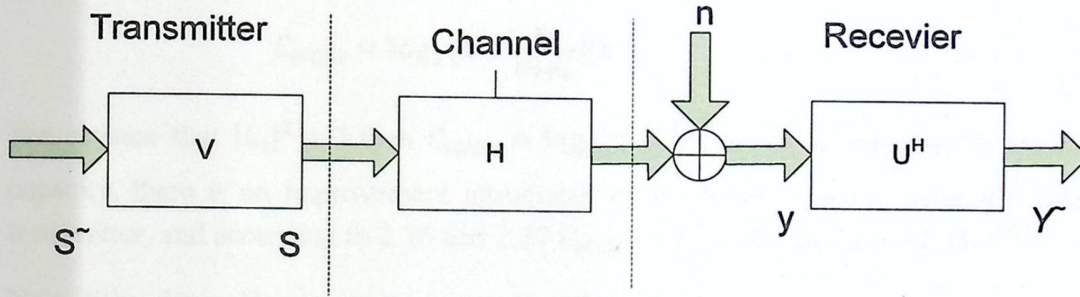


Figure 2.2: Schematic of modal decomposition of $\mathbf{H}$ when the channel is known to the transmitter and receiver

Consider a ZMCSCG signal vector $\tilde{\mathbf{s}}$ ($r \times 1$) where r is the rank of $\mathbf{H}$ to be transmitted, from figure 2.2 we see this vector is multiplied by $\mathbf{V}$ prior transmission, and the received signal $\mathbf{y}$ at the receiver is multiplied by $\mathbf{U}^H$, based on the fact that $\mathbf{H} = \mathbf{U}\mathbf{\Sigma}\mathbf{U}^H$ according to singular value decomposition.⁽¹⁰⁾⁽¹⁴⁾

$$\tilde{\mathbf{y}} = \sqrt{\frac{E_s}{M_T}} \mathbf{\Sigma} \tilde{\mathbf{s}} + \tilde{\mathbf{n}} \quad (2.24)$$

After a long derivation and using lagrangian methods, and based on the water pouring algorithm the capacity of a MIMO random channel can be introduced as

$$C = \max_{\sum_{i=1}^r \gamma_i} \sum_{i=1}^r \log_2 \left(1 + \frac{E_s \gamma_i}{M_T N_0} \lambda_i \right) \quad (2.25)$$

Where γ_i is the energy in the i th sub-channel.

2.6.3 Capacities of SIMO and MISO channels:

We can consider the capacities of SIMO and MISO channels as special cases from the MIMO channels capacity.

In the SIMO case $M_T=1$, $r=1$, and $\lambda = \|\mathbf{h}\|_F^2$, using equation 2.22 for the capacity of the unknown channel we get

$$C_{SIMO} = \log_2(1 + \frac{E_s}{N_0} \|\mathbf{h}\|_F^2) \quad (2.26)$$

And if we assume that $|h_i|^2 = 1$ then $\|\mathbf{h}\|_F^2 = M_R$, $C_{SIMO} = \log_2(1 + \frac{E_s}{N_0} M_R)$

And it's introduced a logarithmic increase in C with M_R , but the knowledge of the channel at the transmitter in this case (SIMO) does not change the capacity.

In the MISO case $M_R=1$, $r=1$, and $\lambda = \|\mathbf{h}\|_F^2$, using equation 2.22 for the capacity of the unknown channel we get

$$C_{MISO} = \log_2(1 + \frac{E_s}{M_T N_0} \|\mathbf{h}\|_F^2) \quad (2.27)$$

We assume that $|h_i|^2 = 1$ then $C_{MISO} = \log_2(1 + \frac{E_s}{N_0})$ which is identical to the SISO channel capacity, there is no improvement introduced by the MISO channel when it's unknown to the transmitter, and according to 2.26 and 2.27 $C_{MISO} < C_{SIMO}$ for the same $\|\mathbf{h}\|_F^2$.⁽¹⁴⁾

Now if the channel known to the transmitter then according to equation 2.8 the capacity of MISO channel given by

$$C_{MISO} = \log_2(1 + \frac{E_s}{N_0} \|\mathbf{h}\|_F^2) \quad (2.28)$$

From equation 2.26 and 2.28 we note that $C_{MISO} = C_{SIMO}$ for the same $\|\mathbf{h}\|_F^2$, they just offer a logarithmic increase in the capacity.

2.7 Capacity of random MIMO channels

Now we'll discuss the capacity when $\mathbf{H}$ is chosen randomly based on Raleigh distribution, which is the real life situation unlike the deterministic ones, so the data rate for such channels is also random.

2.7.1 Ergodic capacity

Ergodic capacity is the average of information rate over the distribution of the elements of the channel matrix $\mathbf{H}$, ergodic capacity is a result of long measurements, since $\mathbf{H}$ is independent and have no relation to the previous one. Based on equation 2.22 that introduced the capacity of a deterministic known MIMO channel, the ergodic capacity is^{(10) (14)}

$$C = \epsilon \left\{ \sum_{i=1}^r \log_2 \left(1 + \frac{\rho}{M_T} \lambda_i \right) \right\} \quad (2.29)$$

Where ρ is the average SNR, ϵ is the expectation of the random channel, now for the case when the channel is unknown to the transmitter, based on equation 2.25 we conclude that the ergodic capacity of a random channel is

$$C = \epsilon \left\{ \sum_{i=1}^r \log_2 \left(1 + \frac{E_s \gamma_i}{M_T N_0} \lambda_i \right) \right\} \quad (2.30)$$

It's clear from the last two equations that the capacity of a random MIMO channel is higher when the channel is known to the transmitter, but in a high SNR case they become close to each other, since the channels start to perform equally at high SNR. ^{(10) (14)}

In [16] the authors provide a summary of ergodic and capacity versus outage results for single-user MIMO channels. These results indicate that the gain in the capacity obtained from multiple antennas totally depends on the available channel information at the receiver or transmitter, the channel signal to noise ratio, and the correlation between the channel gains on each antenna element.

2.7.2 Outage capacity

It's the guaranteed capacity with a certain level of reliability, if we have a q% outage capacity; there is a probability of (100-q) % to get a capacity less than this outage capacity, the outage capacity increases with SNR and the antennas configuration for a certain q%, and its approach the median capacity for large SNR and high antenna configuration. ^{(10) (14)}

2.8 Influence of the fading correlation, LOS, XPD and degeneracy on MIMO capacity

As mentioned earlier H_w assumes a high scattering environment and good antenna separation, such as insufficient scattering and the presence of LOS which causes a Ricean fading, have a high effect on the performance of the wireless systems. we'll study the influence of fading correlation, LOS, XPD in non-fading channel, and the degeneracy on the channel capacity. ^{(10) (6)}

2.8.1 Influence of the spatial fading correlation

Because of the small separation between the antennas at the base station, the signals arriving there usually correlated. To overcome this problem, wireless systems use dipole antennas or antenna arrays separated by distance D, which is more than the coherent distance for that channel. ^{(10) (14)}

The effect of fading correlation for Rayleigh flat fading channel can be modeled as follows

$$H = R_r^{\frac{1}{2}} H_w R_t^{\frac{1}{2}} \quad (2.31)$$

Where $\mathbf{R}_t$ and $\mathbf{R}_r$ are the transmitter and receiver covariance matrices, both $\mathbf{R}_t$ and $\mathbf{R}_r$ are positive semi-definite Hermitian matrices,

Based on the capacity of the channel in the absence of channel knowledge at the transmitter equation 2.21 and equation 2.31

$$C = \log_2 \det(\mathbf{I}_{M_R} + \frac{\rho}{M_T} \mathbf{R}_r^{\frac{1}{2}} \mathbf{H}_w \mathbf{R}_t \mathbf{H}_w^H \mathbf{R}_r^{H/2}) \quad (2.32)$$

For high SNR and $M_R = M_T = M$, and a full rank receiver and transmitter correlation matrices, C can be approximated to

$$C \approx \log_2 \det(\frac{\rho}{M} \mathbf{H}_w \mathbf{H}_w^H) + \log_2 \det(\mathbf{R}_r) + \log_2 \det(\mathbf{R}_t) \quad (2.33)$$

We can note that the receiver and transmitter correlation matrices have the same effect at the capacity, because of the power constrain $\sum_{i=1}^M \lambda_i(\mathbf{R}_r) = M$ this means that $\log_2 \det(\mathbf{R}_r) \leq 0$, and the same for the transmitter correlation matrix, so we can consider both terms as the loss in the capacity due to fading correlation, only when $\mathbf{R}_r = \mathbf{I}_M$ the loss will be zero. ^{(10) (14)}

In [17] the authors studied the effect of spatial correlation on the capacity of MIMO fading channel. They also consider the situations when the channel is unknown and known at the transmitter. The effects of antenna spacing, angle spread, and number of antennas on the capacity are also examined. The results showed that the spatial correlation severely degrade the capacity of MIMO systems. The degradation in the capacity can be reduced by increasing the separation distance between the antenna elements.

2.8.2 Influence of the LOS component

The presence of LOS in the channel will add a term to the equation 2.31 which is the Ricean LOS component $\mathbf{H}_{\text{Ric}}$

$$\mathbf{H} = \mathbf{H}_{\text{Ric}} + \mathbf{R}_r^{\frac{1}{2}} \mathbf{H}_w \mathbf{R}_t^{\frac{1}{2}} \quad (2.34)$$

Equation 2.34 can be rewritten as a two terms, one for the Los component and the other for the fading component, as follows

$$\mathbf{H} = \sqrt{\frac{K}{1+K}} \bar{\mathbf{H}} + \sqrt{\frac{1}{1+K}} \mathbf{H}_w \quad (2.35)$$

Where K is the Ricean K-factor, which is the ratio between the power in the LOS component and the power in the fading component, $K = \infty$ corresponds to a nonfading channel, and $K=0$ corresponds to pure Rayleigh channel. ^{(10) (14)}

In [18] the authors studied the capacity of spatially correlated Rician MIMO channels. They consider the general case with double-sided correlation and arbitrary rank channel means. Then

they derive upper and lower bounds on the capacity. In some particular cases when the numbers of transmit and receive antennas are equal, or the correlation is single sided, they derive more specific bounds which are computationally efficient.

2.8.3 Influence of XPD:

All the models discussed before assumed an identical antenna polarization at both transmitter and receiver, normally we use orthogonal polarized antennas, since they are orthogonal the; vertical antenna just see the signals from the vertical polarized antenna at the other side, the same case for the horizontal one, ideally, no correlation between the signals from orthogonal polarized antennas, but in reality there is some interference between them. ⁽¹⁰⁾⁽¹⁴⁾

The term XPD cross-polarization discrimination tells us how the antenna discriminate its signal from others, and introduce a constant α ($0 \leq \alpha \leq 1$), for $\alpha = 0$ we have a good discrimination and for sure zero interference, but $\alpha = 1$ it implies a poor discrimination and a strong interference, now H for a channel with $M_T=M_R=2$ and assuming a deterministic channel then we have ⁽¹⁰⁾⁽¹⁴⁾

$$H = \begin{bmatrix} 1 & \sqrt{\alpha} \\ \sqrt{\alpha} & 1 \end{bmatrix} \quad (2.36)$$

Now the capacity in the absence of XPD $C(\alpha = 1)$ and in the presence of perfect XPD $C(\alpha = 0)$ can be given by

$$C(\alpha = 1) = \log_2(1 + 2\rho) \quad (2.37)$$

$$C(\alpha = 0) = 2 \log_2(1 + \frac{\rho}{2}) \quad (2.38)$$

We note that we can enhance the capacity at perfect XPD ($\alpha = 0$) with the presence of high SNR, but with low SNR we enhance the capacity with the presence of low XPD ($\alpha = 1$).

2.8.4 Influence of degeneracy:

The degeneracy affect the capacity when we have the keyhole phenomena, which happens when we have a narrow path between the transmitter and the receiver, the whole signals must pass from this narrow path, like a small window or a narrow street, we can consider $H = h_r h_t^T$ where h_r is the channel vector between the receiver and the hole, h_t is the channel vector between the transmitter and the hole, the corresponding channel capacity given by ⁽¹⁰⁾⁽¹⁴⁾

$$c = \log_2 \det (1 + \frac{\rho}{M_T} \|H\|_F^2) \quad (2.39)$$

Although the channel is MIMO, only a logarithmic increase in the capacity happens for increasing SNR, this is similar to the SIMO or MISO cases, since there is only one spatial sub-channel through that hole. ⁽¹⁰⁾⁽¹⁴⁾

2.9 Spatial multiplexing processing techniques:

Which are techniques that deal with each one of the previous cases to improve the performance of the systems, and need to provide more details about these techniques, especially when talking about optimization of a single link. The following section will explain four techniques According to [15]. Figure 2.2 shows these techniques: ⁽¹⁰⁾

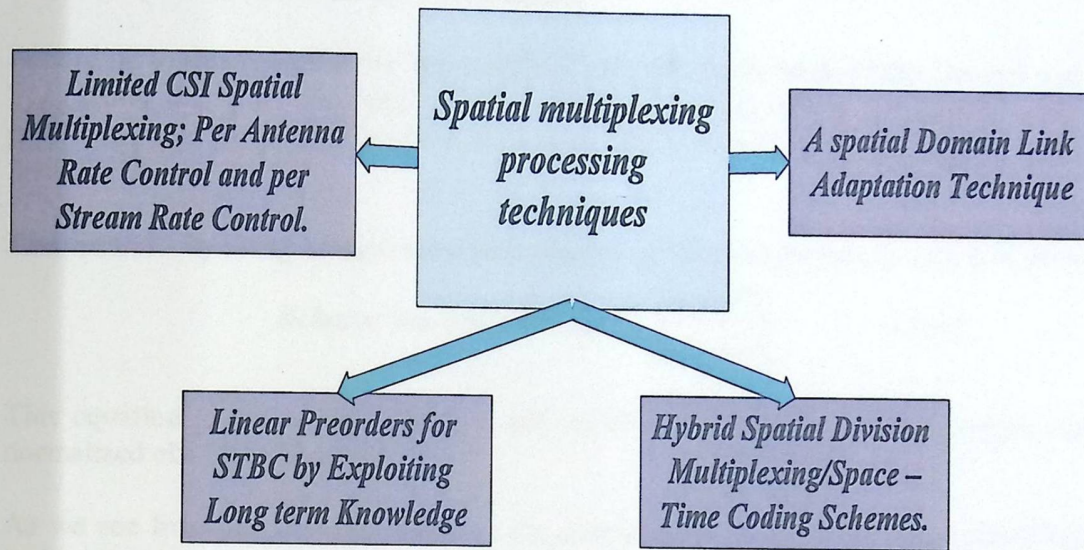


Figure 2.3 Spatial multiplexing processing techniques

2.9.1 A spatial Domain Link Adaptation Technique:

It is a multi-antenna technique that allows hard switching between multi-antenna methods (algorithms), based on monitoring the short term characteristic of the radio channel at the receiver. ⁽¹⁵⁾

In other words in short term characteristic radio channel we can achieved more reliability and further performance improvements, if there are more than one algorithm (method) that the system can switch between them, after deciding which method is better for the actual channel condition, i.e. for strong line of site or receive correlation diversity is suitable more than SMUX. ⁽¹⁵⁾

As we know there is trade-off between diversity and SMUX gain, where SMUX achieve high spectral efficiency by transmit independent data stream, and diversity increase link reliability by introducing redundancy (sent more than one copy from the same signal to combat fading); this trade-off gives the channels degree of freedom to multiplexing and Diversity transmission modes. ⁽¹⁵⁾

There are two methods to measure the trade-off between diversity and SMUX:

The first one using Demmel condition number (K_D) where:

$$K_D = \frac{\lambda_{\min}(HH^H)}{\|H\|^2} \quad (2.40)$$

Where

$\lambda_{\min}$: The smallest eigenvalues of (HH^H)
 $\|H\|^2$: Forbenius norm of the channel

According to this equation the "pure SMUX" depend on the rank of the channel and determined by $\lambda_{\min}$ and the "pure diversity" depends on the measures of the total power over all channel paths measured by $\|H\|^2$. Therefore we can use K_D to switch between diversity transmission and SMUX. ⁽¹⁵⁾

The second - by using relative condition number of the channel matrix which is given by:

$$\text{Relative condition number} = \frac{\lambda_n(HH^H)}{\lambda_{\max}(HH^H)} \quad (2.41)$$

This equation gives us ratio between n th smallest eigenvalues and the largest eigenvalues in normalized channel power.

As we see from the last two methods the transmitter need a single parameter CSI to estimate instantaneously the channel quality and this CSI can be return as feedback from the receiver which has full CSI. ⁽¹⁵⁾

Finally the advantage of this technique (using more than one transmission modes), that it provides further performance improvements, but it need fast feed-back form the receiver to transmitter which considered as disadvantage. ⁽¹⁵⁾

2.9.2 Hybrid Spatial Division Multiplexing/Space –Time Coding Schemes.

This technique is used in open loop multi-antenna to take the advantages of space-time block coding (STBC) and SMUX in order to get further performance improvement. ⁽¹⁵⁾

To understand this technique it must clarify simply STBC, which means spread the symbols in time and space block by block. Here the concern with "the so-called orthogonal STBC which is designed based on an orthogonal structure. ⁽¹⁵⁾

Almouti was the first one who designed the first orthogonal STBC for two transmit antenna.

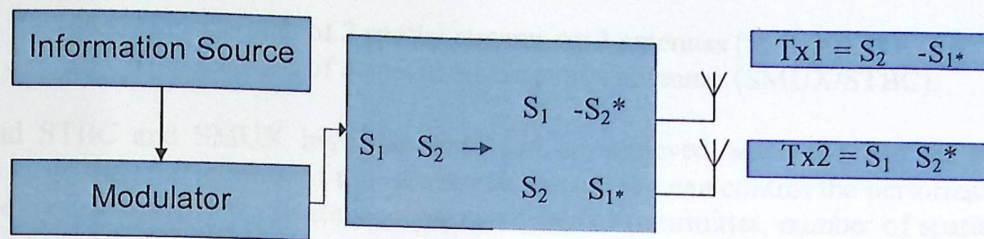


Figure 2.4 a block diagram of the Alamouti space-time encoder

The last figure show a block diagram of Alamouti scheme where the information bits are modulated using M-array modulation, after that the encoder put two modulated symbols i.e. S_1 and S_2 and put them in one block and spread these data in time and space according to the following matrix: ⁽¹⁵⁾⁽¹⁰⁾

$$\begin{bmatrix} S_1 & -S_2^* \\ S_2 & S_1^* \end{bmatrix}$$

In this matrix the rows represent transmit antennas and columns represent symbol intervals. So the first and second antennas transmit S_1 , S_2 respectively in the first time slot and the second time slot they will send $-S_2^*$, S_1^* respectively, this implies that we sent the data in space by using two antenna and in time (transmit the data over different time). ⁽¹⁵⁾⁽¹⁰⁾

Now, this technique gives different trade off between data rate and robustness by transmitting $N-1$ parallel streams on N antennas, one of this stream coded by Almouti code, figure 2.3 show illustration examples. ⁽⁴⁾

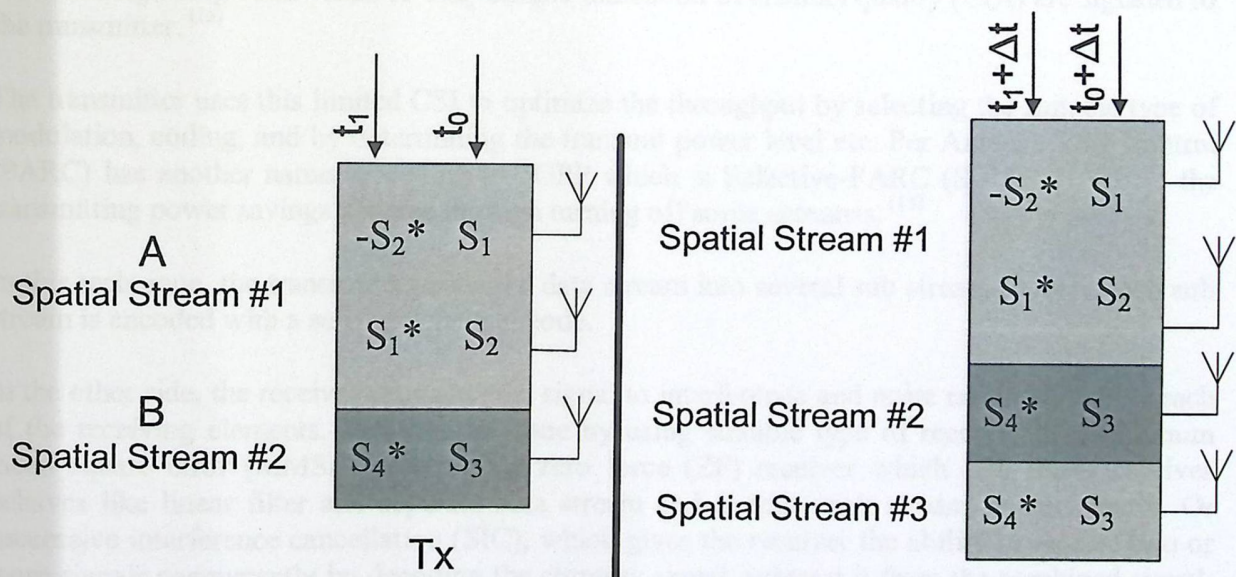


Figure 2.5

- (A): Transmission of 2 spatial streams on 3 antennas (SMUX/STBC).
- (B): Transmission of 3 spatial streams on 4 antennas (SMUX/STBC).

In hybrid STBC and SMUX high data rate can be achieved when the number of transmit antennas large than the number of the receiver antennas. We can control the performance of this technique by select many parameters such as: number of transmitter, number of spatial streams, and type of modulation.⁽¹⁵⁾

2.9.3 Linear Preorders for STBC by Exploiting Long term Knowledge

This technique concentrates on only slowly varying antenna correlations. On the contrary of the fast fading technique which need instantaneous feed back to the transmitter from the receiver, this one need partial CSI that means low rate feed-back link, or get partial CSI by exploiting channel reciprocity which will be explain in section 2.6.2.⁽¹⁵⁾

According to the partial CSI correlation matrix, the transmitters can transmit on the nonzero eigenmodes to reduce the performance deterioration cased by transmit antenna correlations. So this is equivalent abeam-former.⁽¹⁵⁾

2.9.4 Limited CSI Spatial Multiplexing; Per Antenna Rate Control and per Stream Rate Control

Limited CSI SMUX is applicable to mobile devices, which is small and portable; since the difficulty that faces this mobile in sending full CSI to the base station and the restrictions on the available signaling bandwidth, so only simple indication of channel quality (CQI) are signaled to the transmitter.⁽¹⁵⁾

The transmitter uses this limited CSI to optimize the throughput by selecting the suitable type of modulation, coding, and by determining the transmit power level etc. Per Antenna Rate Control (PARC) has another name according to 3GPP which is Selective-PARC (S-PARC), where the transmitting power savings accrue through turning off some antennas.⁽¹⁵⁾

In this technique, the transmitter sends the data stream into several sub streams, where each sub stream is encoded with a separate channel code.

In the other side, the receiver estimates the signal to interference and noise ratio (SINR) for each of the receiving elements. This can be done by using suitable type of receiver like minimum mean square error (MMSE) receiver, or zero force (ZF) receiver which is a linear receiver behaves like linear filter and separate data stream and decode each stream independently. Or successive interference cancellation (SIC), which gives the receiver the ability to receive two or more signals concurrently by decoding the stronger signal, subtract it from the combined signal, and extract the weaker one from the reset.⁽¹⁵⁾⁽¹⁰⁾

After that this SINR feed-back to the transmitter as CQI, the transmitter uses it to determine the suitable modulation, and power level for each sub stream.⁽¹⁵⁾

Chapter 3

Simulation results

- 3.1 Overview.
- 3.2 The flow chart of the Matlab code.
- 3.3 Ideal cases simulation results.
- 3.4 Results tables for the ideal cases.
- 3.5 Effect of the spatial fading correlation.
- 3.6 Effect of the line of sight component.
- 3.7 Effect of the keyhole phenomena (degeneracy).
- 3.8 Effect of the cross-polarization discrimination.
- 3.9 Summary.

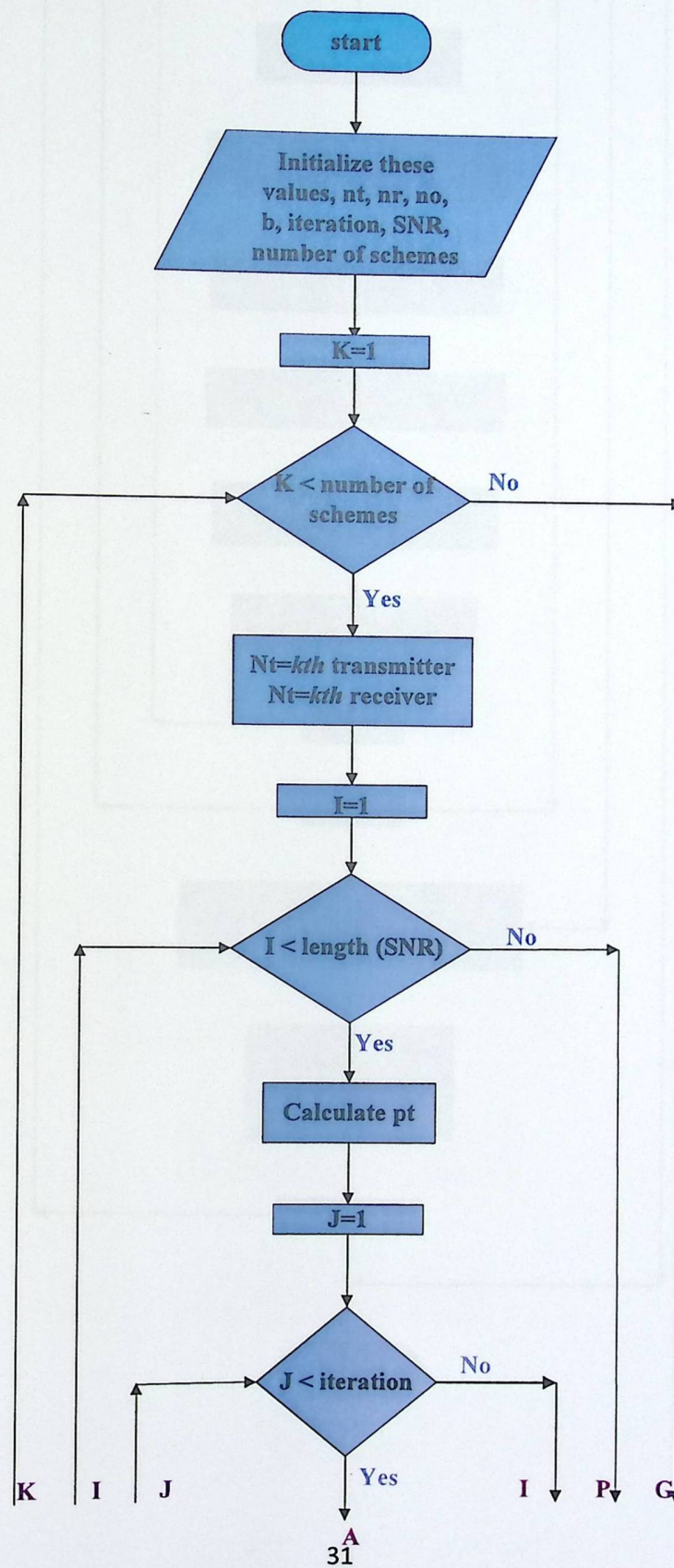
3.1 Overview

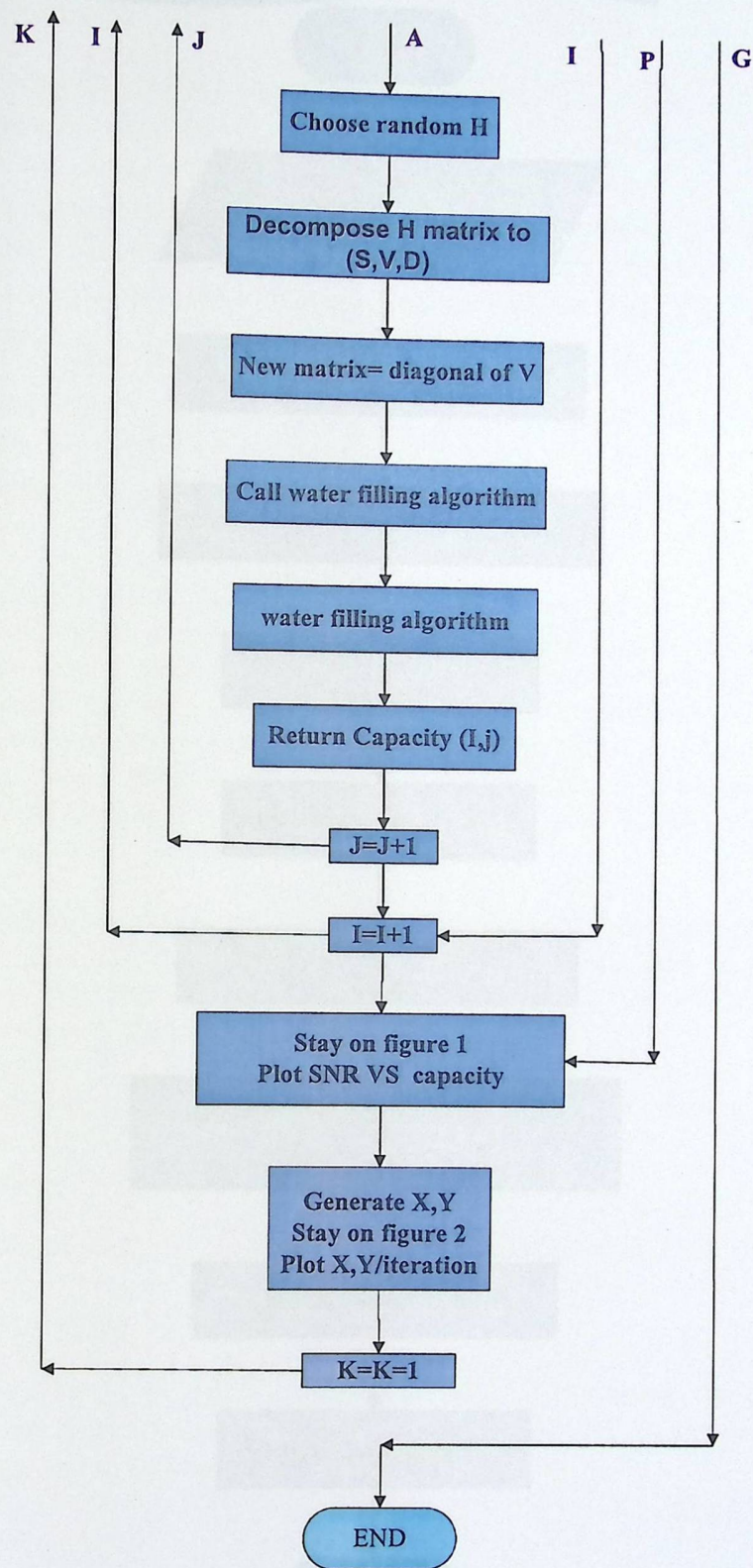
This chapter explains the Matlab code through flow chart, then it shows the results that we conclude after making simulation for SISO, and different schemes of SIMO, MISO and MIMO for different antennas configurations to clarify the relationship between SNR and capacity for each case.

Also, it shows the results of changing some important parameters such as: noise, transmitted power, SNR, number of iteration.

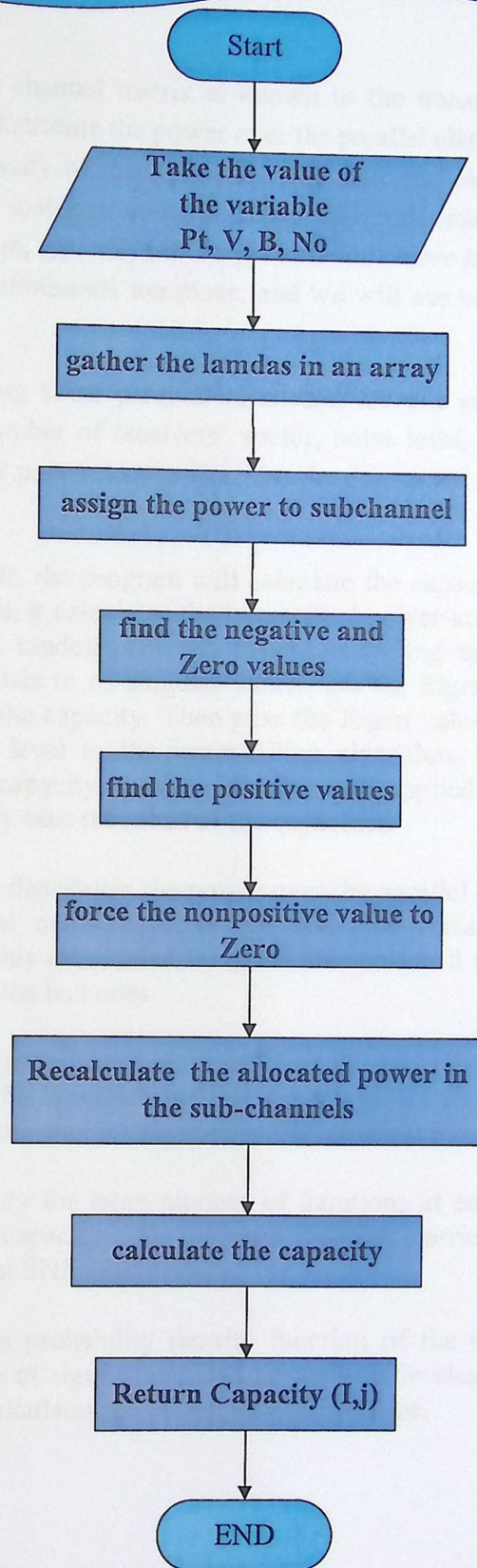
Then it shows the simulation results for the effect of the four real life cases which are XPD, LOS, spatial fading correlation and the keyhole phenomena, the results were showed for different antennas configurations.

3.2 The flow chart of the Matlab code:





Water filling algorithm



Algorithm description:

Since we assume that the channel matrix is known to the transmitter, this program uses the water-filling algorithm to distribute the power over the parallel channels in the MIMO system, in order to calculate the capacity of this system. It calculate the capacity for a large number of different random channel matrices at each SNR value, in order to get the mean of those capacities at each SNR value, typically and to get a smooth curve it must take more than hundred iterations, here it uses ten thousands iterations, and we will see what happens if we reduce the number of iterations.

First of all it starts defining some parameters needed for this simulation like the number of transmitters' vector, the number of receivers' vector, noise level, bandwidth in hertz, signal to noise ratio, and some other parameters to describe the colors and notation used to discriminate each curve.

Now for each value of SNR, the program will calculate the capacity of the system at this SNR and with a given noise level, it calculates the transmitted power according to the noise level and the SNR, also generate a random channel matrix according to Rayleigh distribution, then decompose the channel matrix to its singular values, get the Eigen values of this matrix to use them in the calculation of the capacity. Then pass the Eigen values, the transmitted power, the bandwidth, and the noise level to the water-filling algorithm, in order to use them in the calculation process of the capacity, these procedures will applied for large number of random channel matrices, and finally take the mean of the capacities.

The water-filling algorithm distributes the power over the parallel channels on the basis that the better the channel gets, the more power it gets and vice versa. This is an optimal energy allocation algorithm. And this means that the good channels will transmit at good power, but I will not waste the power in the bad ones.

Since this algorithm only concentrates on good channels and rejects the bad ones during each channel realization, it is to be expected that this method yields a capacity that is equal or better than the situation when the channel is unknown to the transmitter.

After calculating the capacity for large number of iterations at each SNR level, it's typical to calculate the mean of the capacities for different channel matrices, and it will represent the capacity of the system at that SNR level.

The program also plots the probability density function of the eigenvalues, it calculates the probability for a small range of eigenvalues, and normally it divides the eigenvalues range to one hundred small ranges and calculates the probability of each one.

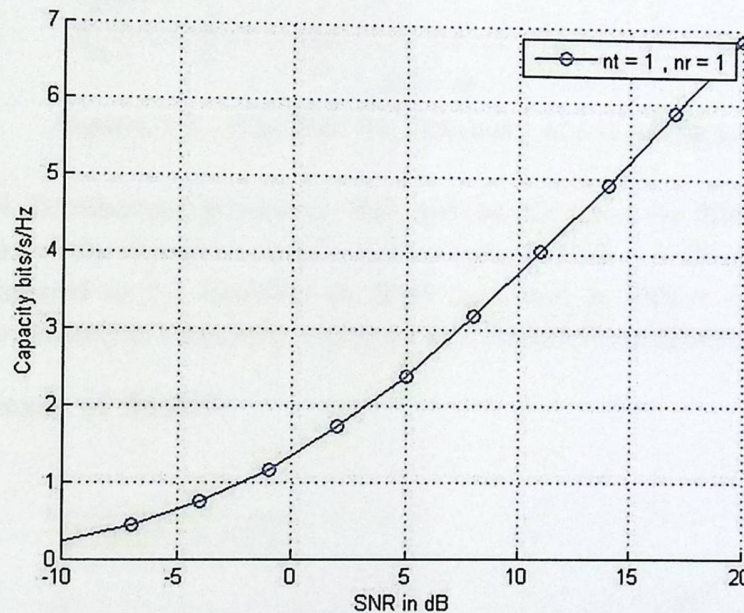
3.3 Simulation results

In this section, we will present the efficiency of the system for SISO, SIMO, MISO and MIMO in different cases, and see the PDF of the eigenvalues, also study the effect of the noise at fixed transmitted power.

3.3.1 Efficiency:

In this section, we will present the efficiency for SISO, SIMO, MISO and MIMO as bits/s/Hz.

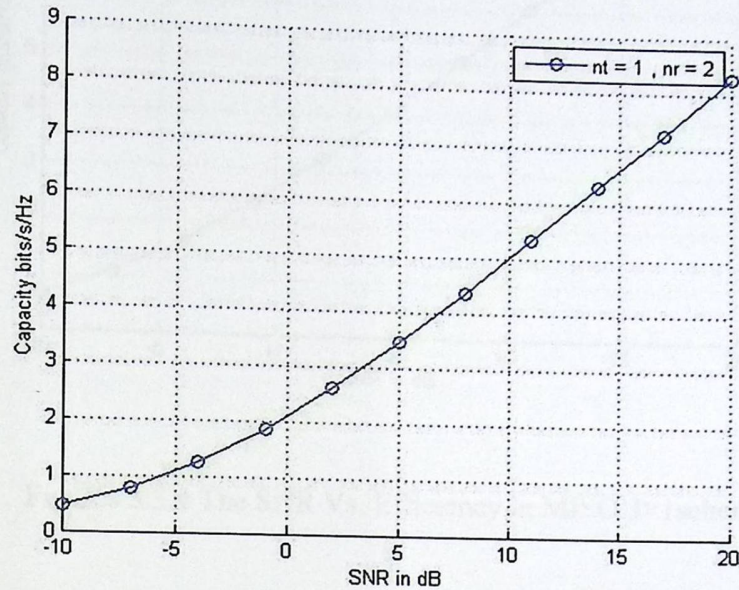
1. Efficiency for SISO:



Figures 3.3.1 The SNR Vs. Efficiency in SISO scheme .

This figure show the relationship between SNR and capacity for SISO system, we notice when SNR increases, the capacity increase, for example at SNR = 5 dB we got approximately 2.3 bits/s/Hz, and at SNR = 15 dB the efficiency increases to approximately 5.2 bits/s/Hz.

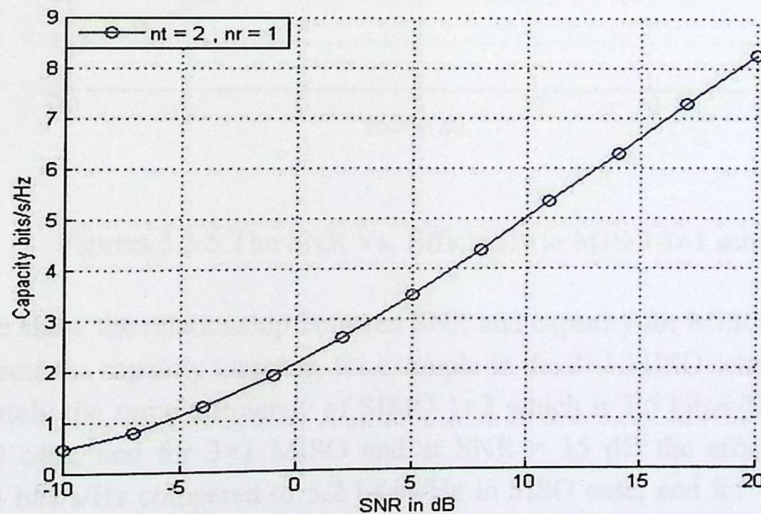
2. Efficiency of SIMO:



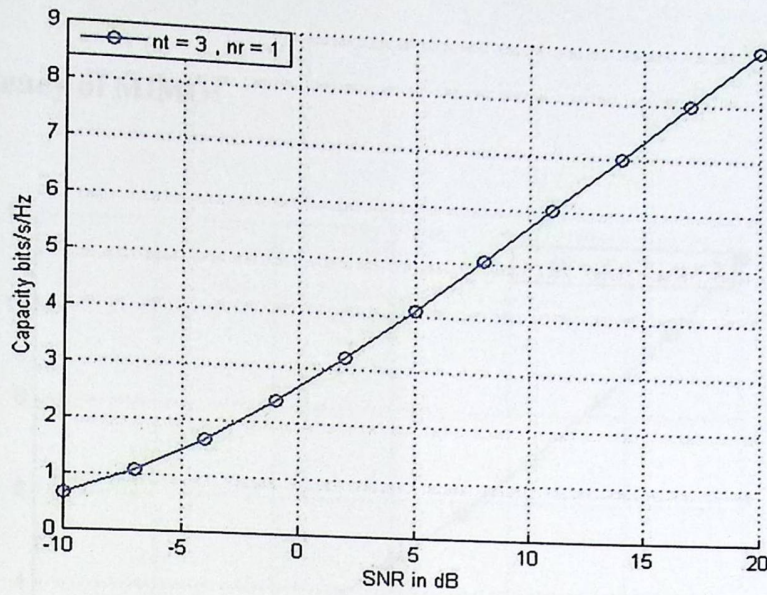
Figures 3.3.2 The SNR Vs. Efficiency in 1 X 2 SIMO scheme.

This figure shows the relationship between SNR and the efficiency for SIMO system, we notice when SNR increases, the capacity increase, for example at SNR = 5 dB we got approximately 3.5 bits/s/Hz compared to 2.3 bits/s/Hz in SISO case, and at SNR = 15 dB the efficiency increases to approximately 6.7 bits/s/Hz compared to 5.2 bits/s/Hz in SISO case.

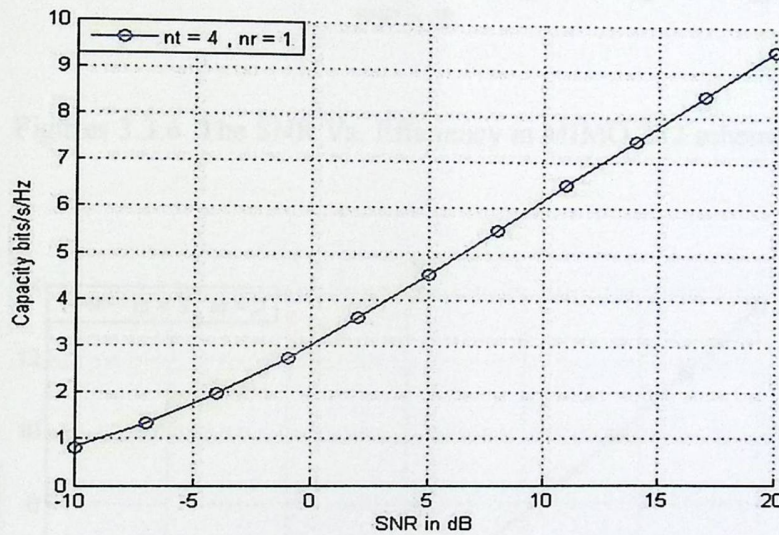
3. Efficiency of MISO:



Figures 3.3.3 The SNR Vs. Efficiency in MISO 2x1 scheme.



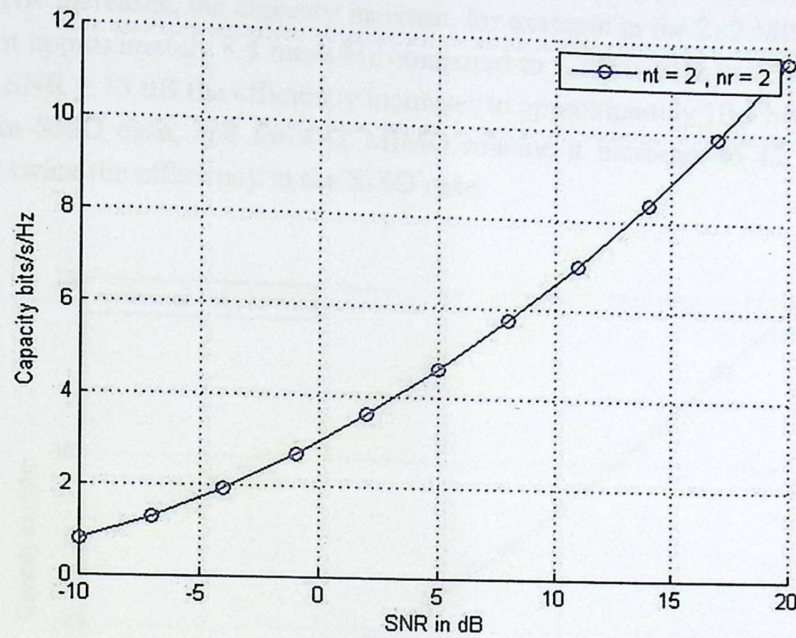
Figures 3.3.4 The SNR Vs. Efficiency in MISO 3×1 schemes.



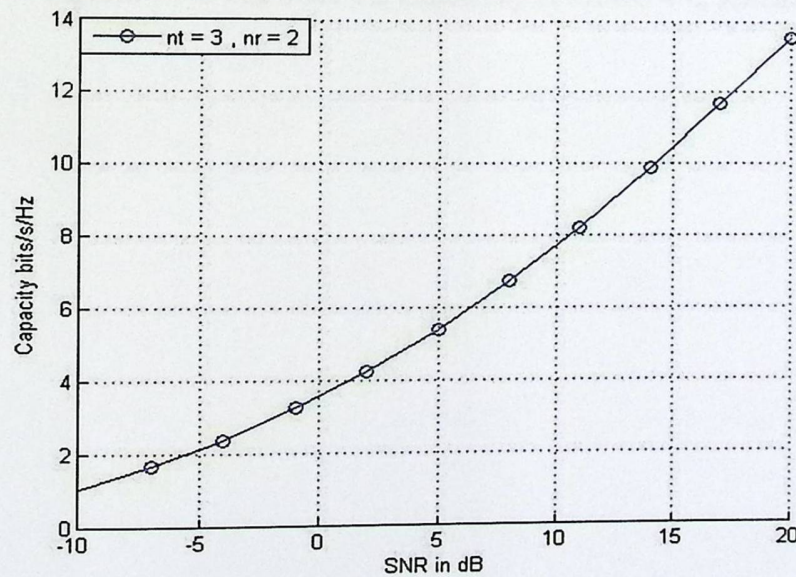
Figures 3.3.5 The SNR Vs. Efficiency in MISO 4×1 scheme.

This figures above show the relationship between SNR and capacity for MISO system, we notice when SNR increases, the capacity increase, for example in the 2×1 MISO scheme at SNR = 5 dB we got approximately the same efficiency of SIMO 1×2 which is 3.5 bits/s/Hz compared to 2.3 bits/s/Hz in SISO case, and for 3×1 MISO and at SNR = 15 dB the efficiency increases to approximately 7.3 bits/s/Hz compared to 5.2 bits/s/Hz in SISO case, and for 4×1 MISO scheme it increases to 7.8 bits/s/Hz.

4. Efficiency of MIMO:

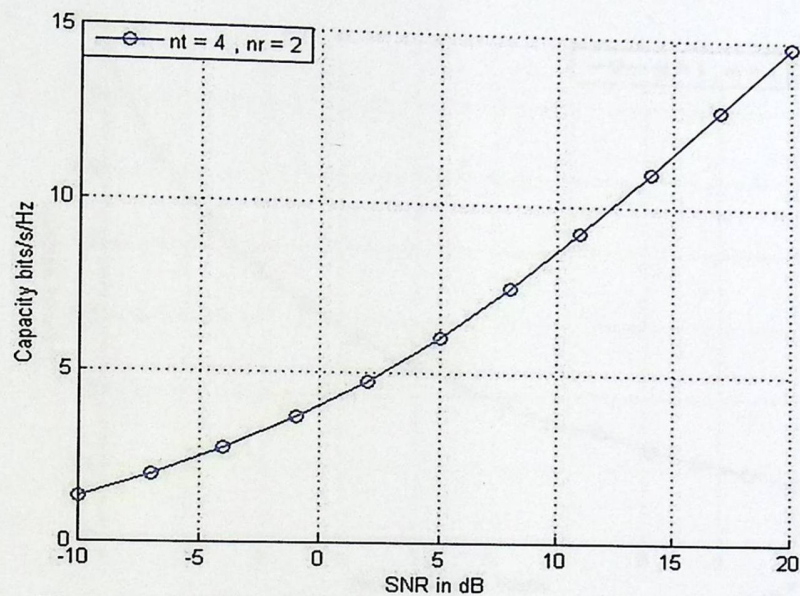


Figures 3.3.6 The SNR Vs. Efficiency in MIMO 2x2 scheme.



Figures 3.3.7 The SNR Vs. Efficiency in MIMO 3x2 scheme.

This figures above show the relationship between SNR and capacity for MIMO system, we notice when SNR increases, the capacity increase, for example in the 2×2 MIMO scheme at SNR = 15 dB we got approximately 8.4 bits/s/Hz compared to 5.2 bits/s/Hz in SISO case, and for 3×2 MIMO and at SNR = 15 dB the efficiency increases to approximately 10.5 bits/s/Hz compared to 5.2 bits/s/Hz in SISO case, and for 4×2 MIMO scheme it increases to 12 bits/s/Hz, which is approximately twice the efficiency in the SISO case.



Figures 3.3.8 The SNR Vs. Efficiency in MIMO 4×2 scheme.

3.3.2 Efficiency versus noise:

In this case we assume a fixed transmitted power which is typically the case, we plot the efficiency of the system versus the noise level at a fixed transmitted power for different MIMO schemes.

1. Efficiency versus noise for SISO:

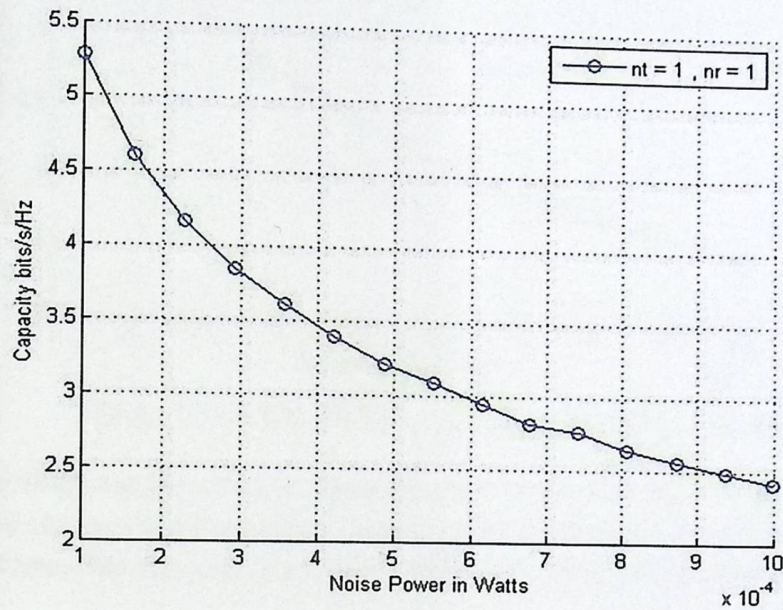


Figure 3.3.9 The SNR Vs. Efficiency in SISO scheme

The above figure illustrates the effect of the noise level on the efficiency of the SISO system and as we see the efficiency of the system decreased from 5.3 bits/s/Hz at a noise level of 0.1 mW to 3.2 bits/s/Hz for noise level of 0.5 mW, and to just 2.4 bits/s/Hz for high noise level of 1 mW.

2. Efficiency versus noise for SIMO:

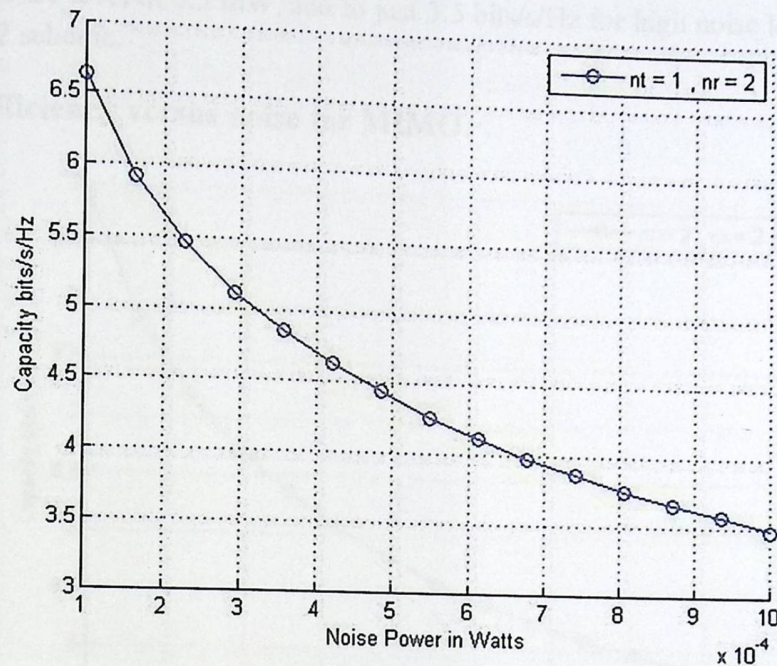


Figure 3.3.10 The SNR Vs. Efficiency in SIMO 1 $\times$ 2 scheme

The above figure illustrates the effect of the noise level on the efficiency of the SIMO 1 $\times$ 2 system, and as we see the efficiency of the system decreased from 6.6 bits/s/Hz at a noise level of 0.1 mW to 4.4 bits/s/Hz for noise level of 0.5 mW, and to just 3.5 bits/s/Hz for high noise level of 1 mW.

3. Efficiency versus noise for MISO:

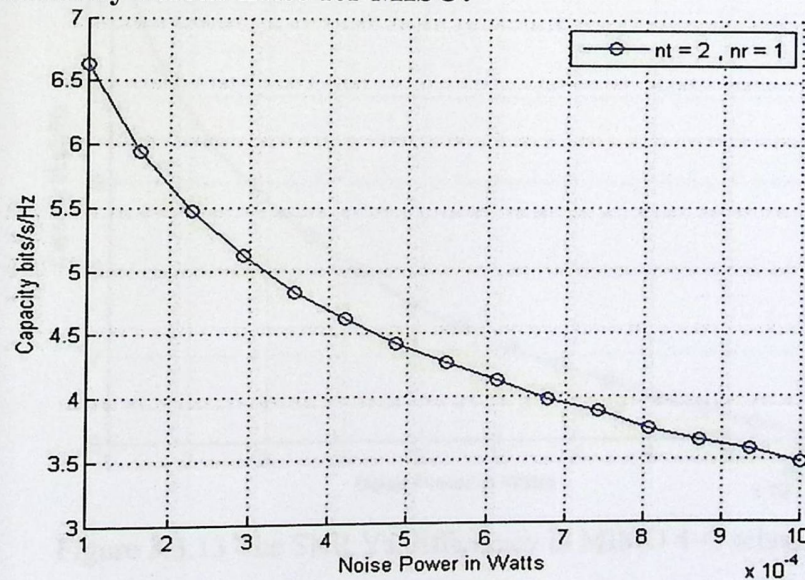


Figure 3.3.11 The SNR Vs. Efficiency in MISO 2 $\times$ 1 scheme.

The above figure shows the effect of the noise on the efficiency of the MISO 2×1 system, and as we see the efficiency of the system decreased from 6.6 bits/s/Hz at a noise level of 0.1 mW to 4.4 bits/s/Hz for noise level of 0.5 mW, and to just 3.5 bits/s/Hz for high noise level of 1 mW, just as the SIMO 1×2 scheme.

4. Efficiency versus noise for MIMO:

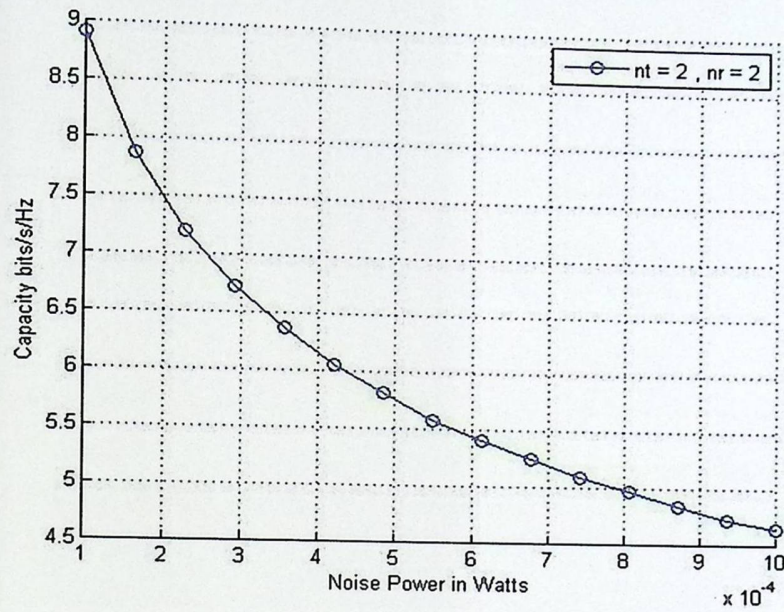


Figure 3.3.12 The SNR Vs. Efficiency in MIMO 2×2 scheme

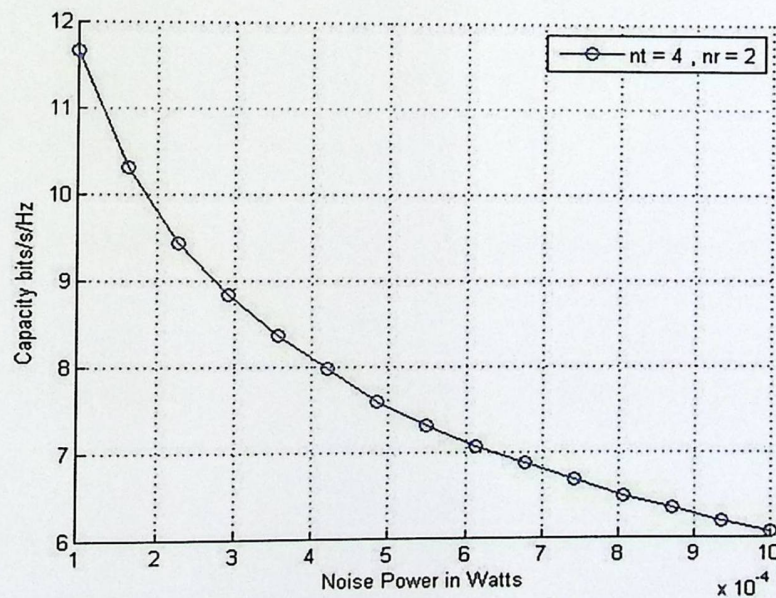


Figure 3.3.13 The SNR Vs. Efficiency in MIMO 4×2 scheme.

The above two figures show the effect of the noise on the efficiency of the MIMO 2×2 and 4×2 systems, and as we see the efficiency of the 2×2 system decreased from 8.9 bits/s/Hz at a noise level of 0.1 mW to 5.75 bits/s/Hz for noise level of 0.5 mW, and to just 4.6 bits/s/Hz for high noise level of 1 mW, now for the 4×2 system the efficiency decreased from 11.8 bits/s/Hz to 7.6 bits/s/Hz to just 6 bits/s/Hz, for the same noise levels as in the first system.

3.4 Summary:

Table 3.1 Summary of the results for the capacity versus the signal to noise ratio:

Case	Conclusion
SISO	Capacity increases as SNR increases, maximum capacity at 20dB is nearly 7 bits/s/Hz.
1 X 2 SIMO	More capacity is achieved than SISO case, at 20dB $\approx$ 8.2 bits/s/Hz.
2 X 1 MISO	It nearly offers the same capacity as the 1 X 2 SIMO.
3 X 1 MISO	More capacity than the previous SIMO case at 20dB $\approx$ 9 bits/s/Hz.
4 X 1 MISO	By using more antenna at the transmitter we can achieve more better capacity.
2 X 2 MIMO	As expected MIMO is the best in providing higher capacities.
3 X 2 MIMO	More capacity than the 2 X 2 scheme because of more transmitter usage.
4 X 2 MIMO	Best than the previous cases we can achieve up to 15bits/s/Hz.

Table 3.2 Summary of the simulation of the efficiency versus noise:

Case	Conclusion
SISO	The efficiency of the SISO decreases as the noise increases we achieve about 2.4 bits/s/Hz for a noise level of 1 mW.
1 X 2 SIMO	The capacity also decreases but at the same noise level 1 X 2 SIMO provides better capacity than the SISO.
2 X 1 MISO	2 X 1 MISO provide the same performance of the 1 X 2 SIMO.
2 X 2 MIMO	2 X 2 MIMO efficiency is better than both SIMO and MISO.
4 X 2 MIMO	By using more transmitting antennas more capacity obtained for the same noise level.

In the following sections (3.5, 3.6, 3.7 and 3.8) we will show the second semester's work which deals with the effect of spatial fading correlation on the ergodic capacity of the MIMO system in which we will show figures illustrates the relation between the capacity and the SNR, and other figures shows the relations between the fading correlation factor and the SNR.

Also the effect of the line of sight component (LOS) on the MIMO's capacity was studied, the results were shown as figures shows the relation between the capacity and the SNR, another figures shows the relation between the K-factor and the SNR.

Another case which is the degeneracy was studied in which we will show the degradation in the capacity when the keyhole phenomena applied, the capacity in such case is compared with that offered in MISO case.

The last one is the XPD which is a mechanism used to enhance the offered capacity, we showed the maximum and minimum enhancement we can obtain by the use of the XPD.

The study on the four cases were shown for many antennas configurations to examine the effect of the number of antennas on the offered ergodic capacity.

3.5 Effect of spatial fading correlation on MIMO efficiency:

3.5.1 Relation between the ergodic capacity and fading correlation factor at SNR=20 dB

Here we will show the results for examining the effect of the spatial fading correlation on the ergodic capacity for different antenna configuration, we will show figures illustrating the relation between the ergodic capacity and the SNR, on the other hand we will show figures that illustrate the relation between the ergodic capacity and the fading correlation coefficient:

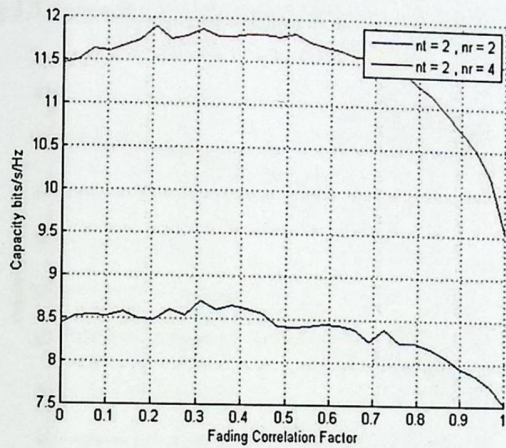


Fig 3.5.1: capacity Vs. correlation factor for 2x2 and 2x4

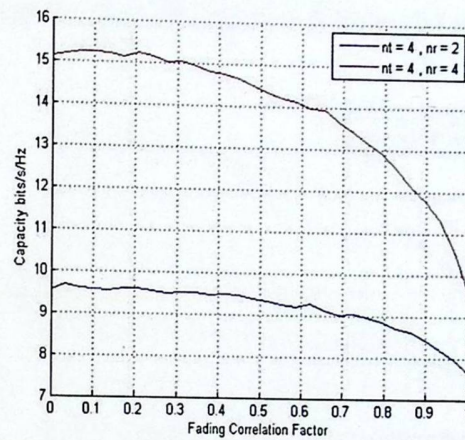


Fig 3.5.2: capacity Vs. correlation factor for 4x2 and 4x4.

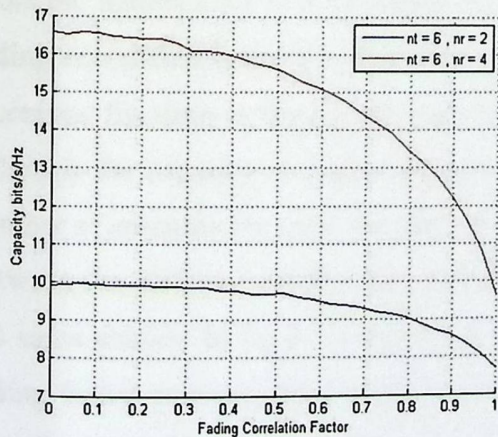


Fig 3.5.3: capacity Vs. correlation factor for 6x2 and 6x4

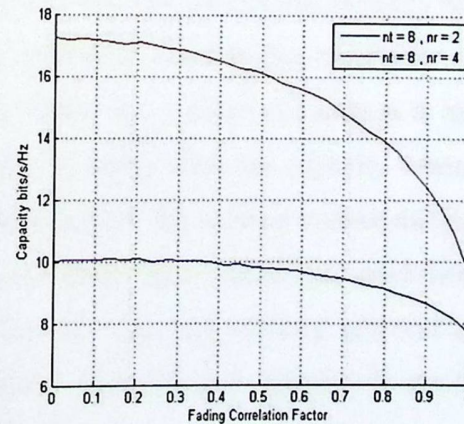


Fig 3.5.4: capacity Vs. correlation factor for 8x2 and 8x4

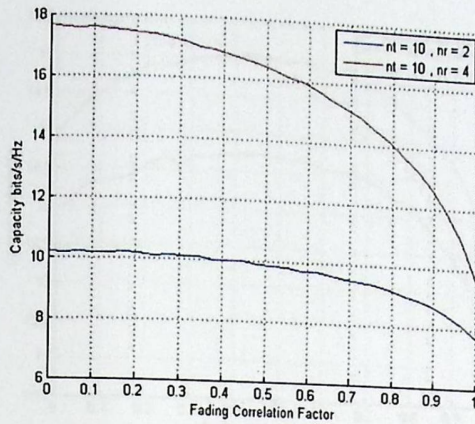


Fig 3.5.5: capacity Vs. correlation factor for 10x2 and 10x4

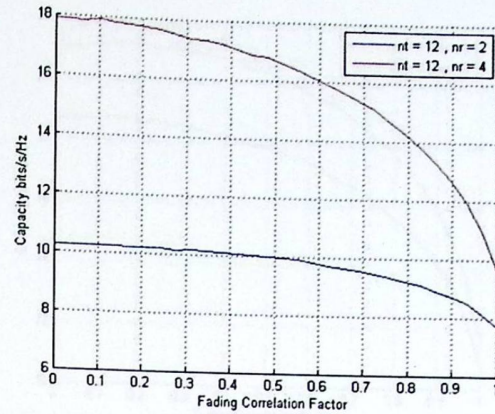


Fig 3.5.6: capacity Vs. correlation factor for 12x2 and 12x4

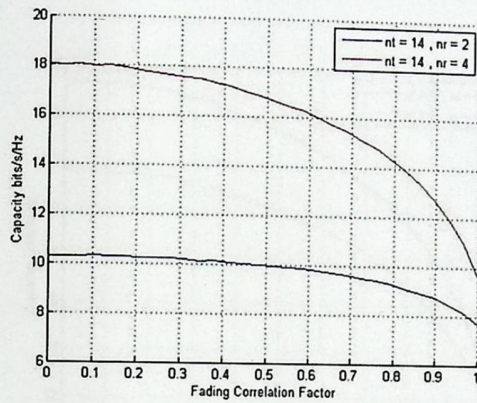


Fig 3.5.7: capacity Vs. correlation factor for 14x2 and 14x4.

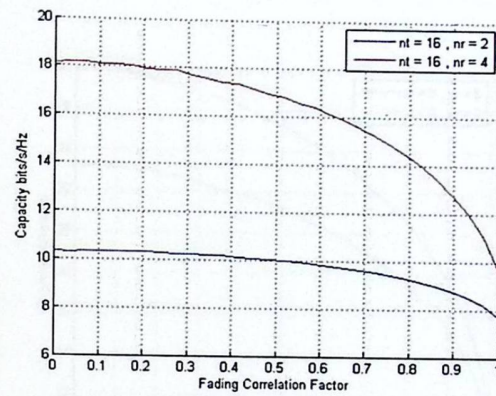


Fig 3.5.8: capacity Vs. correlation factor for 16x2 and 16x4.

From the figures 3.5.1 to 3.5.8 which shows the relation between the ergodic capacity and the fading correlation factor it's clear that the capacity will drop as the fading correlation factor increases, the drop in the ergodic capacity is higher when the number of antennas is higher, although the capacity at higher number of antennas is better than the capacity when less number of antennas are used, the fading effect is high because the receiver cannot distinguish between the different parallel data sub stream because their signals which are modulated on the same carrier. In fig 3.5.1 the result may be non true since the capacity increase as the fading factor increase, this occurs because the number of transmitter antennas is small and there is no enough information to get exact value of capacity.

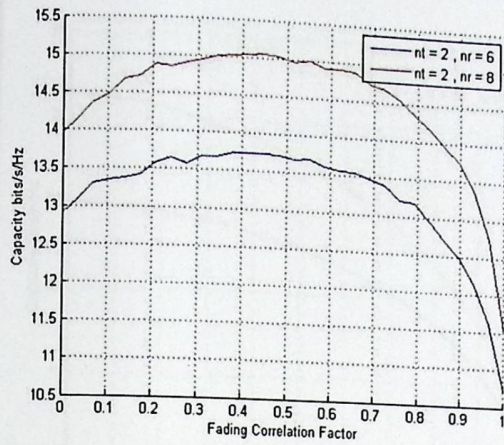


Fig 3.5.9: capacity Vs. correlation factor for 2x6 and 2x8.

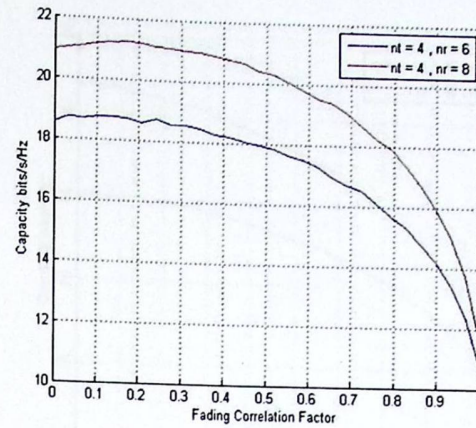


Fig 3.5.10: capacity Vs. correlation factor for 4x6 and 4x8.

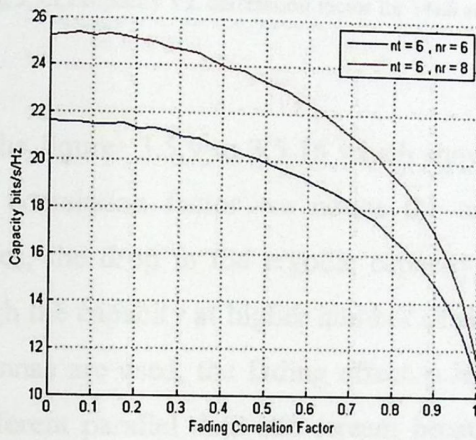


Fig 3.5.11: capacity Vs. correlation factor for 6x6 and 6x8.

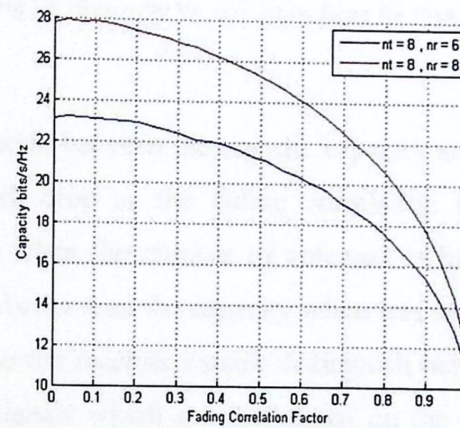


Fig 3.5.12: capacity Vs. correlation factor for 8x6 and 8x8.

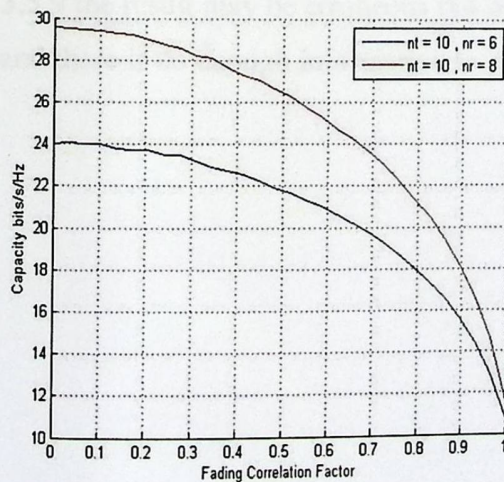


Fig 3.5.13: capacity Vs. correlation factor for 10x6 and 10x8.

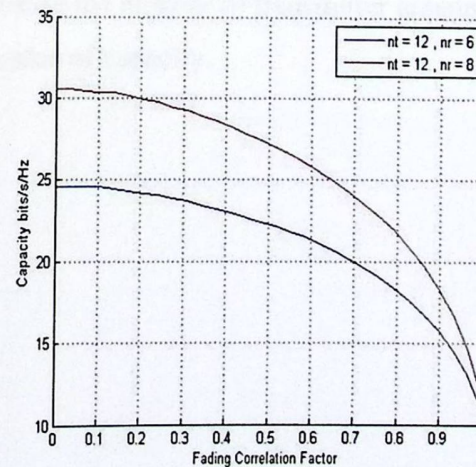
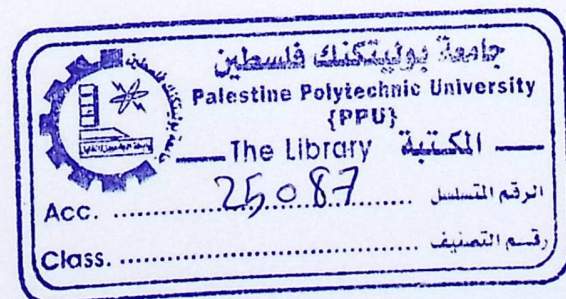


Fig 3.5.14: capacity Vs. correlation factor for 12x6 and 12x8.



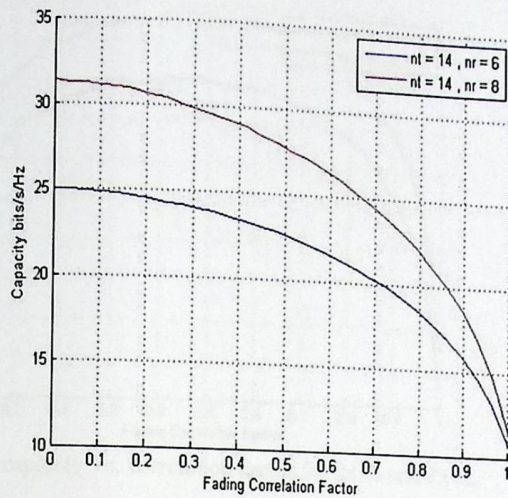


Fig 3.5.15: capacity Vs. correlation factor for 14x6 and 14x8.

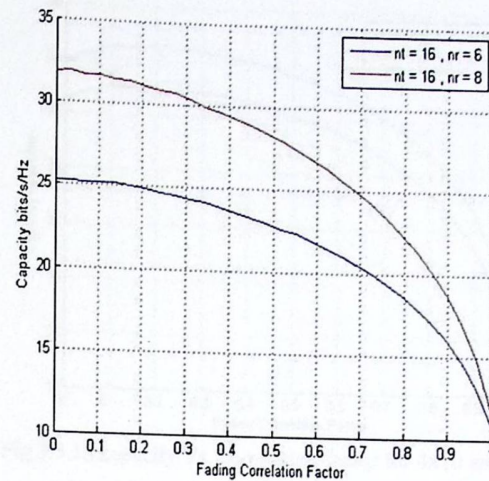


Fig 3.5.16: capacity Vs. correlation factor for 16x6 and 16x8.

From the figures 3.5.9 to 3.5.16 which shows the relation between the ergodic capacity and the fading correlation factor we notice the capacity will drop as the fading correlation factor increases, the drop in the ergodic capacity is higher when the number of antennas is higher, although the capacity at higher number of antennas is better than the capacity when less number of antennas are used, the fading effect is high because the receiver cannot distinguish between the different parallel data sub stream because their signals which are modulated on the same carrier.

In fig 3.5.9 the result may be erroneous this occurs because the number of transmitter antennas is small and there is no enough information to get exact value of capacity.

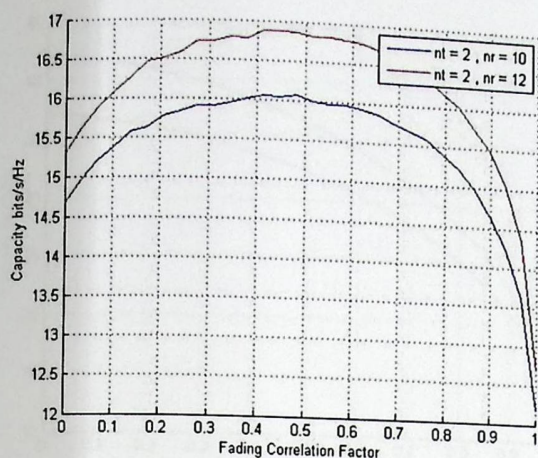


Fig 3.5.17:capacity Vs. correlation factor for 2x10 and 2x12.

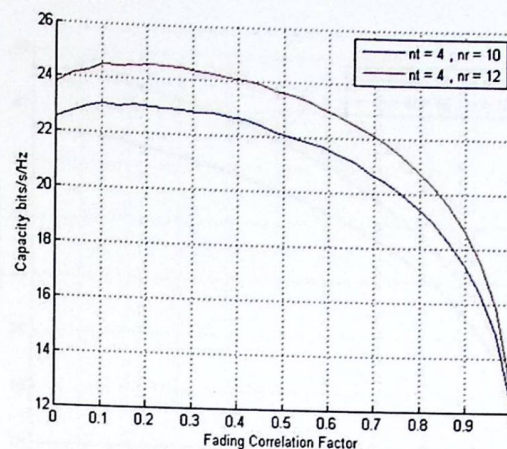


Fig 3.5.18:capacity Vs. correlation factor for 4x10 and 4x12.

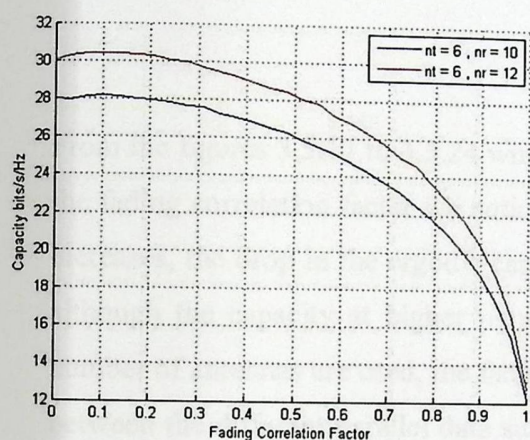


Fig 3.5.19:capacity Vs. correlation factor for 6x10 and 6x12.

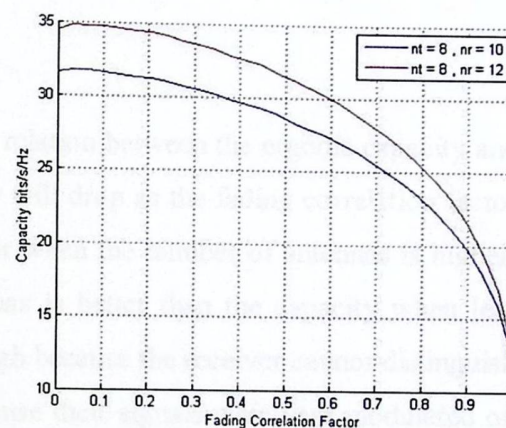


Fig 3.5.20:capacity Vs. correlation factor for 8x10 and 8x12.

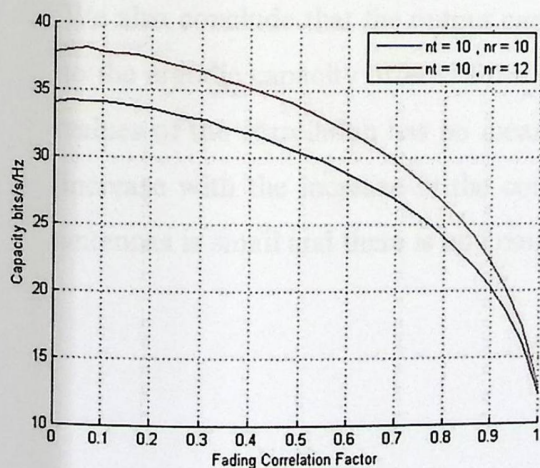


Fig 3.5.21:capacity Vs. correlation factor for 10x10 and 10x12.

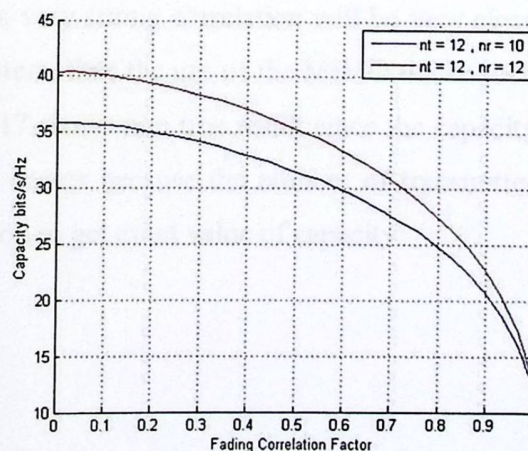


Fig 3.5.22:capacity Vs. correlation factor for 12x10 and 12x12.

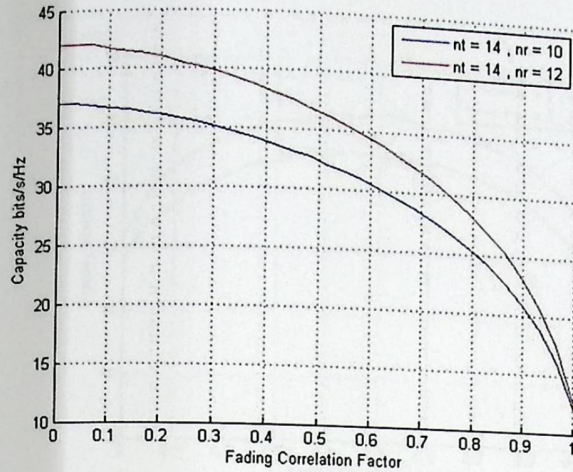


Fig 3.5.23: capacity Vs. correlation factor for 14x10 and 14x12.

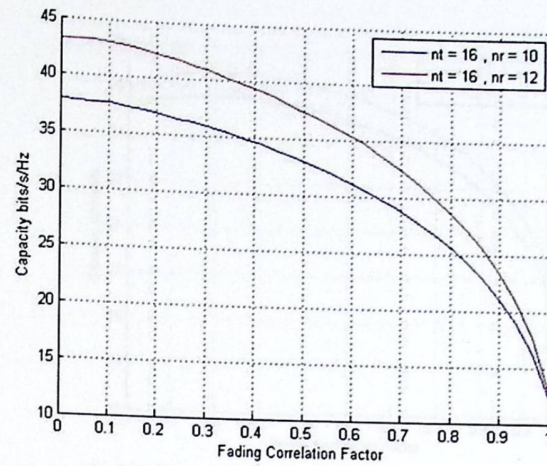


Fig 3.5.24: capacity Vs. correlation factor for 16x10 and 16x12.

From the figures 3.5.17 to 3.5.24 which shows the relation between the ergodic capacity and the fading correlation factor we notice the capacity will drop as the fading correlation factor increases, the drop in the ergodic capacity is higher when the number of antennas is higher, although the capacity at higher number of antennas is better than the capacity when less number of antennas are used, the fading effect is high because the receiver cannot distinguish between the different parallel data sub stream because their signals which are modulated on the same carrier.

We also conclude that the output capacity under a very strong correlation will be very close to the ergodic capacity offered from the SISO system, thus the use of the MIMO under such values of the correlation has no meaning, fig 3.5.17 shows non true result since the capacity increase with the increase in the correlation this occurs because the number of transmitter antennas is small and there is no enough information to get exact value of capacity.

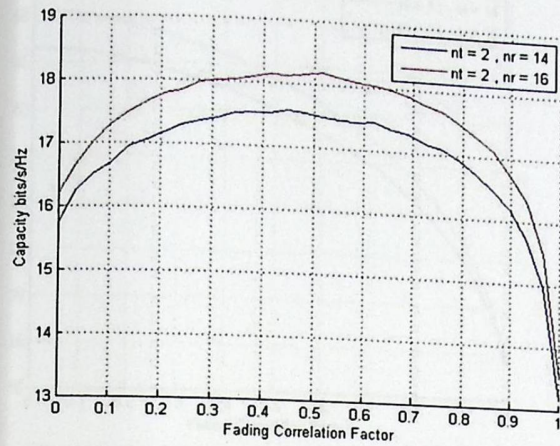


Fig 3.5.25: capacity Vs. correlation factor for 2x14 and 2x16.

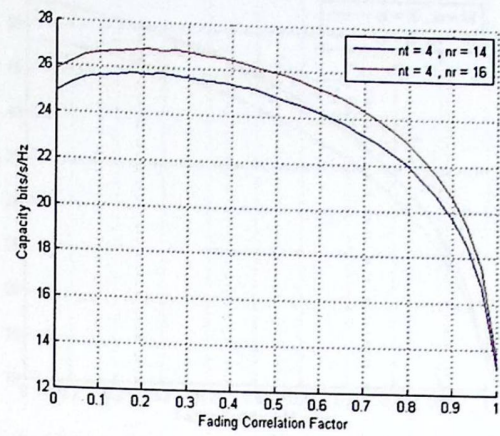


Fig 3.5.26: capacity Vs. correlation factor for 4x14 and 4x16.

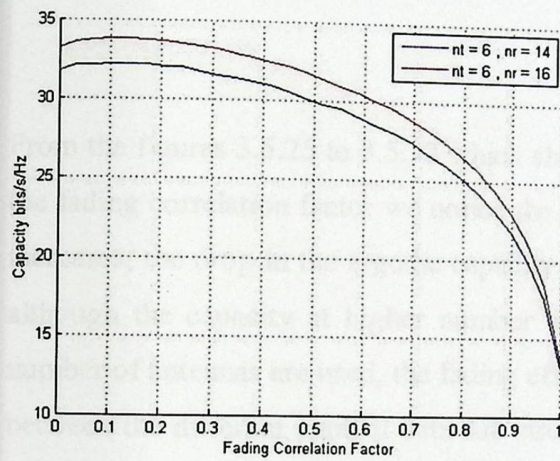


Fig 3.5.27: capacity Vs. correlation factor for 6x14 and 6x16.

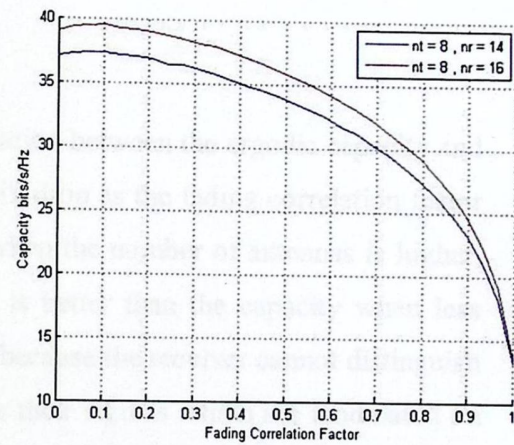


Fig 3.5.28: capacity Vs. correlation factor for 8x14 and 8x16.

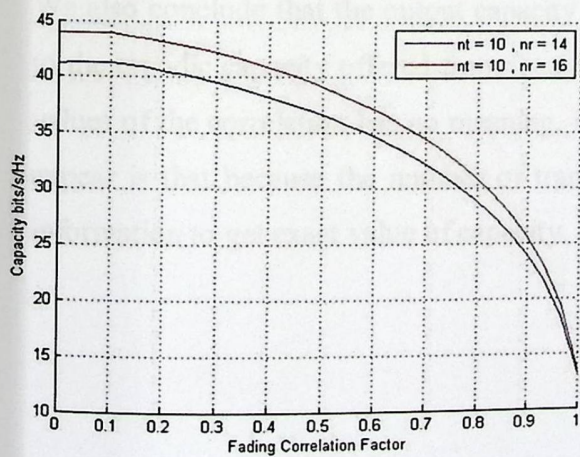


Fig 3.5.29: capacity Vs. correlation factor for 10x14 and 10x16.

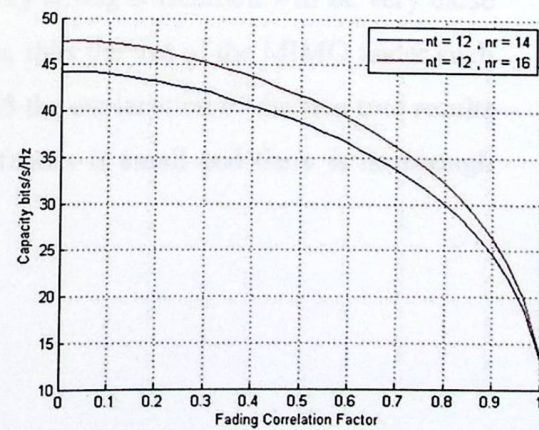


Fig 3.5.30: capacity Vs. correlation factor for 12x14 and 12x16.

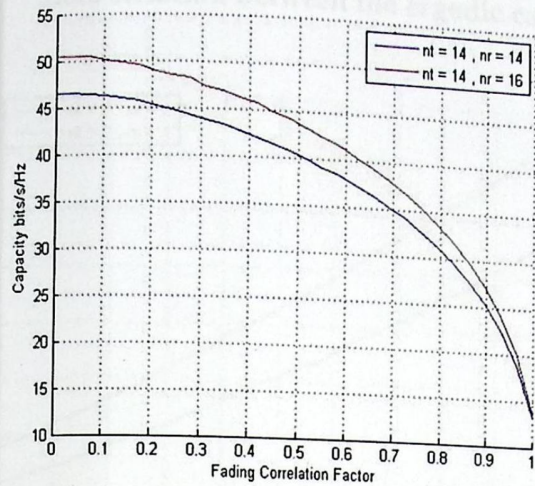


Fig 3.5.31: capacity Vs. correlation factor for 14x14 and 14x16

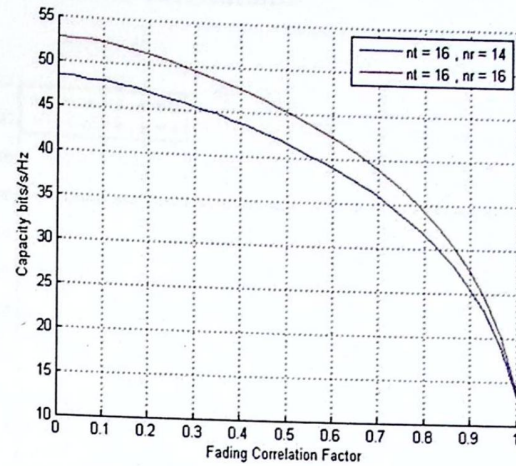


Fig 3.5.32: capacity Vs. correlation factor for 16x14 and 16x16

From the figures 3.5.25 to 3.5.32 which shows the relation between the ergodic capacity and the fading correlation factor we notice the capacity will drop as the fading correlation factor increases, the drop in the ergodic capacity is higher when the number of antennas is higher, although the capacity at higher number of antennas is better than the capacity when less number of antennas are used, the fading effect is high because the receiver cannot distinguish between the different parallel data sub stream because their signals which are modulated on the same carrier.

We also conclude that the output capacity under a very strong correlation will be very close to the ergodic capacity offered from the SISO system, thus the use of the MIMO under such values of the correlation has no meaning, in fig 3.5.25 the explanation of the non true results appear is that because the number of transmitter antennas is small and there is no enough information to get exact value of capacity.

3.5.2 Relation between the ergodic capacity and SNR for no correlation:

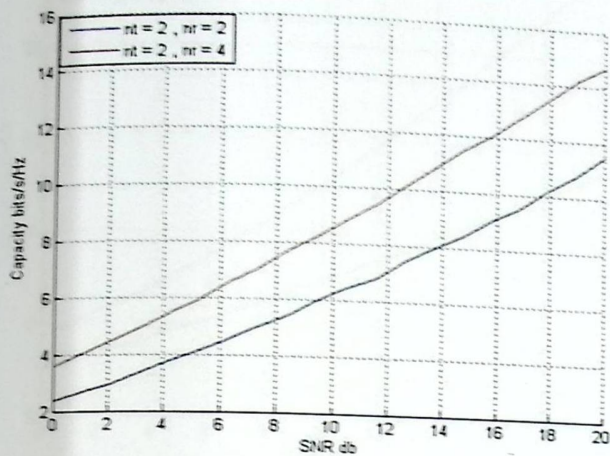


Fig3.5.33:capacity Vs. SNR for 2x2 and 2x4.

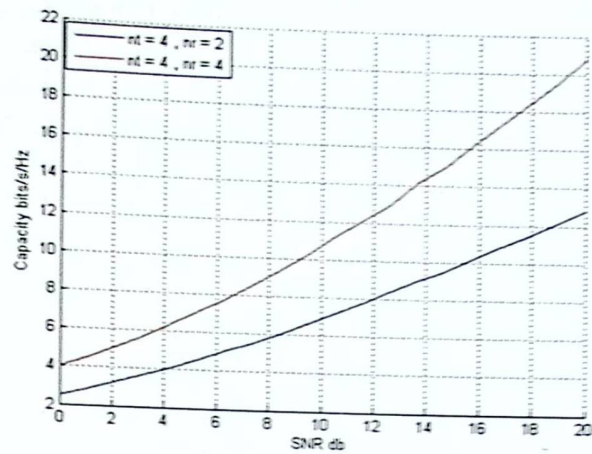


Fig 3.5.34:capacity Vs. SNR for 4x2 and 4x4.

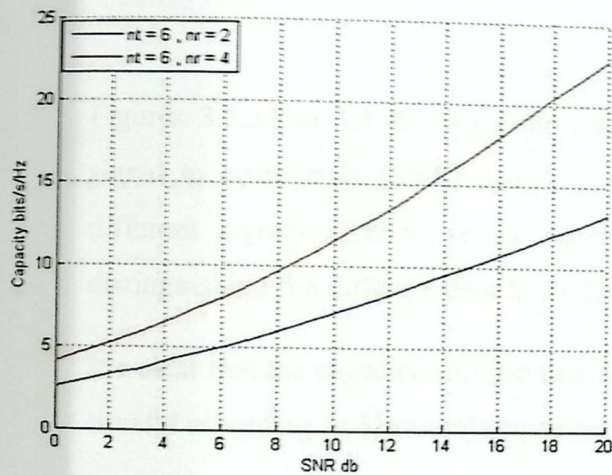


Fig 3.5.35:capacity Vs. SNR for 6x2 and 6x4.

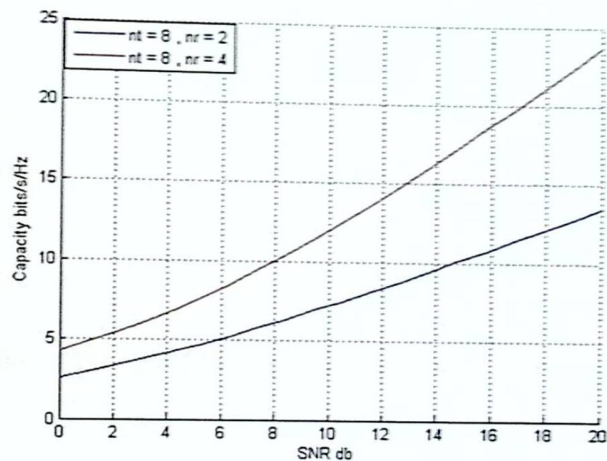


Fig3.5.36:capacity Vs. SNR for 8x2 and 8x4.

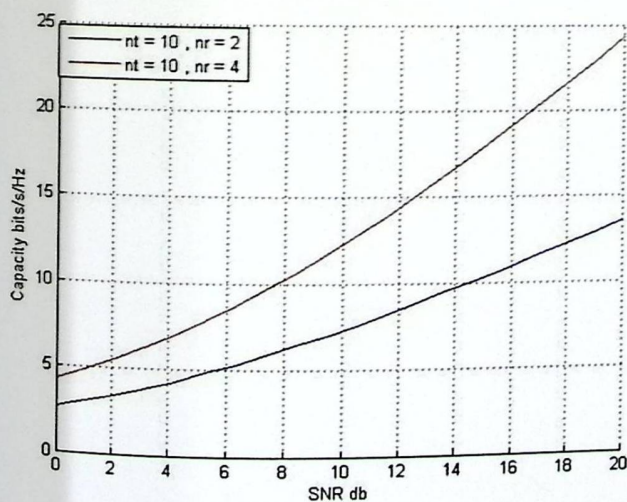


Fig3.5.37:capacity Vs. SNR for 10x2 and 10x4.

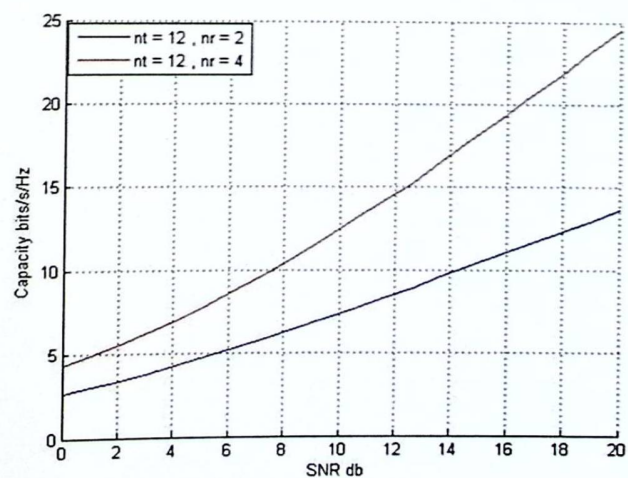


Fig3.5.38:capacity Vs. SNR for 12x2 and 12x4.

3.5.2 Relation between the ergodic capacity and SNR for no correlation:

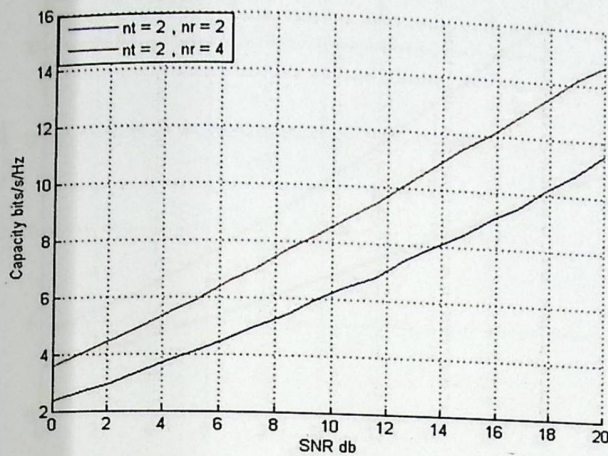


Fig3.5.33:capacity Vs. SNR for 2x2 and 2x4.

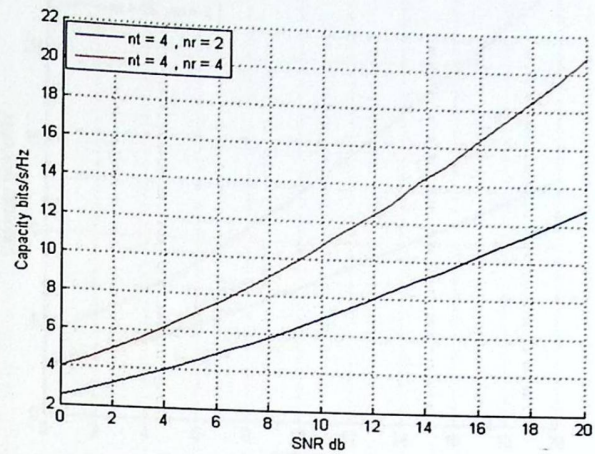


Fig 3.5.34:capacity Vs. SNR for 4x2 and 4x4.

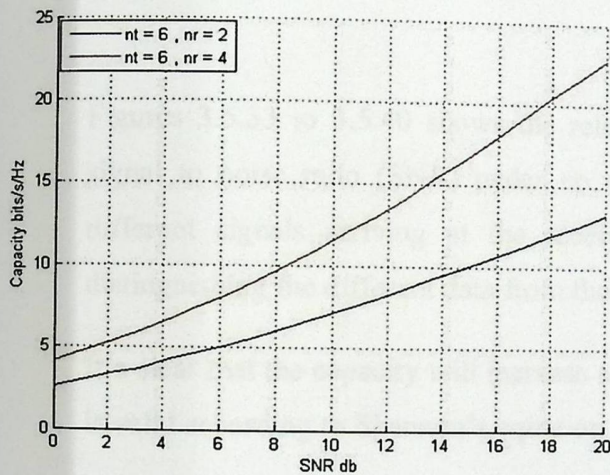


Fig 3.5.35:capacity Vs. SNR for 6x2 and 6x4.

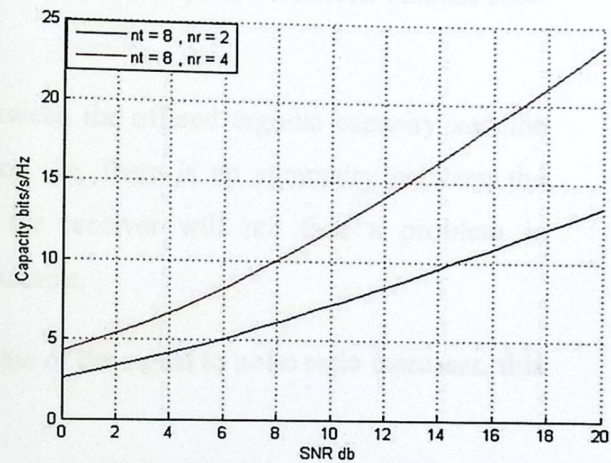


Fig3.5.36:capacity Vs. SNR for 8x2 and 8x4.

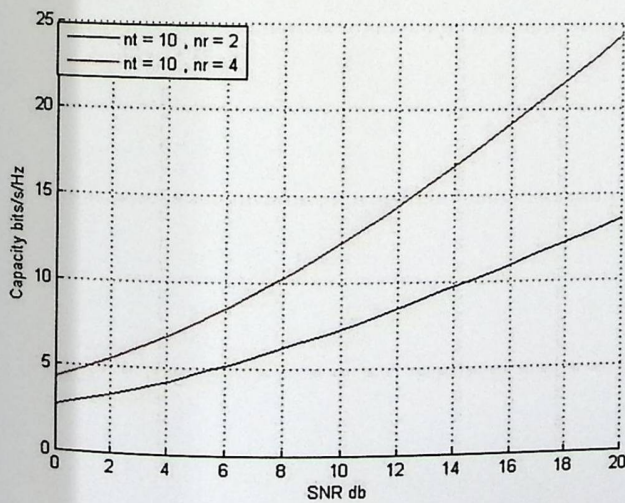


Fig3.5.37:capacity Vs. SNR for 10x2 and 10x4.

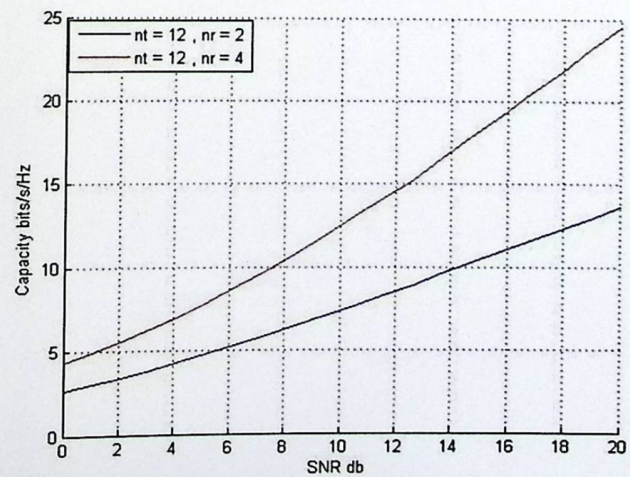


Fig3.5.38:capacity Vs. SNR for 12x2 and 12x4.

3.5.2 Relation between the ergodic capacity and SNR for no correlation:

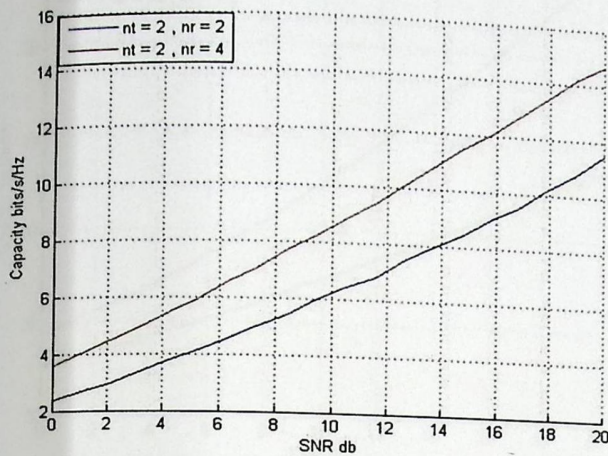


Fig3.5.33:capacity Vs. SNR for 2x2 and 2x4.

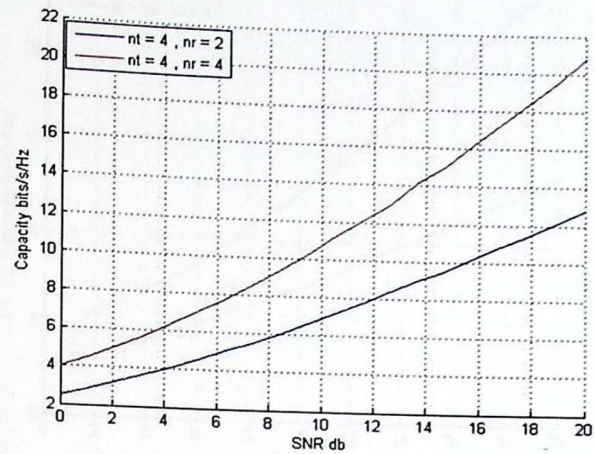


Fig 3.5.34:capacity Vs. SNR for 4x2 and 4x4.

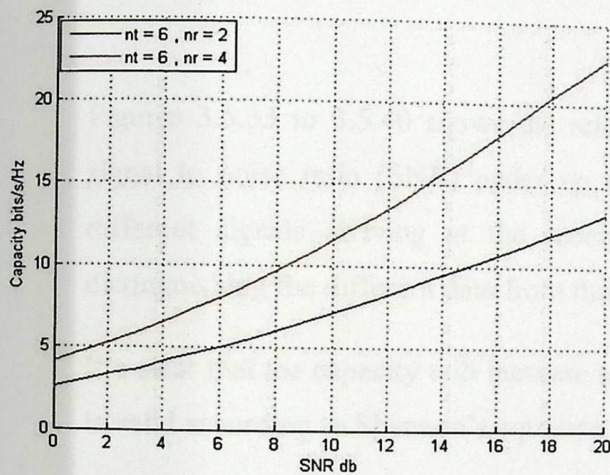


Fig 3.5.35:capacity Vs. SNR for 6x2 and 6x4.

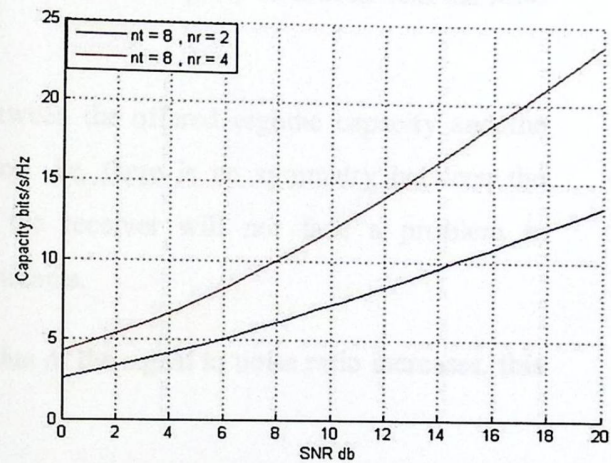


Fig3.5.36:capacity Vs. SNR for 8x2 and 8x4.

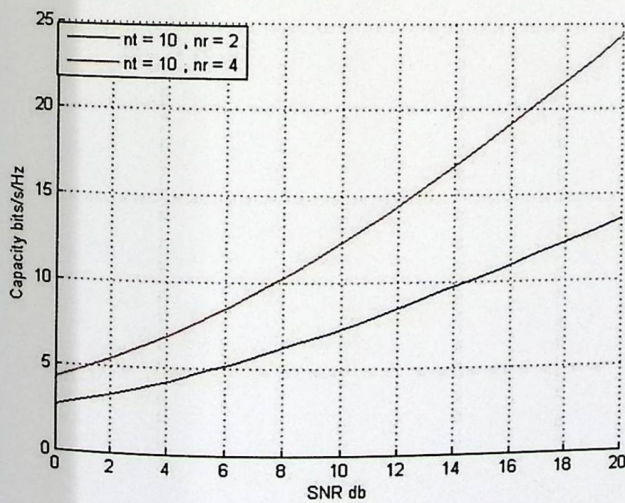


Fig3.5.37:capacity Vs. SNR for 10x2 and 10x4.

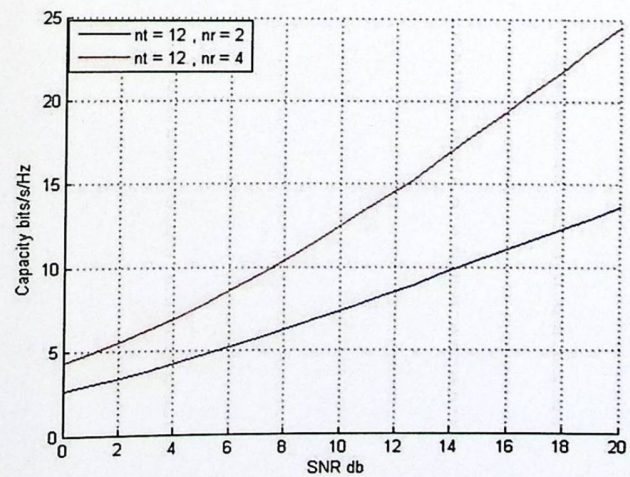


Fig3.5.38:capacity Vs. SNR for 12x2 and 12x4.

3.5.2 Relation between the ergodic capacity and SNR for no correlation:

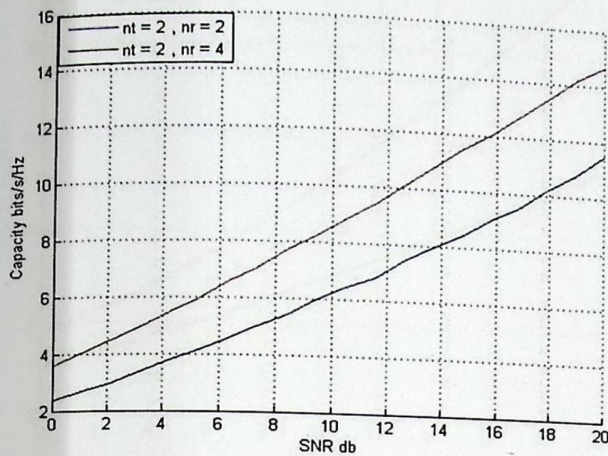


Fig3.5.33:capacity Vs. SNR for 2x2 and 2x4.

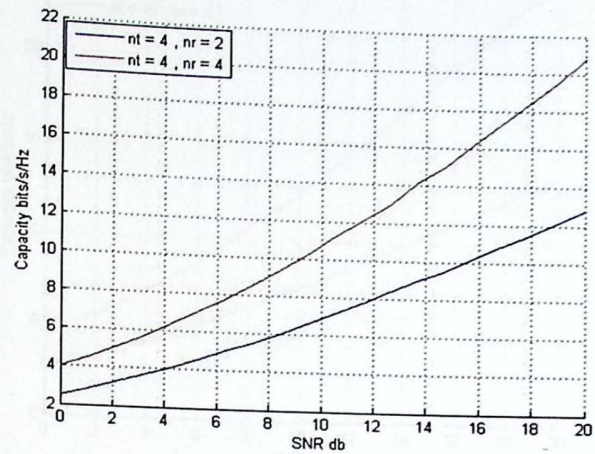


Fig 3.5.34:capacity Vs. SNR for 4x2 and 4x4.

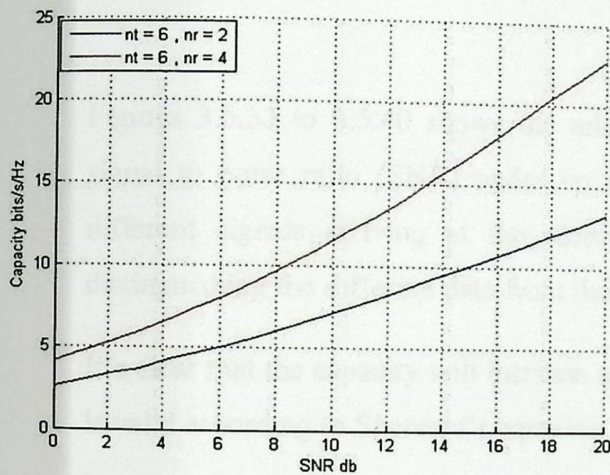


Fig 3.5.35:capacity Vs. SNR for 6x2 and 6x4.

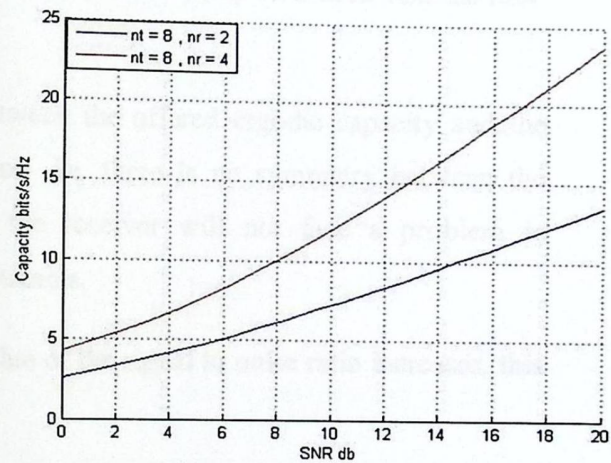


Fig3.5.36:capacity Vs. SNR for 8x2 and 8x4.

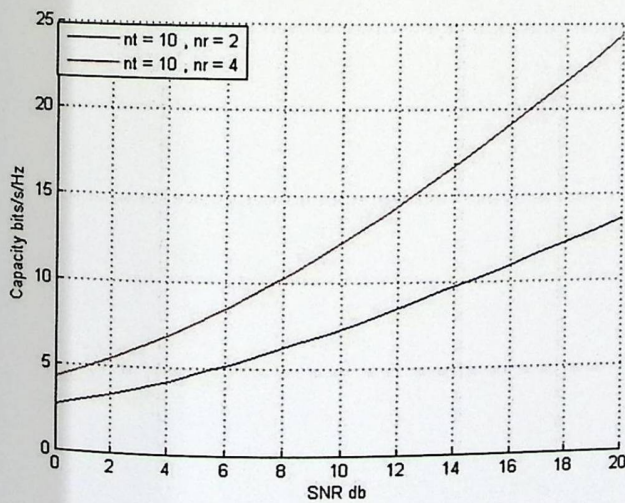


Fig3.5.37:capacity Vs. SNR for 10x2 and 10x4.

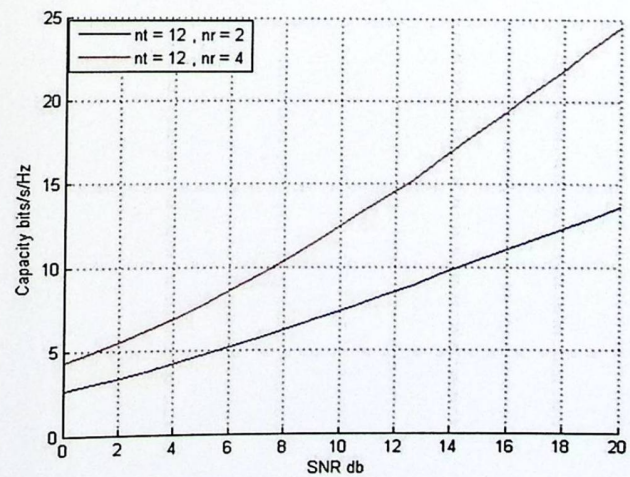


Fig3.5.38:capacity Vs. SNR for 12x2 and 12x4.

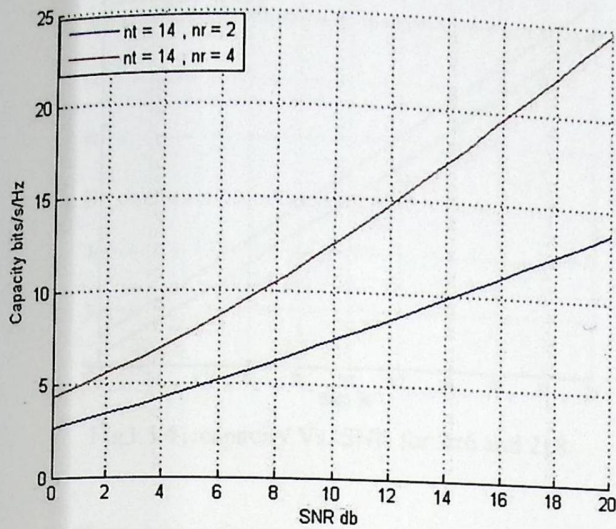


Fig3.5.39:capacity Vs. SNR for 14x2 and 14x4.

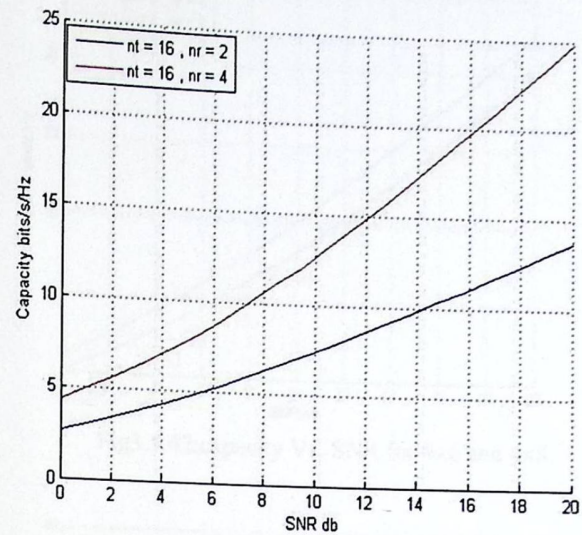


Fig3.5.40:capacity Vs. SNR for 16x2 and 16x4.

Figures 3.5.33 to 3.5.40 shows the relation between the offered ergodic capacity and the signal to noise ratio (SNR) under no correlation .i.e. there is no symmetry between the different signals arriving at the receiver so, the receiver will not face a problem in distinguishing the different data from those sub streams.

It's clear that the capacity will increase as the value of the signal to noise ratio increases, this is valid according to Shannon's equation.

The ergodic capacity offered will be higher if we use more transmit and receive antennas.

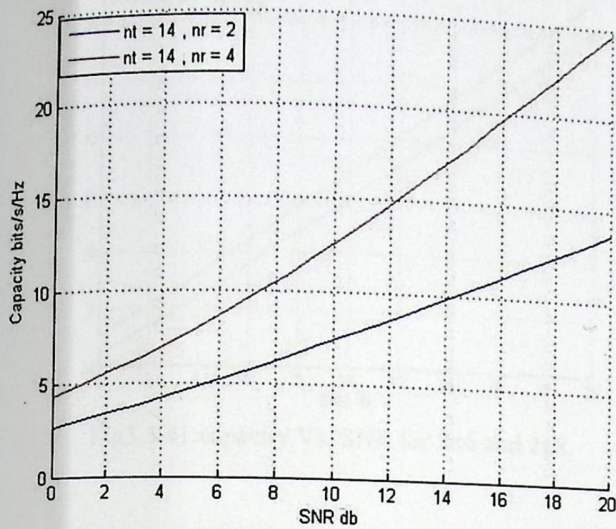


Fig3.5.39:capacity Vs. SNR for 14x2 and 14x4.

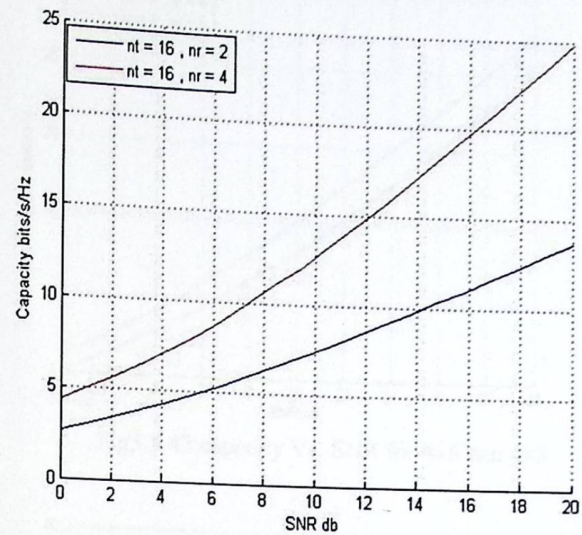


Fig3.5.40:capacity Vs. SNR for 16x2 and 16x4.

Figures 3.5.33 to 3.5.40 shows the relation between the offered ergodic capacity and the signal to noise ratio (SNR) under no correlation .i.e. there is no symmetry between the different signals arriving at the receiver so, the receiver will not face a problem in distinguishing the different data from those sub streams.

It's clear that the capacity will increase as the value of the signal to noise ratio increases, this is valid according to Shannon's equation.

The ergodic capacity offered will be higher if we use more transmit and receive antennas.

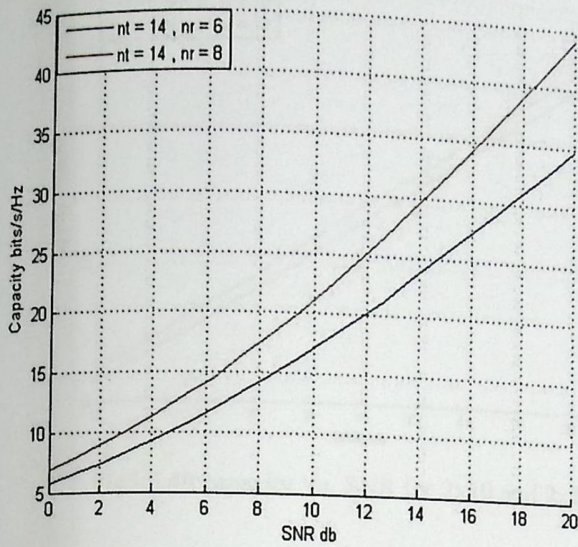


Fig3.5.47:capacity Vs. SNR for 14x6 and 14x8.

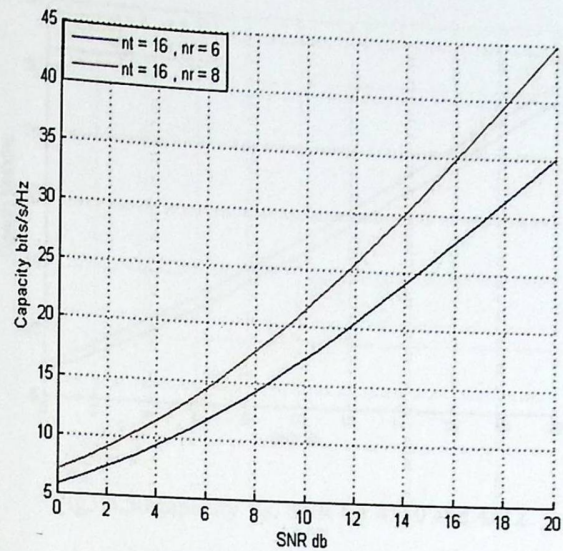


Fig3.5.48:capacity Vs. SNR for 16x6 and 16x8.

Figures 3.5.41 to 3.5.48 shows the relation between the offered ergodic capacity and the signal to noise ratio (SNR) under no correlation i.e. there is no symmetry between the different signals arriving at the receiver so, the receiver will not face a problem in distinguishing the different data from those sub streams.

It's clear that the capacity will increase as the value of the signal to noise ratio increases, this is valid according to Shannon's equation.

The ergodic capacity offered will be higher if we use more transmit and receive antennas. the increase in the capacity will not be high if the number of receiving antenna is increasing for two antennas for the same number of transmitting antennas.

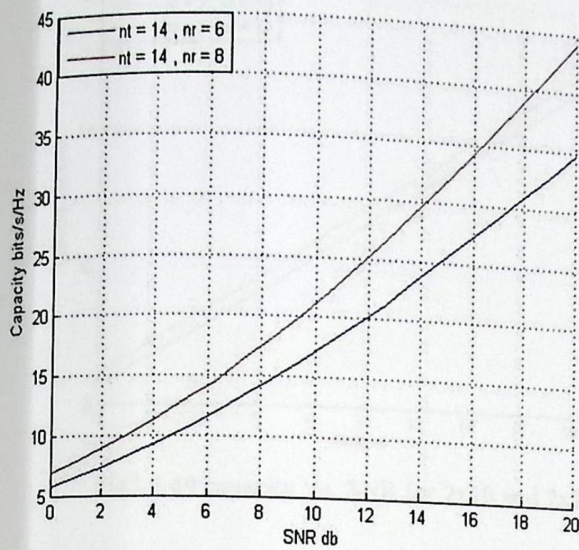


Fig3.5.47:capacity Vs. SNR for 14x6 and 14x8.

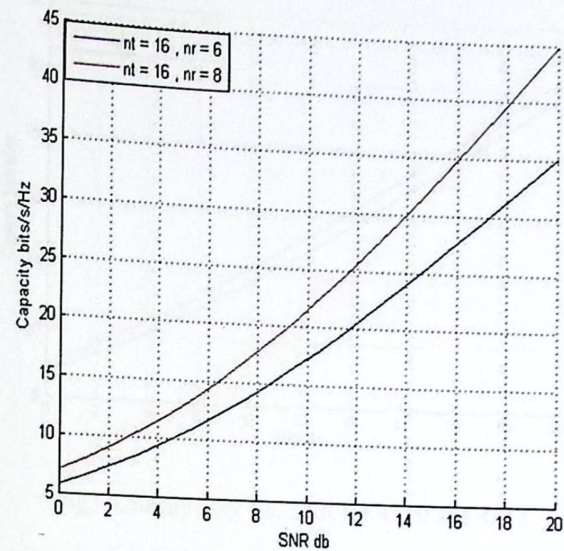


Fig3.5.48:capacity Vs. SNR for 16x6 and 16x8.

Figures 3.5.41 to 3.5.48 shows the relation between the offered ergodic capacity and the signal to noise ratio (SNR) under no correlation .i.e. there is no symmetry between the different signals arriving at the receiver so, the receiver will not face a problem in distinguishing the different data from those sub streams.

It's clear that the capacity will increase as the value of the signal to noise ratio increases, this is valid according to Shannon's equation.

The ergodic capacity offered will be higher if we use more transmit and receive antennas. the increase in the capacity will not be high if the number of receiving antenna is increasing for two antennas for the same number of transmitting antennas.

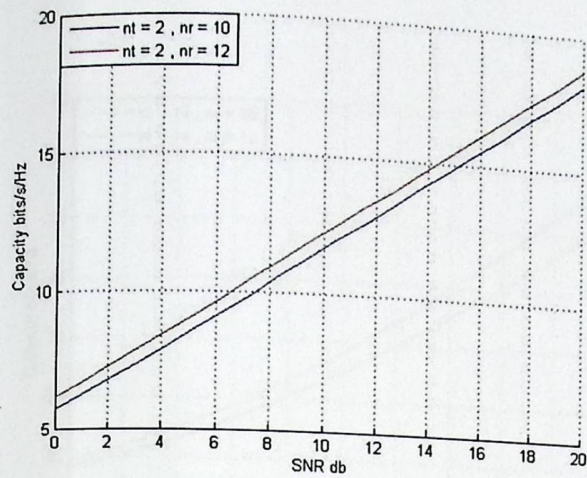


Fig3.5.49:capacity Vs. SNR for 2x10 and 2x12.

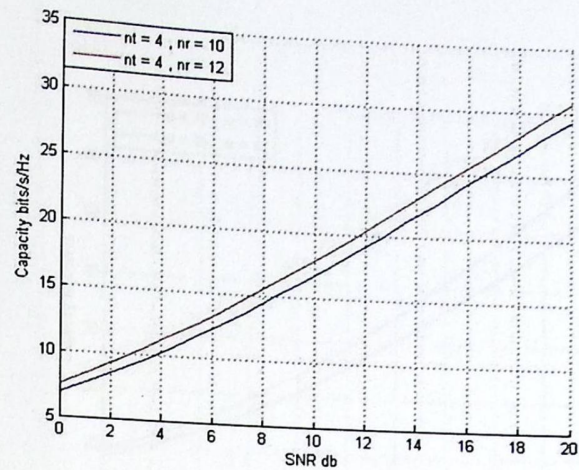


Fig3.5.50:capacity Vs. SNR for 4x10 and 4x12.

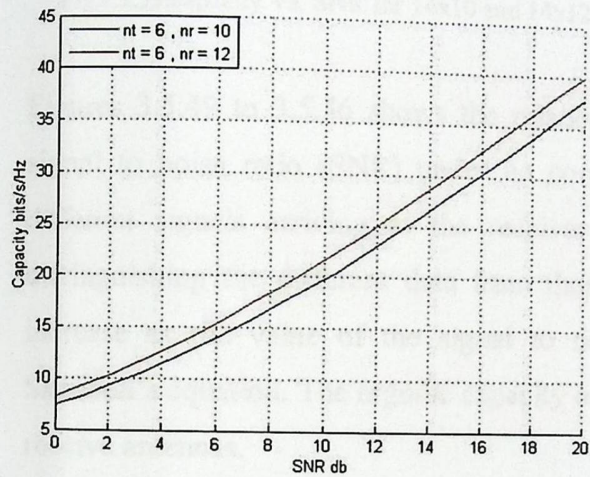


Fig3.5.51:capacity Vs. SNR for 6x10 and 6x12.

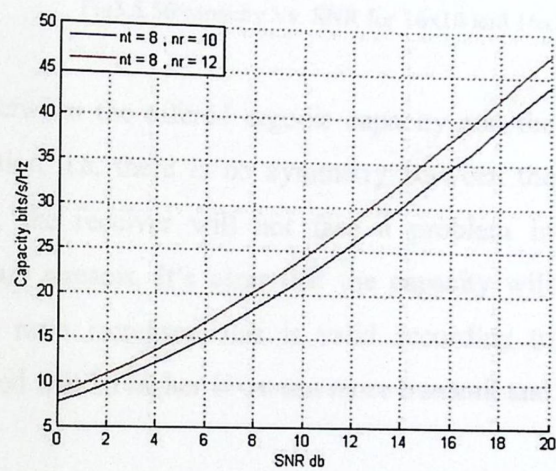


Fig3.5.52:capacity Vs. SNR for 8x10 and 8x12.

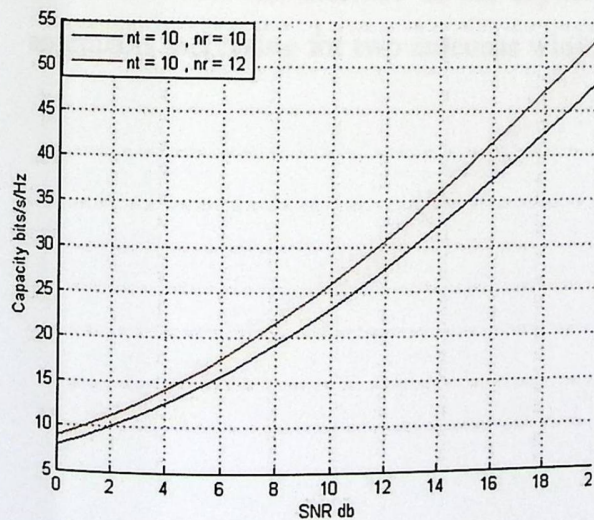


Fig3.5.53:capacity Vs. SNR for 10x10 and 10x12.

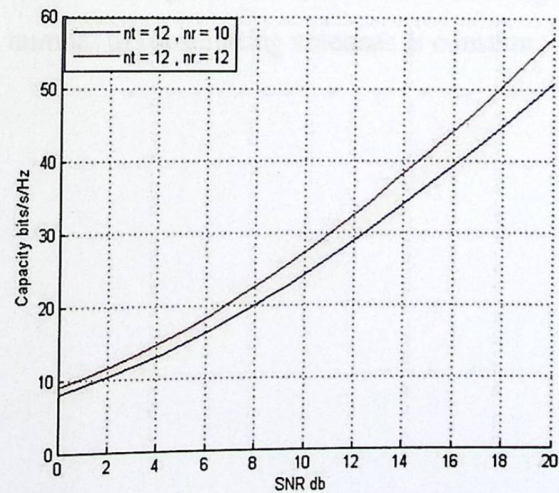


Fig3.5.54:capacity Vs. SNR for 12x10 and 12x12.

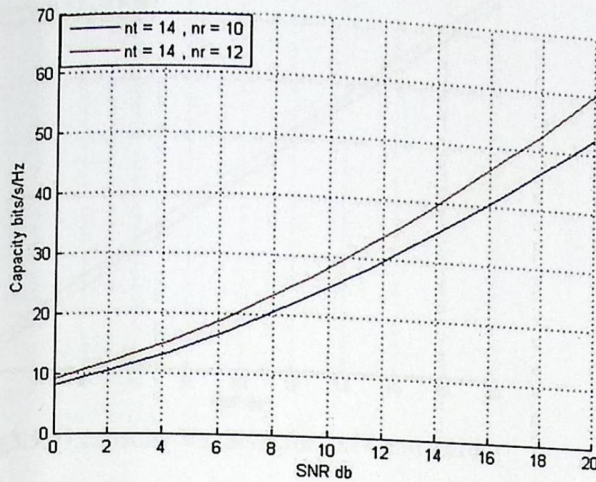


Fig3.5.55:capacity Vs. SNR for 14x10 and 14x12.

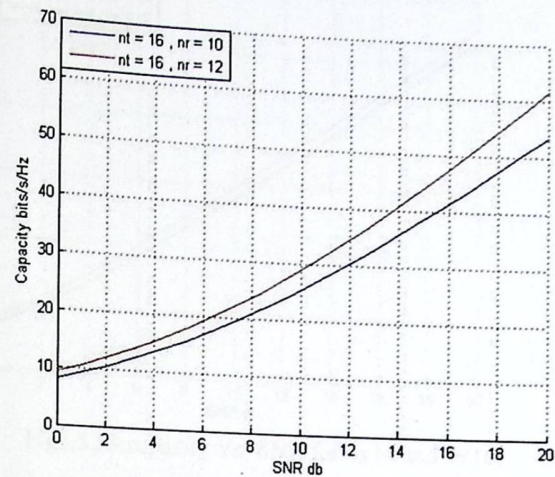


Fig3.5.56:capacity Vs. SNR for 16x10 and 16x12.

Figures 3.5.49 to 3.5.56 shows the relation between the offered ergodic capacity and the signal to noise ratio (SNR) under no correlation .i.e. there is no symmetry between the different signals arriving at the receiver so, the receiver will not face a problem in distinguishing the different data from those sub streams. It's clear that the capacity will increase as the value of the signal to noise ratio increases, this is valid according to Shannon's equation. The ergodic capacity offered will be higher if we use more transmit and receive antennas.

We notice that the increase in the capacity will not be high if the number of receiving antenna is increasing for two antennas while the number of transmitting antennas is constant.

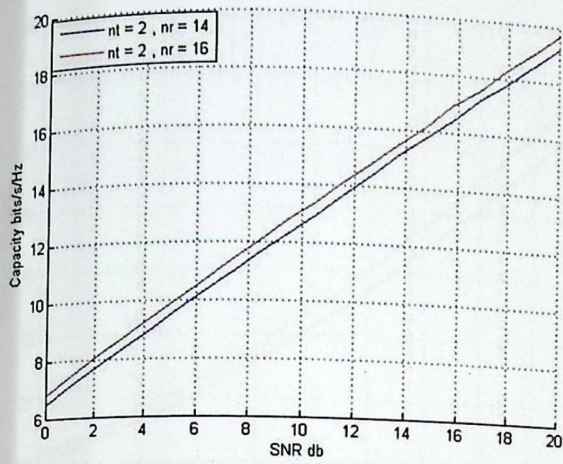


Fig3.5.57:capacity Vs. SNR for 2x14 and 2x16.

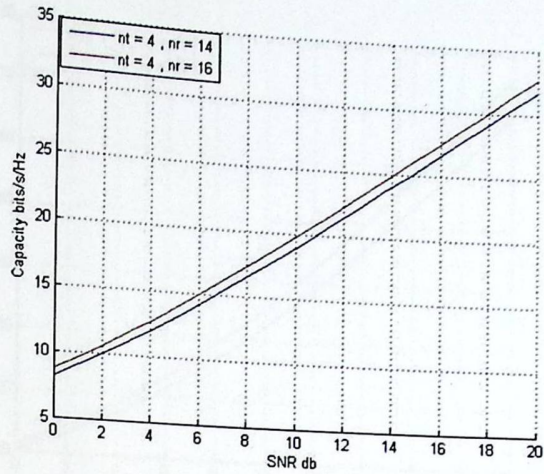


Fig3.5.58:capacity Vs. SNR for 4x14 and 4x16.

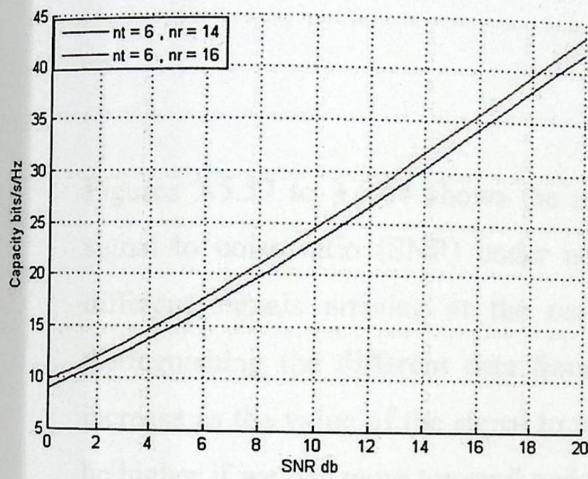


Fig3.5.59:capacity Vs. SNR for 6x14 and 6x16.

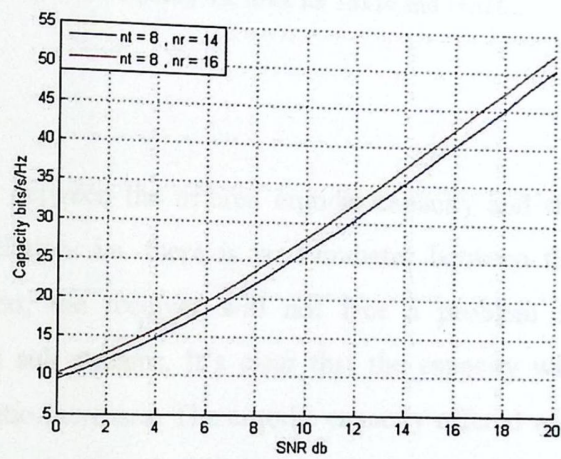


Fig3.5.60:capacity Vs. SNR for 8x14 and 8x16.

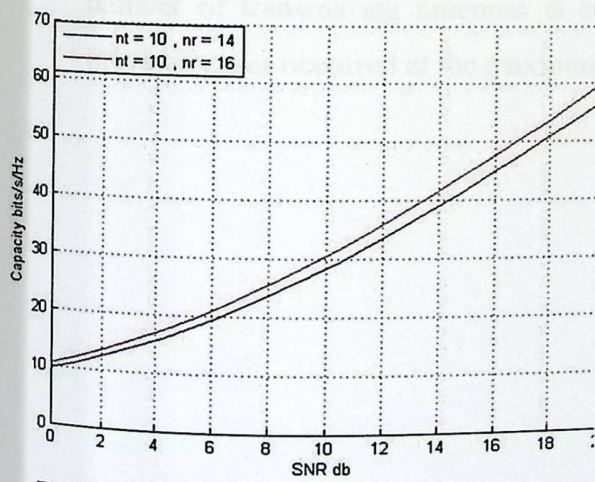


Fig3.5.61:capacity Vs. SNR for 10x14 and 10x16.

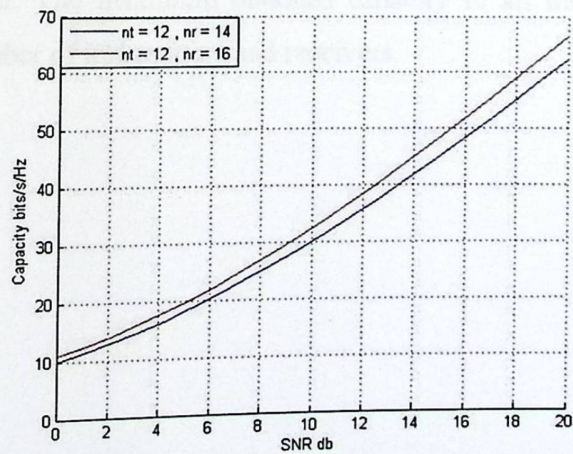


Fig3.5.62:capacity Vs. SNR for 12x14 and 12x16.

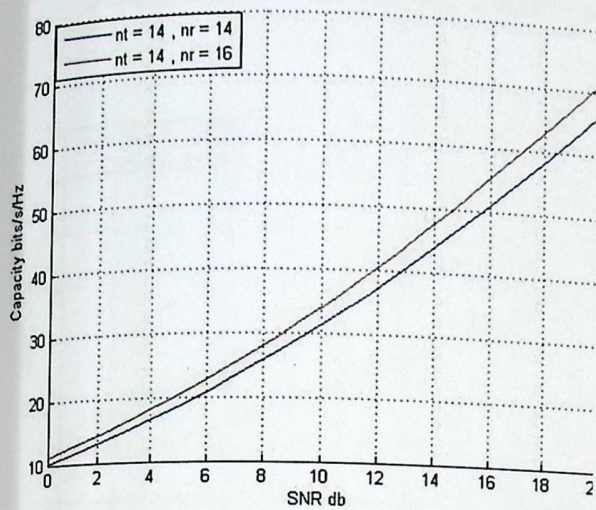


Fig3.5.63:capacity Vs. SNR for 14x14 and 14x16.

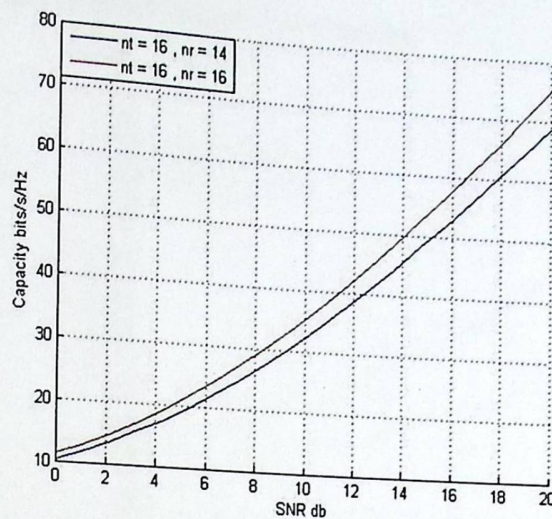


Fig3.5.64:capacity Vs. SNR for 16x14 and 16x16.

Figures 3.5.57 to 3.5.64 shows the relation between the offered ergodic capacity and the signal to noise ratio (SNR) under no correlation .i.e. there is no symmetry between the different signals arriving at the receiver so, the receiver will not face a problem in distinguishing the different data from those sub streams. It's clear that the capacity will increase as the value of the signal to noise ratio increases. The ergodic capacity offered will be higher if we use more transmit and receive antennas. also the increase in the capacity will not be high if the number of receiving antenna is increasing for two antennas while the number of transmitting antennas is constant. The maximum obtained capacity in all the previous cases occurred at the maximum number of transmitters and receivers.

3.5.3 Relation between the ergodic capacity and SNR for 0.7 correlation

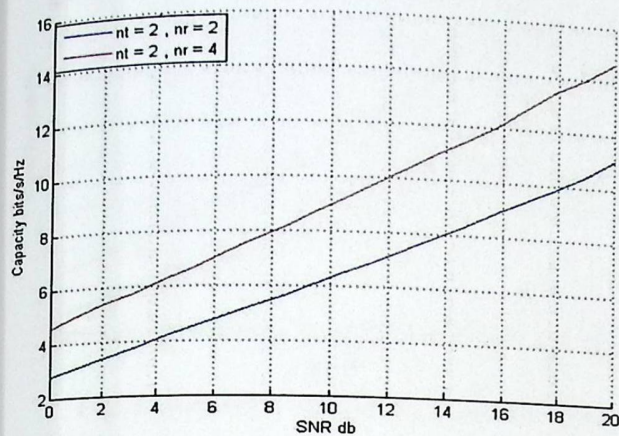


Fig4.1.65: capacity Vs. SNR for 2x2 and 2x4.

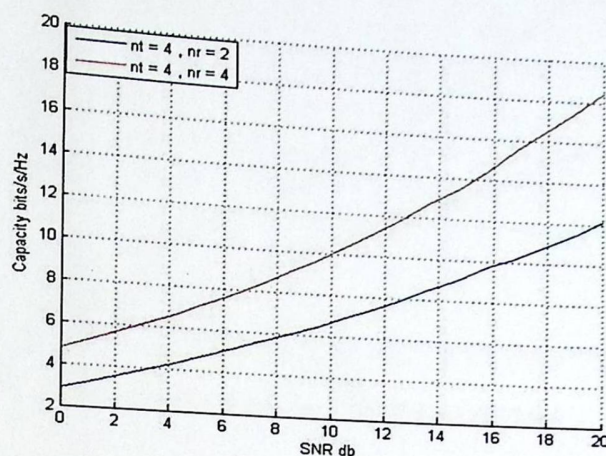


Fig4.1.66: capacity Vs. SNR for 4x2 and 4x4.

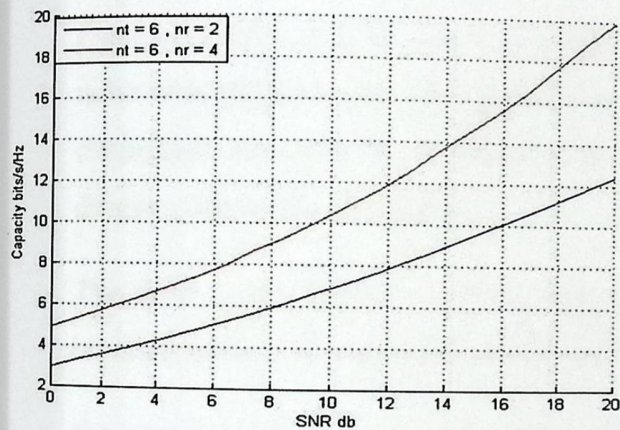


Fig3.5.67: capacity Vs. SNR for 6x2 and 6x4.

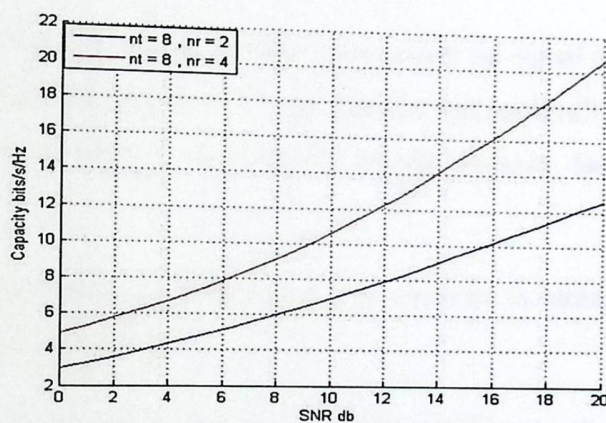


Fig3.5.68: capacity Vs. SNR for 8x2 and 8x4

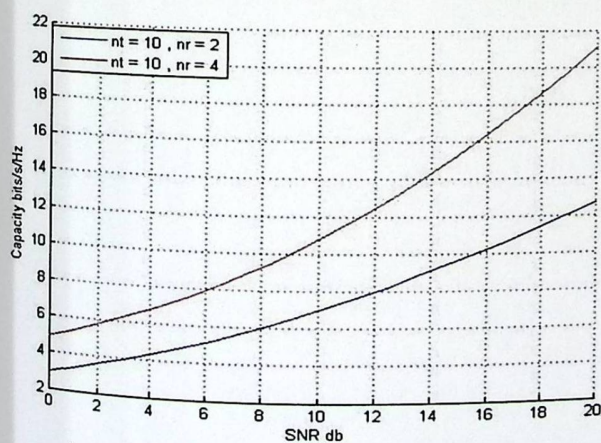


Fig3.5.69: capacity Vs. SNR for 10x2 and 10x4

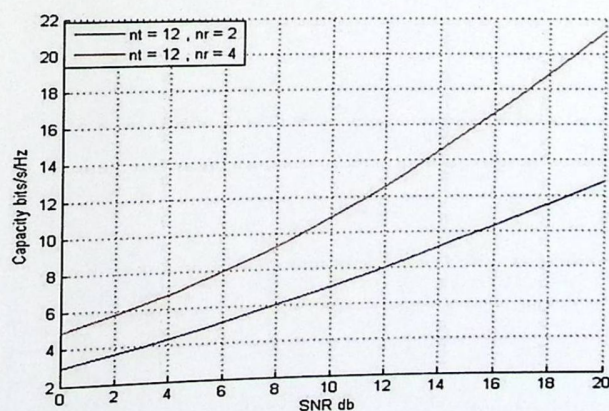


Fig3.5.70: capacity Vs. SNR for 12x2 and 12x4

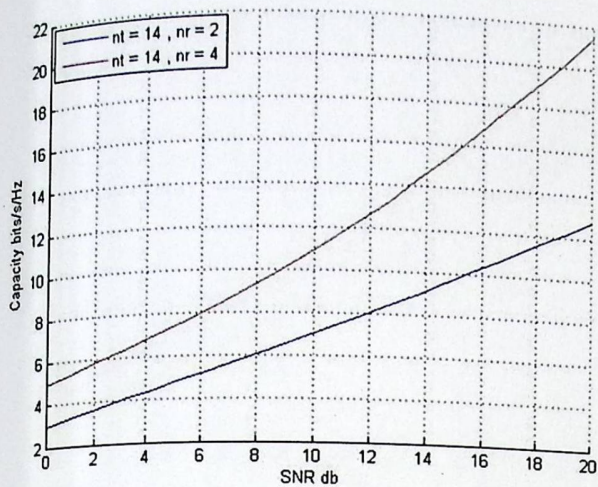


Fig3.5.71:capacity Vs. SNR for 14x2 and 14x4

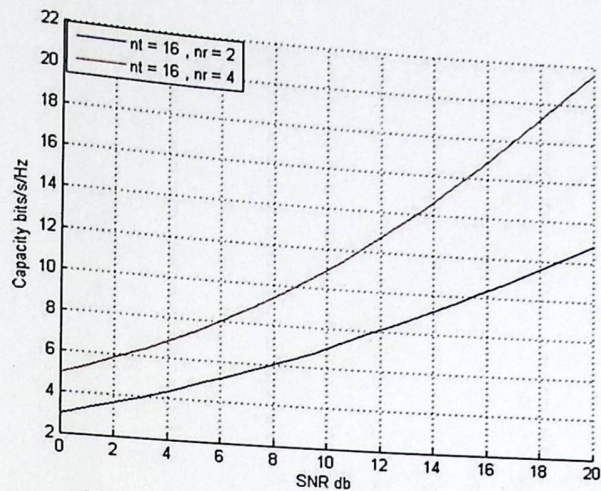


Fig3.5.72:capacity Vs. SNR for 16x2 and 16x4

Figures 3.5.65 to 3.5.72 shows the relation between the offered ergodic capacity and the signal to noise ratio (SNR) under the effect of correlation which equals to 0.7, the receiver will not ideally distinguish between the different received sub streams so the offered ergodic capacity has dropped due to the correlation.

The drop in the capacity will be higher if the number of transmitters and receivers is more, because more correlated data are received at the receiver side.

the capacity will increase as the value of the signal to noise ratio increases. The ergodic capacity offered will be higher if we use more transmit and receive antennas.

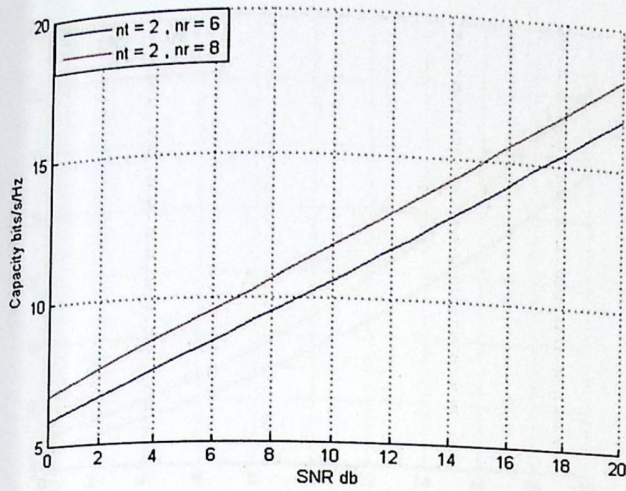


Fig3.5.73:capacity Vs. SNR for 2x6 and 2x8.

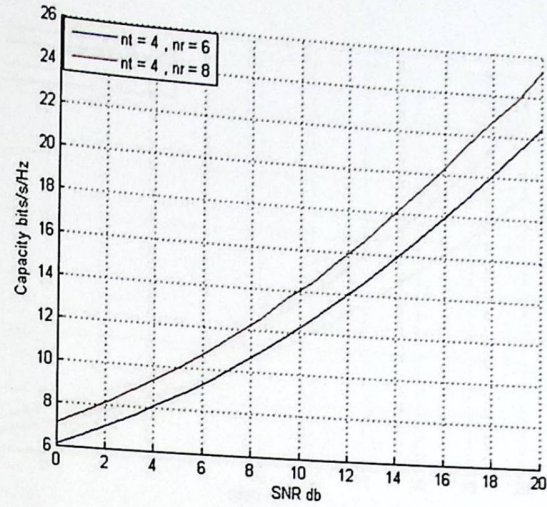


Fig3.5.74:capacity Vs. SNR for 4x6 and 4x8.

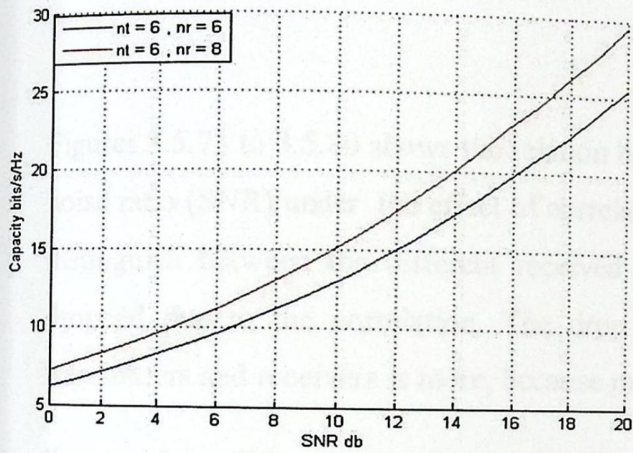


Fig3.5.75:capacity Vs. SNR for 6x6 and 6x8.

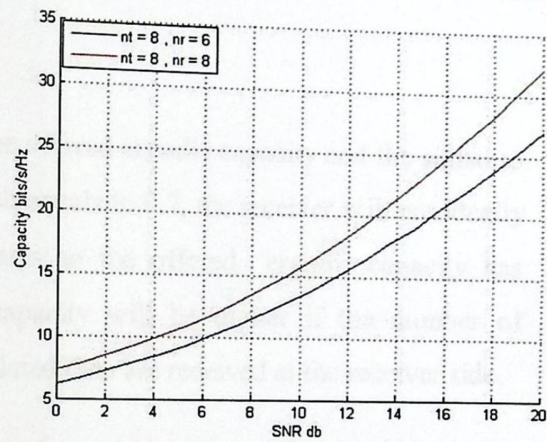


Fig3.5.76:capacity Vs. SNR for 8x6 and 8x8.

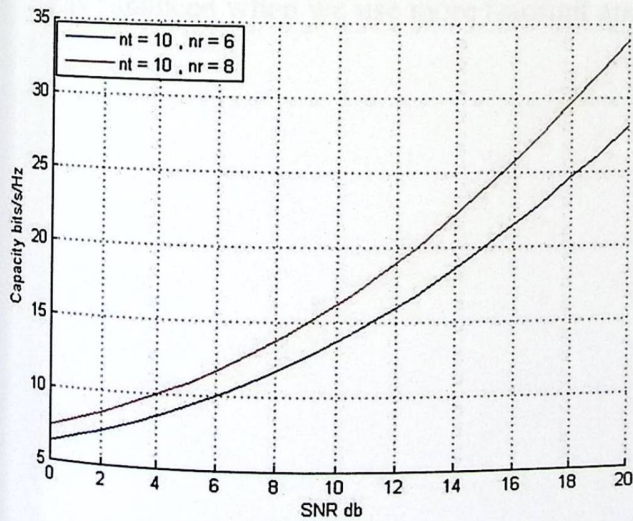


Fig3.5.77:capacity Vs. SNR for 10x6 and 10x8.

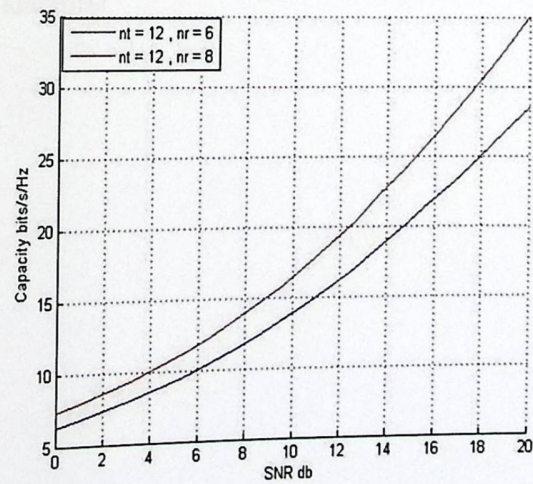


Fig3.5.78:capacity Vs. SNR for 12x6 and 12x8.

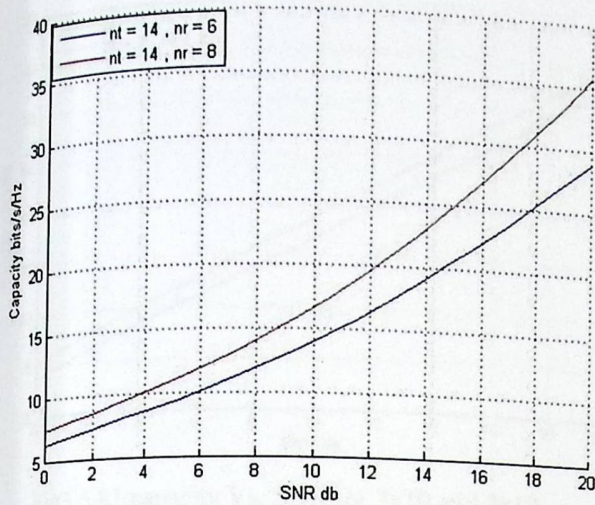


Fig3.5.79:capacity Vs. SNR for 14x6 and 14x8.

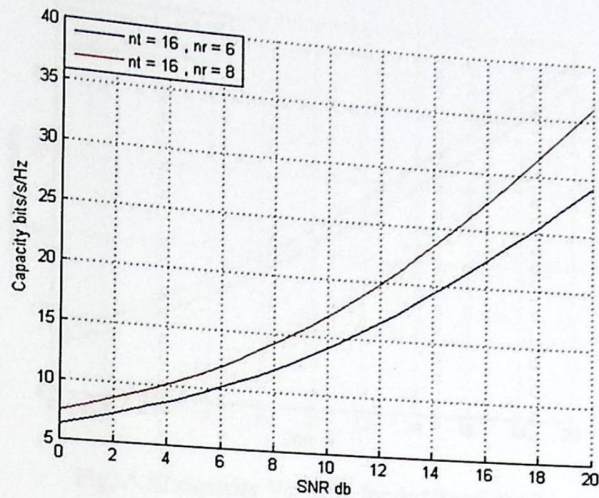


Fig3.5.80:capacity Vs. SNR for 16x6 and 16x8.

Figures 3.5.73 to 3.5.80 shows the relation between the offered ergodic capacity and the signal to noise ratio (SNR) under the effect of correlation which equals to 0.7, the receiver will not ideally distinguish between the different received sub streams so the offered ergodic capacity has dropped due to the correlation. The drop in the capacity will be higher if the number of transmitters and receivers is more, because more correlated data are received at the receiver side.

the capacity will increase as the value of the signal to noise ratio increases. The ergodic capacity has enhanced when we use more transmit and receive antennas.

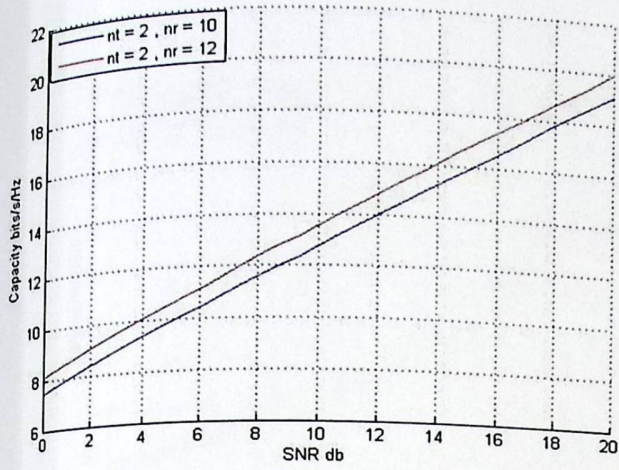


Fig3.5.81:capacity Vs. SNR for 2x10 and 2x12.

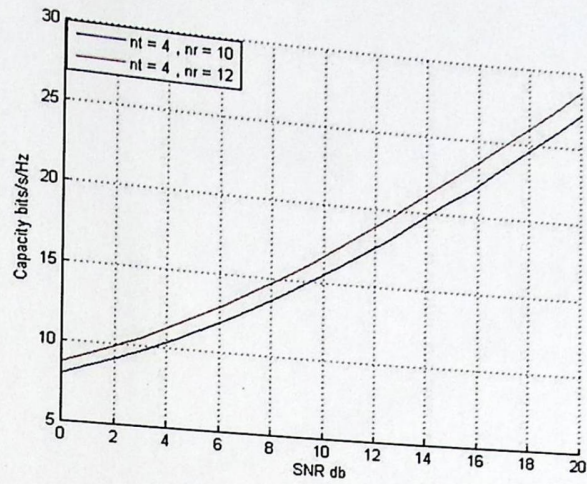


Fig3.5.82:capacity Vs. SNR for 4x10 and 4x12.

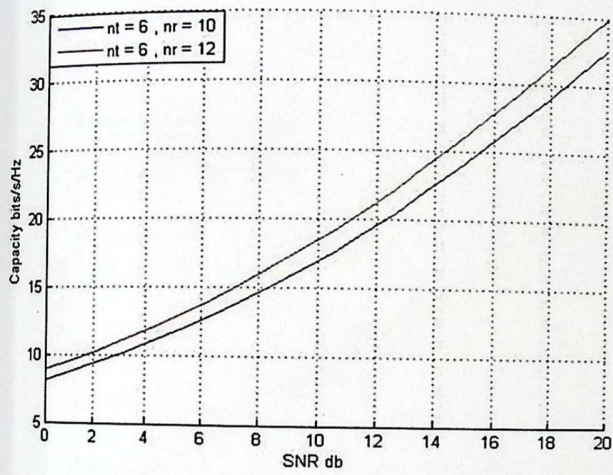


Fig3.5.83:capacity Vs. SNR for 6x10 and 6x12

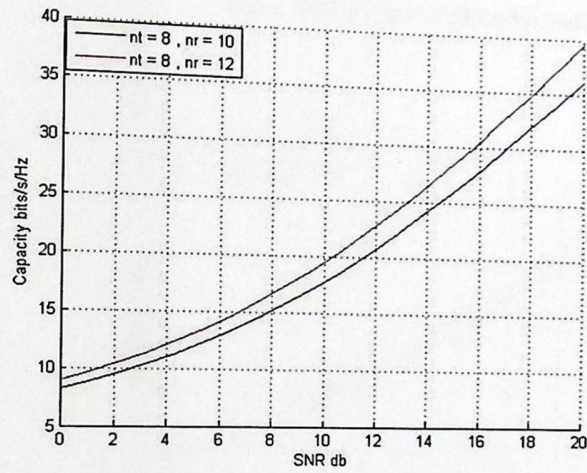


Fig3.5.84:capacity Vs. SNR for 8x10 and 8x12

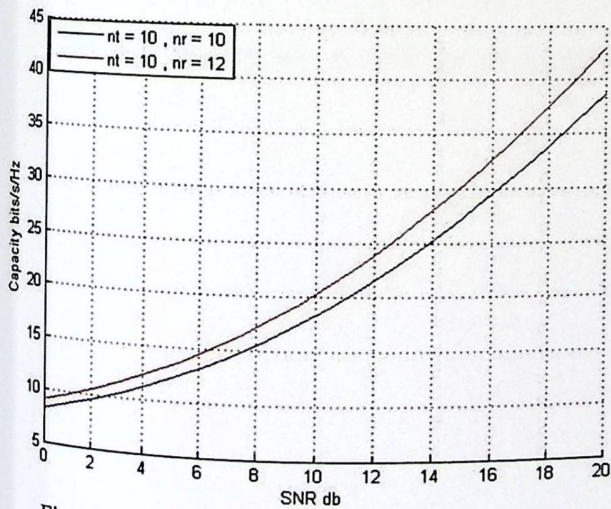


Fig3.5.85:capacity Vs. SNR for 10x10 and 10x12.

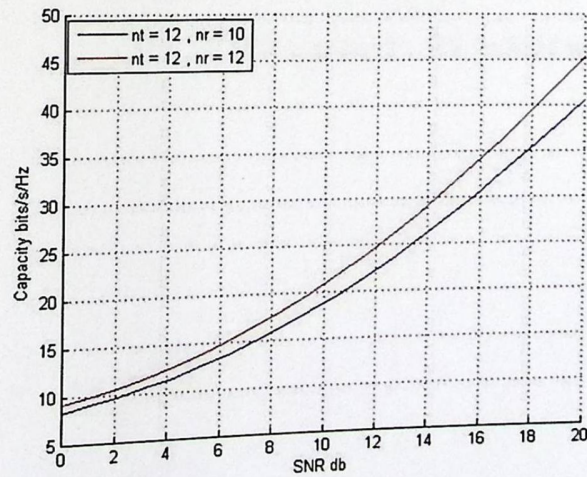


Fig3.5.86:capacity Vs. SNR for 12x10 and 12x12.

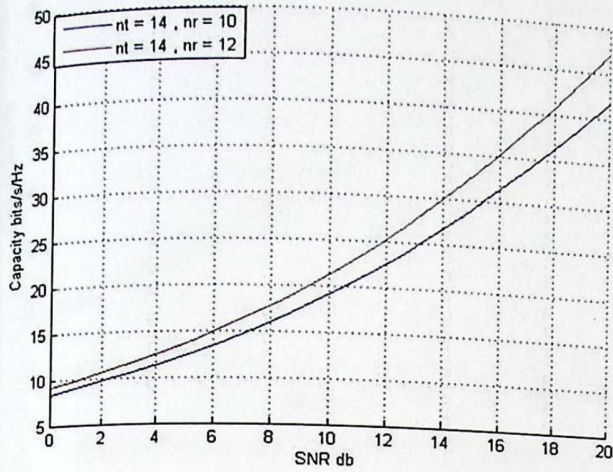


Fig3.5.87:capacity Vs. SNR for 14x10 and 14x12.

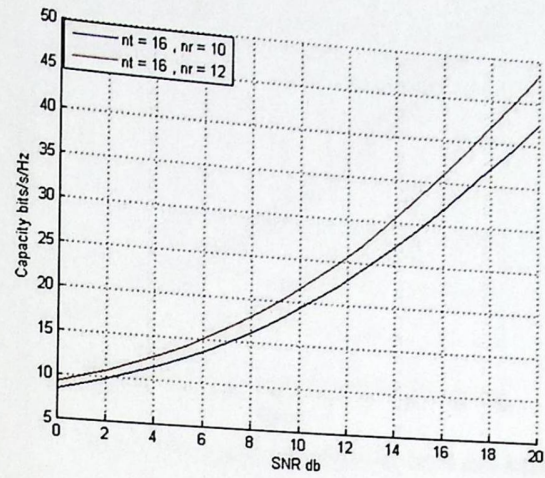


Fig3.5.88:capacity Vs. SNR for 16x10 and 16x12.

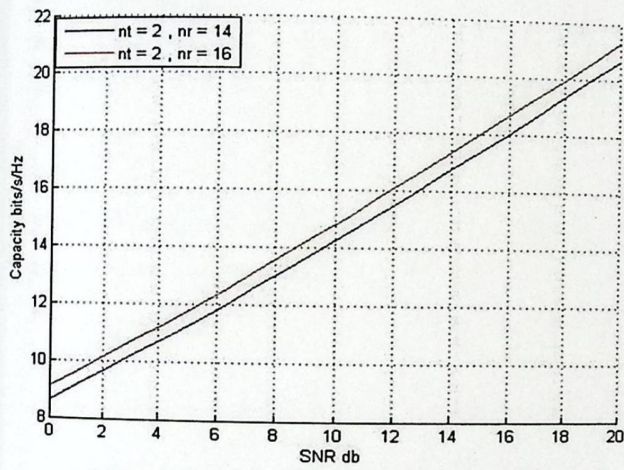


Fig3.5.89:capacity Vs. SNR for 2x14 and 2x16

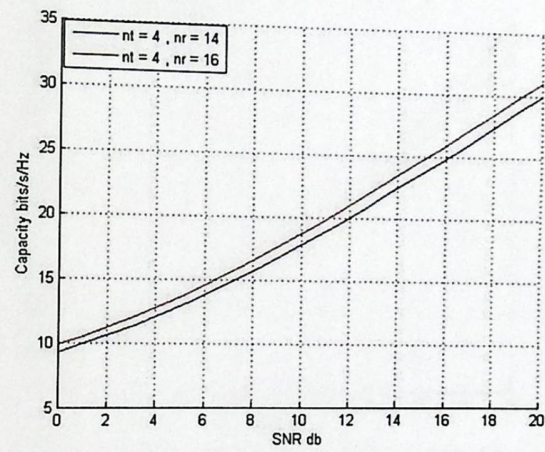


Fig3.5.90:capacity Vs. SNR for 4x14 and 4x16.

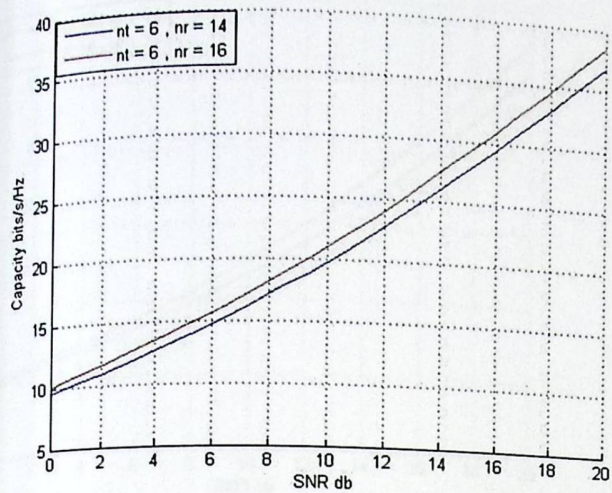


Fig3.5.91:capacity Vs. SNR for 6x14 and 6x16.

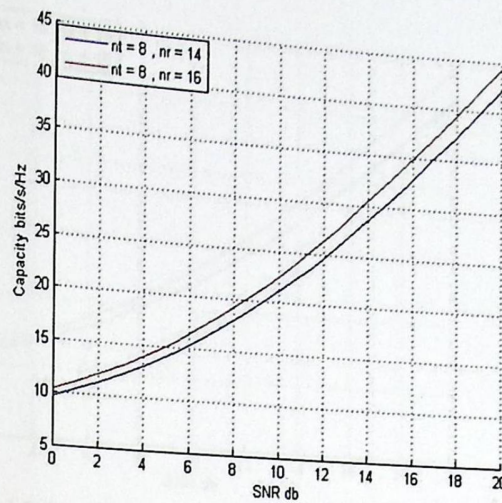


Fig3.5.92:capacity Vs. SNR for 8x14 and 8x16

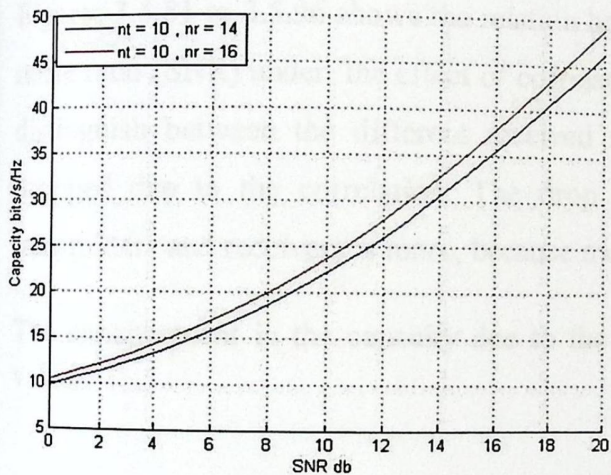


Fig3.5.93:capacity Vs. SNR for 10x14 and 10x16.

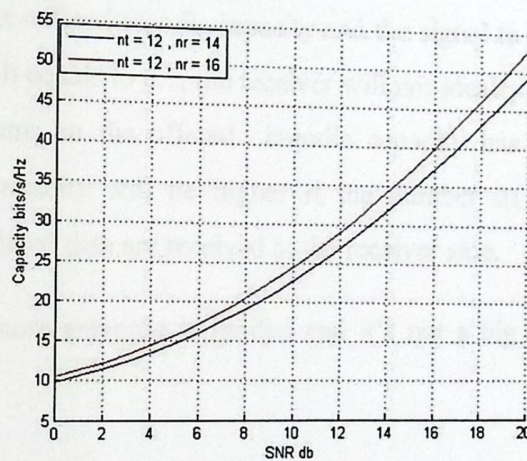


Fig3.5.94:capacity Vs. SNR for 12x14 and 12x16.

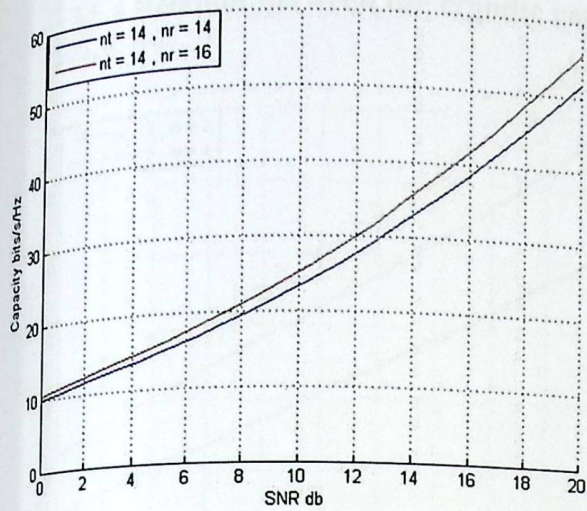


Fig3.5.95:capacity Vs. SNR for 14x14 and 14x16.

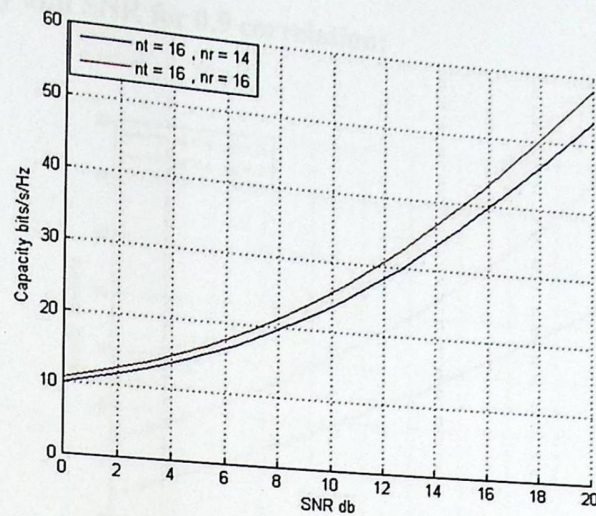


Fig3.5.96:capacity Vs. SNR for 16x14 and 16x16.

Figures 3.5.81 to 3.5.96 shows the relation between the offered ergodic capacity and the signal to noise ratio (SNR) under the effect of correlation which equals to 0.7, the receiver will not ideally distinguish between the different received sub streams so the offered ergodic capacity has dropped due to the correlation. The drop in the capacity will be higher if the number of transmitters and receivers is more, because more correlated data are received at the receiver side.

The enhancement in the capacity due to the use of more antennas is limited and it's not a big value.

3.5.4 Relation between the ergodic capacity and SNR for 0.9 correlation:

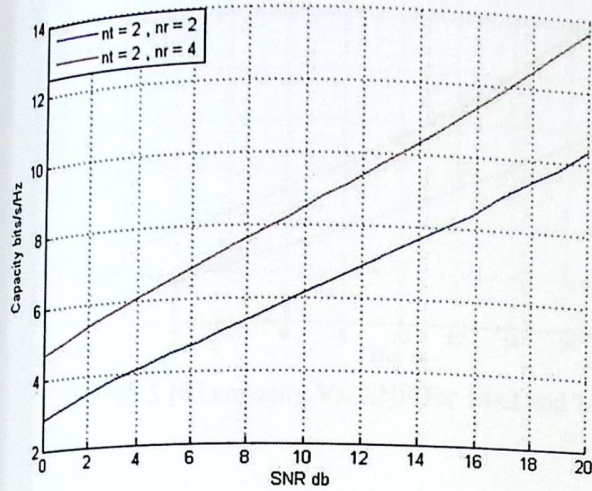


Fig4.1.97:capacity Vs. SNR for 2x2 and 2x4.

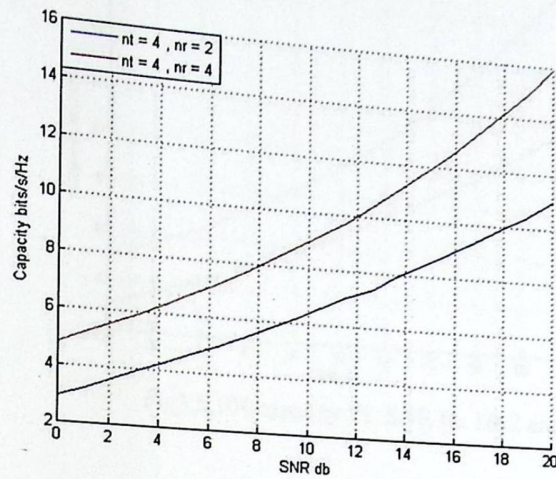


Fig4.1.98:capacity Vs. SNR for 4x2 and 4x4.

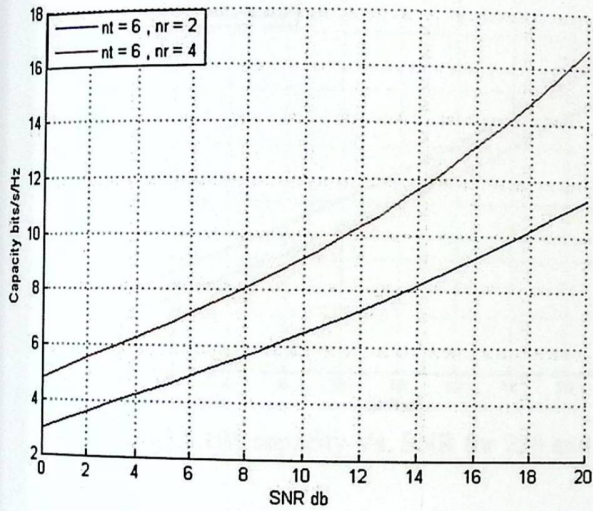


Fig3.5.99:capacity Vs. SNR for 6x2 and 6x4.

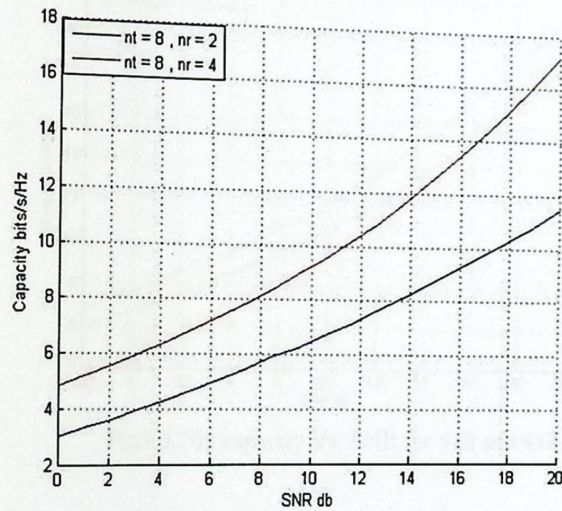


Fig3.5.100:capacity Vs. SNR for 8x2 and 8x4.

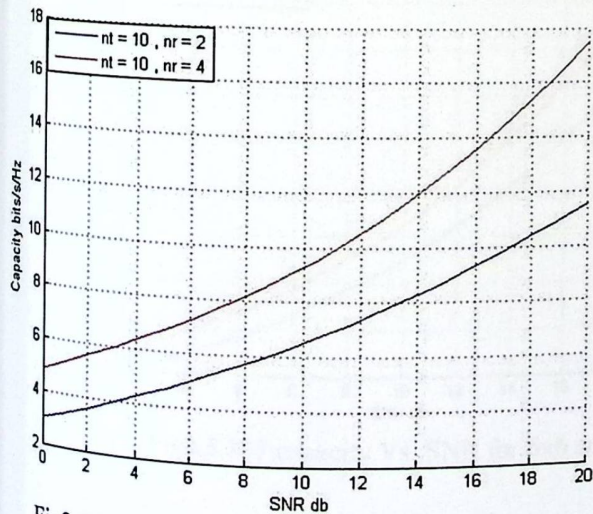


Fig3.5.101:capacity Vs. SNR for 10x2 and 10x4.

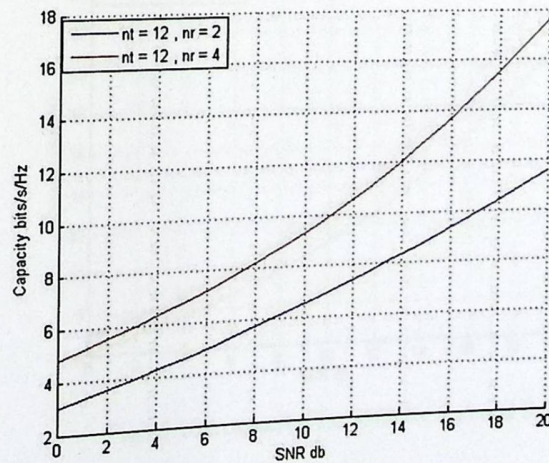


Fig3.5.102:capacity Vs. SNR for 12x2 and 12x4.

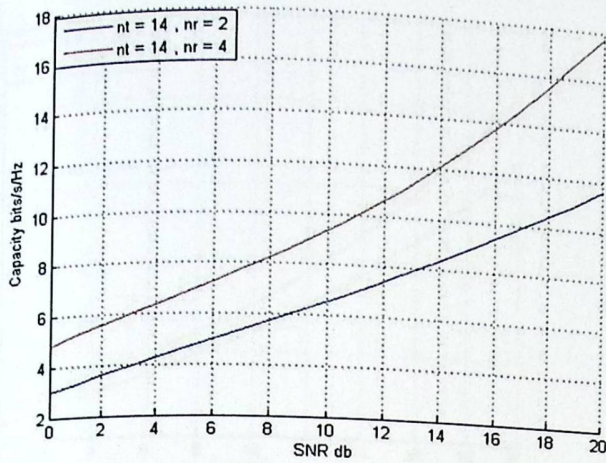


Fig3.5.103:capacity Vs. SNR for 14x2 and 14x4.

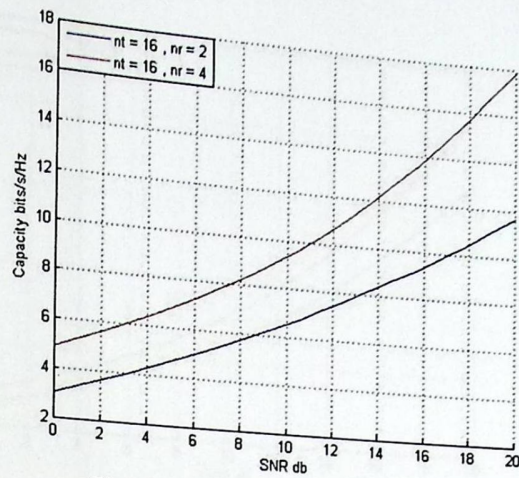


Fig3.5.104:capacity Vs. SNR for 16x2 and 16x4.

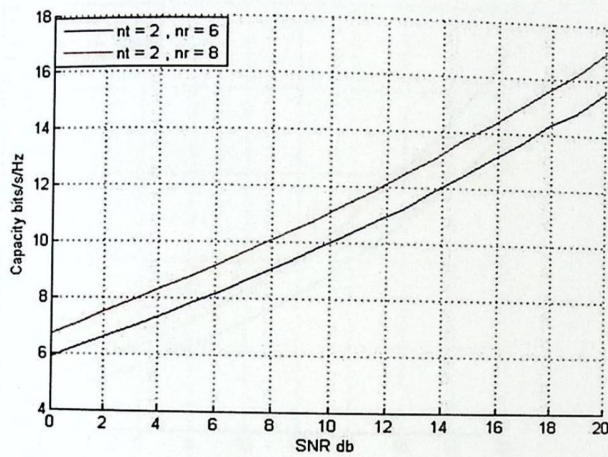


Fig3.5.105:capacity Vs. SNR for 2x6 and 2x8.

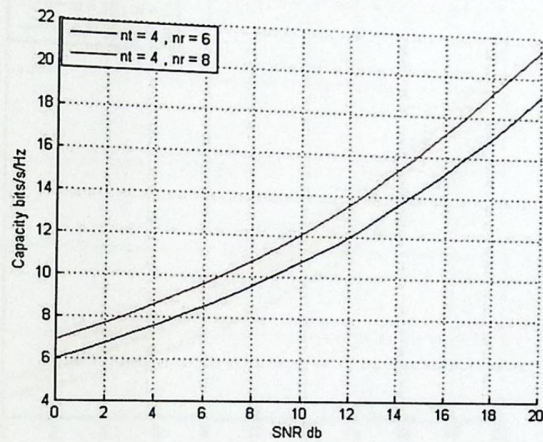


Fig3.5.106:capacity Vs. SNR for 4x6 and 4x8.

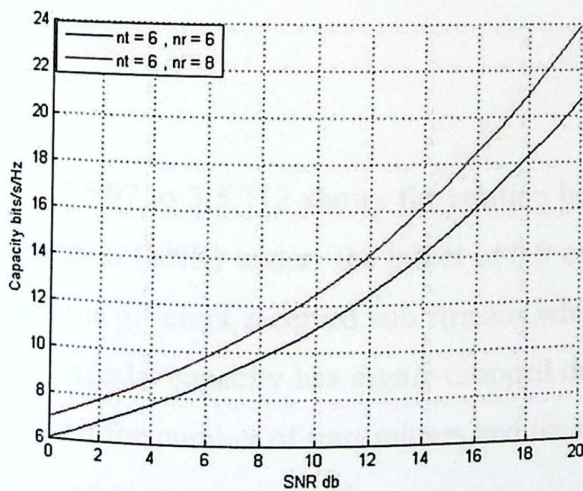


Fig3.5.107:capacity Vs. SNR for 6x6 and 6x8

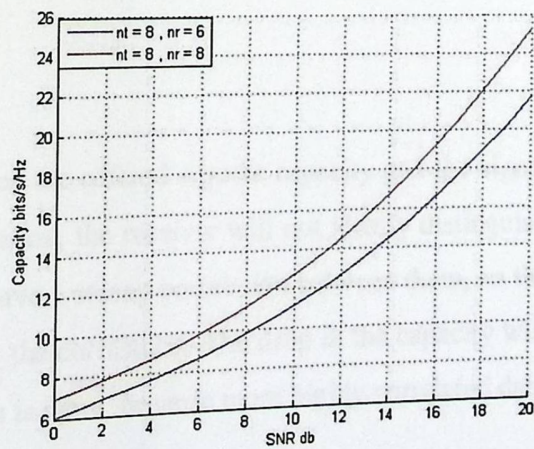


Fig3.5.108:capacity Vs. SNR for 8x6 and 8x8.

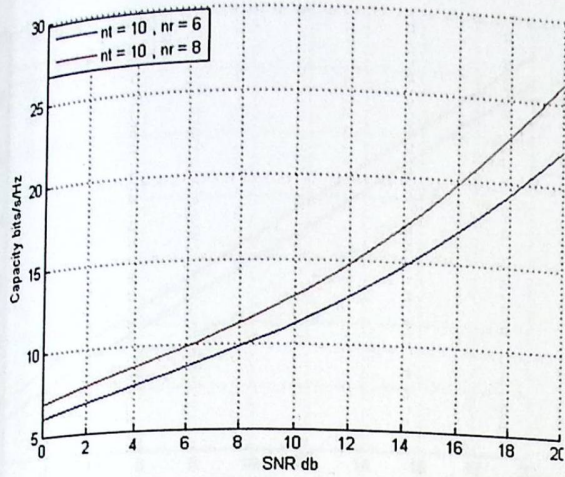


Fig3.5.109:capacity Vs. SNR for 10x6 and 10x8

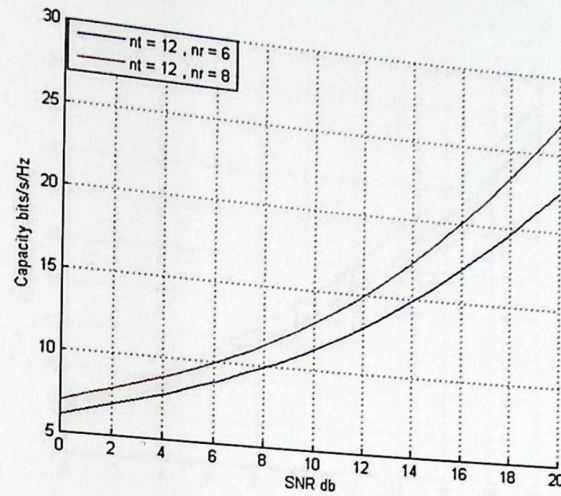


Fig3.5.110:capacity Vs. SNR for 12x6 and 12x8.

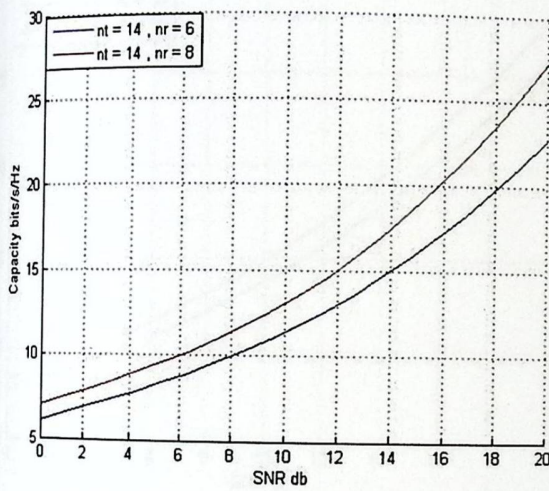


Fig3.5.111:capacity Vs. SNR for 14x6 and 14x8

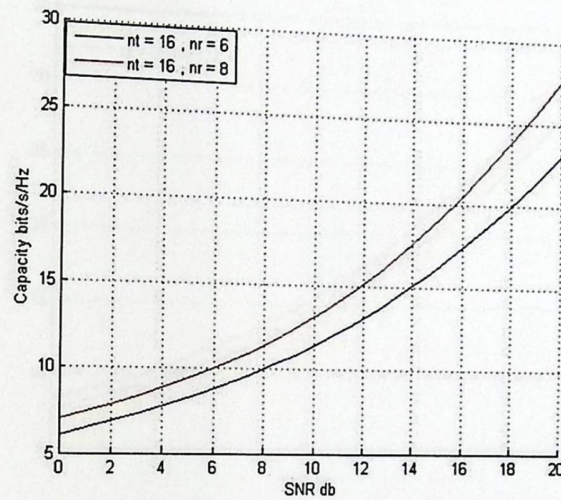


Fig3.5.112:capacity Vs. SNR for 16x6 and 16x8.

Figures 3.5.97 to 3.5.112 shows the relation between the offered ergodic capacity and the signal to noise ratio (SNR) under the effect of 0.9 correlation, the receiver will not ideally distinguish between the different received sub streams which have a strong correlation between them, so the offered ergodic capacity has *highly* dropped due to the correlation. The drop in the capacity will be higher if the number of transmitters and receivers is more, because more highly correlated data are received at the receiver side.

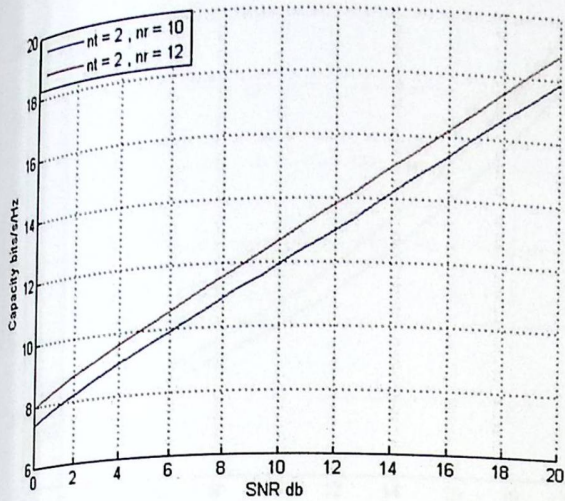


Fig3.5.113: capacity Vs. SNR for 2x10 and 2x12.

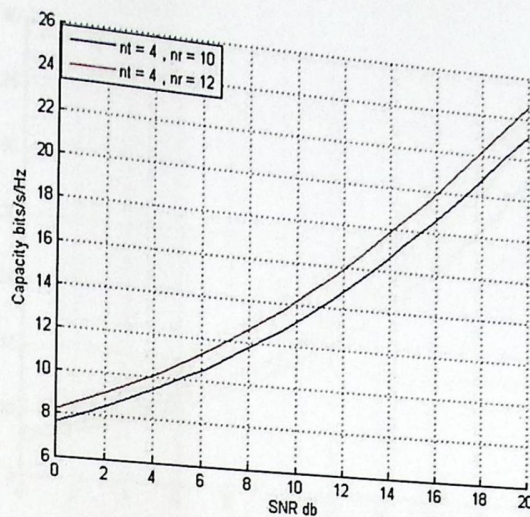


Fig3.5.114: capacity Vs. SNR for 4x10 and 4x12.

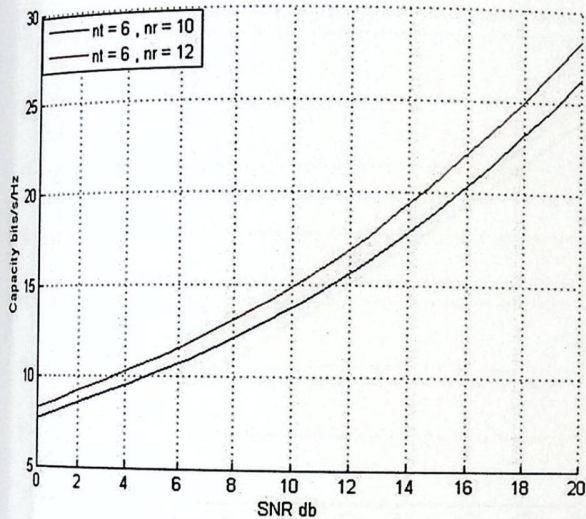


Fig3.5.115: capacity Vs. SNR for 6x10 and 6x12.

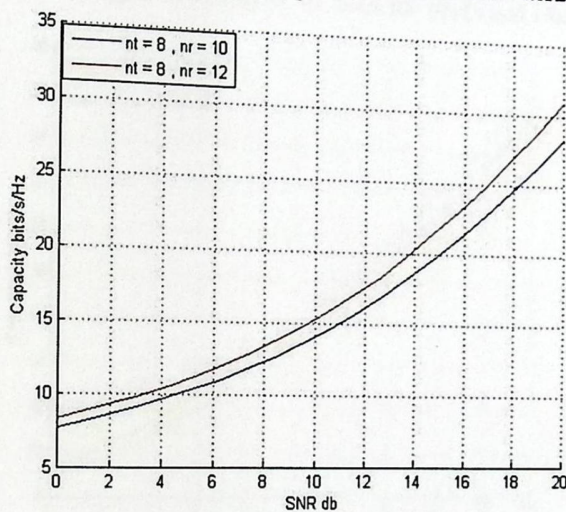


Fig3.5.116: capacity Vs. SNR for 8x10 and 8x12.

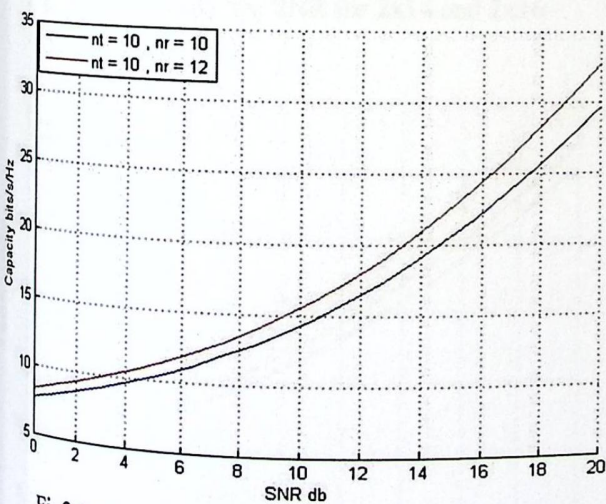


Fig3.5.117: capacity Vs. SNR for 10x10 and 10x12.

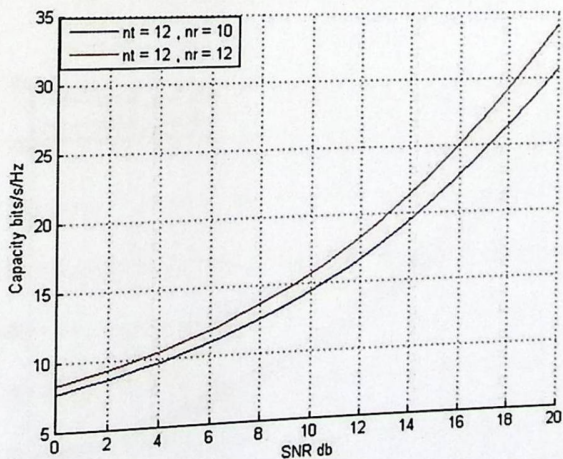


Fig 3.5.118: capacity Vs. SNR for 12x10 and 12x12.

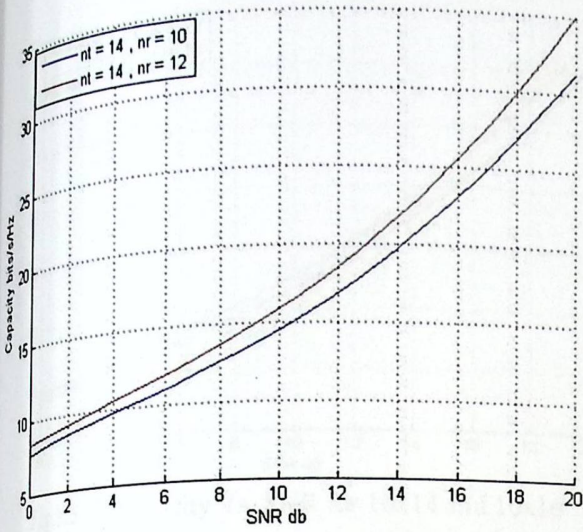


Fig3.5.119:capacity Vs. SNR for 14x10 and 14x12

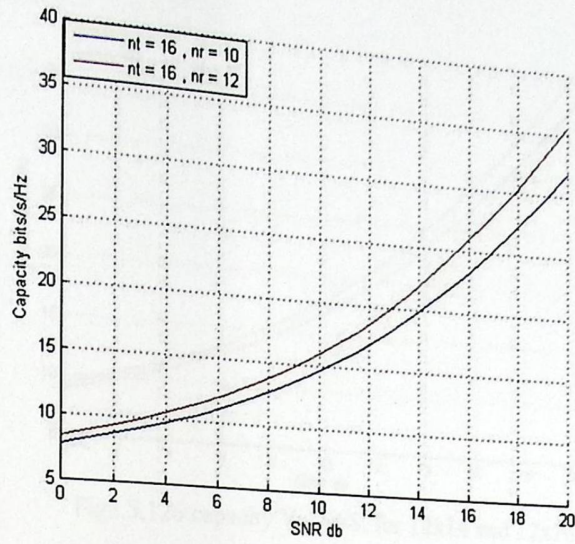


Fig3.5.120:capacity Vs. SNR for 16x10 and 16x12

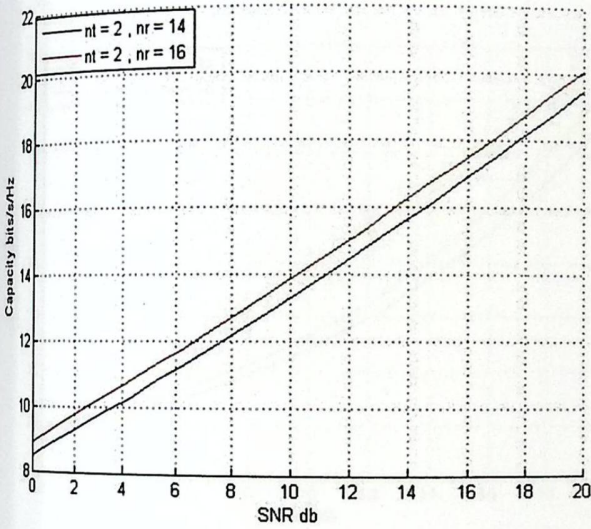


Fig3.5.121:capacity Vs. SNR for 2x14 and 2x16

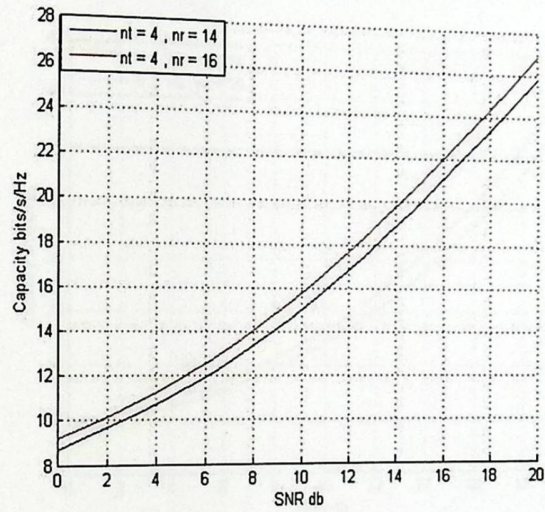


Fig3.5.122:capacity Vs. SNR for 4x14 and 4x16

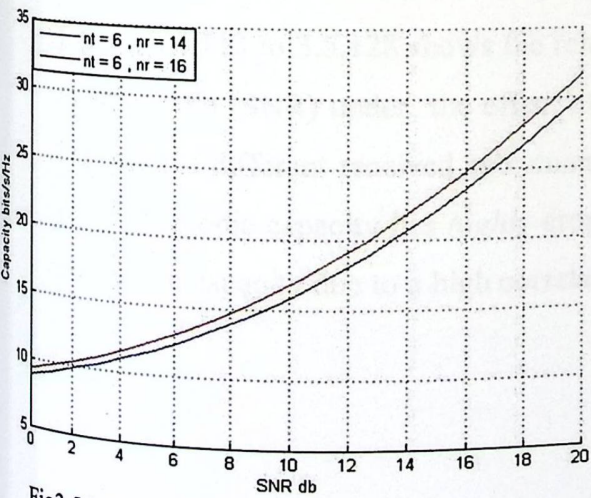


Fig3.5.123:capacity Vs. SNR for 6x14 and 6x16

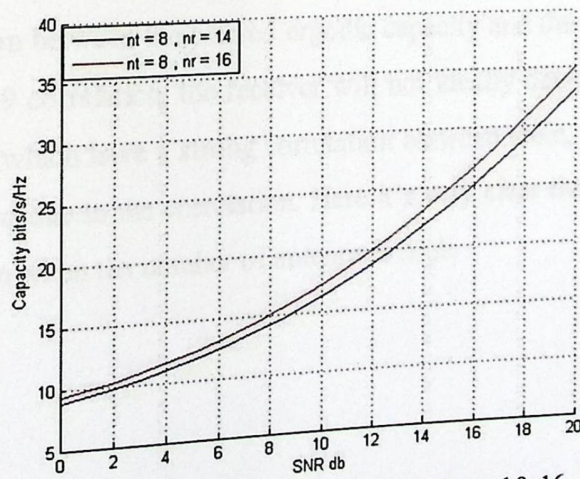


Fig3.5.124:capacity Vs. SNR for 8x14 and 8x16

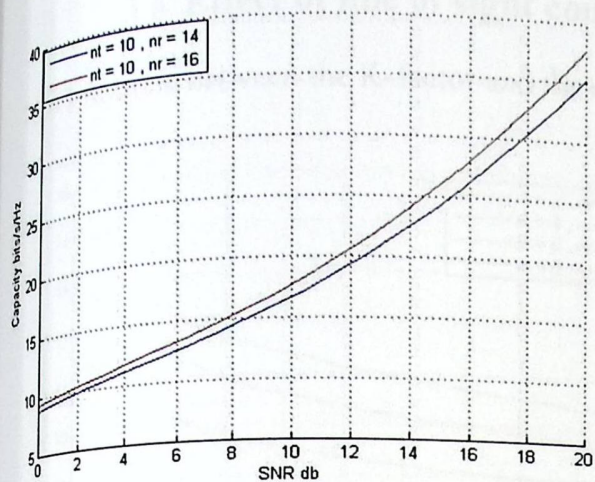


Fig3.5.125:capacity Vs. SNR for 10x14 and 10x16

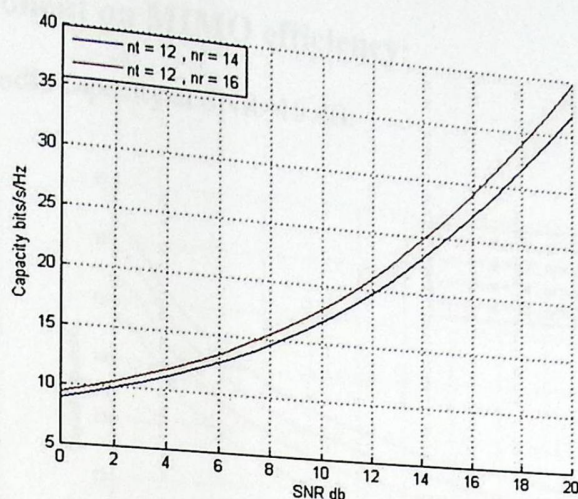


Fig3.5.126:capacity Vs. SNR for 12x14 and 12x16

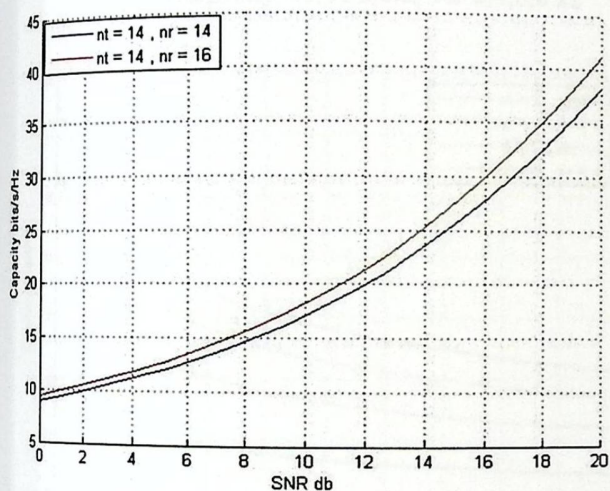


Fig3.5.127:capacity Vs. SNR for 14x14 and 14x16

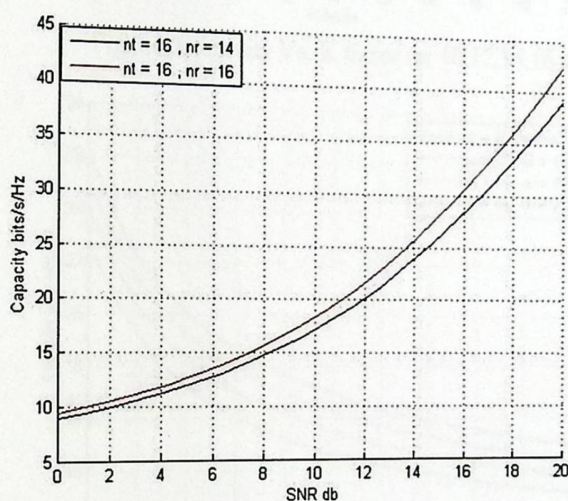


Fig3.5.128:capacity Vs. SNR for 16x14 and 16x16.

Figures 3.5.113 to 3.5.128 shows the relation between the offered ergodic capacity and the signal to noise ratio (SNR) under the effect of 0.9 correlation, the receiver will not ideally distinguish between the different received sub streams which have a strong correlation between them, so the offered ergodic capacity has *highly* dropped due to the correlation. Here it's very clear the large drop in the capacity due to a high correlation when the number of antenna is high.

3.6 Effect of line of sight component on MIMO efficiency:

3.6.1 Relation between the K-factor and the ergodic capacity at SNR=15 dB:

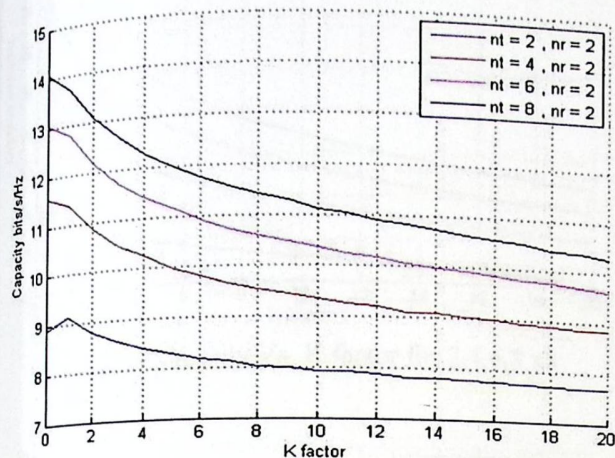


Fig 3.6.1: capacity Vs. K factor for 2,4,6,8 x2

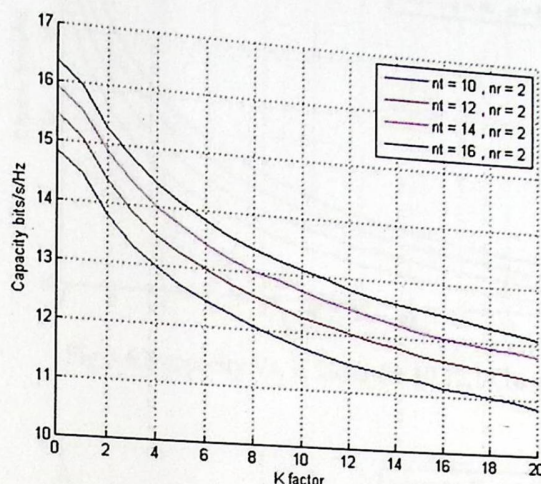


Fig 3.6.2: capacity Vs. K factor for 10,12,14,16 x2

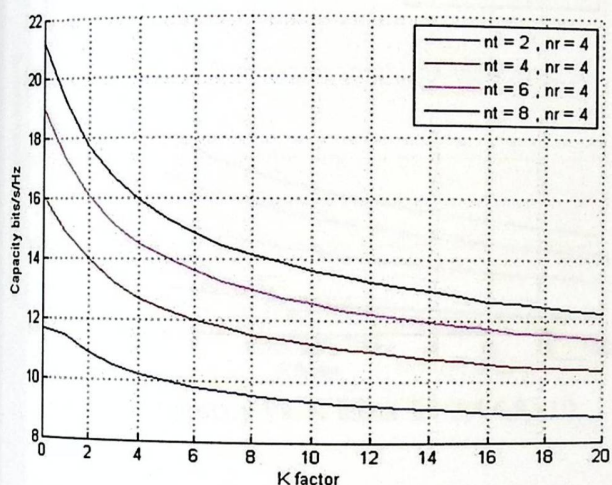


Fig 3.6.3: capacity Vs. K factor for 2,4,6,8 x4

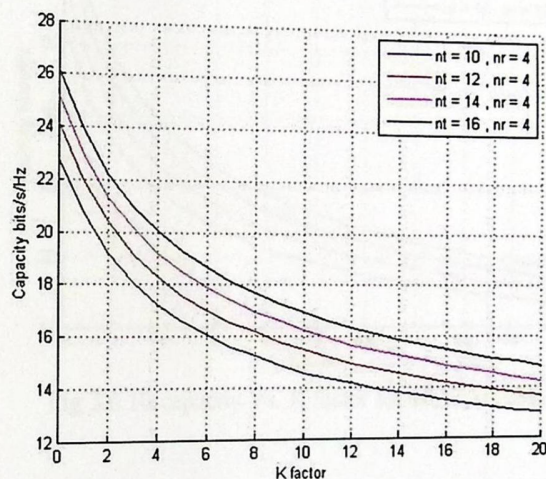


Fig 3.6.4: capacity Vs. K factor for 10,12,14,16 x4

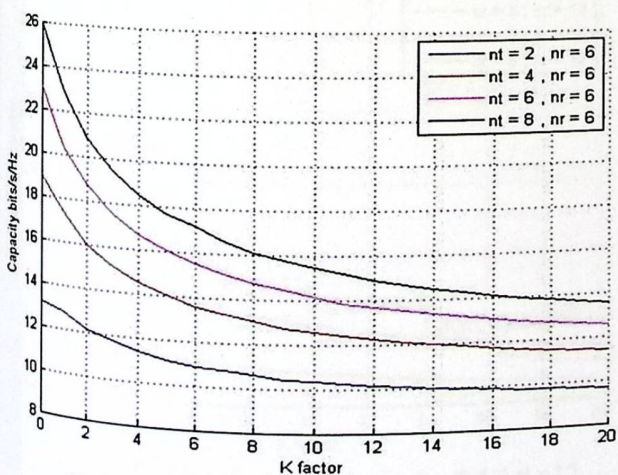


Fig 3.6.5: capacity Vs. K factor for 2,4,6,8 x6

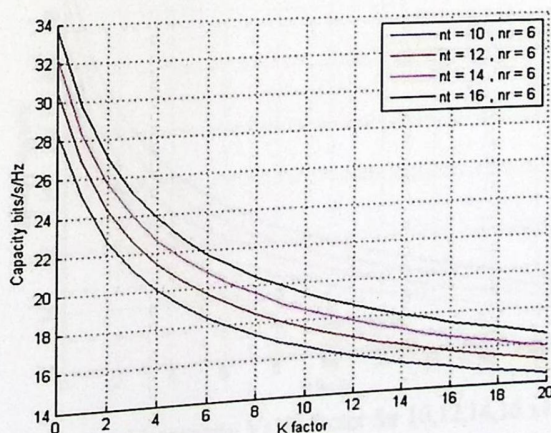


Fig 3.6.6: capacity Vs. K factor for 10,12,14,16 x6

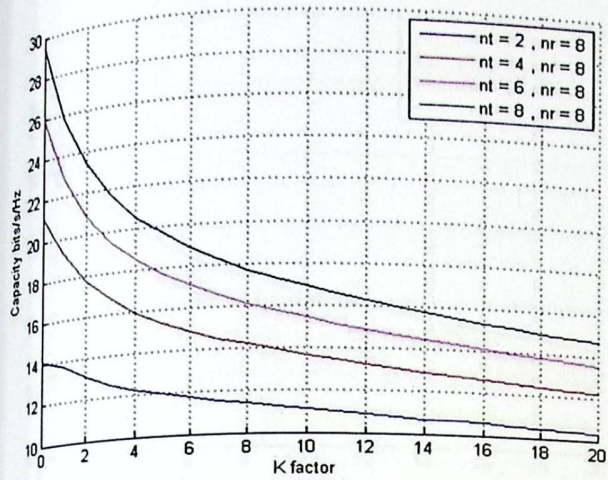


Fig 3.6.7: capacity Vs. K factor for 2,4,6,8 x 8

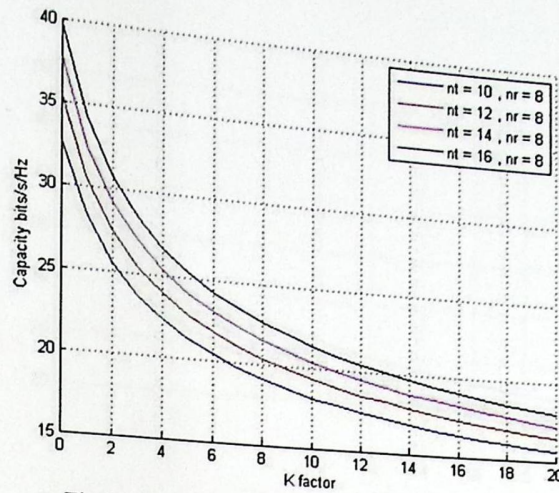


Fig 3.6.8: capacity Vs. K factor for 10,12,14,16 x 8

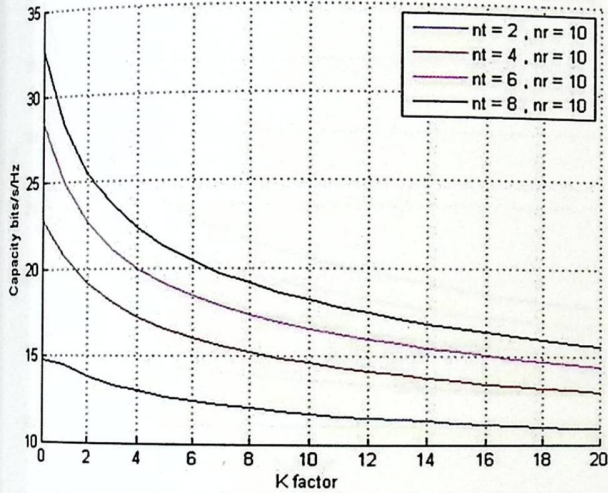


Fig 3.6.9: capacity Vs. K factor for 2,4,6,8 x 10

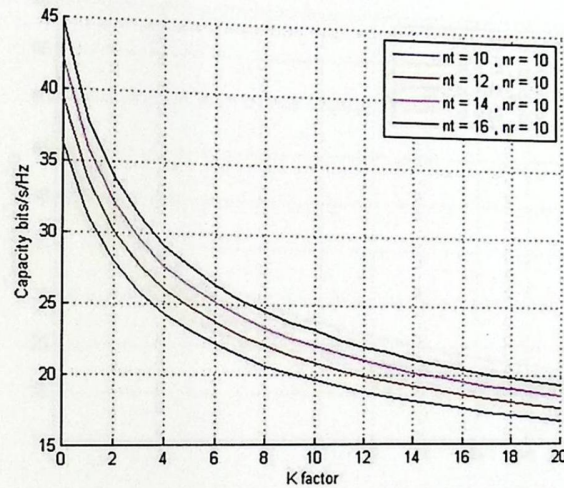


Fig 3.6.10: capacity Vs. K factor for 10,12,14,16 x 10

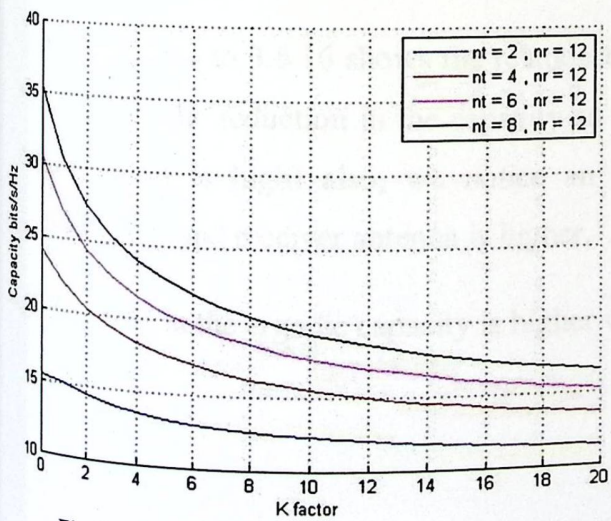


Fig 3.6.11: capacity Vs. K factor for 2,4,6,8 x 12

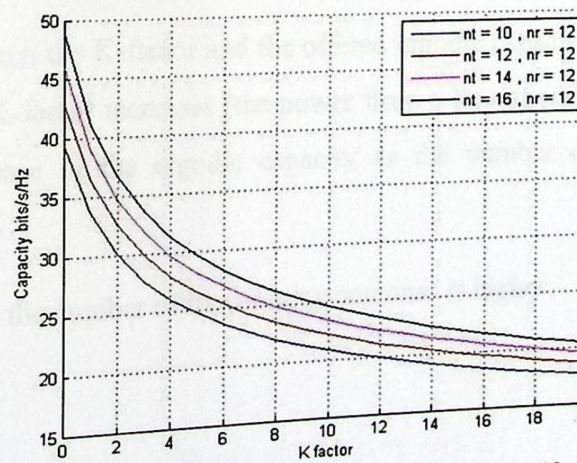


Fig 3.6.12: capacity Vs. K factor for 10,12,14,16 x 12

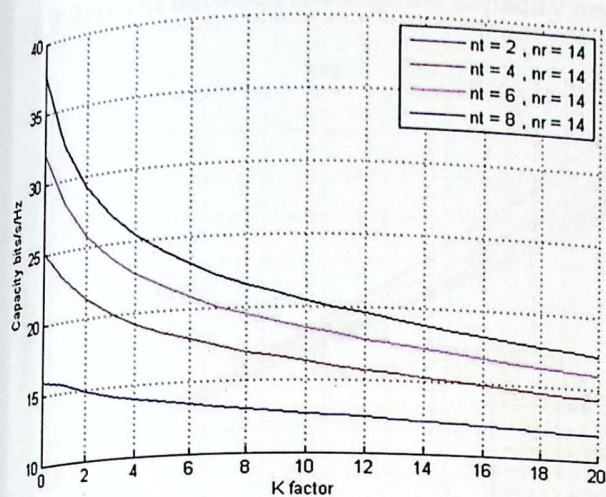


Fig 3.6.13:capacity Vs. K factor for 2,4,6,8 x14

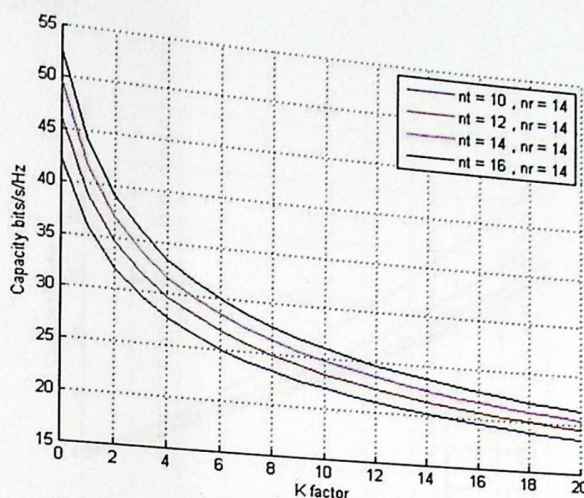


Fig 43.6.14:capacity Vs. K factor for 10,12,14,16 x14

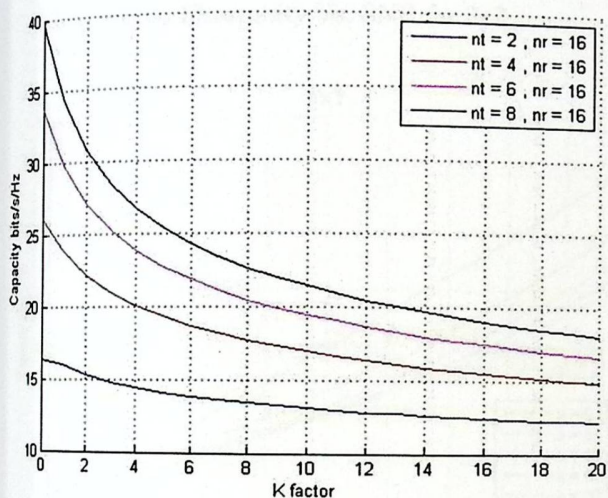


Fig 3.6.15:capacity Vs. K factor for 2,4,6,8 x16

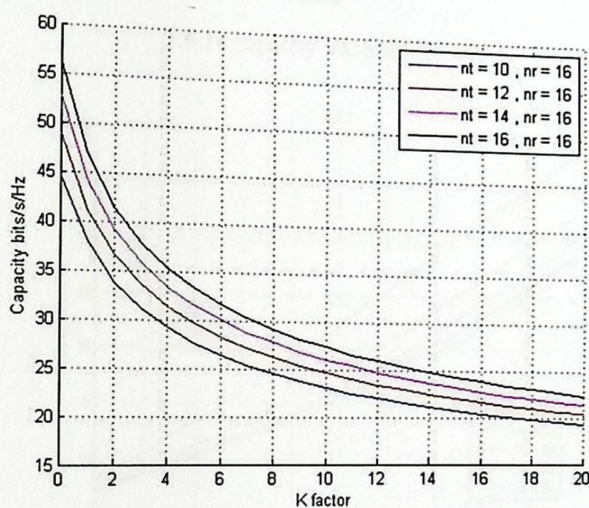


Fig 3.6.16:capacity Vs. K factor for 10,12,14,16 x16

Figures 3.6.1 to 3.6.16 shows the relation between the K-factor and the offered ergodic capacity, we notice the reduction in the capacity as the K-factor increases (the power from a line of sight component is high) also, we notice an increase in the ergodic capacity as the number of transmitter and receiver antenna is higher.

The drop in the ergodic capacity is higher when the number of transmitting antennas is higher.

3.6.2 Relation between the ergodic capacity and the SNR:

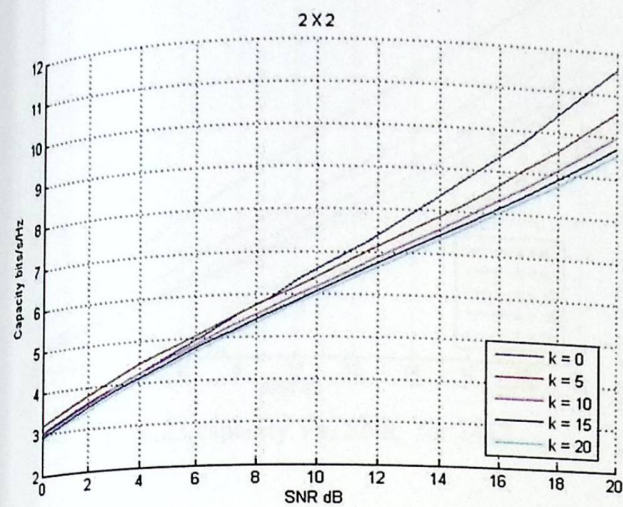
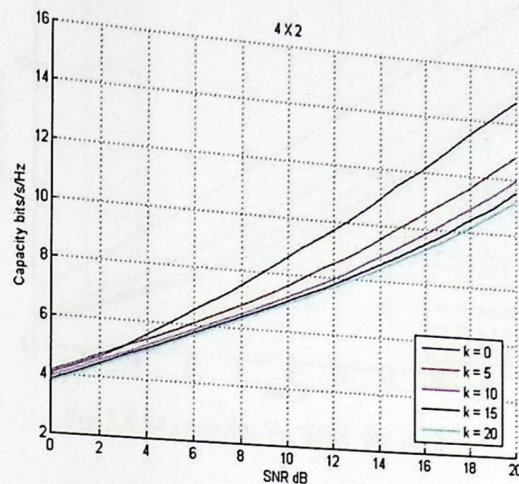


Fig 3.6.17: capacity Vs. SNR for 2x2



3.6.18: capacity Vs. SNR for 4x2

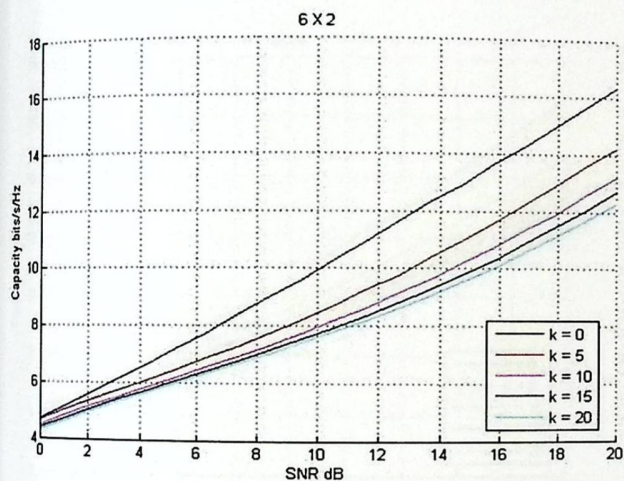


Fig 3.6.19: capacity Vs. SNR for 6x2

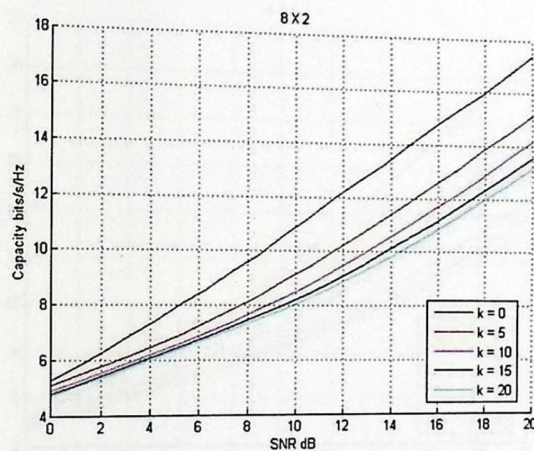


Fig Fig3.6.20: capacity Vs. SNR for 8x2

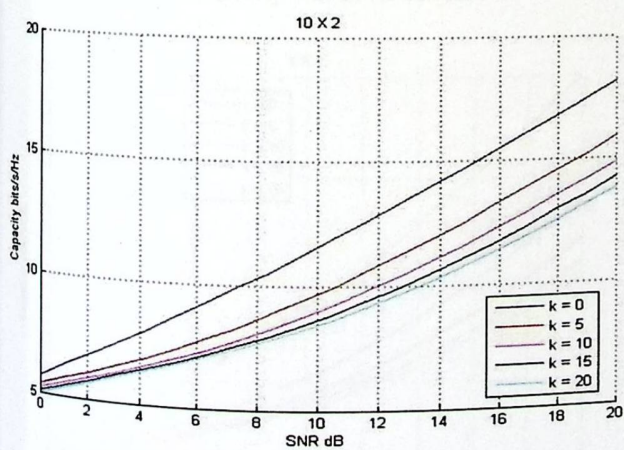


Fig 3.6.21: capacity Vs. SNR for 10x2

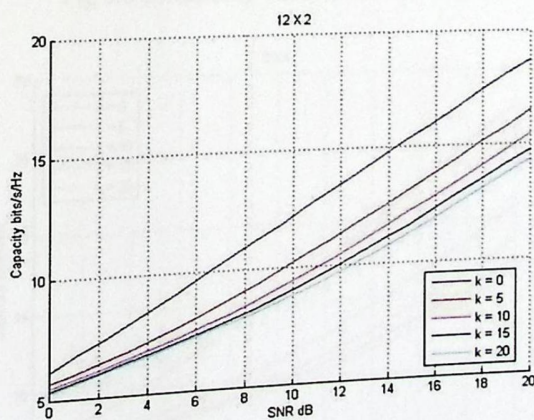


Fig 3.6.22: capacity Vs. SNR for 12x2

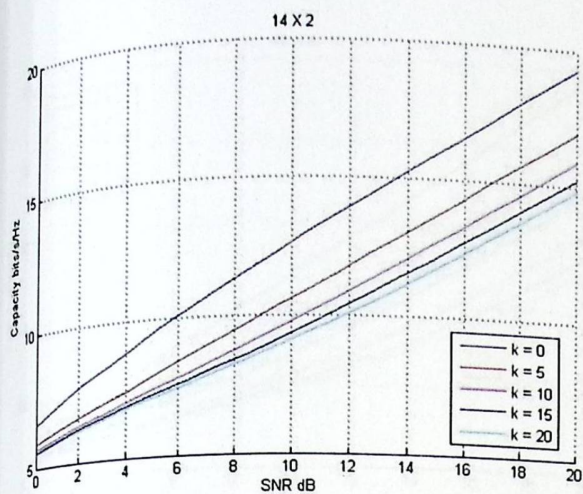


Fig 3.6.23: capacity Vs. SNR for 14x2

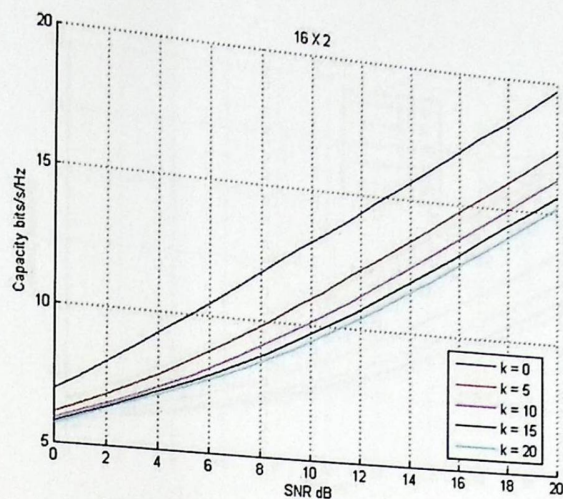


Fig 3.6.24: capacity Vs. SNR for 16x2

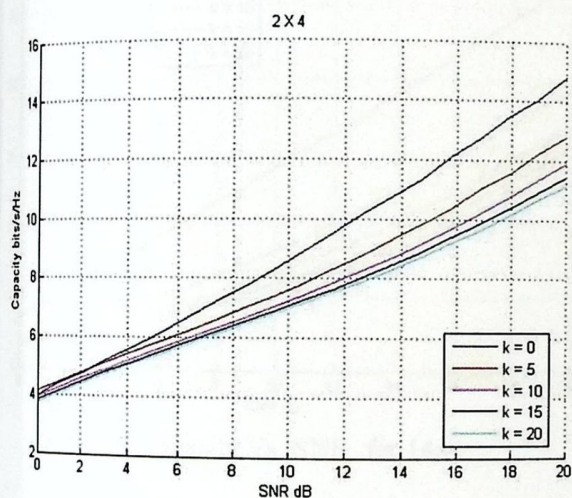


Fig 3.6.25: capacity Vs. SNR for 2x4

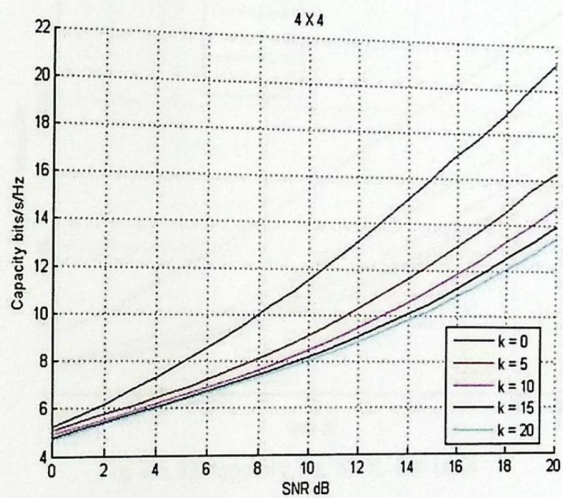


Fig 3.6.26: capacity Vs. SNR for 4x4

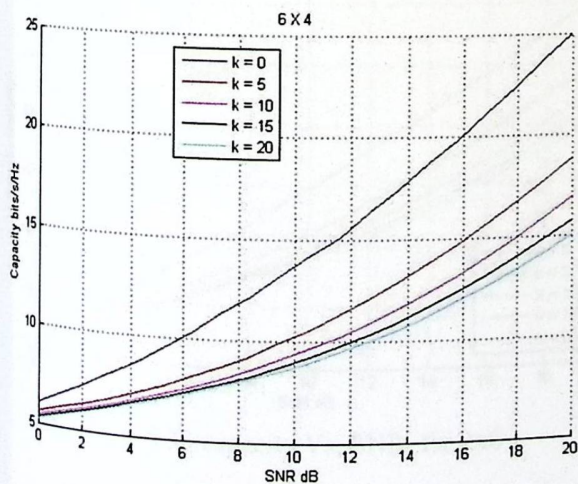


Fig 3.6.27: capacity Vs. SNR for 6x4

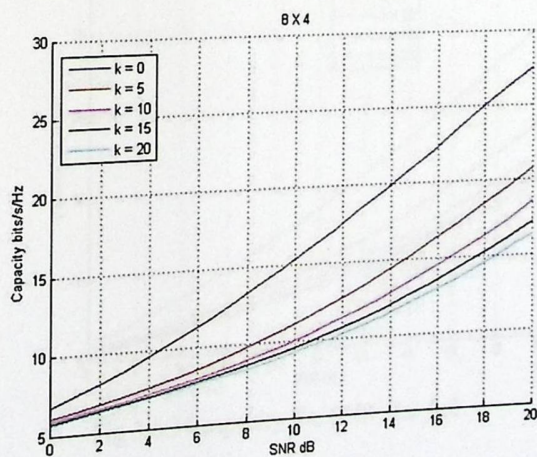


Fig 3.6.28: capacity Vs. SNR for 8x4

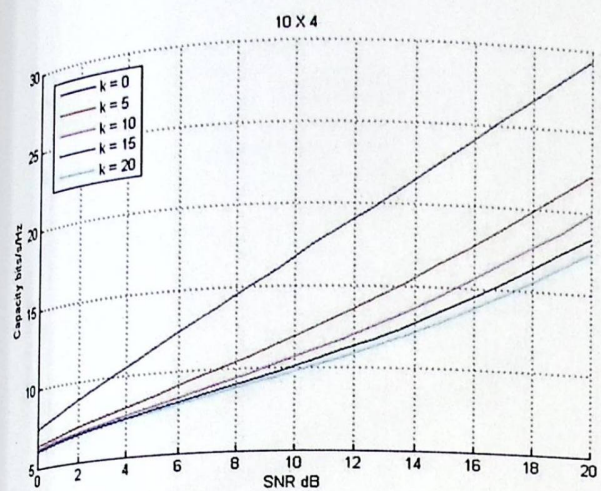


Fig 3.6.29: capacity Vs. SNR for 10x4

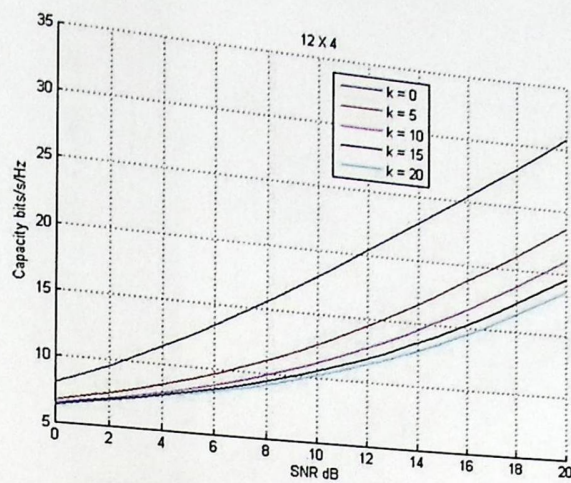


Fig 3.6.30: capacity Vs. SNR for 12x4

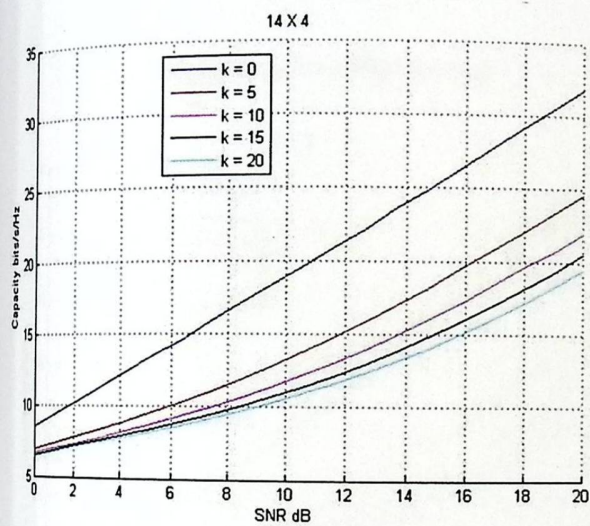


Fig 3.6.31: capacity Vs. SNR for 14x4

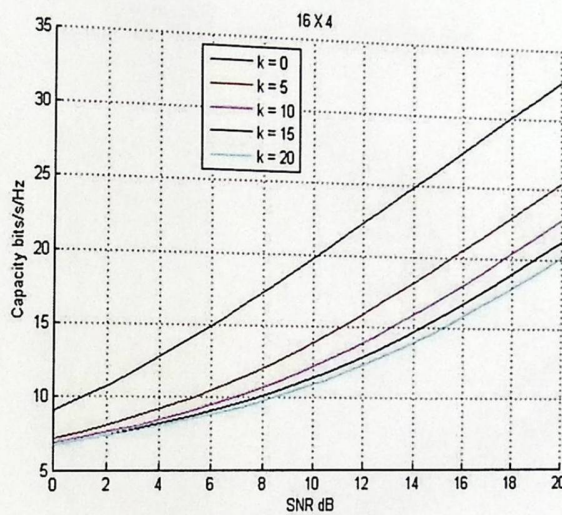


Fig 3.6.32: capacity Vs. SNR for 16x4

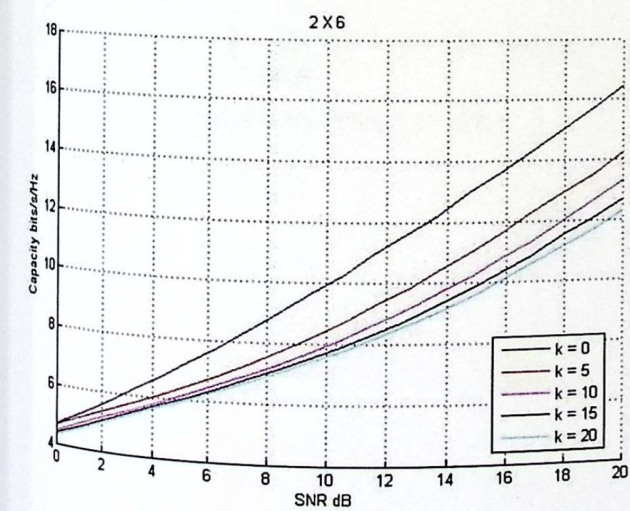


Fig 3.6.33: capacity Vs. SNR for 2x6

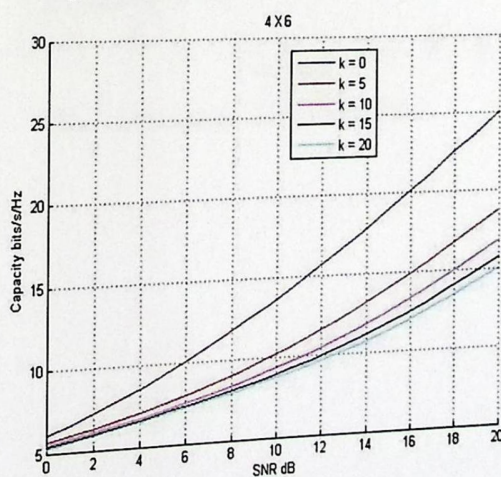


Fig 3.6.34: capacity Vs. SNR for 4x6

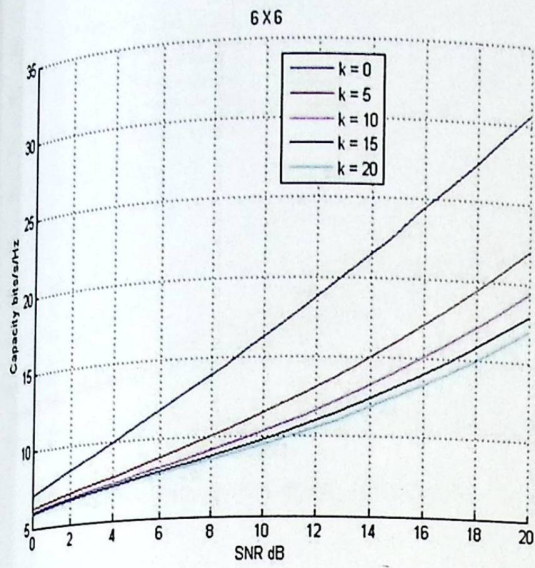


Fig 3.6.35: capacity Vs. SNR for 6x6

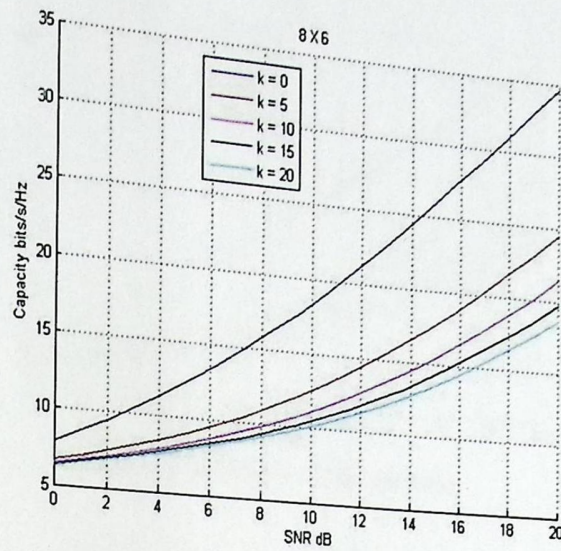


Fig 3.6.36: capacity Vs. SNR for 8x6

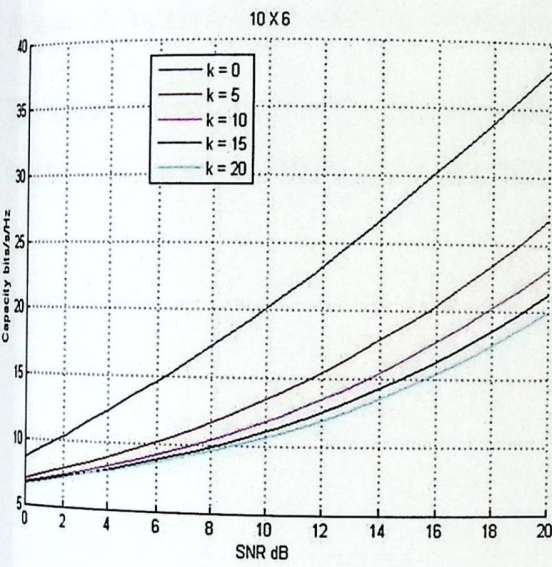


Fig 3.6.37: capacity Vs. SNR for 10x6

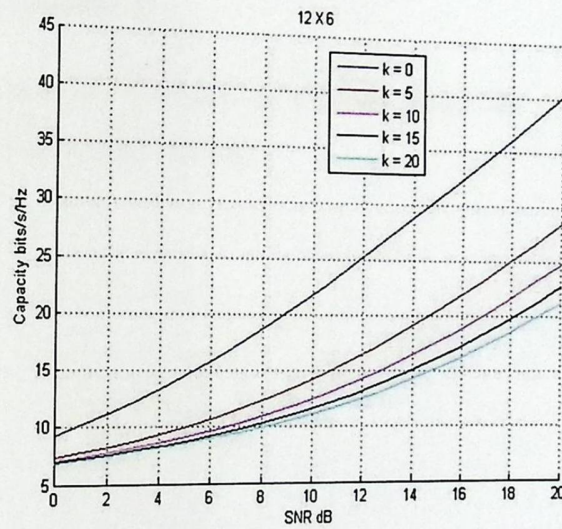


Fig 3.6.38: capacity Vs. SNR for 12x6

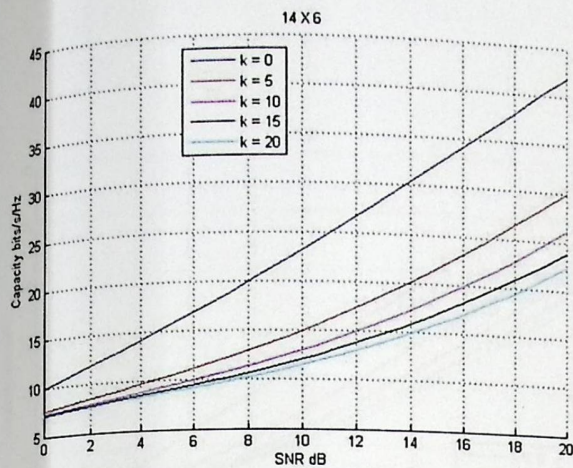


Fig 3.6.39:capacity Vs. SNR for 14x6

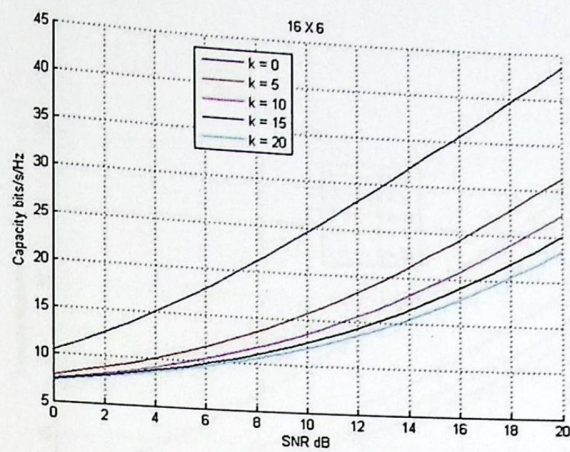


Fig 3.6.40:capacity Vs. SNR for 16x6

Figures 3.6.17 to 3.6.38 shows the relation between the offered ergodic capacity and the SNR for different K-factor values and for different antennas configurations.

We notice the reduction in the capacity as the value of K increases, also we notice the enhancement in the capacity as we use more transmit and receive antennas.

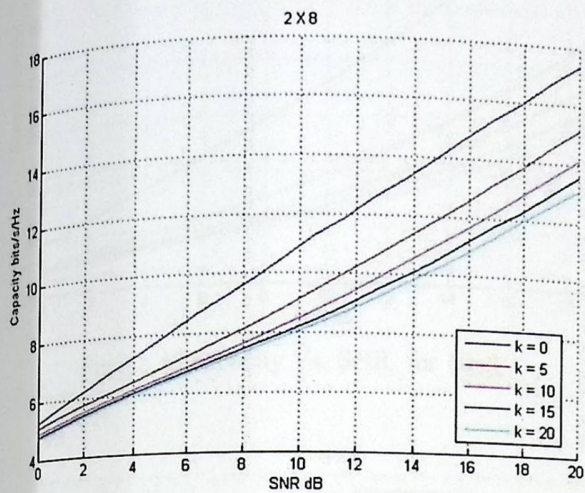


Fig 3.6.41: capacity Vs. SNR for 2x8

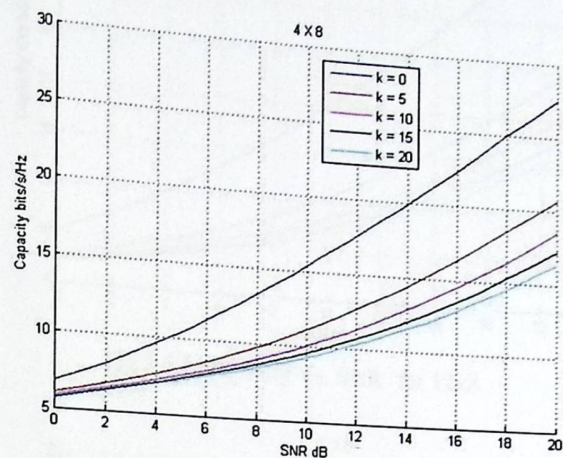


Fig 3.6.42: capacity Vs. SNR for 4x8

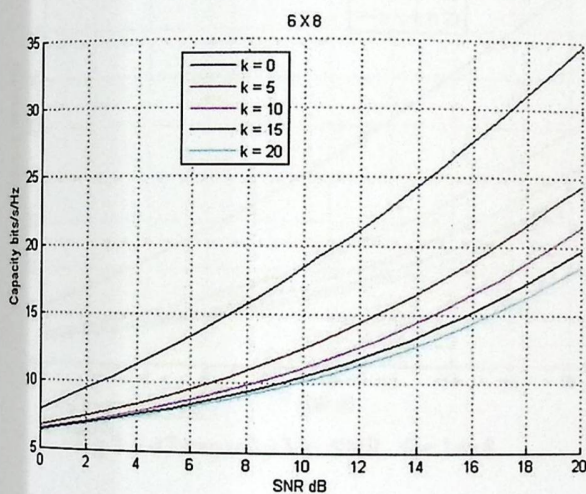


Fig 3.6.43: capacity Vs. SNR for 6x8

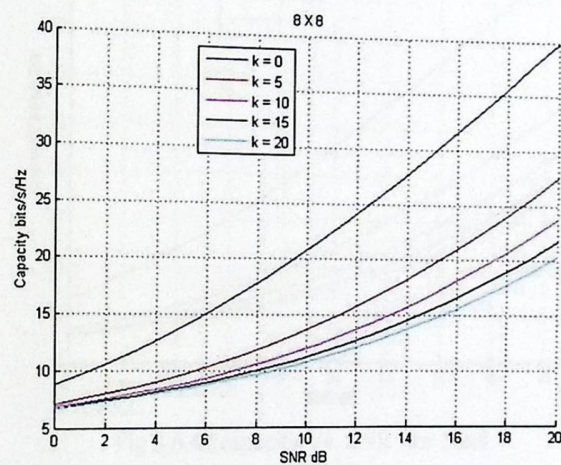


Fig 3.6.44: capacity Vs. SNR for 8x8

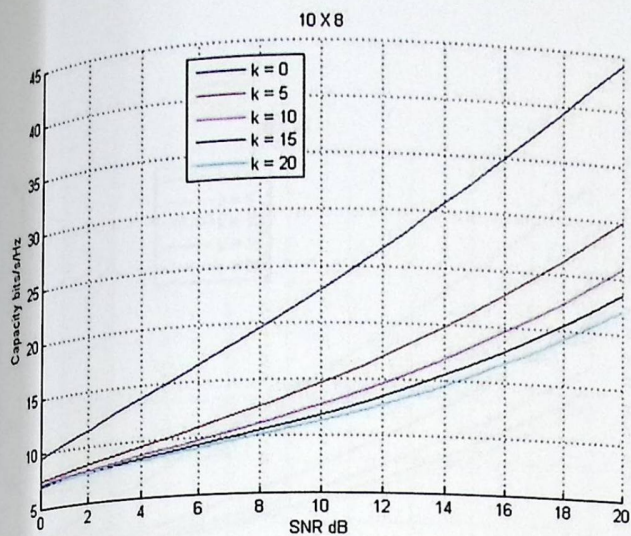


Fig 3.6.45: capacity Vs. SNR for 10x8

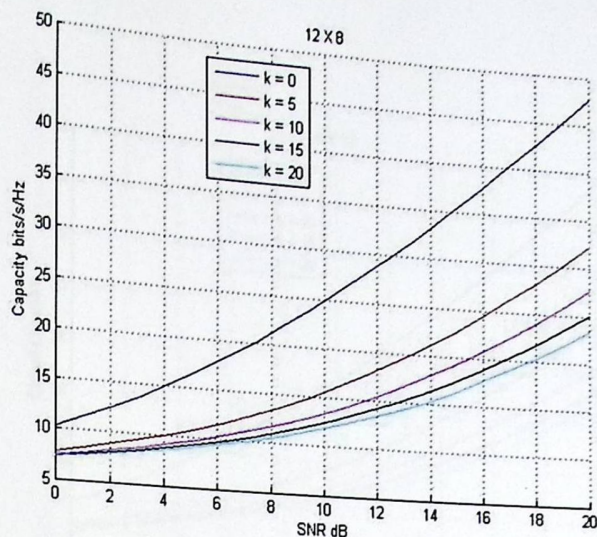


Fig 3.6.46: capacity Vs. SNR for 12x8

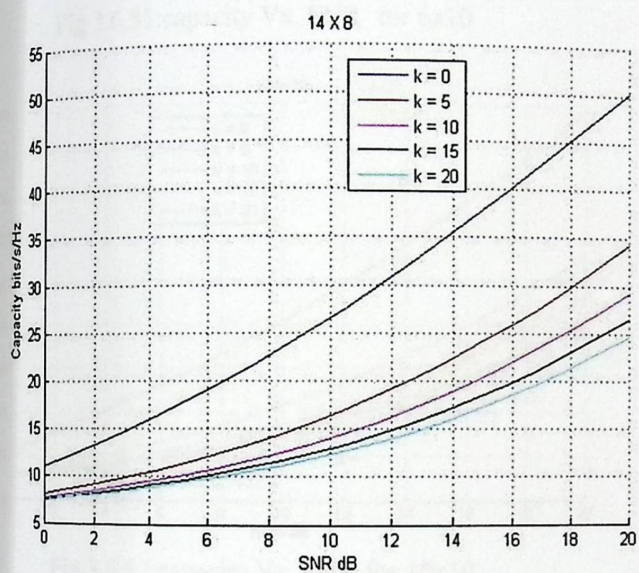


Fig 3.6.47: capacity Vs. SNR for 14x8

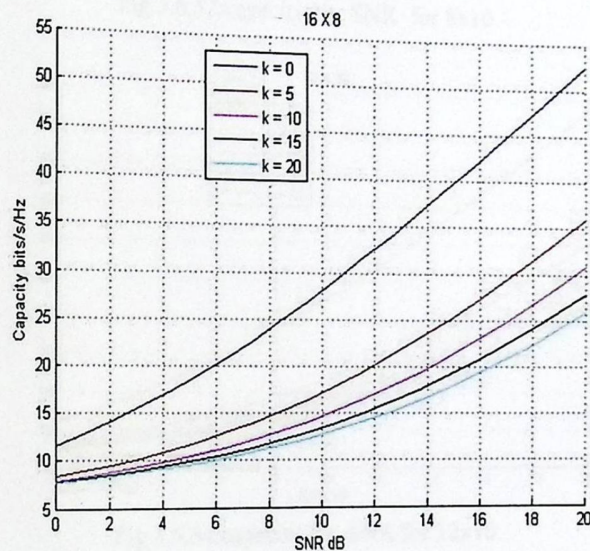


Fig 3.6.48: capacity Vs. SNR for 16x8

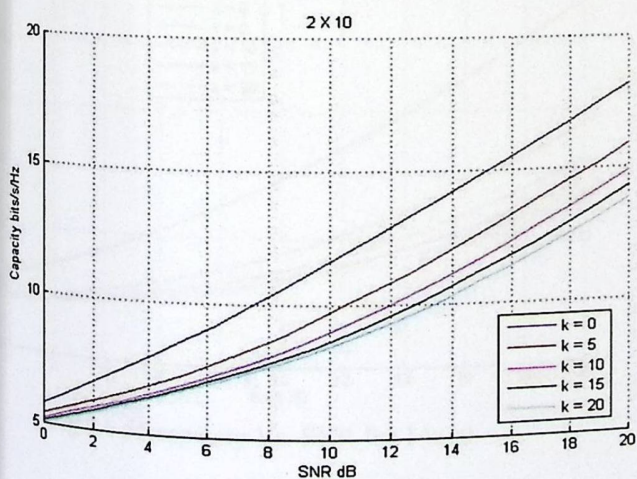


Fig 3.6.49: capacity Vs. SNR for 2x10

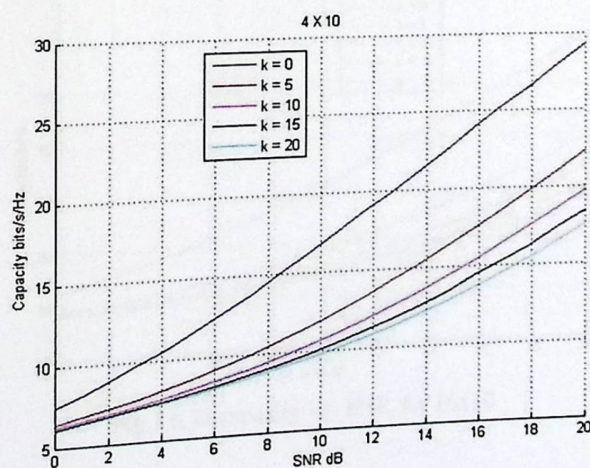


Fig 3.6.50: capacity Vs. SNR for 4x10

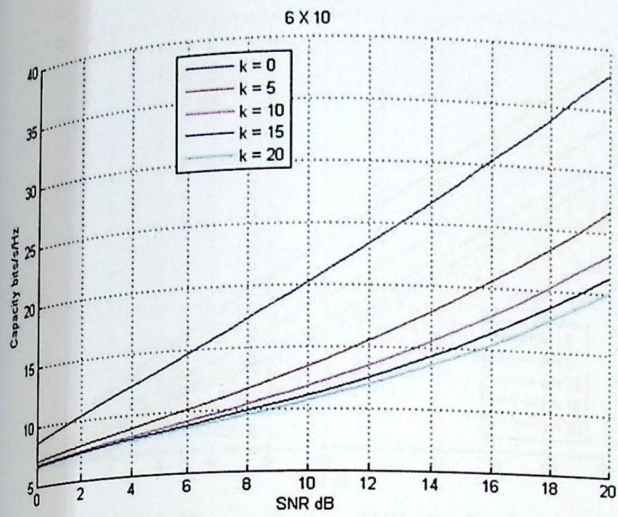


Fig 3.6.51: capacity Vs. SNR for 6x10

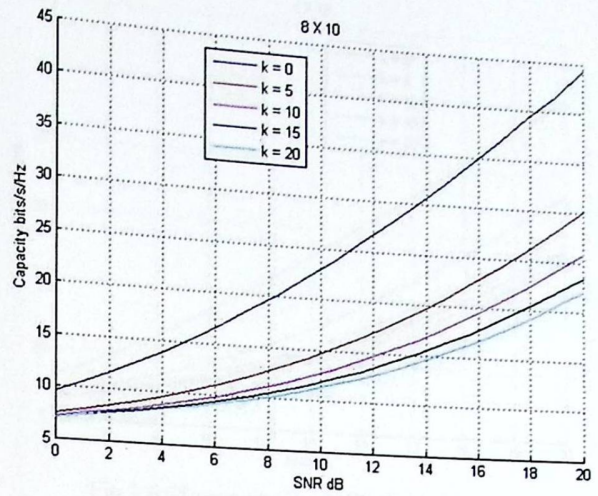


Fig 3.6.52: capacity Vs. SNR for 8x10

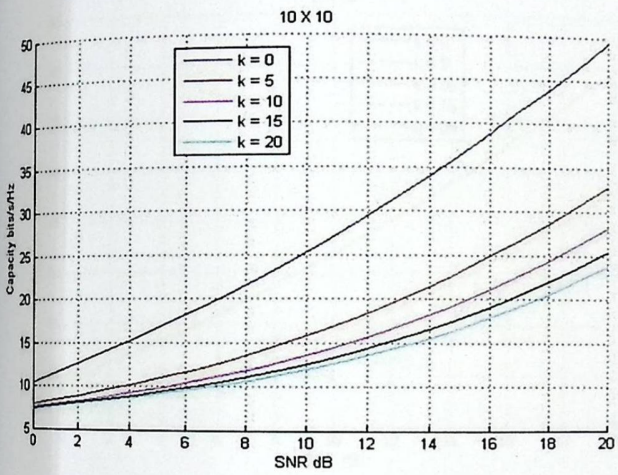


Fig 3.6.53: capacity Vs. SNR for 10x10

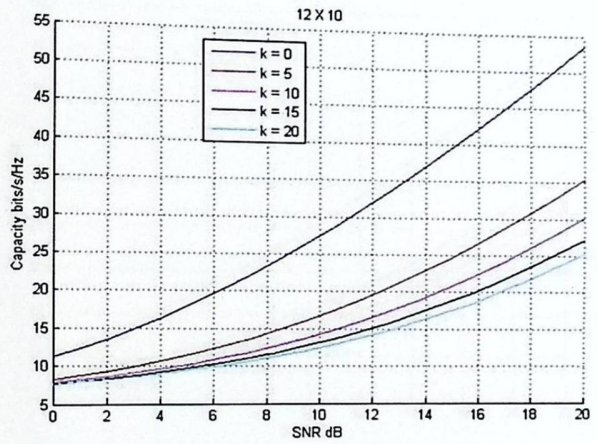


Fig 3.6.54: capacity Vs. SNR for 12x10

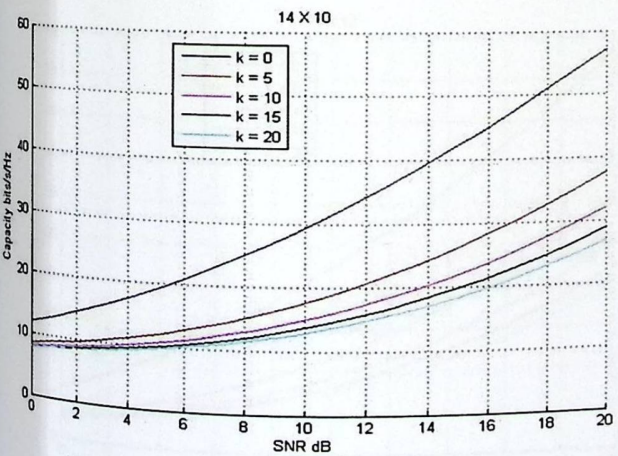


Fig 3.6.55: capacity Vs. SNR for 14x10

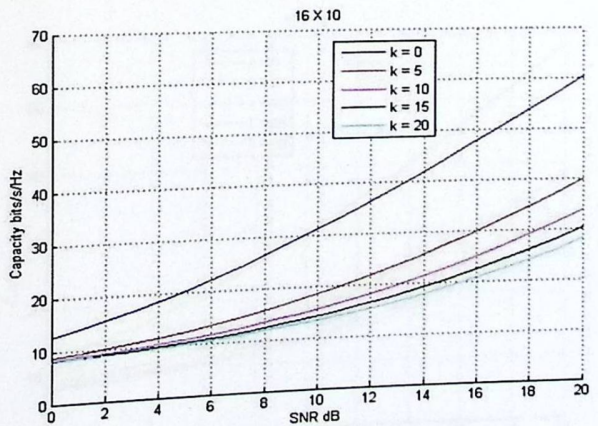


Fig 3.6.56: capacity Vs. SNR for 16x10

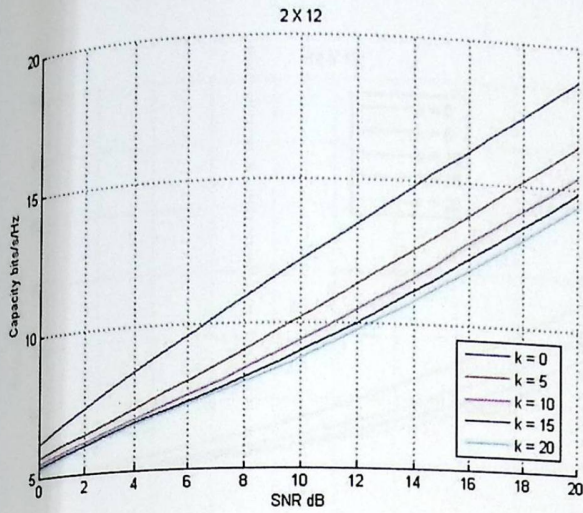


Fig 3.6.57: capacity Vs. SNR for 2x12

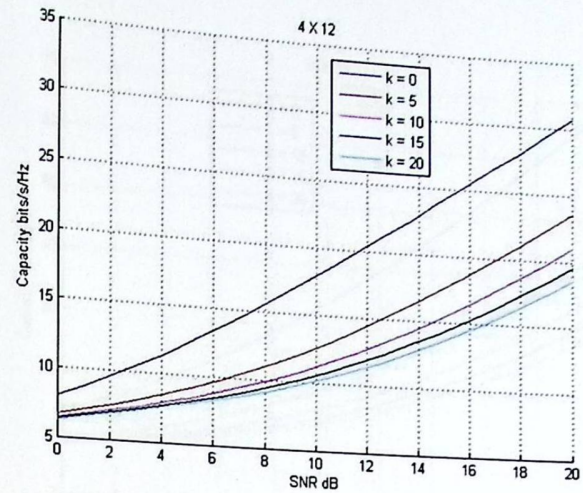


Fig 3.6.58: capacity Vs. SNR for 4x12

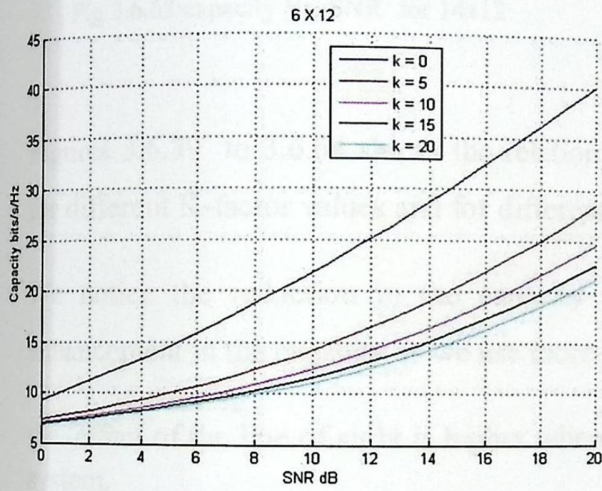


Fig 3.6.59: capacity Vs. SNR for 6x12

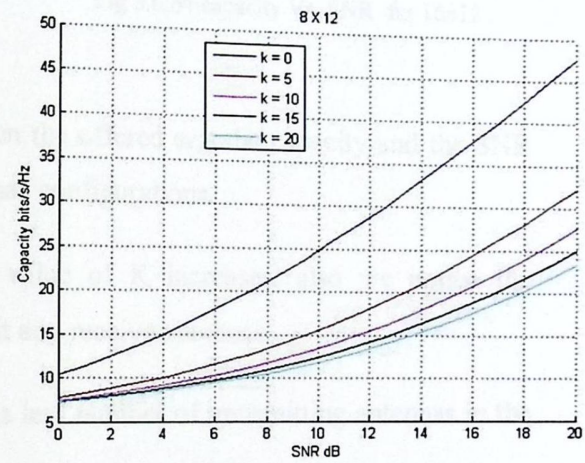


Fig 3.6.60: capacity Vs. SNR for 8x12

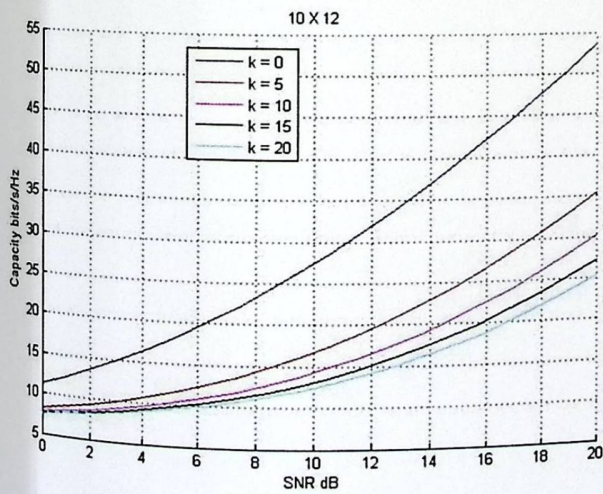


Fig 3.6.61: capacity Vs. SNR for 10x12

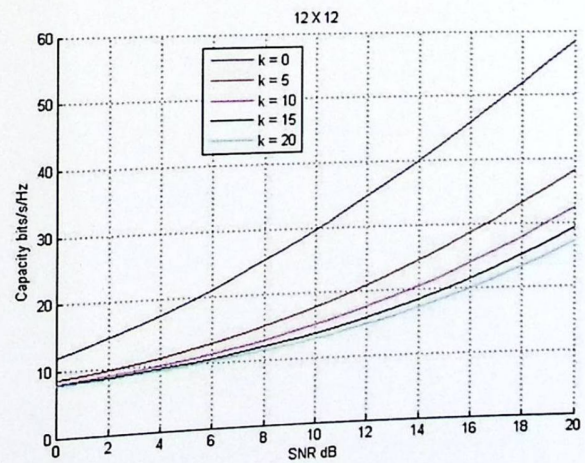


Fig 3.6.62: capacity Vs. SNR for 12x12

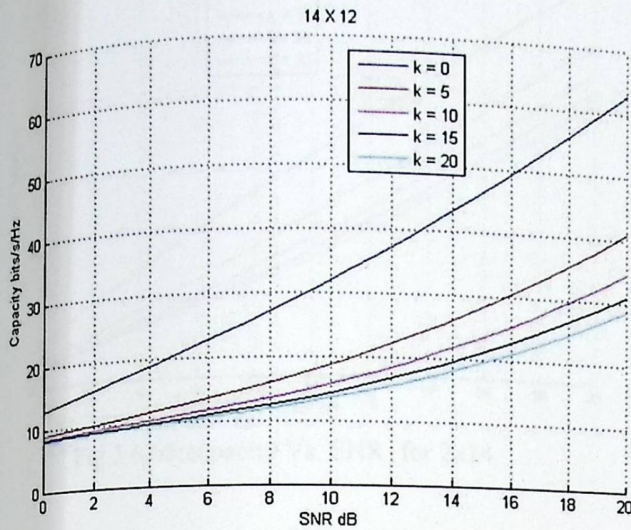


Fig 3.6.63:capacity Vs. SNR for 14x12

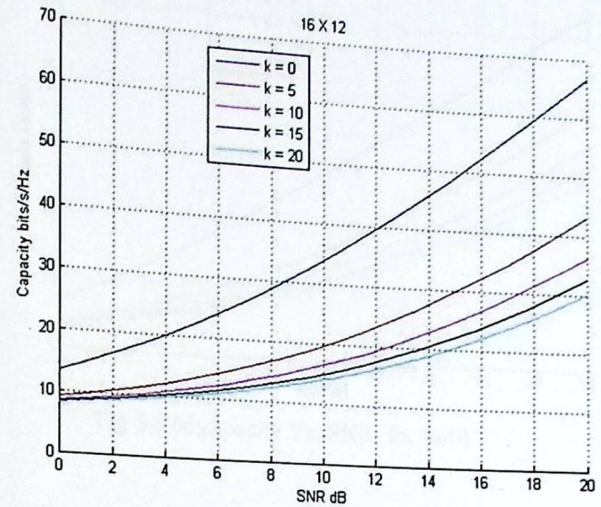


Fig 3.6.64:capacity Vs. SNR for 16x12

Figures 3.6.39 to 3.6.64 shows the relation between the offered ergodic capacity and the SNR for different K-factor values and for different antennas configurations.

We notice the reduction in the capacity as the value of K increases, also we notice the enhancement in the capacity as we use more transmit and receive antennas.

the effect of the line of sight is higher when there is less number of transmitting antennas in the system.

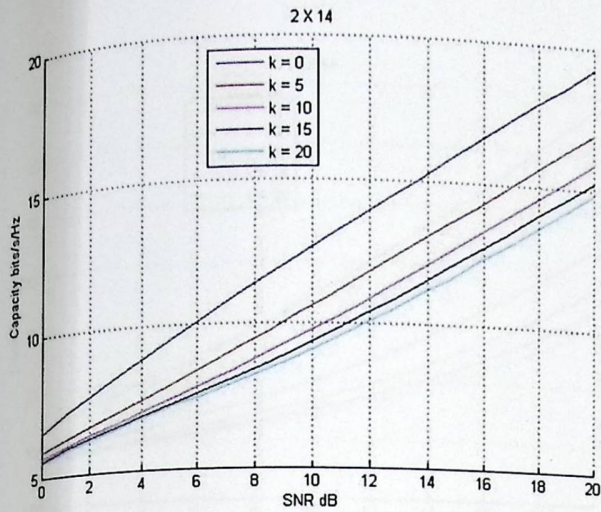


Fig 3.6.65: capacity Vs. SNR for 2x14

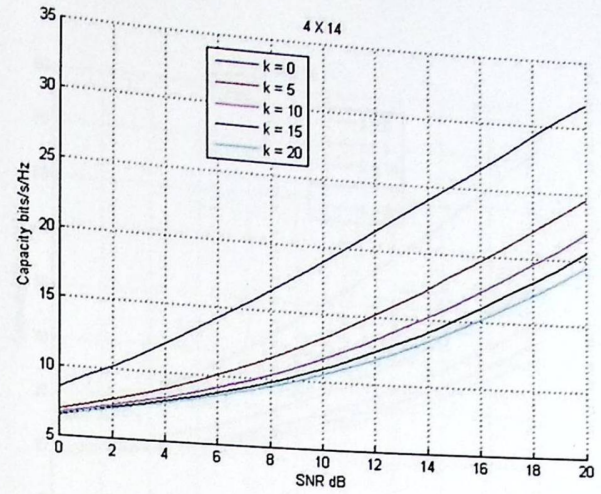


Fig 3.6.66: capacity Vs. SNR for 4x14

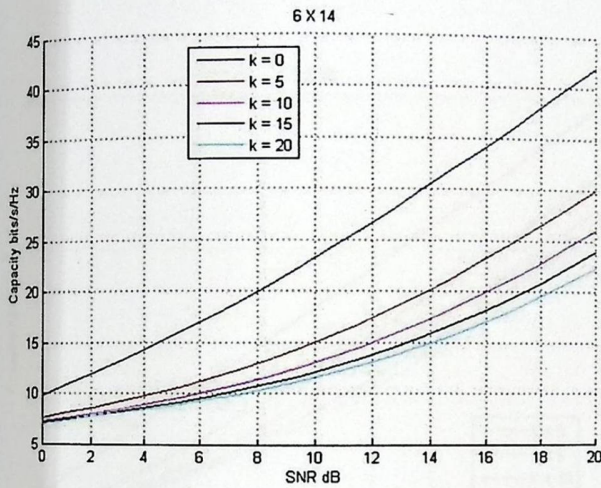


Fig 3.6.67: capacity Vs. SNR for 6x14

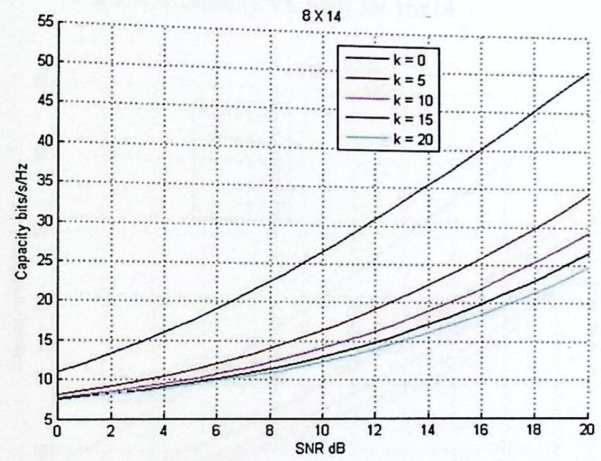


Fig 3.6.68: capacity Vs. SNR for 8x14

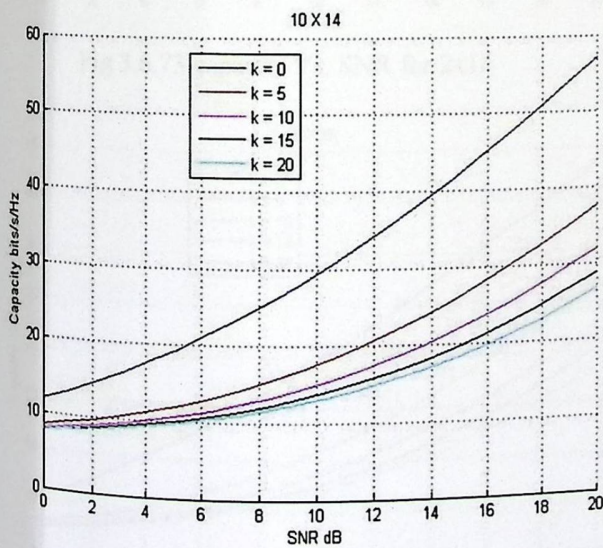


Fig 3.6.69: capacity Vs. SNR for 10x14

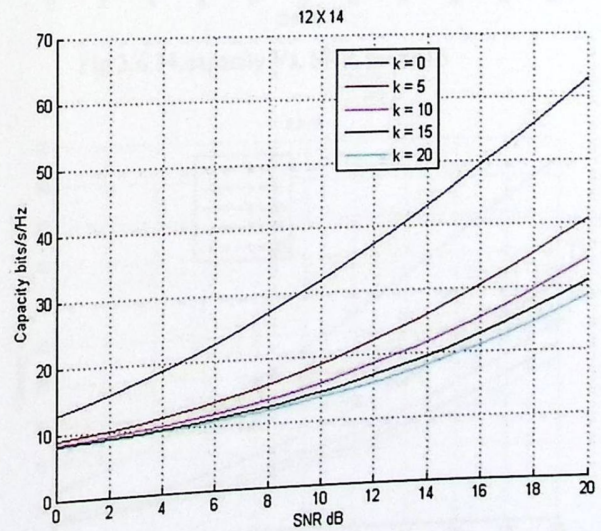


Fig 3.6.70: capacity Vs. SNR for 12x14

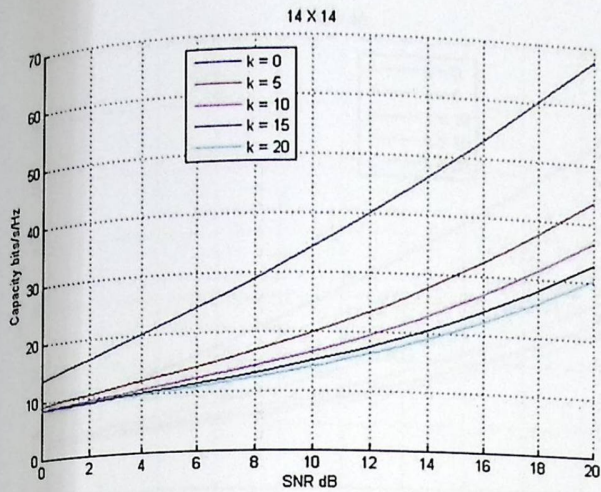


Fig 3.6.71: capacity Vs. SNR for 14x14

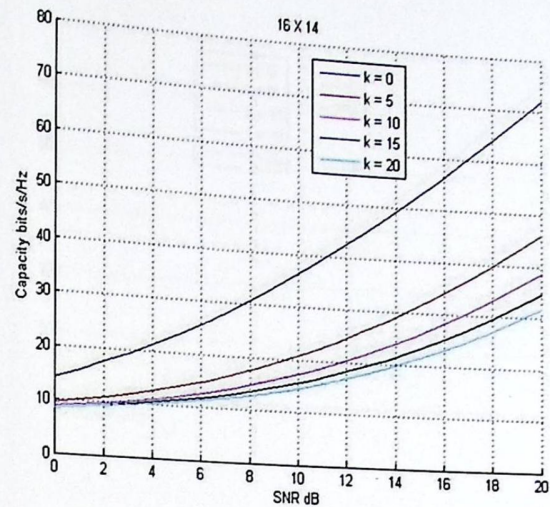


Fig 3.6.72: capacity Vs. SNR for 16x14

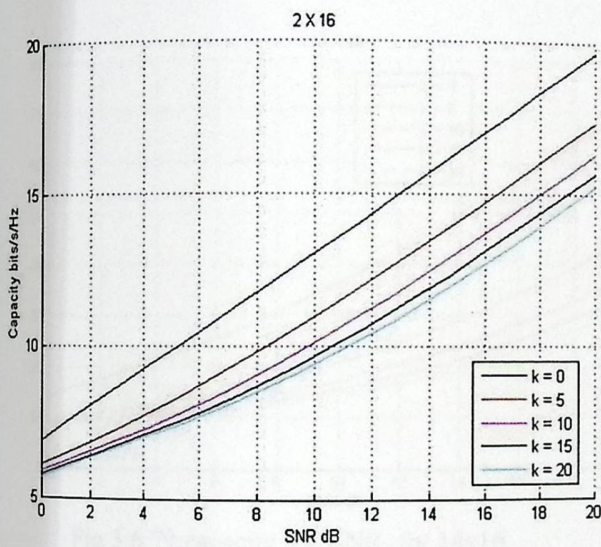


Fig 3.6.73: capacity Vs. SNR for 2x16

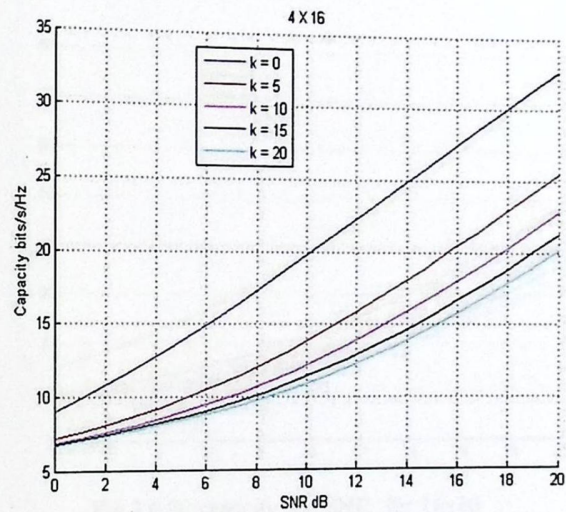


Fig 3.6.74: capacity Vs. SNR for 4x16

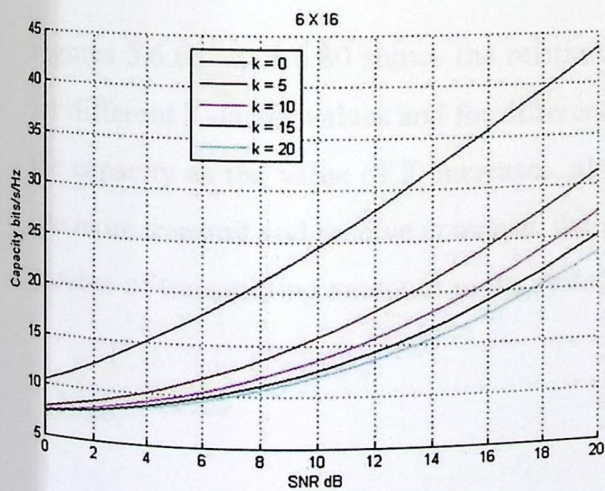


Fig 3.6.75: capacity Vs. SNR for 6x16

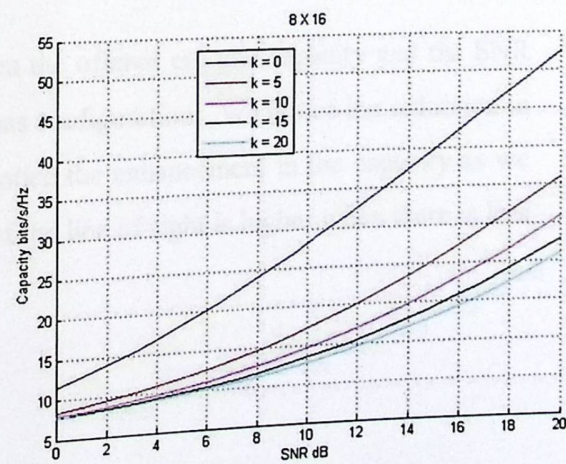


Fig 3.6.76: capacity Vs. SNR for 8x16

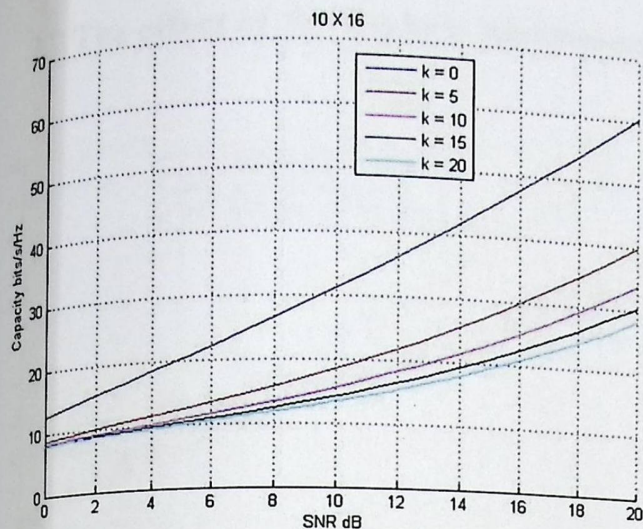


Fig 3.6.77:capacity Vs. SNR for 10x16

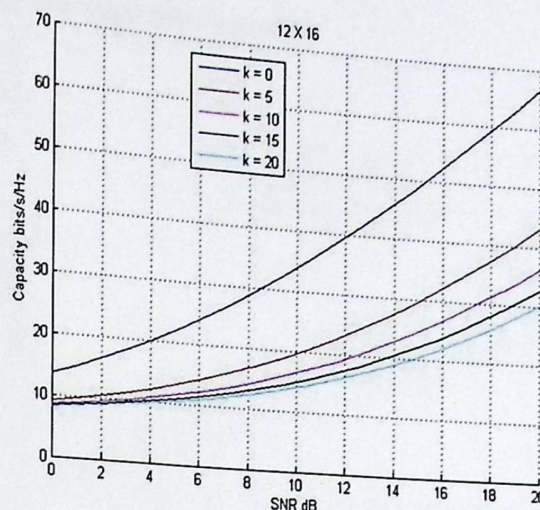


Fig 3.6.78:capacity Vs. SNR for 12x16

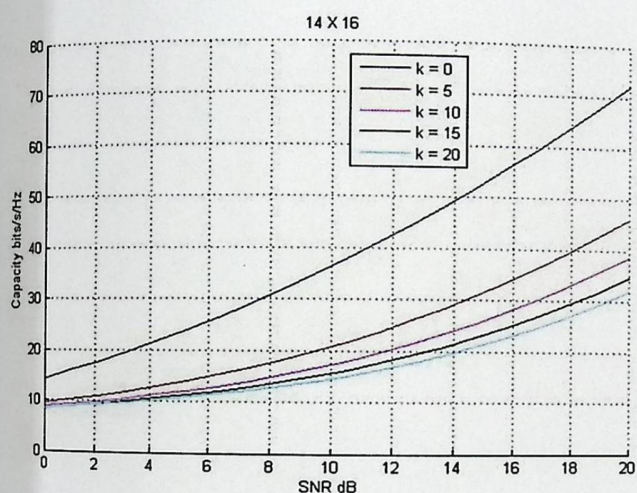


Fig 3.6.79:capacity Vs. SNR for 14x16

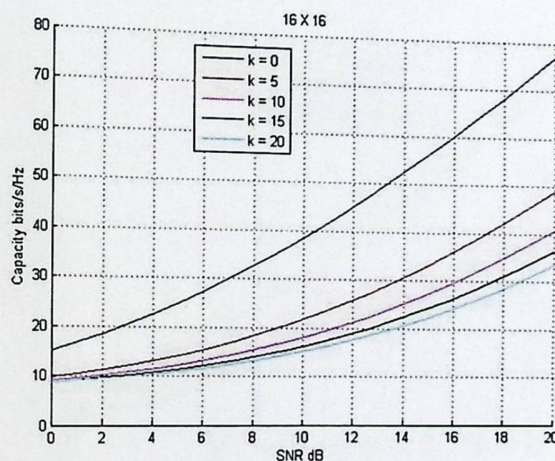


Fig 3.6.80:capacity Vs. SNR for 16x16

Figures 3.6.65 to 3.6.80 shows the relation between the offered ergodic capacity and the SNR for different K-factor values and for different antennas configurations. We notice the reduction in the capacity as the value of K increases, also we notice the enhancement in the capacity as we use more transmit and receive antennas. the effect of the line of sight is higher when there is less number of transmitting antennas in the system.

3.7 The effect of the keyhole phenomena on the ergodic capacity

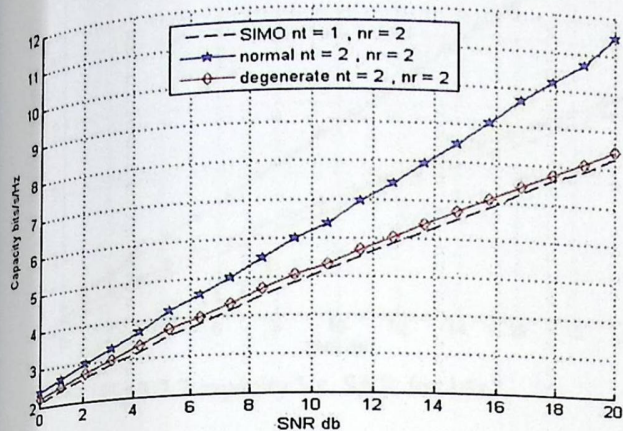


Fig 3.7.1: capacity Vs. SNR for 2x2

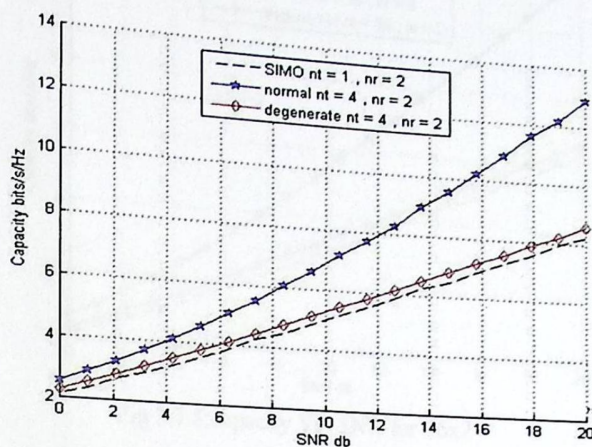


Fig 3.7.2: capacity Vs. SNR for 4x2

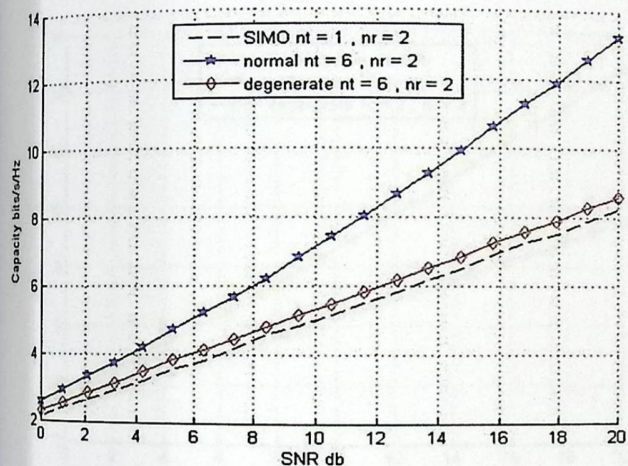


Fig 3.7.3: capacity Vs. SNR for 6x2

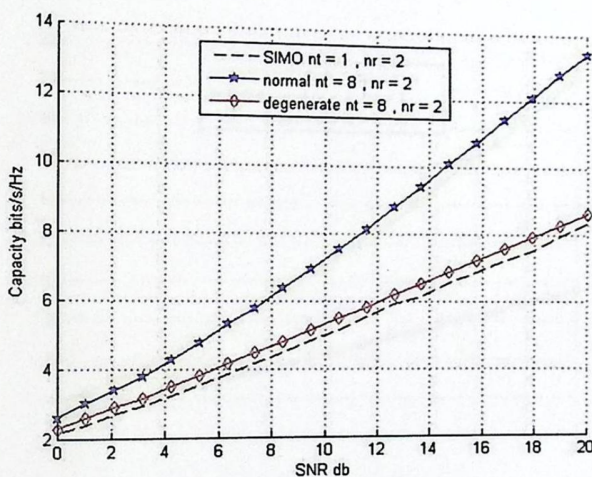


Fig 3.7.4: capacity Vs. SNR for 8x2

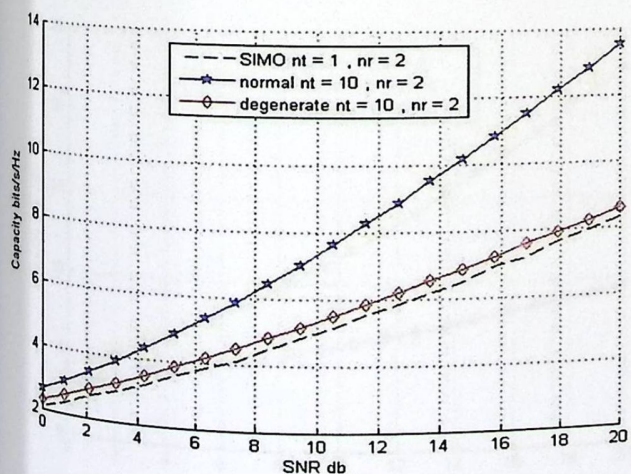


Fig 3.7.5: capacity Vs. SNR for 10x2

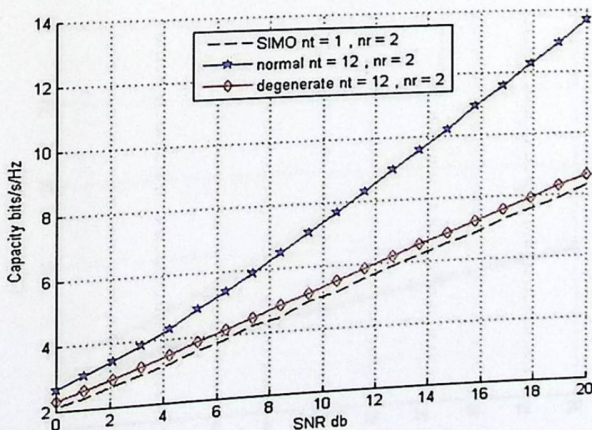


Fig 3.7.6: capacity Vs. SNR for 12x2

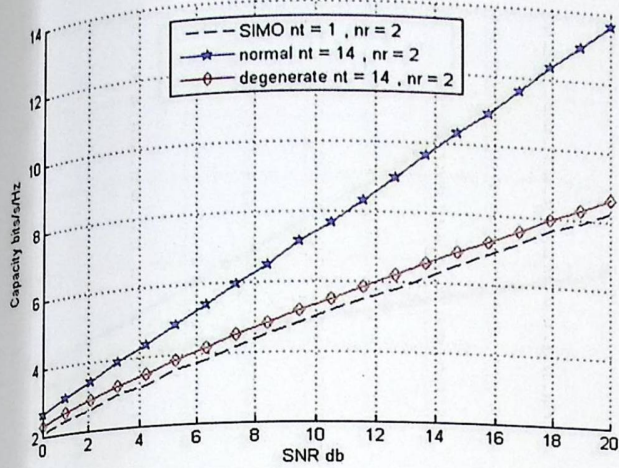


Fig 3.7.7: capacity Vs. SNR for 14x2

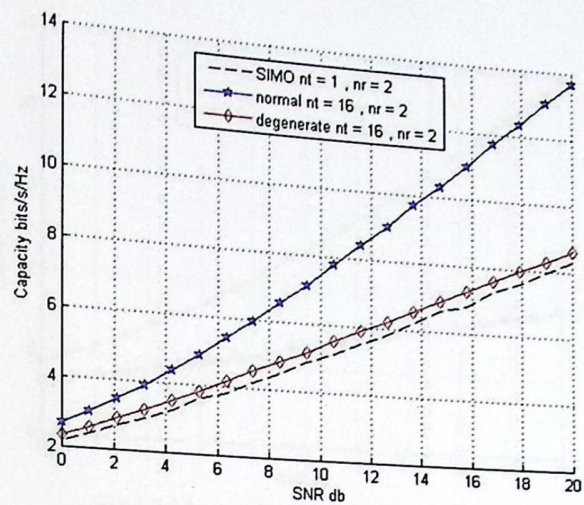


Fig 3.7.8: capacity Vs. SNR for 16x2

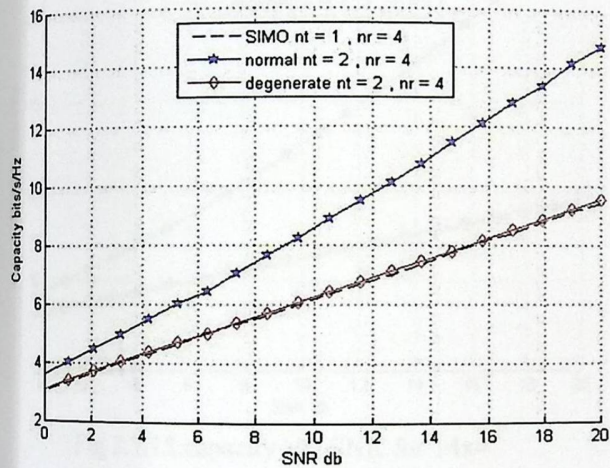


Fig 3.7.9: capacity Vs. SNR for 2x4

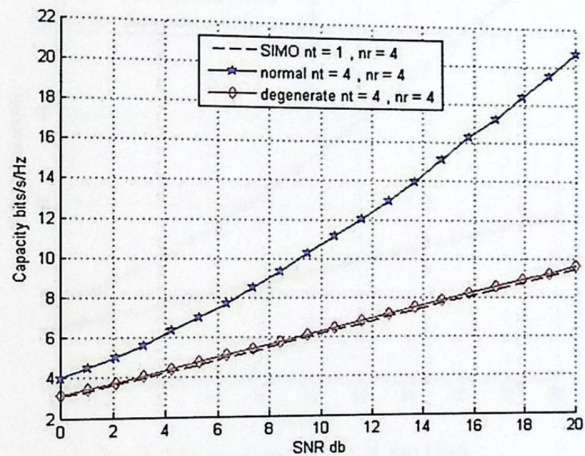


Fig 3.7.10: capacity Vs. SNR for 4x4

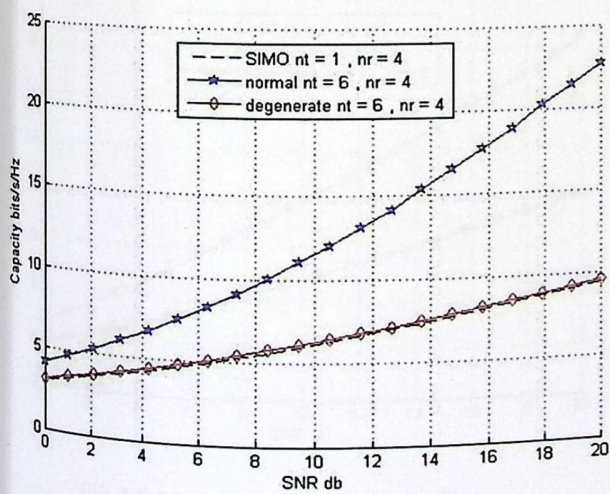


Fig 3.7.11: capacity Vs. SNR for 6x4

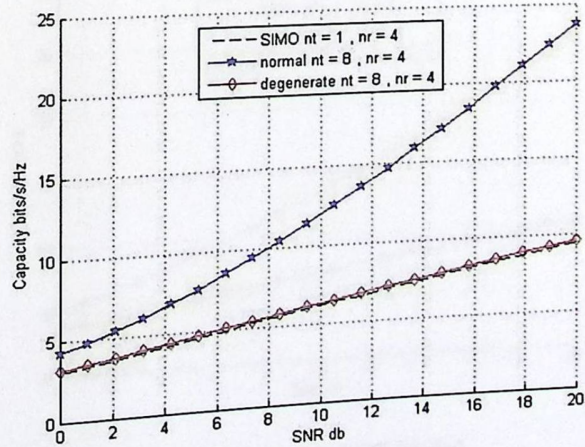


Fig 3.7.12: capacity Vs. SNR for 8x4

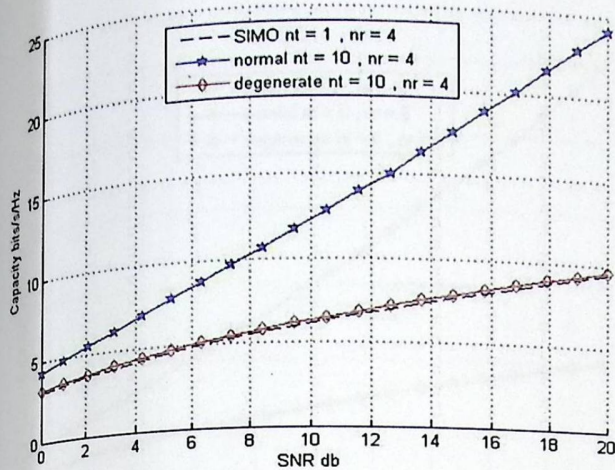


Fig 3.7.13: capacity Vs. SNR for 10x4

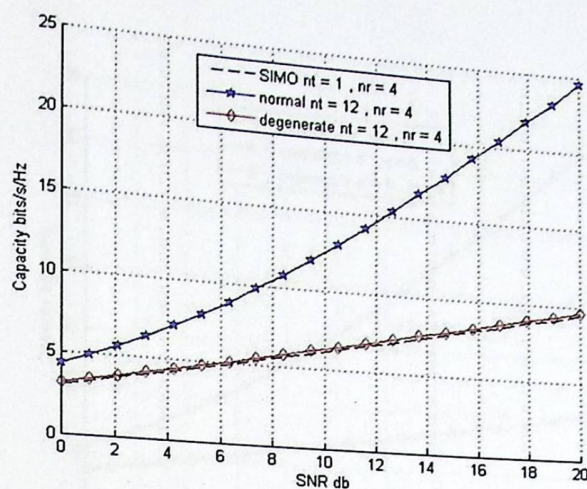


Fig 3.7.14: capacity Vs. SNR for 12x4

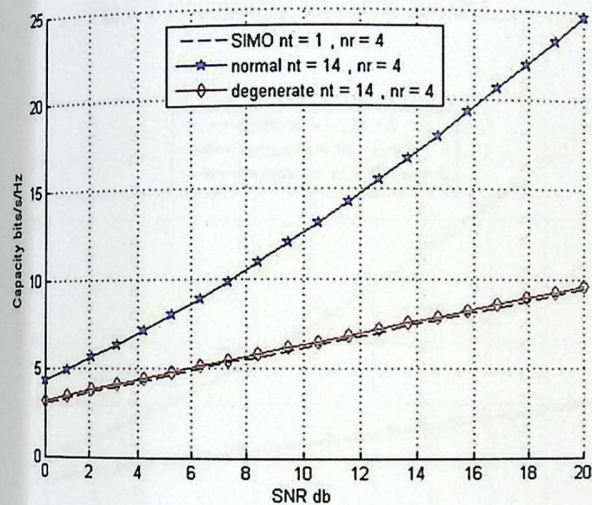


Fig 3.7.15: capacity Vs. SNR for 14x4

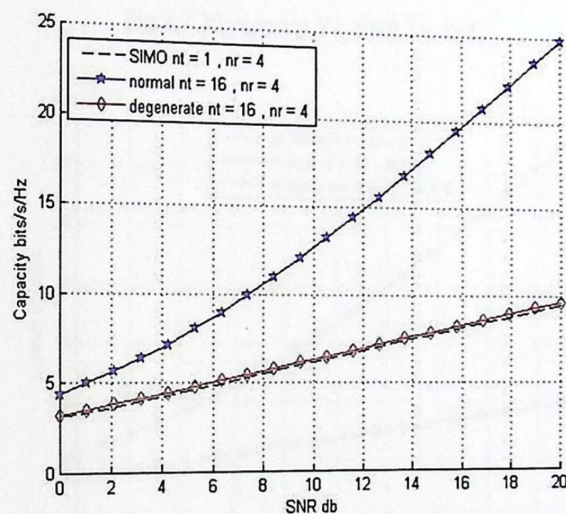


Fig 3.7.16: capacity Vs. SNR for 16x4

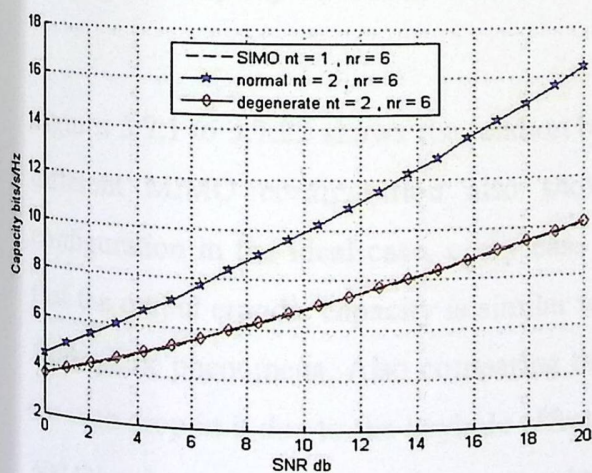


Fig 3.7.17: capacity Vs. SNR for 2x4

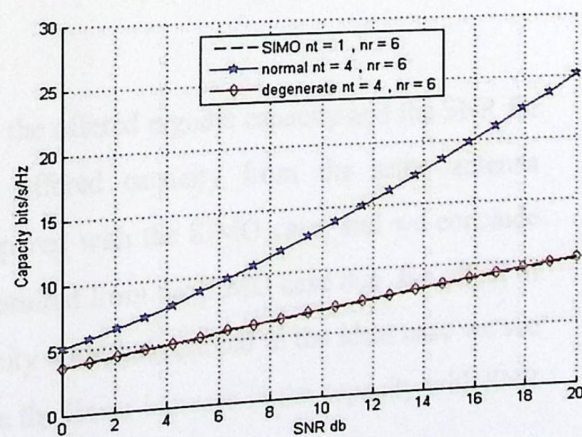


Fig 3.7.18: capacity Vs. SNR for 4x4

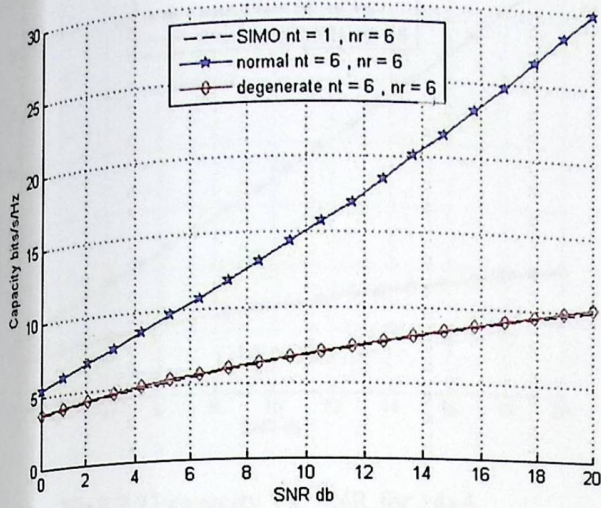


Fig 3.7.19:capacity Vs. SNR for 6x4

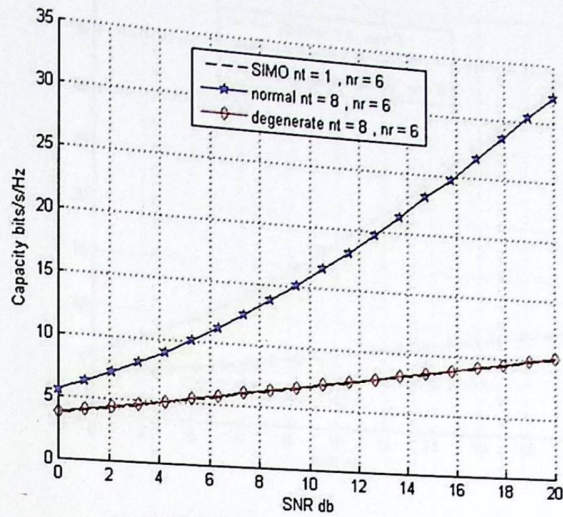


Fig 3.7.20:capacity Vs. SNR for 8x4

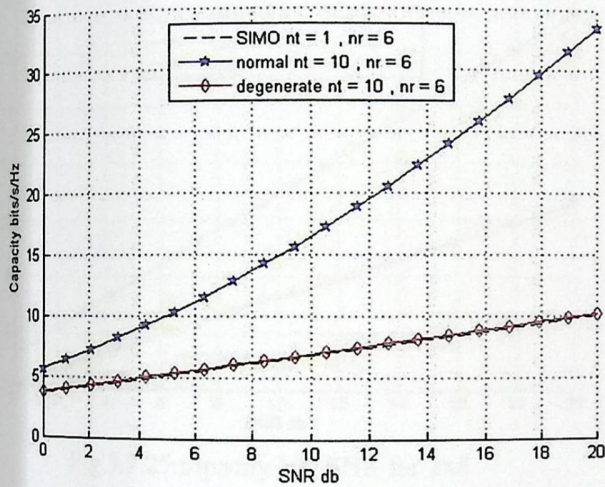


Fig 3.7.21:capacity Vs. SNR for 10x4

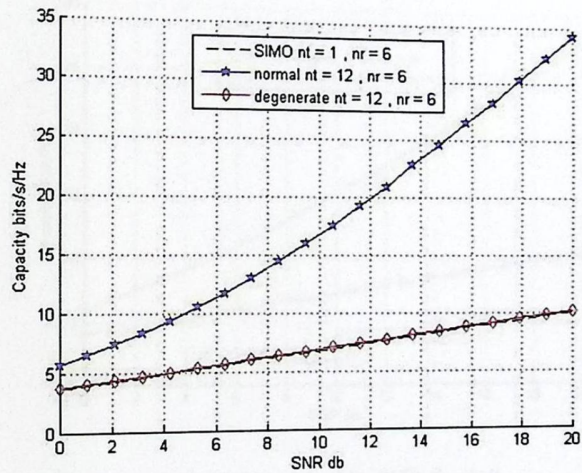


Fig 3.7.22:capacity Vs. SNR for 12x4

Figures 3.7.1 to 3.7.22 shows the relation between the offered ergodic capacity and the SNR for different MIMO configuration also shows the offered capacity from the same antenna configuration in the ideal case, every case is compared with the SIMO case, and we conclude that the output ergodic capacity is similar to that resulted from the SIMO case due the effect of the keyhole phenomena. Also comparing the capacity with that resulted in the ideal case we see the high drop in it due to the keyhole effect, we see the linear increase in the capacity with SNR and the enhancement when using more antennas in the system.

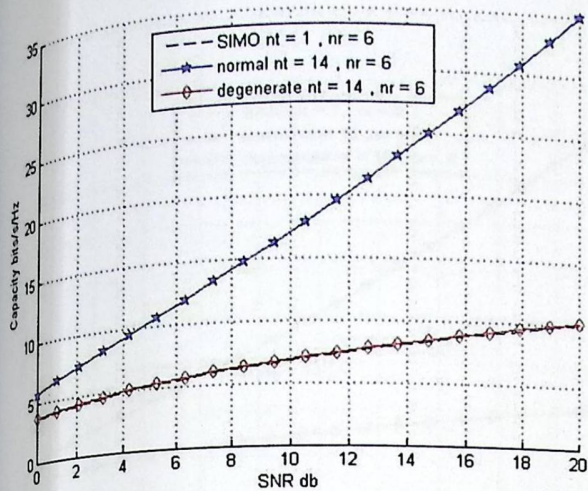


Fig 3.7.23: capacity Vs. SNR for 14x4

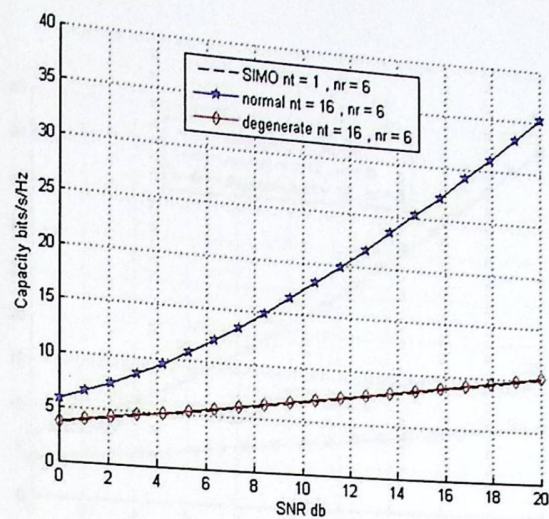


Fig 3.7.24: capacity Vs. SNR for 16x4

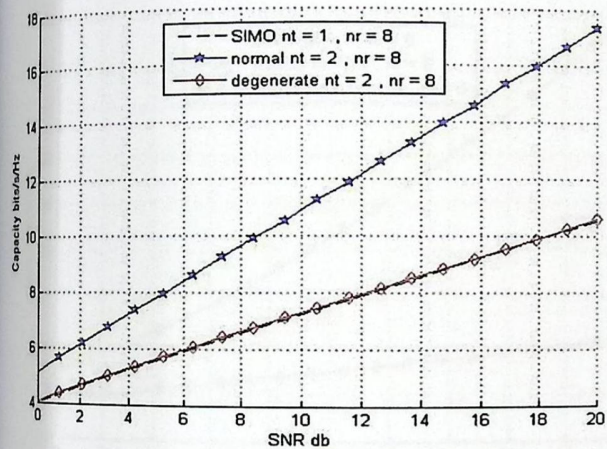


Fig 3.7.25: capacity Vs. SNR for 2x8

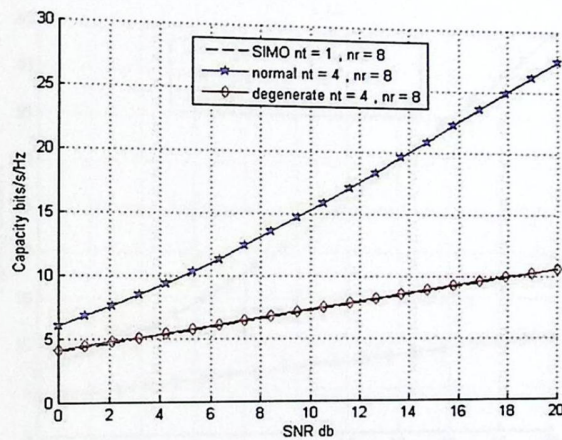


Fig 3.7.26: capacity Vs. SNR for 4x8

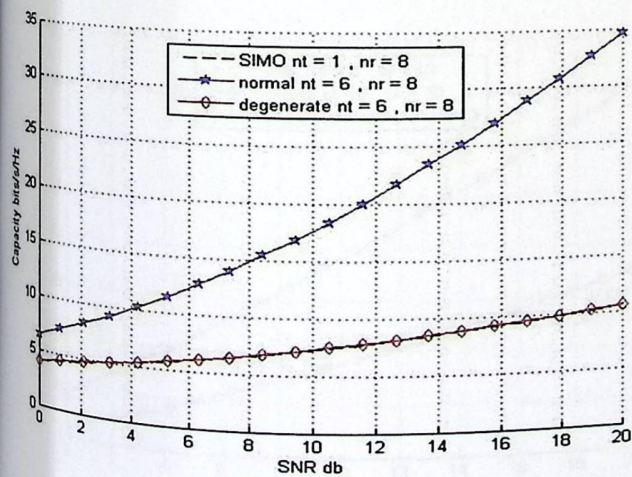


Fig 3.7.27: capacity Vs. SNR for 6x8

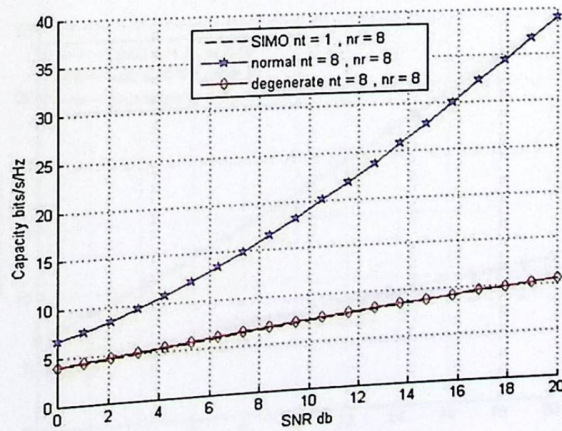


Fig 3.7.28: capacity Vs. SNR for 8x8

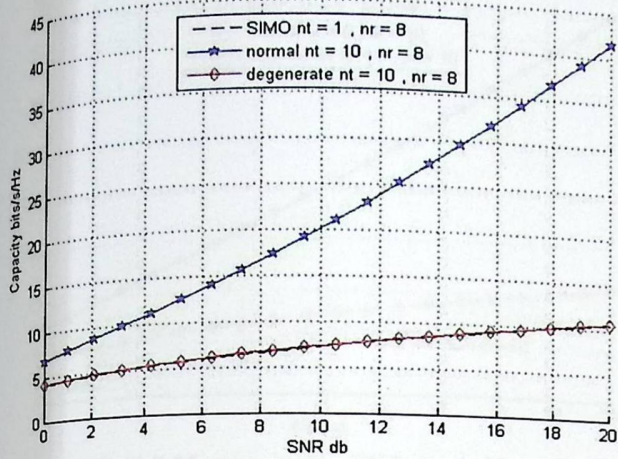


Fig 3.7.29:capacity Vs. SNR for 10x8

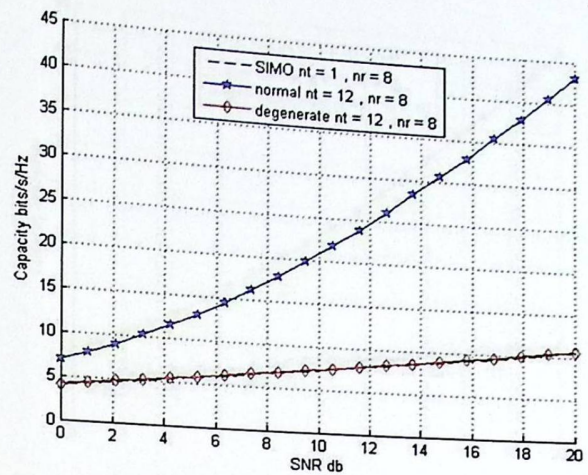


Fig 3.7.30:capacity Vs. SNR for 12x8

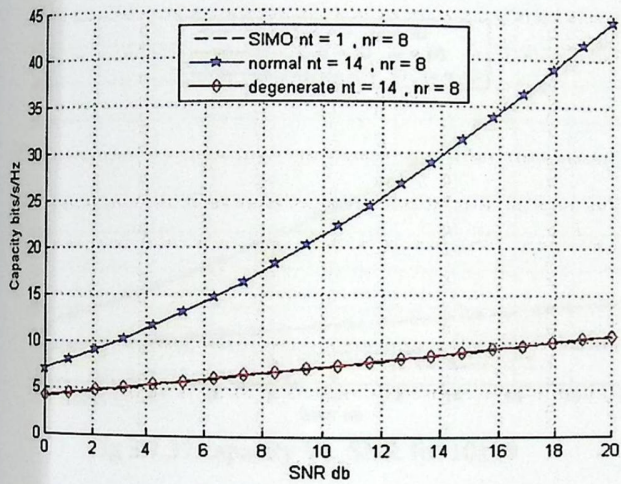


Fig 3.7.31:capacity Vs. SNR for 14x8

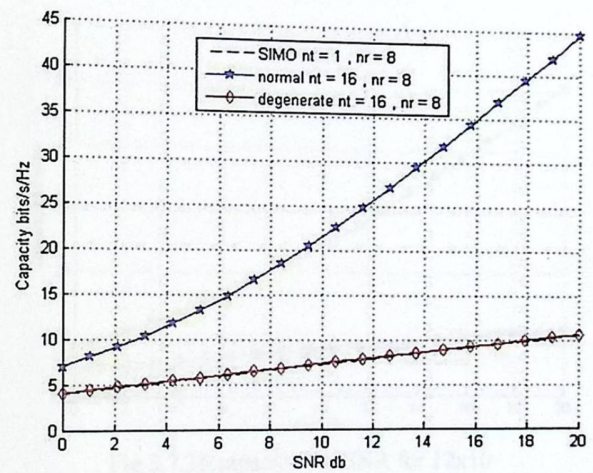


Fig 3.7.32:capacity Vs. SNR for 16x8

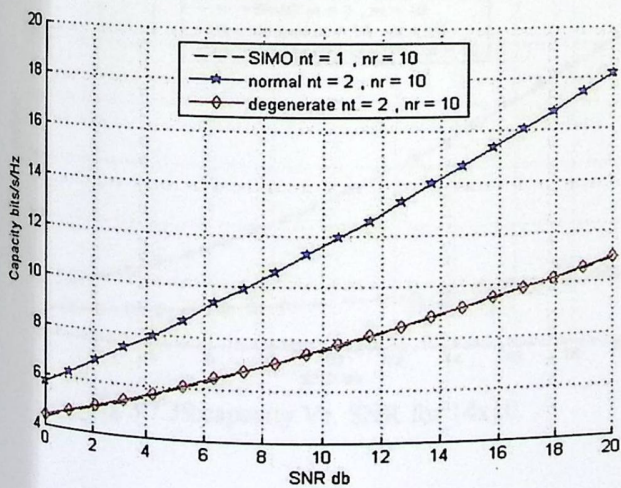


Fig 3.7.33:capacity Vs. SNR for 2x10

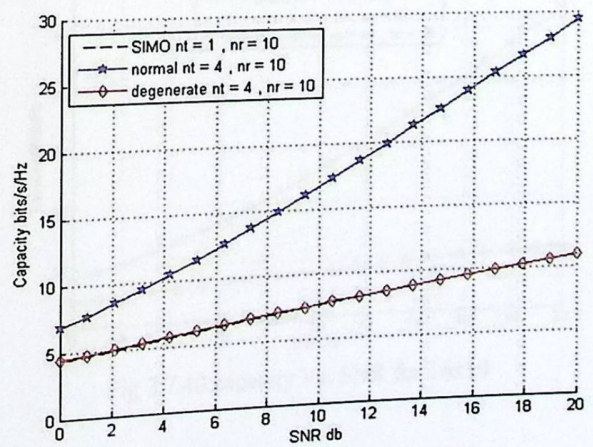


Fig 3.7.34:capacity Vs. SNR for 4x10

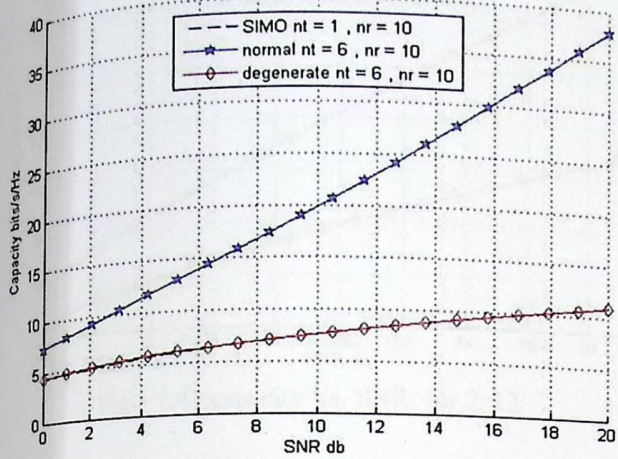


Fig 3.7.35: capacity Vs. SNR for 6x10

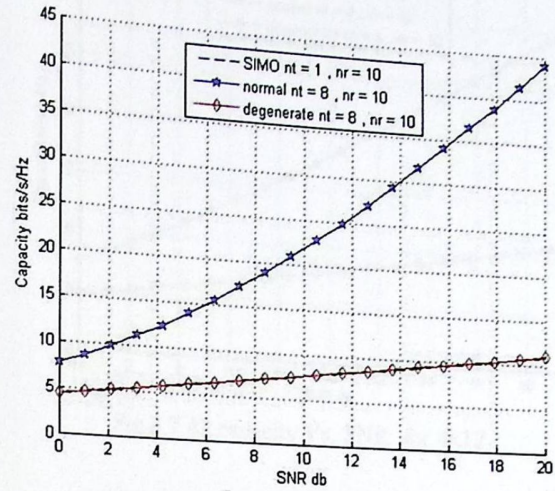


Fig 3.7.36: capacity Vs. SNR for 8x10

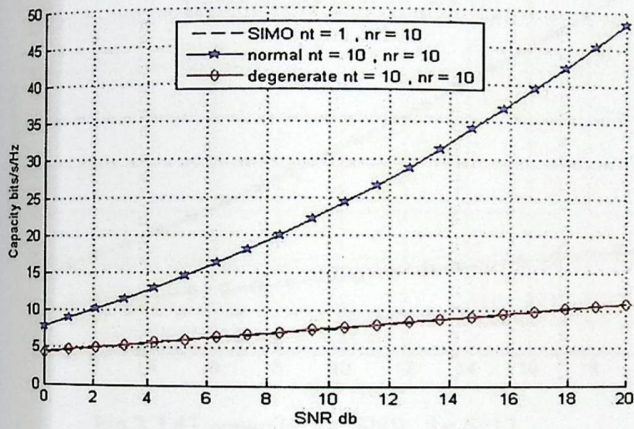


Fig 3.7.37: capacity Vs. SNR for 10x10

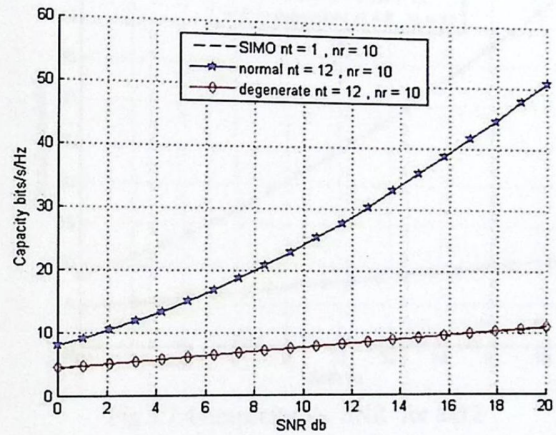


Fig 3.7.38: capacity Vs. SNR for 12x10

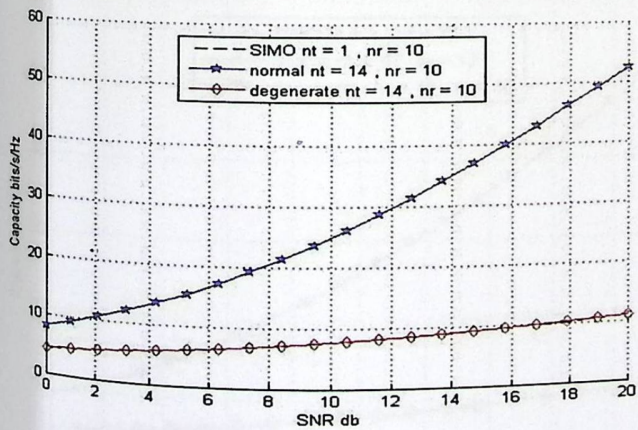


Fig 3.7.39: capacity Vs. SNR for 14x10

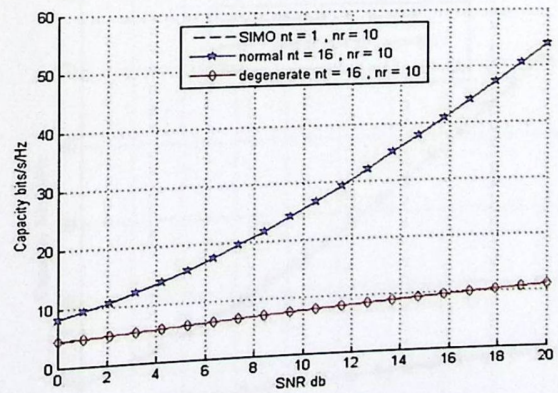


Fig 3.7.40: capacity Vs. SNR for 16x10

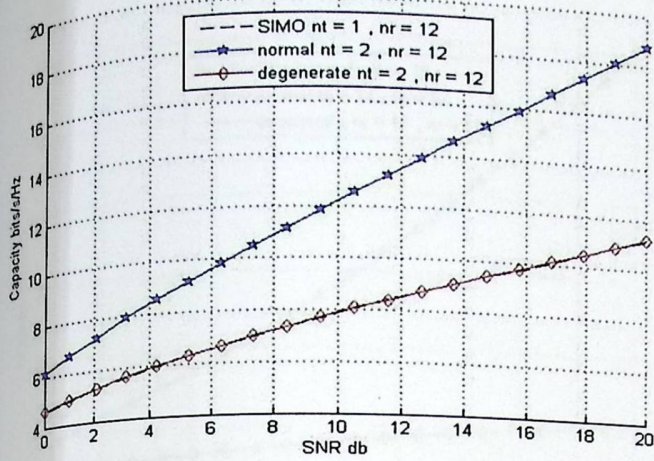


Fig 3.7.41: capacity Vs. SNR for 2x12

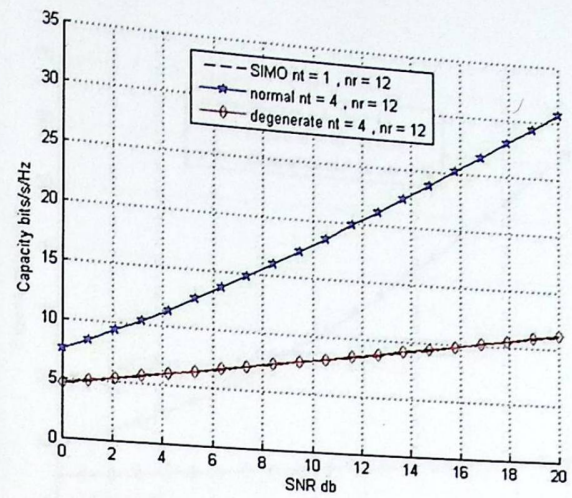


Fig 3.7.42: capacity Vs. SNR for 4x12

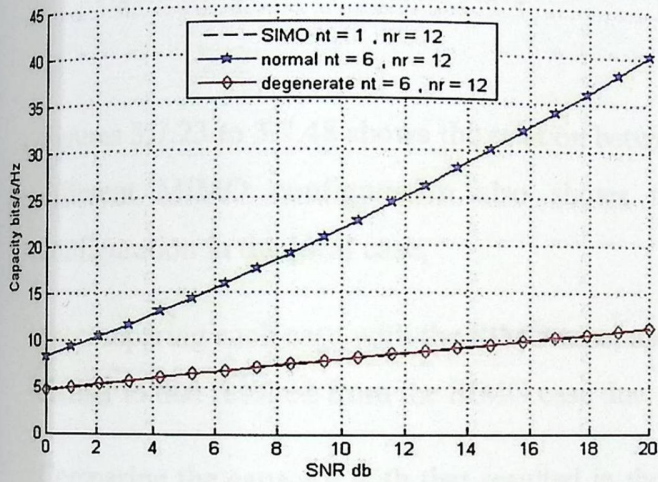


Fig 3.7.43: capacity Vs. SNR for 6x12

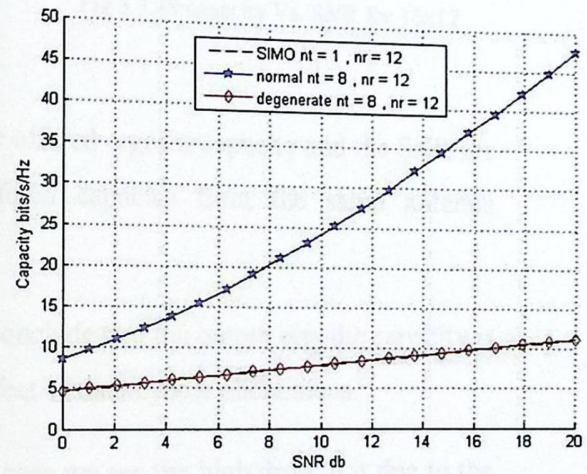


Fig 3.7.44: capacity Vs. SNR for 8x12

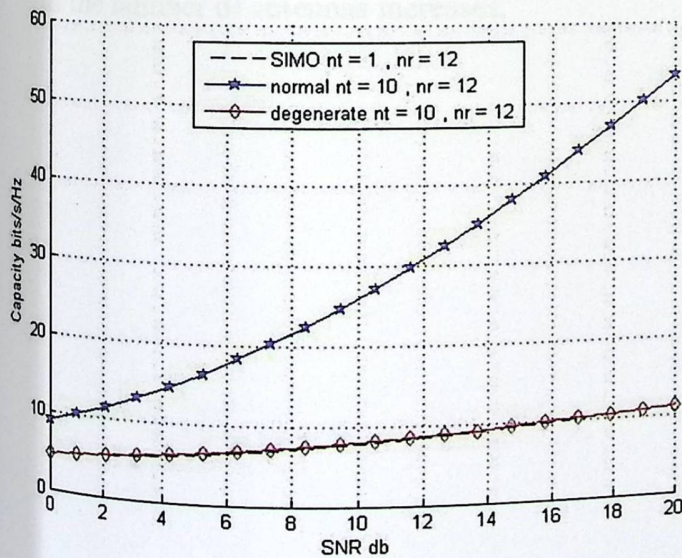


Fig 3.7.45: capacity Vs. SNR for 10x12

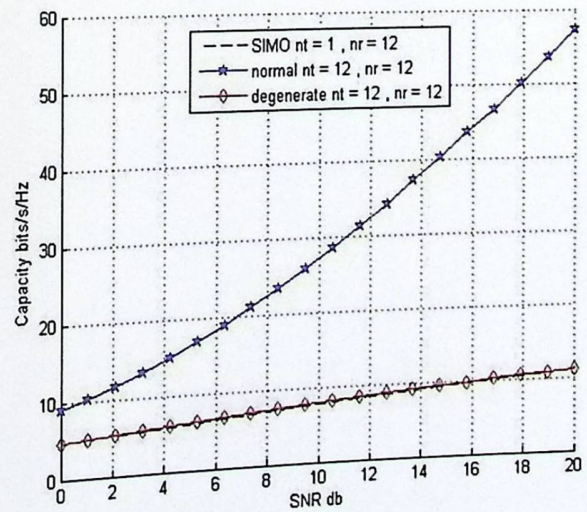


Fig 3.7.46: capacity Vs. SNR for 12x12

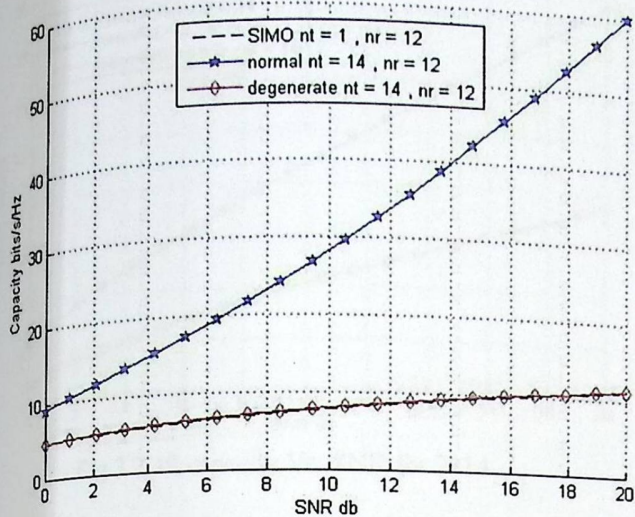


Fig 3.7.47:capacity Vs. SNR for 14x12

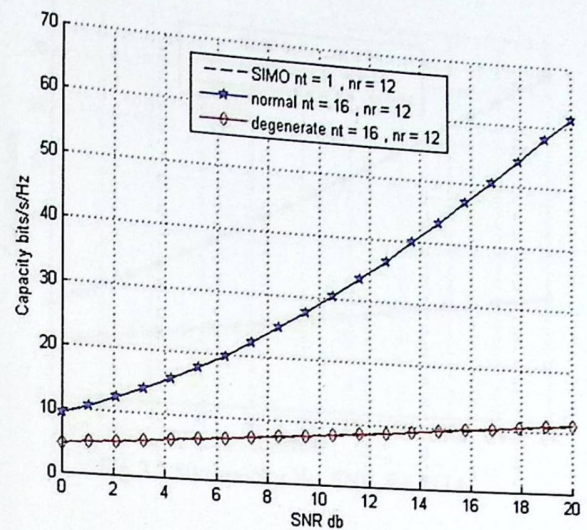


Fig 3.7.48:capacity Vs. SNR for 16x12

Figures 3.7.23 to 3.7.48 shows the relation between the offered ergodic capacity and the SNR for different MIMO configuration also shows the offered capacity from the same antenna configuration in the ideal case,

By comparing each case with the SIMO case, and we conclude that the output ergodic capacity is similar to that resulted from the SIMO case due the effect of the keyhole phenomena.

Comparing the capacity with that resulted in the ideal case we see the high drop in it due to the keyhole effect, Also its clear that the capacity increases linearly with SNR, and the enhancement as the number of antennas increases.

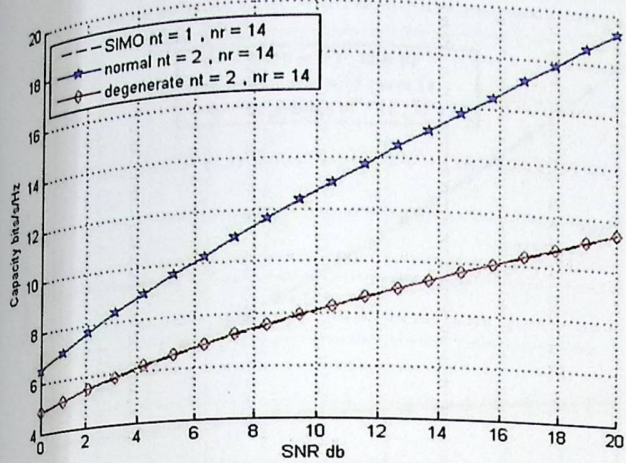


Fig 3.7.49: capacity Vs. SNR for 2x14

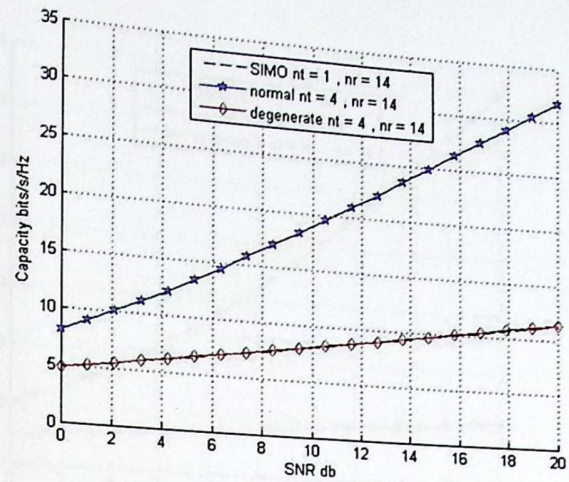


Fig 3.7.50: capacity Vs. SNR for 4x14

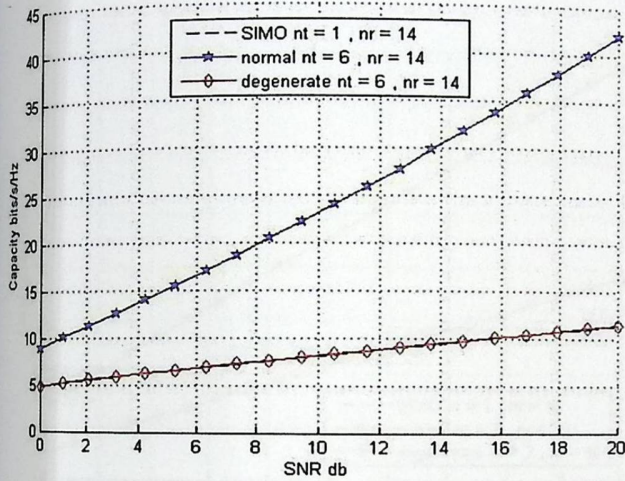


Fig 3.7.51: capacity Vs. SNR for 6x14

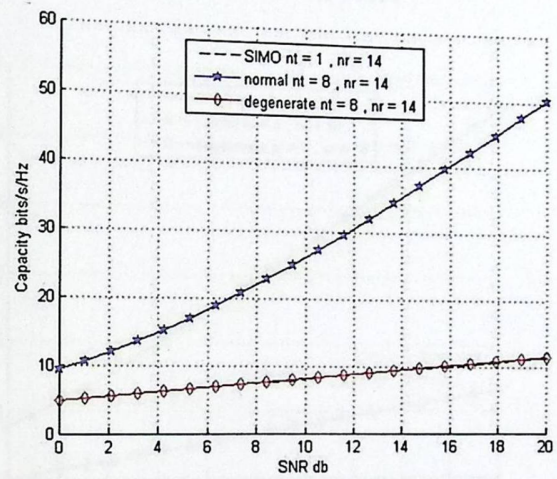


Fig 3.7.52: capacity Vs. SNR for 8x14

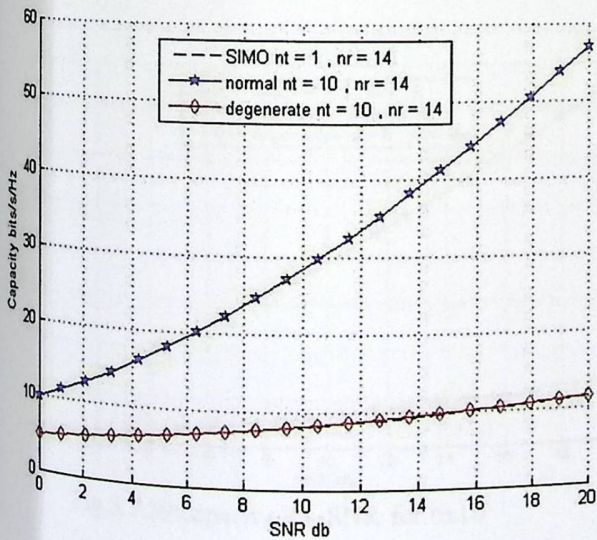


Fig 3.7.53: capacity Vs. SNR for 10x14

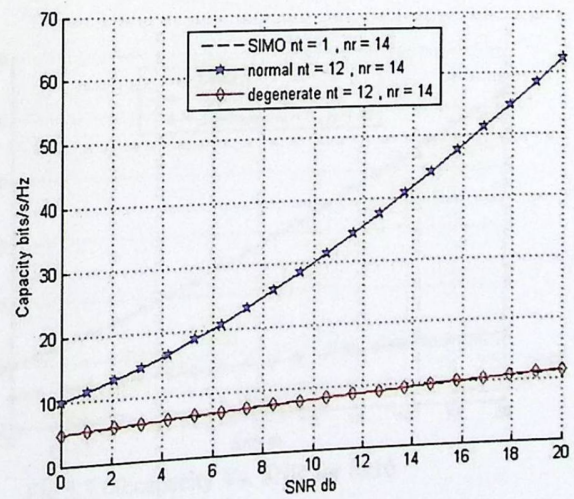


Fig 3.7.54: capacity Vs. SNR for 12x14

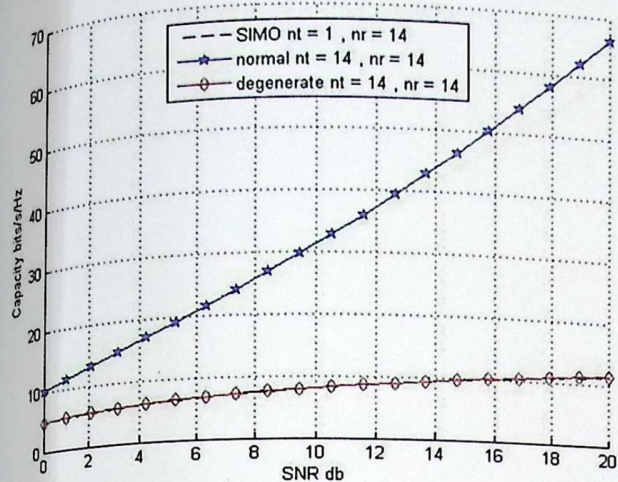


Fig 3.7.55: capacity Vs. SNR for 14x14

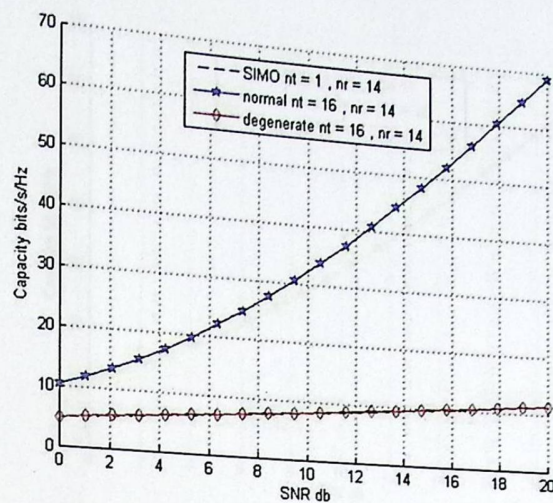


Fig 3.7.56: capacity Vs. SNR for 16x14

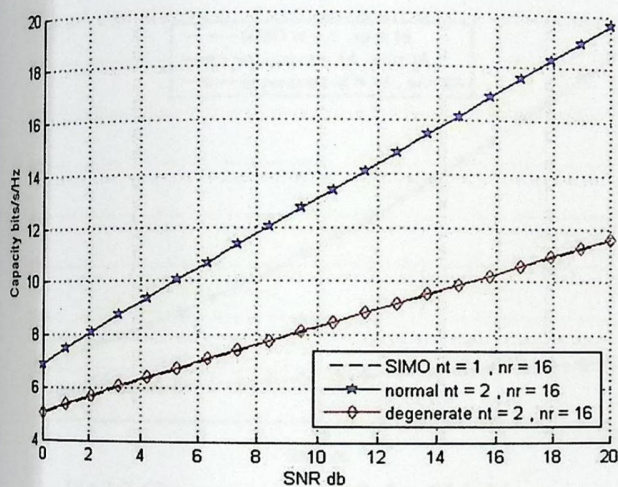


Fig 3.7.57: capacity Vs. SNR for 2x16

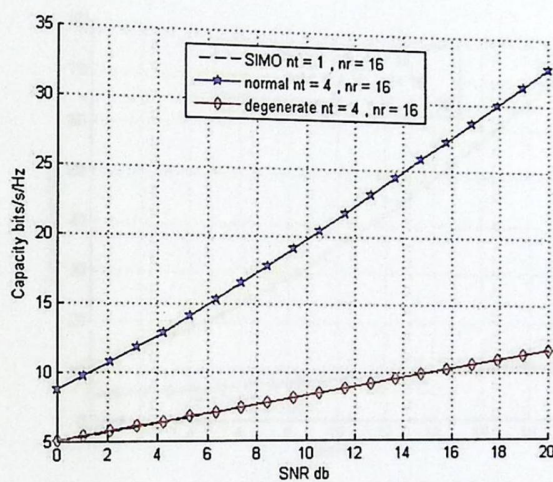


Fig 3.7.58: capacity Vs. SNR for 4x16

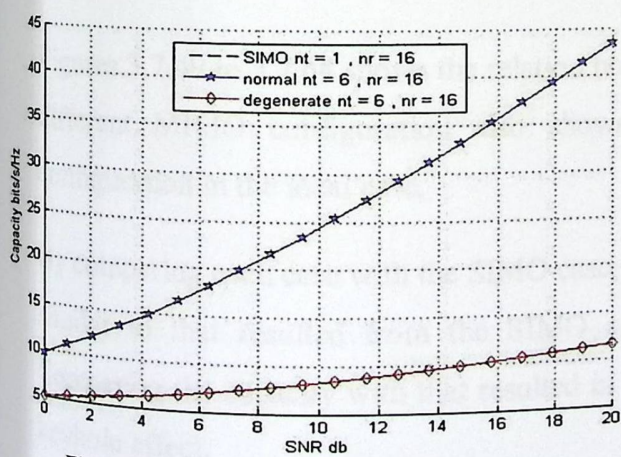


Fig 3.7.59: capacity Vs. SNR for 6x16

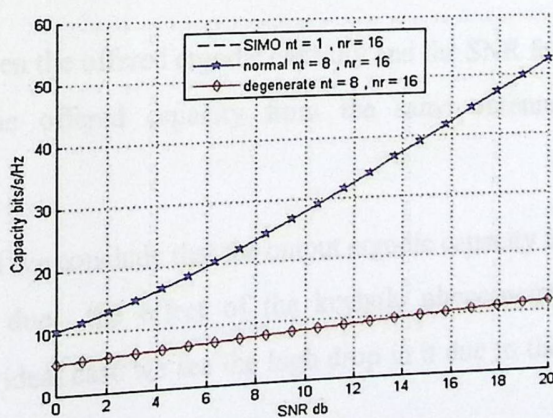


Fig 3.7.60: capacity Vs. SNR for 8x16

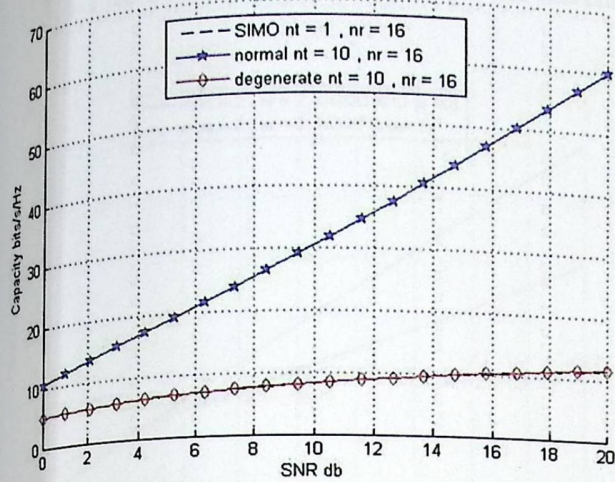


Fig 3.7.61:capacity Vs. SNR for 10x16

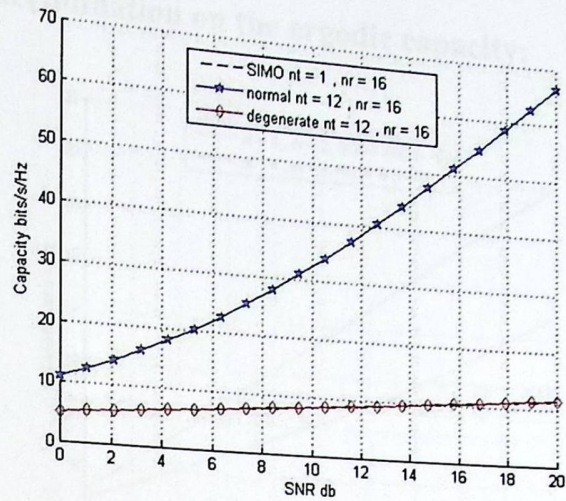


Fig 3.7.62:capacity Vs. SNR for 12x16

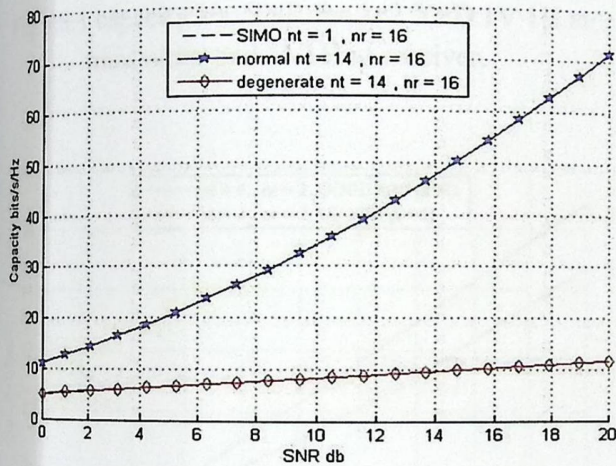


Fig 3.7.63:capacity Vs. SNR for .014x16

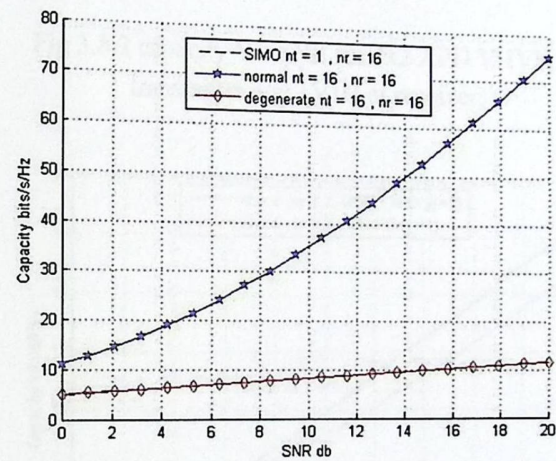


Fig 3.7.64:capacity Vs. SNR for 16x16

Figures 3.7.49 to 3.7.64 shows the relation between the offered ergodic capacity and the SNR for different MIMO configuration also shows the offered capacity from the same antenna configuration in the ideal case,

By comparing each case with the SIMO case, and we conclude that the output ergodic capacity is similar to that resulted from the SIMO case due the effect of the keyhole phenomena. Comparing the capacity with that resulted in the ideal case we see the high drop in it due to the keyhole effect.

Also its clear that the capacity increases linearly with SNR, and the enhancement as the number of antennas increases.

3.8 The effect of the cross-polarization discrimination on the ergodic capacity:

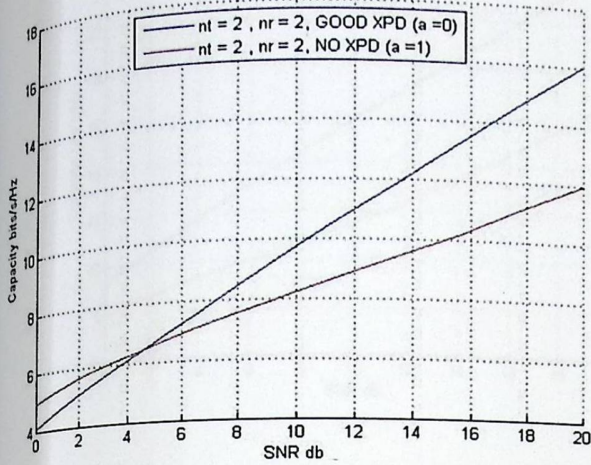


Fig 3.8.1 capacity Vs. SNR for 2x2 XPD 1V 1H at transmitter and 1V1H at receiver.

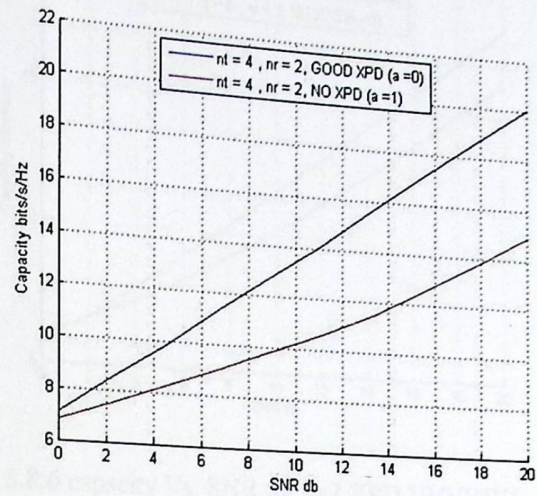


Fig 3.8.2 capacity Vs. SNR for 4x2 XPD VHVH at transmitter and 1V1H at receiver.

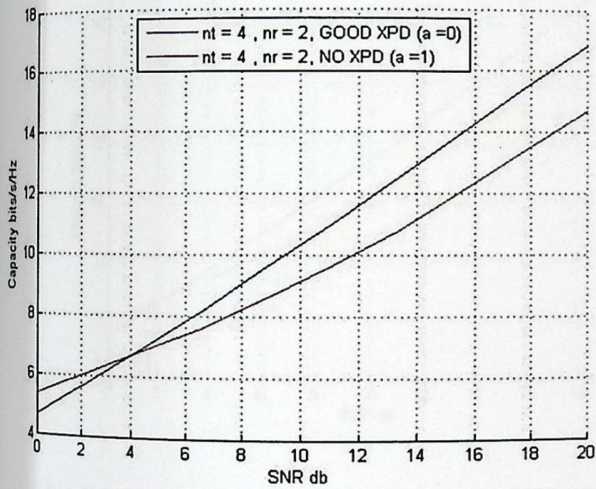


Fig 3.8.3 capacity Vs. SNR for 4x2 XPD VVHH at transmitter and 1V1H at receiver.

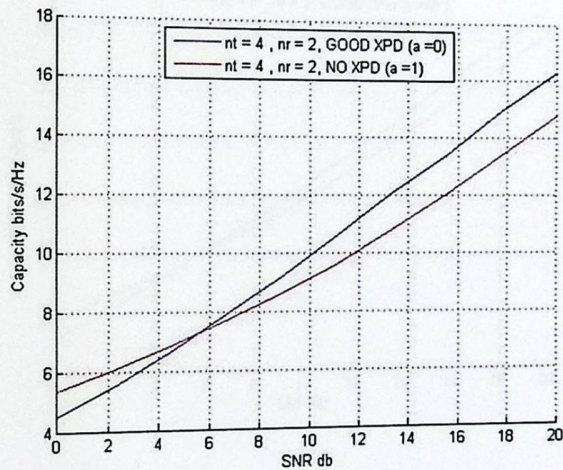


Fig 3.8.4 capacity Vs. SNR for 4x2 XPD VVVH at transmitter and 1V1H at receiver

Here we see the enhancement of the XPD on the ergodic capacity of the MIMO system, the enhancement is better for higher number of transmitters and receivers. Also when we polarize the antennas vertical horizontal consecutively the enhancement will be much better this can be seen clearly by comparing the two curves in Fig 3.8.2.

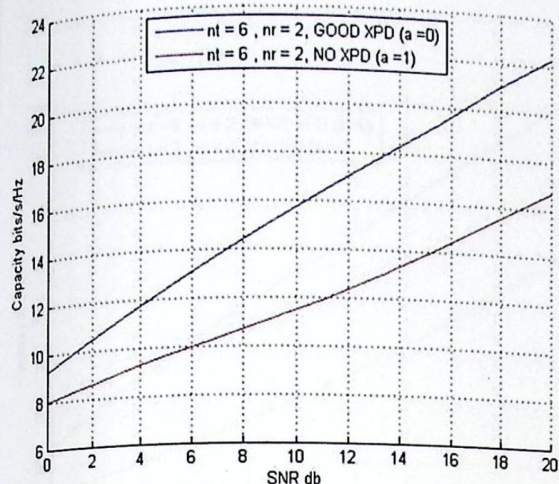


Fig 3.8.5 capacity Vs. SNR for 6x2 XPD VHVHVH at transmitter and 1V1H at receiver

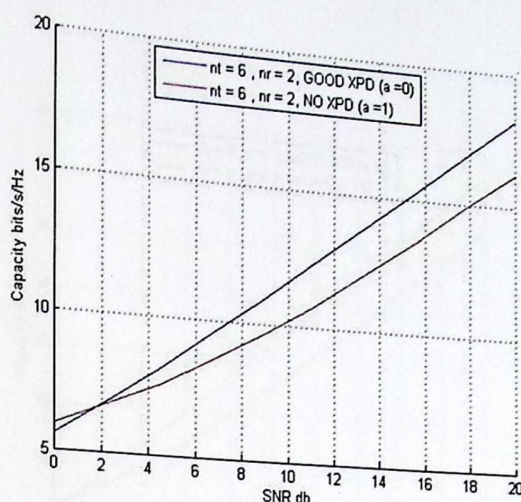


Fig 3.8.6 capacity Vs. SNR for 6x2 XPD VVVHHH at transmitter and 1V1H at receiver.

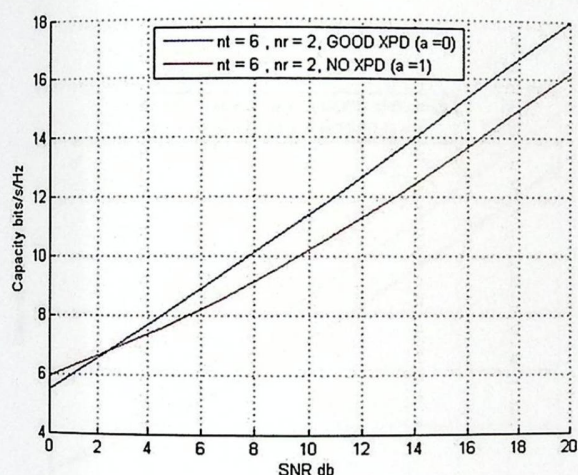


Fig 3.8.7 capacity Vs. SNR for 6x2 XPD V..VHH at transmitter and 1V1H at receiver.

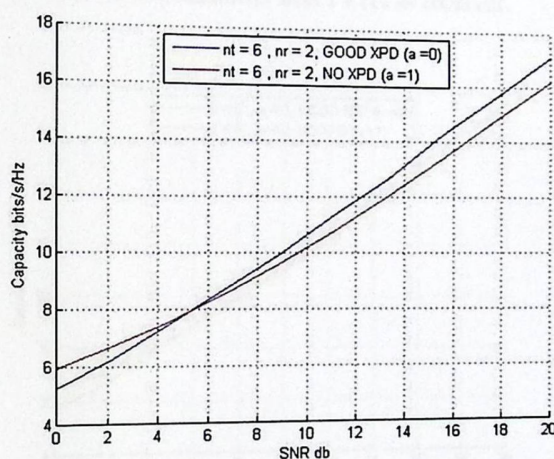


Fig 3.8.8 capacity Vs. SNR for 6x2 XPD V..VH at transmitter and 1V1H at receiver.

Figures 3.8.5 to 3.8.8 shows the enhancement we gain by using the XPD for 6x2 for different configuration of polarized antennas, the minimum enhancement is when the number of vertical or horizontal antenna is one. from Fig 3.8.5 we see that the maximum enhancement is obtained when we polarize the antennas vertical horizontal consecutively.

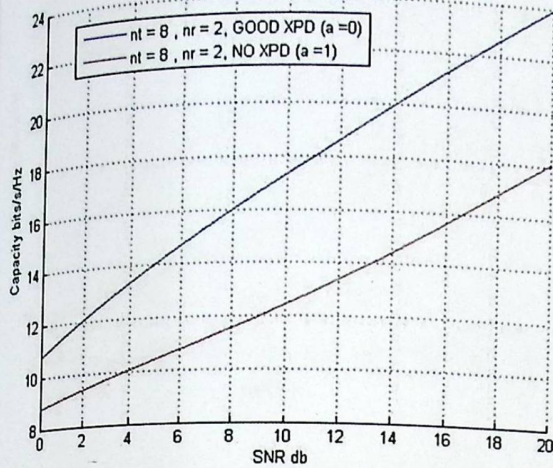


Fig 3.8.9 capacity Vs. SNR for 8x2 XPD
VHVHVHVH at transmitter and 1V1H at receiver.

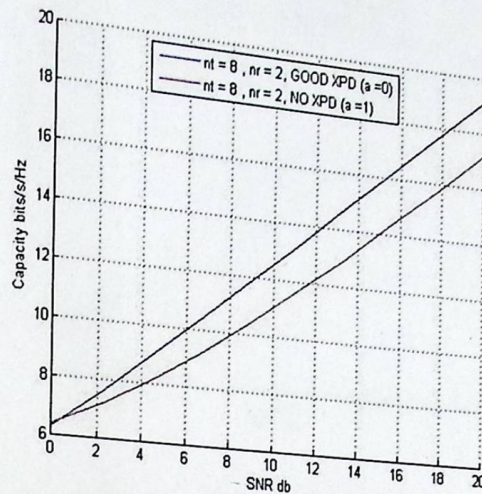


Fig 3.8.10 capacity Vs. SNR for 8x2 XPD
V..VHHHH at transmitter and 1V1H at receiver.

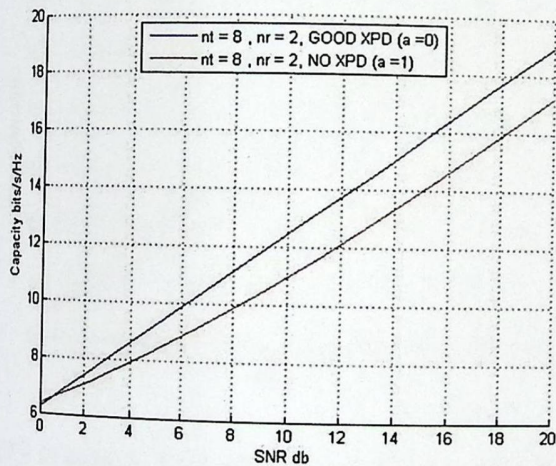


Fig 3.8.11 capacity Vs. SNR for 8x2 XPD
V...VHHH at transmitter and 1V1H at receiver.

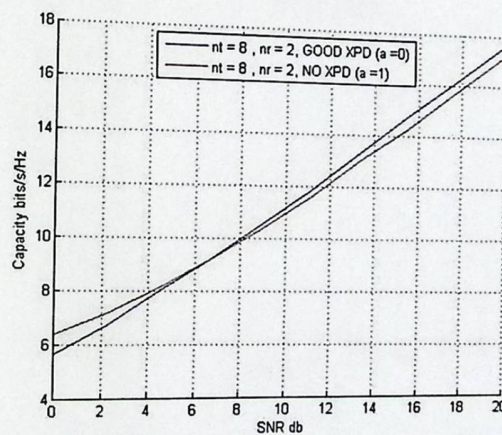


Fig 3.8.12 capacity Vs. SNR for 8x2 XPD V..VH at
transmitter and 1V1H at receiver.

The previous Figures 3.8.9 to 3.8.12 shows the enhancement we gain by using the XPD for 8x2 for different configuration of polarized antennas, from Fig 3.8.9 we see that the maximum enhancement is obtained when we polarize the antennas vertical horizontal consecutively, the minimum enhancement is when the number of vertical or horizontal antenna is one.

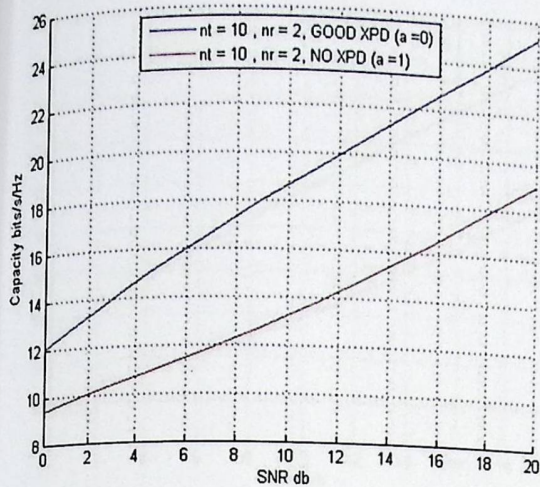


Fig 3.8.13 capacity Vs. SNR for 10x2 XPD VHVHVHVHVH at transmitter and 1V1H at receiver.

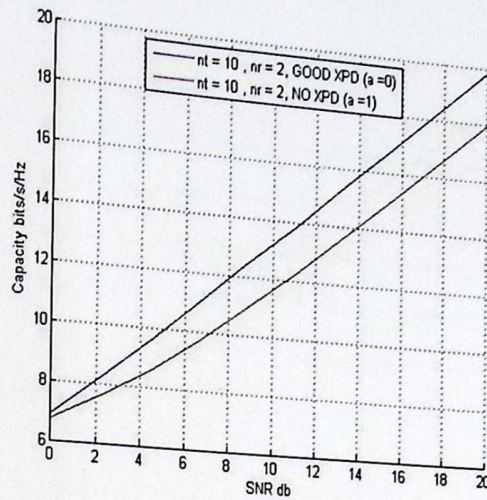


Fig 3.8.14 capacity Vs. SNR for 10x2 XPD V..VH..H at transmitter and 1V1H at receiver

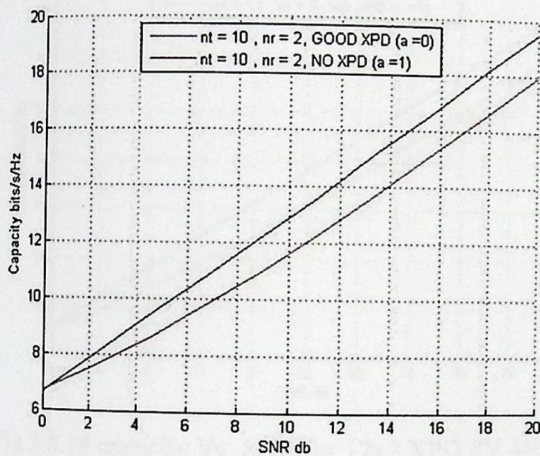


Fig 3.8.15 capacity Vs. SNR for 10x2 XPD V..VHHH at transmitter and 1V1H at receiver

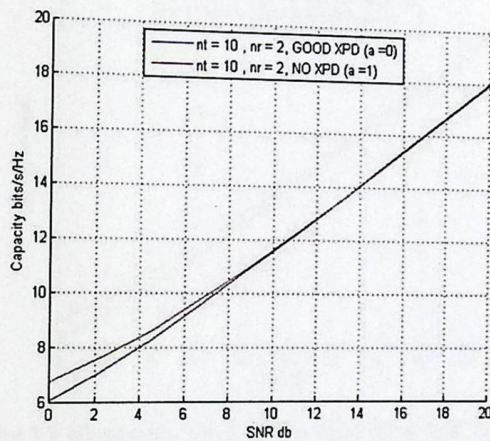


Fig 3.8.16 capacity Vs. SNR for 10x2 XPD V..VH at transmitter and 1V1H at receiver

The figures 3.8.13 to 3.8.16 shows the effect of the XPD for the 10x2 scheme for different antennas polarization configurations, we see that the enhancements provided by the XPD will degrade when the number of vertical antennas is much higher than the number of horizontal antennas and vice versa, the enhancement is maximum when we polarize the antennas vertical consecutively.

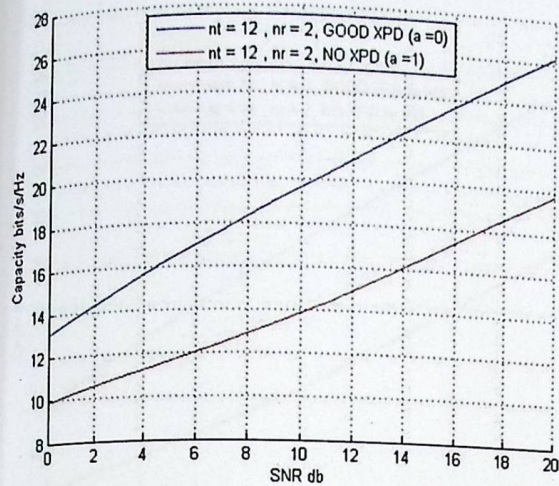


Fig 3.8.17 capacity Vs. SNR for 12x2 XPD VH...VH at transmitter and 1V1H at receiver

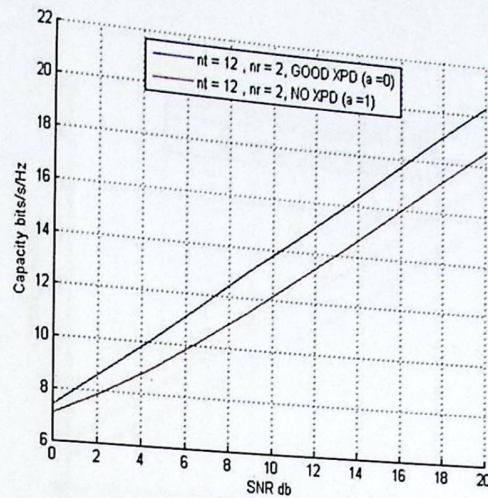


Fig 3.8.18 capacity Vs. SNR for 12x2 XPD 6V 6H at transmitter and 1V1H at receiver

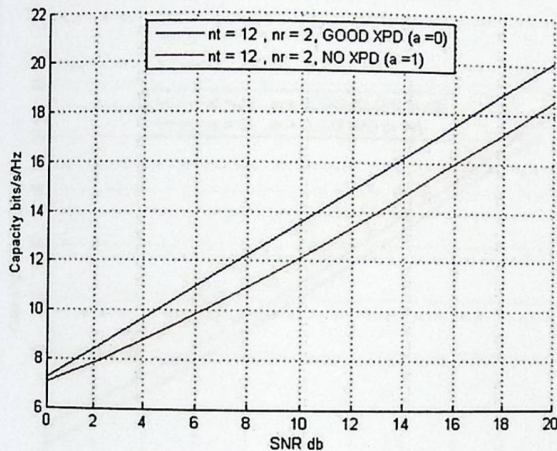


Fig 3.8.19 capacity Vs. SNR for 12x2 XPD 8V 4H at transmitter and 1V1H at receiver

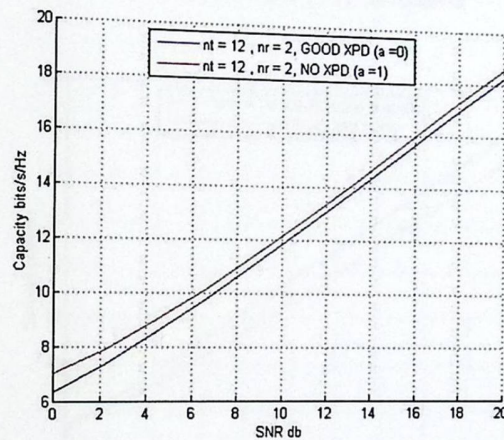


Fig 3.8.20 capacity Vs. SNR for 12x2 XPD 11V 1H at transmitter and 1V1H at receiver

Figures 3.8.17 to 3.8.120 shows the effect of the XPD for the 12x2 scheme for different antennas polarization configurations, we see that the enhancements provided by the XPD will degrade when the number of vertical antennas is much higher than the number of horizontal antennas and vice versa, the enhancement is maximum when we polarize the antennas vertical horizontal consecutively.

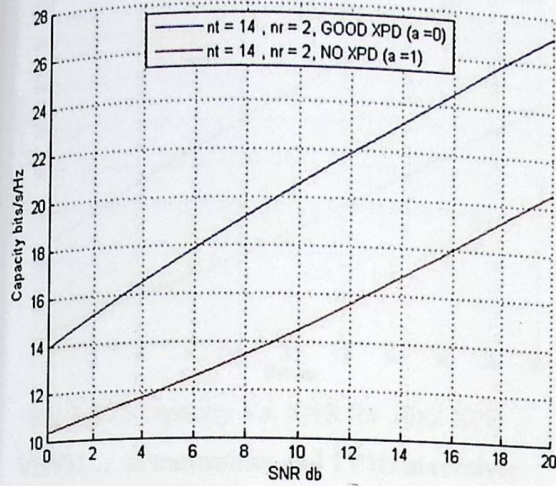


Fig 3.8.21 capacity Vs. SNR for 14x2 XPD VHVH... at transmitter and 1V1H at receiver

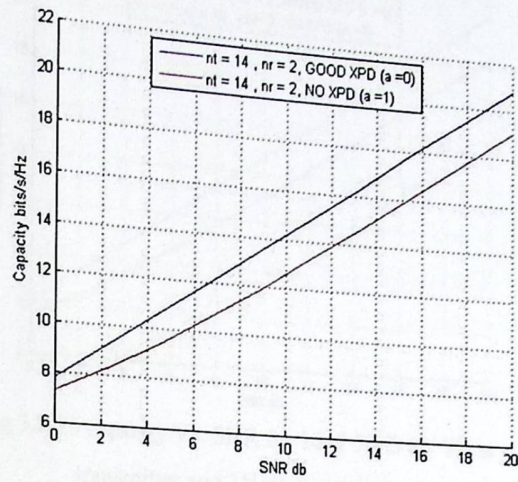


Fig 3.8.22 capacity Vs. SNR for 14x2 XPD 7V 7H at transmitter and 1V1H at receiver

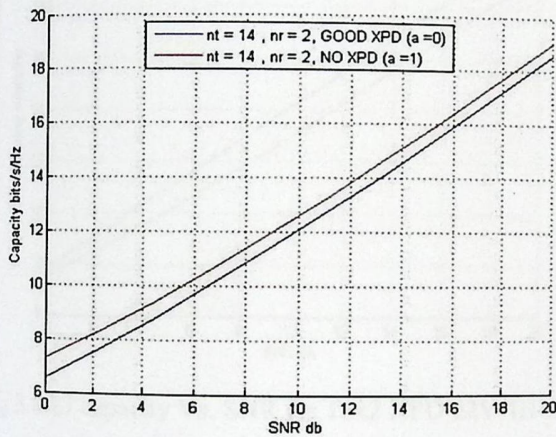


Fig 3.8.23 capacity Vs. SNR for 14x2 XPD 11V 3H at transmitter and 1V1H at receiver

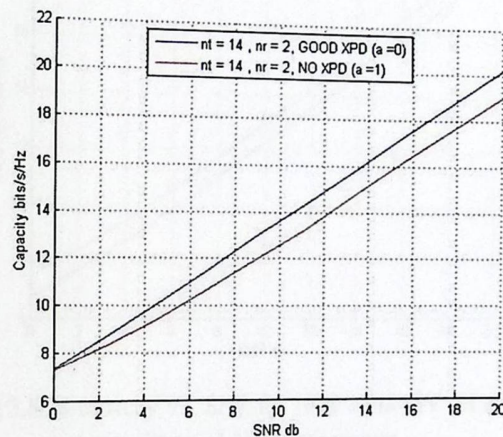


Fig 3.8.24 capacity Vs. SNR for 14x2 XPD 13V 1H at transmitter and 1V1H at receiver

Figures 3.8.21 to 3.8.24 shows the effect of the XPD for the 14x2 scheme for different antennas polarization configurations, we see that the enhancements provided by the XPD will degrade when the number of vertical antennas is much higher than the number of horizontal antennas and vice versa, the enhancement is maximum when we polarize the antennas vertical horizontal consecutively.

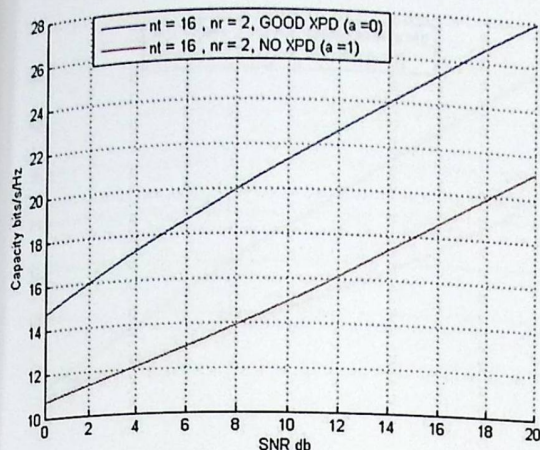


Fig 3.8.25 capacity Vs. SNR for 16x2 XPD VHVH... at transmitter and 1V1H at receiver

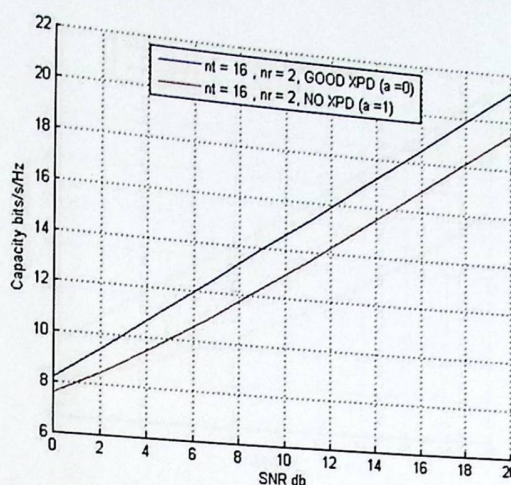


Fig 3.8.26 capacity Vs. SNR for 16x2 XPD 8V 8H at transmitter and 1V1H at receiver

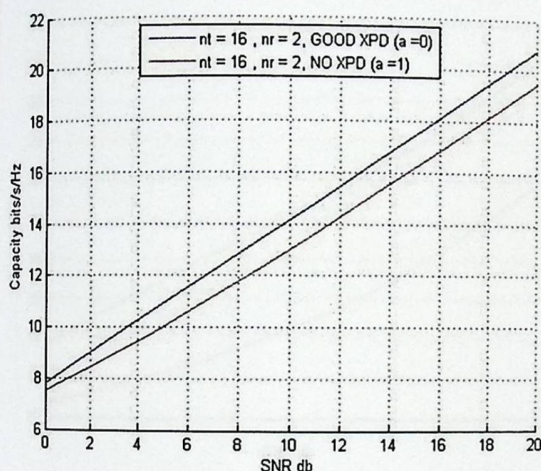


Fig 3.8.27 capacity Vs. SNR for 16x2 XPD 12V 4H at transmitter and 1V1H at receiver

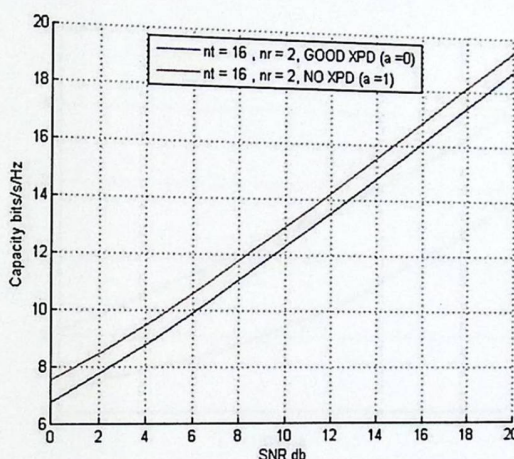


Fig 3.8.28 capacity Vs. SNR for 16x2 XPD 15V 1H at transmitter and 1V1H at receiver

Previous figures shows the enhancement due to the use of the XPD for the 16x2 scheme for different antennas polarization configurations.

The enhancement is maximum when we polarize the antennas vertical horizontal consecutively.

we see that the enhancements provided by the XPD is minimum when the number of vertical antennas is much higher than the number of horizontal antennas and vice versa.

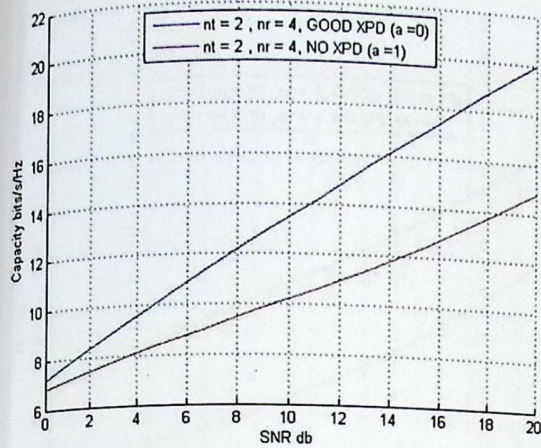


Fig 3.8.29 capacity Vs. SNR for 2x4 XPD 1V 1H at transmitter and 2V2H at receiver

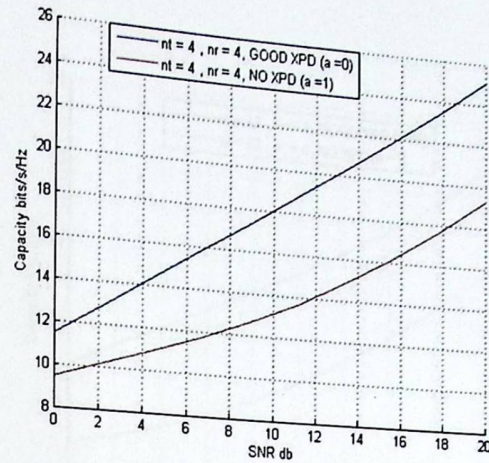


Fig 3.8.30 capacity Vs. SNR for 4x4 XPD 2V 2H at transmitter and 2V2H at receiver

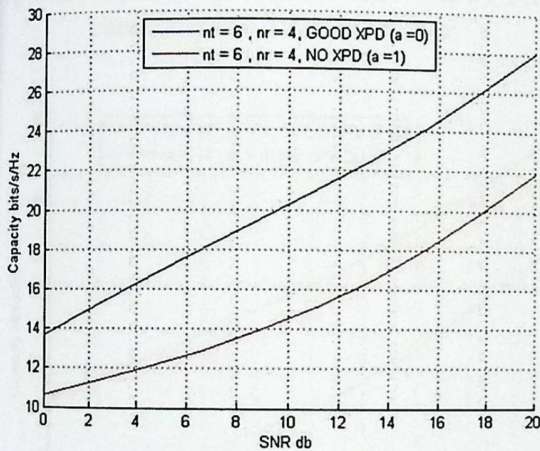


Fig 3.8.31 capacity Vs. SNR for 6x4 XPD 3V 3H at transmitter and 2V2H at receiver

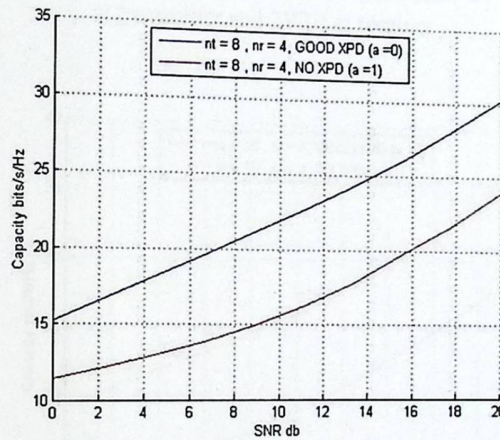


Fig 3.8.32 capacity Vs. SNR for 8x4 XPD 4V 4H at transmitter and 2V2H at receiver

Figures 3.8.29 to 3.8.32 shows the XPD effect for different antenna configuration while the same number of vertical and horizontal antennas at the receiver and the transmitter.

We can see the enhancement due to the use of the XPD of about 6 bits/s/Hz, the enhancement obtained is higher for higher number of transmitters and receivers.

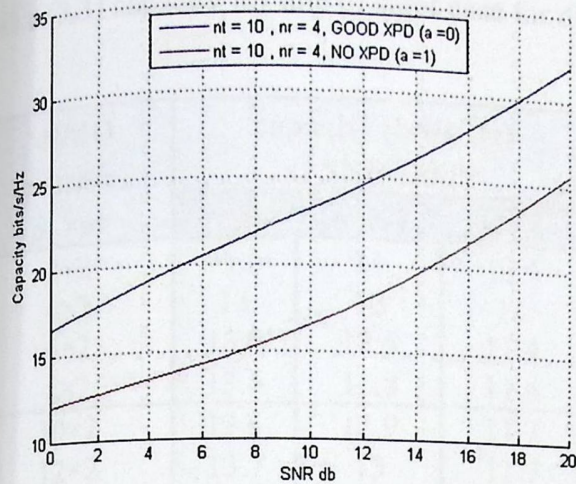


Fig 3.8.33 capacity Vs. SNR for 10x4 XPD 5V 5H at transmitter and 2V2H at receiver

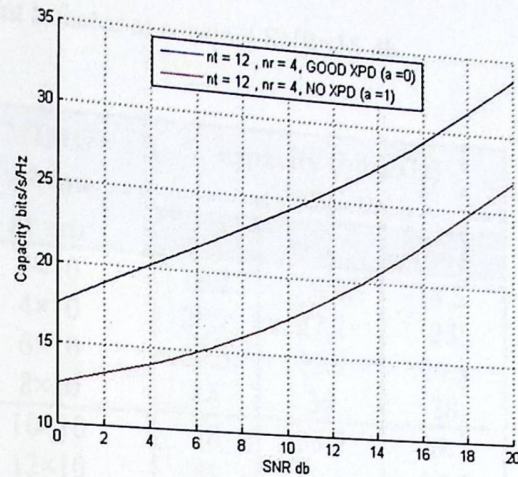


Fig 3.8.34 capacity Vs. SNR for 12x4 XPD 6V 6H at transmitter and 2V2H at receiver

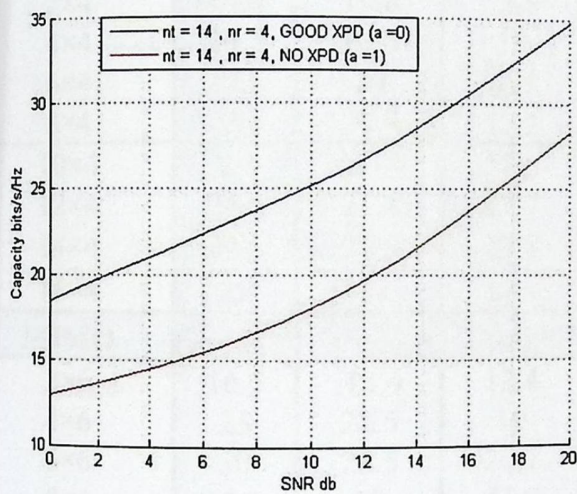


Fig 3.8.35 capacity Vs. SNR for 14x4 XPD 7V 7H at transmitter and 2V2H at receiver

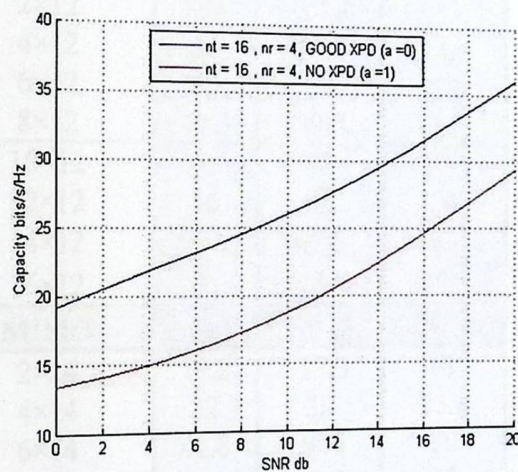


Fig 3.8.36 capacity Vs. SNR for 16x4 XPD 8V 8H at transmitter and 2V2H at receiver

Figures 3.8.33 to 3.8.36 shows the XPD effect for different antenna configuration while the same number of vertical and horizontal antennas at the receiver and the transmitter.

We can see the enhancement due to the use of the XPD of about 6 bits/s/Hz, the enhancement obtained is higher for higher number of transmitters and receivers.

3.9 summary:

Table (3.3) capacity for line of sight case for different k factor at constant SNR=15 db.

MIMO scheme nt × nr	capacity (bit/s/Hz) at SNR=20db			MIMO scheme nt × nr	capacity (bit/s/Hz) at SNR=20db		
	r=0	r=0.7	r=0.9		r=0	r=0.7	r=0.9
2×2	11.5	11	10.4	2×10	18.2	15.7	14.5
4×2	13	12	11	4×10	29.2	27.2	23
6×2	13.2	12.5	11.4	6×10	37.5	32.5	26.5
8×2	13.5	12.8	11.6	8×10	44	36	28
10×2	13.6	12.9	11.7	10×10	48	38.8	29.5
12×2	13.7	13	11.7	12×10	51	40.5	30.7
14×2	13.7	13	11.7	14×10	53	42	32
16×2	13.7	13	11.7	16×10	54	42.5	32.2
MIMO	r=0	r=0.7	r=0.9	MIMO	r=0	r=0.7	r=0.9
2×4	14.9	14.6	13.6	2×12	18.8	16.6	15.5
4×4	20.5	18.5	16	4×12	30	28.5	24.6
6×4	22.5	20	16.8	6×12	40	35	28
8×4	23.6	20.8	17.2	8×12	47.5	39.5	31
10×4	24	21	17.5	10×12	53.5	43	32.5
12×4	24.5	21.4	17.7	12×12	56	45	34
14×4	24.8	21.5	17.8	14×12	60	47.5	35
16×4	25	21.6	17.9	16×12	62	48.5	35.5
MIMO	r=0	r=0.7	r=0.9	MIMO	r=0	r=0.7	r=0.9
2×6	16.5	13.4	12.4	2×14	19.2	17.3	16
4×6	25	22.5	19	4×14	32	30	25.8
6×6	30	25.5	20.7	6×14	41.8	36.5	30
8×6	32.5	27	21.7	8×14	50	42.5	33
10×6	33.8	27.7	22	10×14	57	46	35
12×6	34.5	28	22.5	12×14	62	49.5	37
14×6	35	29	22.8	14×14	66	52	38
16×6	35.3	23.5	27.9	16×14	68	54	39
MIMO	r=0	r=0.7	r=0.9	MIMO	r=0	r=0.7	r=0.9
2×8	17.5	14.7	13.7	2×16	19.6	17.9	16.8
4×8	27.5	22.5	21.2	4×16	33	31	27
6×8	34.5	29.2	24	6×16	43.2	38.5	32
8×8	39.2	32.5	25.3	8×16	52.5	44.5	35
10×8	42	34	26.5	10×16	60	48.5	35.7
12×8	43	35	27	12×16	64	53	40
14×8	44	35.6	27.5	14×16	71	56	41
16×8	45	36.5	27.7	16×16	76	57.5	42.5

Table (3.4) capacity in fading correlation case for different correlation factor at constant SNR=20 db.

MIMO scheme nt × nr	capacity (bit/s/HZ) at SNR=15db		MIMO scheme nt × nr	capacity (bit/s/HZ) at SNR=15db	
	k=10	k=20		k=10	k=20
2×2	8	7.8	2×10	11.5	10.8
4×2	9.2	8.9	4×10	14.7	12.7
6×2	11.4	9.7	6×10	16.4	14.4
8×2	11.5	10.3	8×10	18	15.6
10×2	11.7	10.8	10×10	19.6	16.8
12×2	12.3	11.3	12×10	21.3	17.5
14×2	12.8	11.7	14×10	22.1	19
16×2	13.1	12.1	16×10	23.2	19.5
MIMO	k=10	k=20	MIMO	k=10	k=20
2×4	9.4	8.8	2×12	12.5	11.5
4×4	10.6	10.3	4×12	15.6	13.8
6×4	12.6	11.3	6×12	17.4	15.4
8×4	13.7	12.2	8×12	19.2	16.6
10×4	14.6	13	10×12	20.7	17.5
12×4	15.4	13.6	12×12	22.2	18.5
14×4	16.3	14.3	14×12	23.5	19.5
16×4	17	15	16×12	24.5	20.5
MIMO	k=10	k=20	MIMO	k=10	k=20
2×6	10.5	9.6	2×14	12.5	12
4×6	12.8	11.5	4×14	16.5	14
6×6	14.1	12.8	6×14	18.5	16.2
8×6	15.5	13.5	8×14	20.5	17.5
10×6	16.5	14.5	10×14	22.8	18
12×6	17.7	15	12×14	23.5	19.3
14×6	18.7	16	14×14	25	20
16×6	19.4	16.8	16×14	26	21.5
MIMO	k=10	k=20	MIMO	k=10	k=20
2×8	11	12.2	2×16	13	12.2
4×8	13.8	15	4×16	17	15
6×8	15.5	16.7	6×16	19.5	16.7
8×8	17	18.7	8×16	22	18.7
10×8	19	19.5	10×16	23.5	19.5
12×8	20.3	20.5	12×16	25	20.5
14×8	21.3	21.5	14×16	26	21.5
16×8	22.7	23.5	16×16	27.7	22.5

Table (3.5) capacity for line of sight case for different k factor at constant SNR=20db.

MIMO scheme nt × nr	capacity (bit/s/HZ) at SNR=20db				
	k=0	k=5	k=10	k=15	k=20
2×2	11.6	10.6	10	9.8	9.7
4×2	14.8	12.8	12	11.8	11.1
6×2	16.4	14.2	13.4	12.8	12.4
8×2	17.5	15.2	14.2	13.6	13.2
10×2	18.2	16	14.6	14.2	13.6
12×2	18.6	16.6	15.6	14.6	14.2
14×2	19.2	17	16	15.3	14.8
16×2	19.7	17.4	16.3	16.6	15.3
MIMO	k=0	k=5	k=10	k=15	k=20
2×4	14.8	12.8	11.8	11.4	11.2
4×4	21.2	16.3	14.8	14	13.5
6×4	25	18.7	16.7	15.8	15
8×4	27.5	21	18.3	16.9	16.3
10×4	29	22.3	19.2	18.3	17.3
12×4	31	23.5	21.1	19.6	18.6
14×4	32	24.4	21.9	20.6	19.6
16×4	32.6	25.4	22.9	21.5	20
MIMO	k=0	k=5	k=10	k=15	k=20
2×6	16.4	14.2	13.3	12.7	12.4
4×6	25	18.7	16.6	15.7	15
6×6	30.8	22	19.6	17.9	17
8×6	34.8	24.2	21.6	20	18.8
10×6	37.7	26.6	23.1	21.4	20
12×6	40	28.5	25	22.5	21
14×6	42	30	26	24	22.5
16×6	43.5	31.5	27.4	25	23.5
MIMO	k=0	k=5	k=10	k=15	k=20
2×8	17.4	13.2	14	13.6	13
4×8	27.5	20.8	18.4	17.2	16.3
6×8	35	24.2	21.5	19.9	18.7
8×8	40	27.2	23.5	22	20.5
10×8	44	30	26	23.8	22
12×8	48	32.5	27.5	25	23.4
14×8	50.5	34.1	29.4	26.2	25
16×8	53	36.1	30.9	28.1	25.9

Table (3.6) capacity for line of sight case for different k factor at constant SNR=20db.

MIMO scheme nt x nr	capacity (bit/s/HZ) at SNR=20db				
	k=0	k=5	k=10	k=15	k=20
2x10	18.2	16	14.8	14.2	13.8
4x10	29.3	22.2	19.7	18.3	17.7
6x10	37.7	26.4	23.2	21.7	20
8x10	44.3	30	26	23.8	22
10x10	49.4	32.3	28.1	25.6	23.6
12x10	53.7	35.6	30.6	27	25.3
14x10	57.3	37.7	32.3	28.5	26.5
16x10	60.8	44	33.6	30.7	38.2
MIMO	k=0	k=5	k=10	k=15	k=20
2x12	17.6	17.8	15.3	14.6	13.6
4x12	30.6	23.5	21.1	19.3	18.5
6x12	40	28.5	25	22.5	21.5
8x12	47.5	32.5	28.1	25	23.1
10x12	53.7	35.6	30.6	26.9	25.3
12x12	58.5	38.1	32.3	28.9	27
14x12	63.2	41.4	34.5	30.9	28.2
16x12	66.8	43.4	36.3	32.7	30
MIMO	k=0	k=5	k=10	k=15	k=20
2x14	18.4	19	17	15.8	14.6
4x14	31.5	24.5	22	20.7	19.3
6x14	41.5	30	26	24	22.4
8x14	50.7	34.3	29.1	26.6	25
10x14	57.3	37.7	32.7	27	28.5
12x14	63.5	41.5	35	31	29
14x14	67	44	36	33	31
16x14	71.5	46	38	34.5	32
MIMO	k=0	k=5	k=10	k=15	k=20
2x16	19.6	17.4	16.4	15.8	15.4
4x16	32.5	25.8	22.7	21.3	20.4
6x16	43	31.5	27.5	25	23.7
8x16	52.8	35.7	31.4	27.8	26.4
10x16	61	40	34	30.7	28.5
12x16	66	42.7	36.8	33	30
14x16	72	46	38	35	32
16x16	77	48.5	41	36	33.5

Table (3.7) capacity in degeneracy case at constant SNR=20db

MIMO scheme nt × nr	capacity (bit/s/Hz) at SNR=20db		MIMO scheme nt × nr	capacity (bit/s/Hz) at SNR=20db	
	normal case	degenerate case (=SIMO 1×2)		normal case	degenerate case (=SIMO 1×10)
2×2	11.3	8.6	2×10	18.2	11
4×2	13	8.6	4×10	29.7	11
6×2	13.3	8.6	6×10	33	11
8×2	13.6	8.6	8×10	44.5	11
10×2	13.7	8.6	10×10	47.8	11
12×2	13.8	8.6	12×10	50.7	11
14×2	13.8	8.6	14×10	53.3	11
16×2	13.9	8.6	16×10	54	11
MIMO	normal case	degenerate case (=SIMO 1×4)	MIMO	normal case	degenerate case (=SIMO 1×12)
2×4	14.8	9.5	2×12	19	11.4
4×4	20.8	9.5	4×12	31	11.4
6×4	22.5	9.5	6×12	40	11.4
8×4	23.8	9.5	8×12	48	11.4
10×4	24	9.5	10×12	54	11.4
12×4	24.5	9.5	12×12	58	11.4
14×4	24.9	9.5	14×12	60	11.4
16×4	25	9.5	16×12	62	11.4
MIMO	normal case	degenerate case (=SIMO 1×6)	MIMO	normal case	degenerate case (=SIMO 1×14)
2×6	16.5	10.2	2×14	19.2	11.6
4×6	25	10.2	4×14	32.2	11.6
6×6	30	10.2	6×14	42.5	11.6
8×6	32.5	10.2	8×14	50	11.6
10×6	33.5	10.2	10×14	57	11.6
12×6	34.5	10.2	12×14	63	11.6
14×6	35	10.2	14×14	66.5	11.6
16×6	35.2	10.2	16×14	69.5	11.6
MIMO	normal case	degenerate case (=SIMO 1×8)	MIMO	normal case	degenerate case (=SIMO 1×16)
2×8	17.4	10.7	2×16	19.8	11.8
4×8	27.5	10.7	4×16	33	11.8
6×8	35	10.7	6×16	44	11.8
8×8	39	10.7	8×16	53	11.8
10×8	42.3	10.7	10×16	60	11.8
12×8	43.7	10.7	12×16	67	11.8
14×8	44.5	10.7	14×16	72	11.8
16×8	45	10.7	16×16	78	11.8

Table (3.8) capacity in degeneracy case at constant SNR=20db

MIMO scheme nt x nr	capacity (bit/s/Hz) at SNR=20db			
	nt	nr		
			GOOD XPD (a=0)	NO XPD (a=1)
2x2	1V1H	1V1H	16	
4x2	2(VH)	1V1H	20	12
	2V2H	1V1H	17	15
	3V1H	1V1H	16.5	14.8
				14.7
6x2	3(VH)	1V1H	22.5	
	3V3H	1V1H	1824	16.8
	4V2H	1V1H	18	16.4
	5V1H	1V1H	17.2	16.2
				16.2
8x2	4(VH)	1V1H	24	18
	4V4H	1V1H	19	17.4
	5V3H	1V1H	18.9	17.2
	7V1H	1V1H	17.7	17.2
10x2	5(VH)	1V1H	25.2	19
	5V5H	1V1H	19.8	18
	7V3H	1V1H	19.5	18
	9V1H	1V1H	18	18
12x2	6(VH)	1V1H	26.2	19.8
	6V6H	1V1H	20.4	18.8
	8V4H	1V1H	20.2	18.6
	11V1H	1V1H	18.3	18.6
14x2	7(VH)	1V1H	27.2	20.2
	7V7H	1V1H	21	19
	11V3H	1V1H	19	18.6
	13V1H	1V1H	20.2	19
16x2	8(VH)	1V1H	23	21
	8V8H	1V1H	21	19.4
	12V4H	1V1H	20.8	19.4
	15V1H	1V1H	19.5	18.8
2x4	1V1H	2V2H	20	15
4x4	2V2H	2V2H	25	19
6x4	3V3H	2V2H	28	22
8x4	4V4H	2V2H	30	24
10x4	5V5H	2V2H	32	25.2
12x4	6V6H	2V2H	34	27
14x4	7V7H	2V2H	35	28
16x4	8V8H	2V2H	36	29

References:

1. Andrea Goldsmith, Wireless communications, University of CAMBRIDGE Press , 2005.
2. Rysavy, research, transition to 4G 3gpp broadband evolution to IMT advanced, Rysavy research, September 2010.
3. <http://www.3gpp.org/A-few-Mbps-ought-to-make-just>
4. <http://www.3gpp.org/The-Transition-to-4G>
5. Sami Tabbane, ITU-D/ITU-T Seminar on Standardization and Development of Next Generation Networks for the Arab Region, Manama (Bahrain), 29 April - 2 May 2007.
6. Report ITU-R M.2134, Requirements related to technical performance For IMT-Advanced radio interface(s).
7. rogyaswami Paulraj and others, Introduction to Space -Time Wireless Communications, The Press syndicate of the University of CAMBRIDGE, UK, 2006.
8. Theodore S.Rappaport. Wireless Communications principles and practice, Prentice Hall BTR Upper Saddle River, second Edition .pages (67-77,208,385-390)
9. Roberto Togneri Christopher J.S. desilva, Fundamentals of Information Theory and Coding Design, Routledge, middle town New Jersey.
10. Mohinder Jankiraman, Space time Codes and MIMO System, Artech House universal personal communication series, London 2004
11. Mustafa Ergen, Mobile Broadband Including WiMAX and LTE.
12. 3GPP mobile broadband innovation path to 4G: release 9, release 10 and beyond: HSPA+, LTE/SAE and LTE-Advanced.
13. Erik Dahlman, 3G Evolution: HSPA and LTE for mobile broadband
14. Arogyaswami Paulraj, Rohit Nabar and DhananjayGore .Introduction to Space -Time Wireless Communications .UK. Published by the Press syndicate of the University of CAMBRIDGE, 2006.
15. Information Society Technologies, Assessment of Advance Beamforming and MIMO Technologies D2.7 ver 1.1,2005.
16. Capacity Limits of MIMO Channels, Andrea Goldsmith and others, IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, VOL. 21, NO. 5, JUNE 2003.
17. Capacity Limits of MIMO Channels, Andrea Goldsmith and others, IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, VOL. 21, NO. 5, JUNE 2003

18. Effects of Spatial Correlation and Associated Parameters on the Capacity of MIMO fading Channels, M. A. Saeed, B. M. Ali, M. Ismail, S. Khatun, Faculty of Engineering, University Putra Malaysia, IEEE, 2005.
19. Matlab simulation about the effect of LOS and XPD on ergodic capacity of a MIMO system with CSI known at transmitter, Khalid Hijjeh, Ayman Aldasht, Mohammad Quttaineh, Mutasem Fanasheh. Palestine cellular communication-palestine, Palestine polytechnic university, IEEE, 2011.

18. Effects of Spatial Correlation and Associated Parameters on the Capacity of MIMO fading Channels, M. A. Saeed, B. M. Ali, M. Ismail, S. Khatun, Faculty of Engineering, University Putra Malaysia, IEEE, 2005.
19. Matlab simulation about the effect of LOS and XPD on ergodic capacity of a MIMO system with CSI known at transmitter, Khalid Hijjeh, Ayman Aldasht, Mohammad Quttaineh, Mutasem Fanasheh. Palestine cellular communication-palestine, Palestine polytechnic university, IEEE, 2011.

Appendix A

THE MATLAB CODE

% in this program a highly scattered environment is considered.

% the capacity of a MIMO channel with n_t transmit antenna and n_r receive Antenna is analyzed.

% the power in parallel channel (after decomposition) is distributed as water-filling algorithm

% the pdf of the matrix lamada elements is depicted too.

clear all

close all

clc

$n_t_V = [1 \ 2 \ 3 \ 2 \ 4];$

$n_r_V = [1 \ 2 \ 2 \ 1 \ 2];$

% the program will show the result for the first element in the n_t vector % and the first element with the vector n_r , the second with the second, and so % on . I.e. 1×1 , 2×2 , 3×2 , 2×1 , 4×2 .

$N_0 = 1e-4;$

% this represents the noise level in the channels, its 0.1 mW

$B = 1;$

$Iteration = 1e4;$

% must be greater than $1e2$ to have more accuracy

% At each SNR level the program will take 10000 random H's to find the % capacity for each one of them, then it will plot the mean of the all values.

$SNR_V_db = -10:3:20;$

% The range of the SNR from -10 to 20 increasing 3dB at each time

$SNR_V = 10.^{(SNR_V_db/10)};$

% Converting the SNR from dB units to unit-less

$color = ['b'; 'r'; 'g'; 'k'; 'c'];$

% to determine the colors of the curves.

$notation = ['-o'; '->'; '<-'; '-^'; '-s'];$

% To differentiate between the curves.


```

Capacity=zeros(length(SNR_V),Iteration); %Pre-allocation of the capacity matrix in order to
speed up the program %execution

for k = 1 : 5
    %Because we study different cases
    nt = nt_V(k);
    nr = nr_V(k);
    %To choose the kth element from the nt vector

    for i = 1 : length(SNR_V)
        Pt = N0 * SNR_V(i);
        %Calculate the total power based on SNR and noise
        levels

        for j = 1 : Iteration
            H = random('rayleigh',1,nr,nt);
            %Generate a Rayleigh fading channel matrix nr*nt

            [S V D] = svd(H);
            % Decompose H matrix to its singular value
            decomposition

            landas(:,j) = diag(V);

            [Capacity(i,j) PowerAllo] = WaterFilling_alg(Pt,V,B,N0);

            %Calling the function which called Water -Filling_
            algorithm and return Capacity (i,j) Power-Allo

        end
    end
    figure(1);

    hold on

    plot(SNR_V_db,mean(Capacity,2),notation(k,:), 'color',color(k,:))

    figure(2);

    hold on

    [y,x] = hist(reshape(landas,[1,min(nt,nr)*Iteration]),100);

    plot(x,y/Iteration, 'color',color(k,:));

    clear landas
end
f1 = figure(1)
legend_str = [];
for i = 1 : length(nt_V)
    legend_str = [ legend_str ; ...

```



```
{['nt = ', num2str(nt_V(i)), ' ', nr = ', num2str(nr_V(i))']};
```

```
end
```

```
legend(legend_str)
```

```
grid on
```

```
set(f1, 'color', [1 1 1])
```

```
xlabel('SNR in dB')
```

```
ylabel('Capacity bits/s/Hz')
```

```
f2 = figure(2)
```

```
legend(legend_str)
```

```
grid on
```

```
set(f2, 'color', [1 1 1])
```

```
ylabel('pdf of elements in matrix  $\mathbf{H}$  in svd decomposition of matrix  $\mathbf{H}$ ')
```


WATER-FILLING ALGORITHM CODE

% Water-Filling in Optimizing the Capacity

function [Capacity PowerAllo]= WaterFilling_alg(PtotA,V,B,N0) % Initialization

ChA = diag(V);
ChA = ChA + eps;

% gather the lamdas in an array

NA = length(ChA);

% the number of sub-channels allocated to

H = ChA.^2/(B*N0);

% the parameter relate to SNR in sub- channels ,
assign the power to sub-channel

PowerAllo = (PtotA + sum(1./H))/NA - 1./H; %Calculate the initial value of the allocated
power vector

while(length(find(PowerAllo < 0))>0)

% test if there still any non-positive values in the
power allocated so as to repeat the calculation

IndexN = find(PowerAllo <= 0);

% find the negative and Zero values

IndexP = find(PowerAllo > 0);

%find the positive values

MP = length(IndexP);

% how many positive value we have

PowerAllo(IndexN) = 0;

%force the non-positive value to Zero

ChAT = ChA(IndexP);

HT = ChAT.^2/(B*N0);

PowerAlloT = (PtotA + sum(1./HT))/MP - 1./HT; % Recalculate the value of the
allocated power in the sub-channels

PowerAllo(IndexP) = PowerAlloT;
end

PowerAllo = PowerAllo.';
Capacity = sum(log2(1+ PowerAllo.' .* H));

%calculate the capacity

Effect of Fading correlation Fading correlation factor Vs. Ergodic capacity

```

clear all
close all
clc
Iteration = 1e3;
SNR_V_db = linspace(0,20,20);
SNR_V = 10.^(SNR_V_db/10);

color = ['b';'r';'g';'k';'c';'m';'y';'r'];
nr = [14 16];
fading_correlation_factor = linspace(0,1,30)

for k=1:8
    nt = 2*k*ones(4,1)
    for i=1:2
        for s=1:30
            rt=eye(nt(i),nt(i));
            rr=(1-
fading_correlation_factor(s))*eye(nr(i),nr(i))+fading_correlation_factor(s)*o
nes(nr(i),nr(i));
            for(j=1:Iteration)
                H=(random('rayleigh',1,nr(i),nt(i)));
Capacityk(s,j)=log2(det(eye(nr(i))+(sqrtm(rr)*H*rt*H'*sqrtm(rr'))*(SNR_V(15)/
nt(i))));
            end
        end
        f1 = figure(k);
        hold on
        plot(fading_correlation_factor,mean(Capacityk),'color',color(i,:));
        grid on
    end
    legend_str = [];

for n=1:2
    legend_str = [ legend_str ;...
    {'nt = ',num2str(nt(n)),' , nr = ',num2str(nr(n))}]];
end

legend(legend_str)
grid on
set(f1,'color',[1 1 1])
xlabel('Fading Correlation Factor')
ylabel('Capacity bits/s/Hz')
end

```


Effect of Fading correlation SNR Vs. Ergodic capacity

```

clear all
close all
clc
Iteration = 1e3;
SNR_V_db = linspace(0,20,20);
SNR_V = 10.^(SNR_V_db/10);
color = ['b'; 'r'; 'g'; 'k'; 'c'; 'm'; 'y'; 'r'];
nr = [14 16];
fading_correlation_factor = 0.9; % we need to see what is the progress while
reducing correlations
for k=1:8
    nt = 2*k*ones(4,1)
    for i=1:2
        for s=1:20
            rt=eye(nt(i),nt(i));
            rr=(1-
fading_correlation_factor(1))*eye(nr(i),nr(i))+fading_correlation_factor(1)*o
nes(nr(i),nr(i));
            for(j=1:Iteration)
                H=(random('rayleigh',1,nr(i),nt(i)));

Capacityk(s,j)=log2(det(eye(nr(i))+(sqrtm(rr)*H*rt*H'*sqrtm(rr'))*(SNR_V(s)/n
t(i))));
            end
        end
        f1 = figure(k);
        hold on
        plot(SNR_V_db,mean(Capacityk'),'color',color(i,:));
        grid on
    end

    legend_str = [];

for n=1:2
    legend_str = [ legend_str ; ...
        {'nt = ',num2str(nt(n)), ' , nr = ',num2str(nr(n))}];
end

legend(legend_str)
grid on
set(f1,'color',[1 1 1])
xlabel('SNR db')
ylabel('Capacity bits/s/Hz')
end

```


Effect of line of sight component K-factor Vs ergodic capacity (at SNR=15 dB)

```

clear all
close all
clc

N0 = 1e-4;
B = 1;
Iteration = 1e3; % must be greater than 1e2

SNR_V_db = 15;
SNR_V = 10^(SNR_V_db/10);

color = ['b'; 'r'; 'm'; 'k'];
for f=2:2
    nt_V = [2 4 6 8];

    for i=1:4
        nt = nt_V(i);
        nr = 2;
        Pt = N0 * SNR_V;
        for k=0:20
            for(j = 1 : Iteration)
                H = ((k/(1+k))^0.5)*ones(nt,nr)+(1/(1+k))^0.5*(random('rayleigh',1,nt,nr));
                [S V D] = svd(H);
                [Capacity(k+1,j) PowerAllo] = WaterFilling_alg1(Pt,V,B,N0);
            end
        end
        f1 = figure(f);
        hold on
        plot([0:20],mean(Capacity'),'color',color(i,:))
        grid on
    end

    legend_str = [];
    for( i = 1 : length(nt_V))
        legend_str = [ legend_str ; ...
            {'nt = ',num2str(nt_V(i)),' , nr = ',num2str(nr)}]};
    end
    legend(legend_str)
    grid on
    set(f1,'color',[1 1 1])
    xlabel('K factor')
    ylabel('Capacity bits/s/Hz')
end

```


Effect of line of sight component SNR Vs. Ergodic capacity

```
clear all
close all
clc
```

```
N0 = 1e-4;
B = 1;
Iteration = 1e3; % must be greater than 1e2
```

```
SNR_V_db = linspace(0,20,20);
SNR_V = 10.^(SNR_V_db/10);
k=0:5:20
color = ['b'; 'r'; 'm'; 'k'; 'c'];
ntt=[2 4 6 8 10 12 14 16]
```

```
for f=1:8
    nt=ntt(f);
    nr=16;
    for i=1:5
        for s=1:20
            Pt = N0 * SNR_V(s);
            for(j = 1 : Iteration)
```

```
                H=((k(i)/(1+k(i)))^0.5)*ones(nt,nr)+(1/(1+k(i)))^0.5*(random('rayleigh',1,nt,
                nr));
```

```
                [S V D] = svd(H);
```

```
                [Capacity(s,j) PowerAllo] = WaterFilling_alg1(Pt,V,B,N0);
```

```
            end
```

```
        end
```

```
        f1 = figure(f);
```

```
        hold on
```

```
        plot(SNR_V_db,mean(Capacity),'color',color(i,:))
```

```
        grid on
```

```
    end
```

```
    legend_str = [];
```

```
    for( i = 1 : 5)
```

```
        legend_str=[ legend_str ;...
```

```
        {'k = ',num2str(k(i))}]]];
```

```
    end
```

```
    legend(legend_str, 'Location', 'Best')
```

```
    grid on
```

```
    set(f1,'color',[1 1 1])
```

```
    xlabel('SNR dB')
```

```
    ylabel('Capacity bits/s/Hz')
```

```
end
```


Effect of the keyhole phenomena capacity Vs. SNR

```

clear all
close all
clc
Iteration = 1e3;
SNR_V_db=linspace(0,30,10);
color =
['b';'r';'g';'k';'c';'m';'y';'r';'b';'r';'g';'k';'c';'m';'y';'r';'b';'r';'g';
'k';'c';'m';'y';'r'];
k=0;

for i=1:20

    nt =[2 2 2 2 4 4 4 4 6 6 6 6 8 8 8 8 10 10 10 10];
    nr =[2 4 6 8 2 4 6 8 2 4 6 8 2 4 6 8 2 4 6 8];

    for s=1:10
        for(j=1:Iteration)
            H=(random('rayleigh',1,nr(i),nt(i)));

Capacity(s,j)=log2(1+((trace(H*H'))*(10^(SNR_V_db(s)/10))/(nt(i))));
            end
        end

        f1 = figure(k+1);
        hold on
        plot(SNR_V_db,mean(Capacity),'color',color(i,:))
        clear landas
        grid on
        legend_str = [];

for i=1:20

    legend_str =[ legend_str ;...
        {'nt = ',num2str(nt(i)),' , nr = ',num2str(nr(i))}]];

end

legend(legend_str)
grid on
set(f1,'color',[1 1 1])
xlabel('SNR db')
ylabel('Capacity bits/s/Hz')

end

```


Effect of the cross-polarization discrimination SNR Vs. Ergodic capacity

```
clear all
close all
clc
```

```
SNR_V_db = linspace(0,20,10);
SNR_V = 10.^(SNR_V_db/10);
Iteration = 1e3;
```

```
k=0;
N0 = 1e-4;
B = 1;
color = ['b'; 'r'; 'g'; 'k'];
```

```
for i=2
    nt=[2 4 6 8 10 12 14 16];
    nr=4*ones(1,8);
```

```
    for s=1:10
```

```
        Pt = N0 * SNR_V(s);
        rt=eye(nt(i),nt(i));
        rr=eye(nr(i),nr(i))
        rt=((ones(nt(i),nt(i))-
eye(nt(i),nt(i))))*.7)+eye(nt(i),nt(i));
```

```
        for j=1:Iteration
```

```
            a=0;
            x=[a 1];
            y=[1 a];
            b= repmat([ repmat(x, 1,nt(i)/2); repmat(y, 1,nt(i)/2)],2,1);
            hw=(random('rayleigh',1,nr(i),nt(i)));
            H=b.*(sqrtm(rr)*hw*sqrtm(rt));
            [S V D] = svd(H);
            landas(:,j) = diag(V);
            [Capacity1(s,j) PowerAllo] = WaterFillingqqq(Pt,V,B,N0);
```

```
        end
```

```
    for(j = 1 : Iteration)
```

```
        a=1;
        x=[a 1];
        y=[1 a];
        b= repmat([ repmat(x, 1,nt(i)/2); repmat(y, 1,nt(i)/2)],2,1);
        hw=(random('rayleigh',1,nr(i),nt(i)));
        H=b.*(sqrtm(rr)*hw*sqrtm(rt));
        [S V D] = svd(H);
        landas(:,j) = diag(V);
        [Capacity2(s,j) PowerAllo] = WaterFillingqqq(Pt,V,B,N0);
```

```
    end
```

```
end
```



```

f1 = figure(i);

hold on
plot(SNR_V_db,mean(Capacity1'),'color',color(1,:))

hold on
plot(SNR_V_db,mean(Capacity2'),'color',color(2,:))

clear landas
grid on

legend_str = [];

legend_str=[ legend_str ;...
    {'nt = ',num2str(nt(i)),' ', nr = ',num2str(nr(i))',' GOOD XPD (a =0)
'}];
legend_str=[ legend_str ;...
    {'nt = ',num2str(nt(i)),' ', nr = ',num2str(nr(i))',' NO XPD (a =1)
'}];

legend(legend_str, 'Location', 'Best')
grid on
set(f1,'color',[1 1 1])
xlabel('SNR db')
ylabel('Capacity bits/s/Hz')
end

```

Appendix B

Selected Math Basics:

B.1 Hermitian Operation:

The Hermitian of a matrix (vector) is defined as the transposed matrix (vector) with complex conjugate elements

$$A^H = (A^*)^T$$

Also the following rule are exists:

- $(jA + iB)^H = j^* A^H + i^* B^H$
- $(AB)^H = B^H A^H$
- $(A^H)^H = A$
- $(A^{-1})^H = (A^H)^{-1}$
- $A^H = A^T$ for real-valued matrices
-

B.2 Frobenius norm :

The Frobenius norm of an arbitrary $N \times M$ matrix A is defined as

$$\|A\|_F = \sqrt{\sum_{i=1}^N \sum_{j=1}^M |A_{i,j}|^2} = \sqrt{\text{tr}\{AA^H\}}$$

Obviously, the squared Frobenius norm is $\|A\|_F^2 = \text{tr}\{AA^H\}$

B.3 Rank:

For an arbitrary matrix A , the largest number r of linearly independent columns always equals the largest number of linearly independent rows. This number r is called the rank of a matrix and is denoted by $r = \text{rank}(A)$. From this definition, it follows directly that the rank of an $N \times M$ matrix is always less than or equal to the minimum of N and M :

$$r = \text{rank}(A) \leq \min(N, M)$$

The rank of the product AA^H is the same rank of A , $\text{rank}(AA^H) = \text{rank}(A)$

B.4 Hermitian Matrix:

Hermitian Matrix A square matrix A is called Hermitian if it equals its complex conjugate transposed version.

$$A = A^H$$

Hermitian matrices have the following properties:

- All diagonal elements $A_{i,i}$ are real.
- For each element, $A_{i,j} = A_{j,i}^*$ holds.
- $AA^H = A^H A$ holds because the matrix A is normal.

- the determinant $\det(\mathbf{A})$ is real.
- all eigenvalues λ_i of an Hermitian matrix are real.
- the eigenvectors $\mathbf{x}_i$ of a real symmetric matrix or an Hermitian matrix are orthogonal to each other, if they belong to different eigenvalues λ_i .

B.5 Positive Semidefinite Matrix:

A Hermitian $N \times N$ matrix $\mathbf{A}$ is called positive semidefinite if there exist $\mathbf{B}$ such that $\mathbf{B}\mathbf{B}^H = \mathbf{A}$, $\mathbf{B}$ is called the square root of $\mathbf{A}$. Also A Hermitian matrix is positive semidefinite if and only if all eigenvalues are real and nonnegative, so that $\lambda_i \geq 0$ for $1 \leq i \leq N$ holds.

B.6 Singular Value Decomposition:

For any arbitrary $N \times M$ matrix $\mathbf{A}$ we can decompose it using singular value decomposition (SVD). A matrix $\mathbf{A}$ with rank r can be expressed as $\mathbf{A} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^H$

with the unitary $N \times N$ matrix $\mathbf{U}$ and the unitary $M \times M$ matrix $\mathbf{V}$. The columns of $\mathbf{U}$ contain the eigenvectors of $\mathbf{A}\mathbf{A}^H$ and the columns of $\mathbf{V}$ contain the eigenvectors of $\mathbf{A}^H\mathbf{A}$. The matrix $\mathbf{\Sigma}$ is an $N \times M$ diagonal matrix with nonnegative, real-valued elements σ_k on its diagonal. Denoting the eigenvalues of $\mathbf{A}\mathbf{A}^H$ and, therefore, also of $\mathbf{A}^H\mathbf{A}$ with λ_k , $1 \leq k \leq r$, the diagonal elements σ_k are the positive square roots of λ_k , $\sigma_k = \sqrt{\lambda_k}$

They are called singular values of $\mathbf{A}$. For the matrix containing the singular values, we obtain

$$\mathbf{\Sigma} = \left(\begin{array}{ccc|ccc} \sigma_1 & 0 & \dots & 0 & 0 & 0 \\ 0 & \sigma_2 & \dots & 0 & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & \sigma_r & 0 & 0 \\ 0 & 0 & \ddots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & 0 & 0 & 0 \end{array} \right)$$

Appendix c

MATLAB SIMULATIONS ABOUT THE EFFECT OF LOS AND XPD ON ERGODIC CAPACITY OF A MIMO SYSTEM WITH CSI KNOWN AT TRANSMITTER

Khaled Hijjeh⁽¹⁾, Ayman Al-Dasht⁽²⁾, Muhammad Quttaineh⁽²⁾, Mutasem Fanasheh⁽²⁾
(1) Palestinian Cellular Communication, Palestine. Email: Khaled.Hijjeh@jawwal.ps
(2) B.Sc. Students at Palestine Polytechnic University, Hebron, Palestine

Abstract: The paper studies through Matlab simulations the effect of the line of sight component (LOS) and cross polarization discrimination (XPD) on the ergodic capacity of a MIMO system. Both cases were studied for different MIMO configurations. Random Rayleigh channel fading was considered in the simulation to represent near realistic cases, and channel state information (CSI) is assumed known at the transmitter. The results showed that the LOS degraded the capacity of MIMO systems. The degradation in capacity can be reduced by using more transmitters. Regarding the XPD the simulations shows that it enhances the MIMO capacity at high SNR.

INTRODUCTION

The need for wireless communications providing high data rates has increased in order to support the future 4G network users [1]. But these systems are facing many problems that reduce their performance, such as the threats from propagation channel's environment, the fading due to the multipath environment, Path losses, interference, and noise [3][4]. Beside all these problems the wireless links capacity has a certain limit which was defined by Claudy Shannon's equation [5]. Shannon stated that the capacity of the channel will increase as long as they system uses wider bandwidth and larger signal to noise ratio (SNR). However, the bandwidth is a scarce resource, also manipulating transmitter power has limitations; accordingly the wireless systems are limited in capacity.

To boost the wireless systems capacity the spatial multiplexing feature of the MIMO systems were widely used. Spatial multiplexing offers a linear increase in the transmission rate for the same bandwidth and with no additional power waste. The bit stream is split into many low rate bit streams, modulated and transmitted simultaneously from the antennas.

This paper studies the behavior of MIMO system's ergodic capacity under two cases: the first is when a LOS is present in the system, which is usually a limiting factor for MIMO systems, since it forces the channel to deviate from Rayleigh i.i.d [8]. The second is when XPD is applied at the receiver end of the MIMO system, which enhance the ergodic capacity at high SNR [9][7]. The simulations were based on known CSI at the transmitters and receivers, and apply Random Rayleigh fading environments to approximate the results to the real life conditions. At the transmitter side this paper applies the Water Filling technique which relies on previous knowledge about the channel's behavior towards the receiver based on the rule that the best path takes the better power and less power

to the null one [10]. At the receiver, having complete knowledge of the channel, would recover these bit streams and combines them so as to recover the original bit stream [6][7].

MIMO SYSTEM MODEL

Consider a narrowband MIMO Rayleigh fading channel with M_T transmit and M_R receive antennas. The channel can be described by a $M_R \times M_T$ channel transfer matrix $H(\tau, t)$, whose entries are i.i.d. complex Gaussian random variables with zero mean. The entry $h_{i,j}$ of matrix $H(\tau, t)$ represents the fading coefficient from the j^{th} transmit antenna element to the i^{th} receive antenna element. The system's input-output relationship can be described as:

$$y(t) = H(\tau, t) * s(t) \quad (1)$$

Where

$$H(\tau, t) = \begin{bmatrix} h_{1,1}(\tau, t) & h_{1,2}(\tau, t) & \dots & h_{1,M_T}(\tau, t) \\ h_{2,1}(\tau, t) & h_{2,2}(\tau, t) & \dots & h_{2,M_T}(\tau, t) \\ \vdots & \vdots & \ddots & \vdots \\ h_{M_R,1}(\tau, t) & h_{M_R,2}(\tau, t) & \dots & h_{M_R,M_T}(\tau, t) \end{bmatrix}$$

$$s(t) = [s_1(t) s_2(t) \dots s_{M_T}(t)]^T \text{ is } M_T \times 1 \text{ vector}$$

$$y(t) = [y_1(t) y_2(t) \dots y_{M_R}(t)]^T \text{ is } M_R \times 1 \text{ vector}$$

CASE ONE: CAPACITY OF MIMO FADING CHANNELS IN THE PRESENCE OF LOS COMPONENT

This paper simulated the ergodic capacity, which is the average information averaged on all channel states. This is because the channel is random and it has a variable nature [11]. The ergodic capacity of a random MIMO channel at the presence of channel knowledge at both the transmitter and the receiver is given by [10]:

$$C = \epsilon \left\{ \sum_{i=1}^r \log_2 \left(1 + \frac{E_s \gamma_i}{N_0 M_T} \lambda_i \right) \right\} \quad (2)$$

Where:

- λ_i : is the energy in the i^{th} sub-channel,
- γ_i : is the Eigen value of the channel matrix,
- E_s : is the bit energy,
- N_0 : is the noise power,
- M_T : is the number of transmit antennas, and
- r : represents the total number of antenna elements at the receiver.

The presence of LOS in the channel will make a change on the channel matrix H , which can be represented as [10]

$$\mathbf{H} = \sqrt{\frac{K}{1+K}} \bar{\mathbf{H}} + \sqrt{\frac{1}{1+K}} \mathbf{H}_w \quad (3)$$

Where

- $\sqrt{\frac{K}{1+K}} \bar{\mathbf{H}}$: is the LOS component of the channel and
- $\sqrt{\frac{1}{1+K}} \mathbf{H}_w$: is the fading component which assumes uncorrelated fading,
- The elements of $\bar{\mathbf{H}} = \mathbf{1}_{nr} \times \mathbf{1}_{nt}$ [7][9]
- K : is the Rician K -factor, which is the ratio between the power in the LOS component and the power in the fading component. $K = \infty$ corresponds to a nonfading channel, and $K=0$ corresponds to pure Rayleigh channel. [10].
- $\mathbf{H}_w$: is a random fading matrix with unit variance and circularly symmetric complex Gaussian entries.

CASE TWO: CAPACITY OF MIMO FADING CHANNELS IN THE PRESENCE OF XPD

The term XPD describes how the MIMO antenna can discriminate its signal from others through introducing a constant α ($0 \leq \alpha \leq 1$). For $\alpha = 0$ the MIMO antenna will have a good discrimination for sure zero interference. At $\alpha = 1$ it implies a poor discrimination and a strong interference [7][10]. Assuming a deterministic channel with M_T and M_R elements at each end of the MIMO antenna system in the presence of XPD, the channel matrix $\mathbf{H}$ can be given by:

$$\mathbf{H} = \beta \odot \mathbf{R}_r^{\frac{1}{2}} \mathbf{H}_w \mathbf{R}_t^{\frac{1}{2}} \quad (4)$$

$$\beta = \begin{bmatrix} \beta_{1,1} & \beta_{1,2} & \dots & \beta_{1,M_T} \\ \beta_{2,1} & \beta_{2,2} & \dots & \beta_{2,M_T} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{M_R,1} & \beta_{M_R,2} & \dots & \beta_{M_R,M_T} \end{bmatrix}$$

Where:

- $\beta_{i,j} = \sqrt{\alpha}$ when $i \neq j$, and
- $\beta_{i,j} = 1$ when $i = j$.

Capacity in the absence of XPD ($\alpha = 1$) and in the presence of perfect XPD ($\alpha = 0$) can be given by [10]:

$$C(\alpha = 1) = \log_2(1 + 2\rho) \quad (5)$$

$$C(\alpha = 0) = 2 \log_2 \left(1 + \frac{\rho}{2} \right) \quad (6)$$

In the light of these equations this paper examines the effect of LOS component, and XPD for different values of K [0 to 20] with a fixed value of SNR which is about 11 dB. Matlab simulations will be applied for different MIMO schemes up to 16×2 .

SIMULATIONS ANALYSIS

The paper's simulation results show the relation between the LOS component and the capacity of the spatial MIMO system, and between the signal to noise ratio and the capacity for different values of the K factor.

A. Case One LOS simulations:

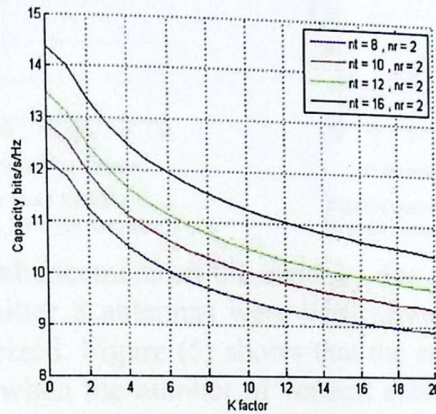


Fig (1): Capacity versus K-factor for (8,10,12,16) $\times$ 2

Figure (1) shows the relation between the K-factor and the capacity of the system for different number of receivers, it's also shown that as long as the factor K increases the capacity of the system will decrease and the drop will be larger as the number of transmitters and receivers is higher. At K=1 there is a break off point on the curve and it happens because the receiver and transmitter are still learning about the channel condition. However, as the number of transmitters and receivers increase its effect will decrease.

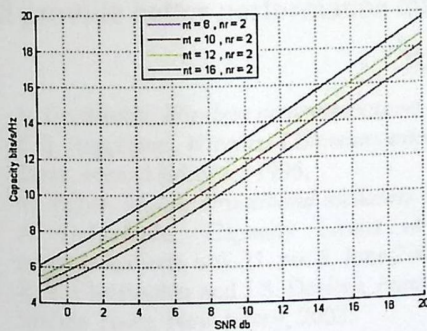


Fig (2) Capacity versus SNR for (8,10,12,16) $\times$ 2 and K=0

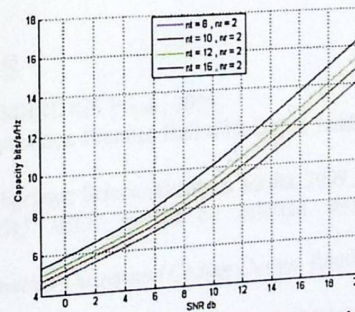


Fig (3): Capacity versus SNR for (8,10,12,16) $\times$ 2 and K=10

Figure (2) shows the relation between the signal to noise ratio and the capacity in the no LOS case when K=0 for different number of transmitters. It's shown that as long as the SNR increases the capacity of the system will increase almost semi-linearly. Figure (3) shows the relation between the signal to noise ratio and the capacity for different number of transmitters at K-factor equal 10. Here it's shown that as long as the SNR increases the capacity of the system will increase in log scale and for higher number of transmit antennas the offered capacity is high.

B. Case two XPD simulations:

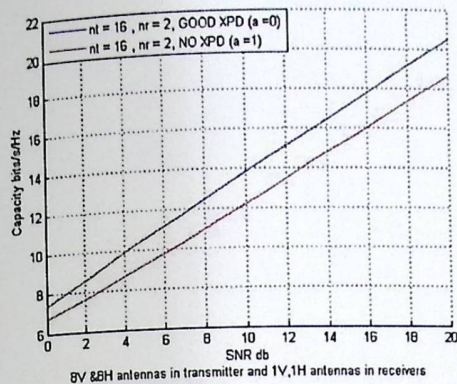


Fig (4) capacity versus SNR for 16×2 XPD. 8V, 8H at the transmitter and 1V, 1H at the receiver

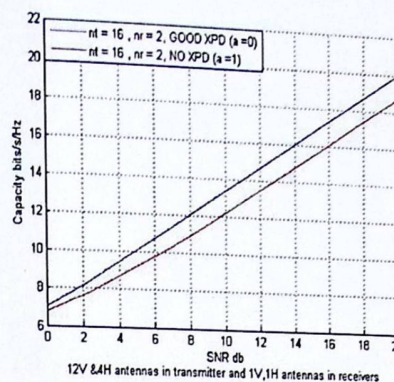


Fig (5) Capacity versus SNR for 16×2 XPD. 12V, 4H at the transmitter and 1V, 1H at the receiver.

Figure (4) shows the enhancement on the capacity due to the use of the XPD, in this case at the transmitter 8 antennas were vertically polarized and 8 antennas were horizontally polarized. Figure (5) shows that the enhancements provided by the XPD will degrade when the number of vertical antennas is much higher than the number of horizontal antennas and vice versa.

CONCLUSION

In this paper we investigated two real life cases which are the cross polarization discrimination and the line of sight component. The study showed that the ergodic capacity of the system will be affected by the LOS and it will degrade as the power from the line of sight component increases. At high SNR high capacity will be obtained, as the number of transmit antennas increases. The XPD has positive effect on the capacity and the effect will be better if the number of vertical antennas is close to the number of horizontal antennas. At high SNR high XPD will provide better performance than low XPD.

REFERENCES

- [1] A. Goldsmith, *Wireless communications*. University of CAMBRIDGE Press, 2005.
- [2] T. S. Rappaport, *Wireless Communications principles and practice*. Prentice Hall BTR Upper Saddle River, second Edition, 1995.
- [3] M. Ergen, *Mobile Broadband including WiMAX and LTE*. Springer Science Business Media, 2009.
- [4] A. Goldsmith, "Capacity Limits of MIMO Channels," *IEEE journal on selected areas in communications*, vol. 21, no. 5, June 2003.
- [5] R. T. Christopher and J. S. Desilva, *Fundamentals of Information Theory and Coding Design*. Routledge, Middle Town, New Jersey, 2002.
- [6] E. Dahlman, *2-3G Evolution HSPA and LTE for Mobile Broadband*. Linacre House, Jordan Hill, Oxford, OX2 8DP, 2008.
- [7] A. Paulraj, R. Nabar and D. Gore, *Introduction to Space-Time Wireless Communications*. UK. Published by the Press syndicate of the University of CAMBRIDGE, 2006.
- [8] M. Matthaiou, A. M. Sayeed and J. A. Nossek, "Maximizing LoS MIMO Capacity Using Reconfigurable Antenna Arrays," 2010 International ITG Workshop on Smart Antennas, 2010.
- [9] C. Oestges and B. Clerckx, *MIMO Wireless Communications From Real-World Propagation to Space-Time Code Design*. Academic Press, June 4, 2007.
- [10] M. Jankiraman, *Space time Codes and MIMO System*. Artech House universal personal communication series, London 2004.
- [11] E. Biglieri, *MIMO Wireless Communications*. University of CAMBRIDGE Press, 2007.