This report contains an executive summary of the literature search carried out under contract number AY 4252 (510010100) to provide an initial study of multiple in multiple out technology. The summary presented here gives an overview of MIMO and the potential capacity gains it provides, the factors that limit this capacity, and reported MIMO measurements and models. Also a number of topics have been identified for further study.

The detailed summary of all the reviewed papers, book chapters, presentations and lecture notes are included separately in the document entitled 'Literature Search'.

List of Symbols

C	Channel capacity
H	Channel matrix
I	identity matrix
N, n, n_t	Number of receive antennas
M, m, n_r	Number of transmit antennas
R	correlation matrix
r	correlation coefficient
λ	wavelength
λ_i	Eigenvalue
σ_i	Singular value
ρ	Signal to noise ratio
ε_i	Optimum value for waterfilling

GLOSSARY OF TERMS

AOA	Angle Of Arrival
ASIC	Application Specific Integrated Circuit
AWGN	Additive White Gaussian Noise
BLAST	**B**ell Laboratories **La**yered **S**pace **T**ime
CDMA	Code Division Multiple Access
CLR	Correlated Low Rank
DOA	Direction of Arrival
DOD	Direction of Departure
DOF	Degrees of Freedom
DSP	Digital Signal Processing
ED	Effective Dimensionality
EDGE	Enhanced Data rate for Global Evolution
EDOF	Effective Degrees Of Freedom
FDD	Frequency Division Duplex
GSM	*Groupe Speciale Mobile* or Global System for Mobile Communication
HDTV	High Definition Television
HF	High Frequency
H-S	Hybrid Selection
iid	independent identically distributed
LOS	Line of Sight
MEA	Multi-Element Array
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MMSE	Minimum Mean Square Error
NLOS	Non Line Of Sight
OFDM	Orthogonal Frequency Division Multiplexing
OSIC	Ordered Successive Interference Cancellation
pdf	probability density function
QAM	Quadrature Amplitude Modulation
Rx	Receiver
SIMO	Single Input Multiple Output
SNR	Signal to Noise Ratio
SISO	Single Input Single Output
Tx	Transmitter
UHR	Uncorrelated High Rank
ULA	Uniform Linear Array
ULR	Uncorrelated Low Rank
UMTS	Universal Mobile Telecommunication System
WLAN	Wireless Local Area Network
WPMC	Wireless Personal Multimedia Communication
3G	Third Generation
4G	Fourth Generation

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1. Introduction

Multiple antennas can be used either at the transmitter or at the receiver or at both. These various configurations are referred to as multiple input single output, MISO, single input multiple output, SIMO or multiple input multiple output, MIMO. The SIMO and MISO architectures are a form of receive and transmit diversity schemes respectively. While it is also possible to use MIMO architecture for combined transmit and receive diversity, this study is mainly concerned with the application of the multiple antenna technology for the parallel transmission of data or spatial multiplexing. This technology promises high bit rates in a narrow bandwidth and as such it is of high significance to spectrum regulators.

The literature search identified a large number of papers, book chapters, conference sessions and presentations concerned with MIMO technology. Therefore, the reviewed list is not exhaustive. However, it aims to cover the main topics of concern from the Radiocommunications Agency point of view. The number of articles reviewed, are 93 papers, 5 presentations, 1 book chapter, 1 technical report, and 2 lecture notes. These fall within the following categories: background and theory of MIMO, simulation of MIMO systems, models of MIMO channels, measurements of MIMO channels and MIMO systems, effects of the LOS and keyholes on MIMO capacity, antenna aspects and processing and coding. Table 1 gives a summary of these categories and the articles that fall within each category as well as the total number in each column.

This report presents a summary of the topics reviewed and proposed research topics for further study.

2. Basic concept and background

The concept of MIMO was first introduced by Jack Winters, (paper 68), in 1987 for two basic communication systems. These are 1. Communication between multiple mobiles and a base station with multiple antennas. 2. Communication between two mobiles each with multiple antennas. Hence, one can attribute the concept of MIMO and ad-hoc communications using multiple antennas at both ends, be it for the same unit or using multiple units to this paper.

Subsequently, the papers of Foschini (papers 1 and 2) presented the analytical basis of MIMO systems and proposed two suitable architectures for its realisation known as vertical BLAST, and diagonal BLAST. In the proposed BLAST system the data stream is divided into blocks which are distributed among the transmit antennas. The difference between the two architectures is the way the data blocks are distributed among the antennas. In vertical BLAST sequential data blocks are distributed among consecutive antenna elements, whereas in diagonal BLAST, they are circularly rotated among the antenna elements. For the example of transmit antennas 1 to 4, data block a is always assigned to antenna 1, b to antenna 2, c to antenna 3 and d to antenna 4 for vertical BLAST. In diagonal BLAST, the data blocks assigned to antennas 1-4 in the first burst are a b c d, in the second burst b c d a, in the third burst c d a b and in the fourth burst d a b c. While diagonal BLAST offers the advantage of circulating the data blocks among the antennas, which avoids the same data block being transmitted over the same channel, it requires more processing power.

The basic motive of BLAST was to increase the data rate in a constrained spectrum. The initial application of MIMO was envisaged for indoor WLAN, fixed wireless access networks, wireless local loop, and building-to-building wireless communications. Later, other applications were proposed such as metropolitan voice/data wireless networks (UMTS, EDGE, and 4^{th} generation networks), very high speed fixed and mobile wireless (point to multipoint), acoustic communications, and broadcast systems (HDTV) (paper 63).

In principle, MIMO aims to separate data streams occupying the same bandwidth relying on the de-correlation of the multiple received signals in the presence of multipath. Therefore, the fundamental analysis of MIMO systems is based on the assumption of independent flat Rayleigh fading and constrained total power (papers 68, 1 and 2). In addition, the data are transmitted in bursts, such that the channel can be assumed quasi-stationary and that the channel is known at the receiver through the transmission of a training sequence (papers 85-86) but not necessarily at the transmitter. The training sequence enables the receiver to acquire adequate knowledge of the channel coefficients to extract the multiple data streams. The required training interval grows approximately linearly with the number of transmit antennas. To maximise the overall transmission rate, the number of transmit antennas is chosen such that half of the interval is used for training and half the interval for data transmission. Channel knowledge at the transmitter is generally considered to be beneficiary in the sense that the transmitter can optimise its transmission on the 'good channels', adaptively. In the case of time division duplex channels this requires the channel to be stationary. Hence, this approach is not necessarily practical since it requires the channel coefficients to be fed back to the transmitter at the rate at which the channel is changing. In addition to the stationary requirement, in the case of frequency division duplex, FDD channels, the coefficients would have to be transmitted on a different frequency. Since FDD channels are not reciprocal, the feedback approach might not be optimum. While adaptive MIMO can give higher channel capacity, its practical application needs the proper estimation of the coherent time of the channel, particularly in outdoor environments where high Doppler shifts are expected and can be on the order of 35 Hz at 2 GHz even for a stationary user (UMIST measurements in Manchester city centre). To overcome the fast feedback constraint some researchers propose the feedback of the spatial mean of the channel coefficients instead of the instantaneous coefficients (paper 87). This is seen to enhance the channel capacity in the case of correlated channels.

MIMO is a narrowband concept where the assumption of flat fading holds, and therefore, the majority of the channel capacity expressions are given for the narrowband case. Essential to this assumption is the measurement of the coherent bandwidth of the channel. The wideband case or the frequency selective channel is seen to provide diversity gain.

Table 1 indicates that the majority of publications are concerned with the theory of MIMO, and the analysis, modelling, and simulation of channel limitations on the MIMO capacity. Paper 78 gives a comprehensive list of channel models for MIMO systems most of which were identified in the rest of the papers in the column. The models are classified as physical and non-physical. The non-physical models are essentially statistical models. The paper identifies seven physical models some of which are based on the distribution of scatterers, others are based on the parameters of the multipath components.

3. Capacity equations

The following section gives the basic capacity expressions for the ideal channel including the deterministic and ergodic channel. This is followed by a discussion of the limiting factors of the channel capacity and the corresponding capacity expressions.

3.1 Basic capacity expressions

A MIMO system (figure 1) can be considered as a network with transmission paths connecting each input to each output.

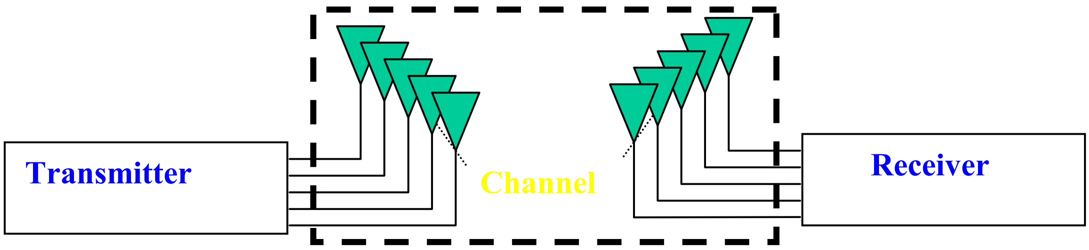

Figure 1 MIMO architecture

For n by m antennas, and for a narrowband communication system, this results in a transmission matrix with complex coefficients of the form

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \ldots h_{1n} \\ h_{21} & h_{22} & h_{23} \ldots h_{nm} \\ \ldots\ldots & & \\ h_{m1} & h_{m2} & h_{m3} \ldots h_{mn} \end{bmatrix}$$

The expressions for MIMO capacity as well as MISO, SIMO and SISO capacity are included in paper 2. These were derived under a number of assumptions summarised in paper 1 and listed below.

1. Transmitted signal has fixed narrow bandwidth such that the channel can be considered flat fading i.e. the transfer function is a complex scalar. The transmitted signals on the different antennas are assumed to be statistically independent Gaussians.
2. Total transmitted power is independent of the number of transmit antennas i.e. when the antennas are increased to n, the total power is divided equally between the antennas so that power per antenna = P_t/n.
3. Noise at the receiver is AWGN. The noise at each of the antenna outputs is independent and of identical power N.

4. Received signal at each antenna is the sum of all the transmitted signals. The average power at the output of each receiving antenna is P. Average power is spatial average.
5. Average SNR at each receive antenna, ρ=P/N.
6. Matrix channel impulse response is g(t) and is equal to n by m. h(t) denotes the normalised form of g(t) where each element of h(t) has a spatial average power loss of unity (i.e. $g = \sqrt{\frac{\rho}{n}} h$)
7. The data are transmitted in bursts, which are assumed to be long enough to apply information theory and short enough to assume that the channel coefficients do not change during a single burst of data i.e. quasi-stationary. For example for several Msymb/s with several thousand symbols in a burst the channel changes on a scale of seconds.
8. The channel is unknown to the transmitter but is tracked at the receiver: need to transmit a training sequence.
9. The channel is assumed to be Rayleigh distributed. For half a wavelength separation between elements, H is approximated by a matrix having independent identically distributed (iid), complex, zero-mean, unit-variance entries:
   - H_{ij} =Normal(0,1/√2) +j Normal(0,1/√2)
   - The magnitude squared of each element is a chi-squared variate with two degrees of freedom denoted by χ_2^2 but normalised so the expected value is 1, i.e. $E|H_{ij}|^2=1$.

Under assumptions 1-8 the capacity equation for a MIMO system is

$$C = \log_2 \det\left[I_m + \frac{\rho}{n} HH^{tc} \right] \text{b/s/Hz} \qquad (1.a)$$

$$C = \log_2 \det\left[I + \frac{\rho}{n} R \right] \text{b/s/Hz} \qquad (1.b)$$

where tc stands for complex conjugate transpose, R is the normalised channel correlation matrix whose components are given by $r_{ij} = \sum_k h_{ik} h_{jk}^*$ where the index i is for receive antenna and j is for transmit antenna and takes into account the effects of correlation at both the transmit and receive ends. Equation 1.b is based on the assumptions that the channel matrix is normalised such that

$$\sum_{i,j=1}^{n} \left| h_{ij} \right|^2 = n$$

and all the received powers are equal so $\sum_{j=1}^{n} \left| h_{ij} \right|^2 = 1$ (papers 6 and 7). Most simulation results are presented under assumption 9 above as in Figure 2 which gives examples of channel capacity for different antenna numbers for Rayleigh iid channels. The figure shows that at 25 dB SNR the capacity varies from about 7 b/s/Hz for a single transmit single receive system to about 52 b/s/Hz for an 8 by 8 MIMO system.

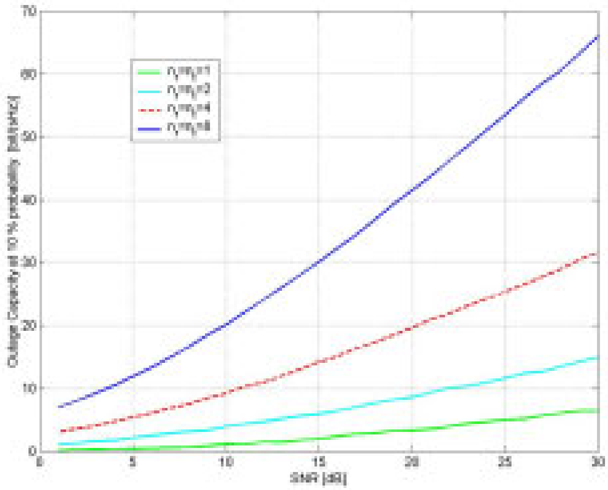

Figure 2. MIMO capacity with iid assumption (after presentation 1).

In paper 18, it is proposed to express the channel matrix as ideal iid matrix, which is modified by the correlation coefficients at the transmitter and at the receiver. This results in the following alternative form for equation 1.b

$$C = \log_2\left(\det\left(I_m + \frac{\rho}{n}\phi_R H \phi_T H^{tc}\right)\right) \text{b/s/Hz} \qquad (1.c)$$

where ϕ_T, ϕ_R are the covariance matrices of the transmit and receive arrays, respectively.

For the frequency selective channel the capacity is given as the sum or the integral of the narrowband channel, (papers 28, 52) that is

$$C = \frac{1}{B}\int \log_2 \det\left(\mathrm{I}_m + \frac{\rho}{n}\mathrm{H}(f)\mathrm{H}^{tc}(f)\right) df \ \text{ b/s/Hz} \qquad (1.d)$$

Alternate expressions to equation 1.a can be given in terms of the eigenvalues of the HH^{tc}, or in terms of the singular values of H. The capacity expression in terms of the eigenvalues is given as (presentation 1, paper 4)

$$C \ \sum_{i=1}^{k} \log_2\left[1 + \frac{\rho}{n}\lambda_i\right] \text{ b/s/Hz} \qquad (2.a)$$

where in the above equation $k \leq \min[n,m]$ is the rank of the matrix, which is ideally equal to the min(n, m), and λ_i is the ith eigenmode of HH^{tc}. The corresponding expression in terms of the singular values is

$$C = \left\{\sum_{i=1}^{k} \log_2\left(1 + \frac{\rho}{n}\sigma^2{}_i\right)\right\} \text{b/s/Hz} \qquad (2.b)$$

Note: the singular values of H are the square root of the eigenvalues of HH^{tc}.

Expression 2.a enables the visualisation of the MIMO channel as a number of parallel SISO pipes with gains equal to the respective eigenvalues. If the channel is known at the transmitter, the capacity can be enhanced by using the 'good channels' i.e. those with the highest gain by applying an unequal power distribution. This results in a capacity expression given by [presentation 1]

$$C = \sum_{i=1}^{k} \log_2 \left[1 + \frac{p_i}{\sigma^2} \lambda_i \right] \text{b/s/Hz} \qquad (2.c)$$

where p_i is the power in the ith pipe which can be determined from a water-filling solution where $\frac{1}{\lambda_1} + P_1 = ... = \frac{1}{\lambda_k} + P_k$ such that the total transmitted power remains the same as for the equal power distribution case and σ^2 is the noise power.

For the case when the channel matrix is equal to the identity matrix (the case of orthogonal parallel channels) equation 2.a reduces to

$$C = \min[n,m] \log_2 [1 + (\rho / n)] \text{ b/s/Hz} \qquad (3.a)$$

$$C = n \log_2 [1 + (\rho / n)] \rightarrow (\rho / \ln(2) \quad as \quad n \rightarrow \infty) \text{ b/s/Hz} \qquad (3.b)$$

where n=m

That is the capacity increases linearly with the smaller number of transmit, receive anetnnas rather than logarithmically as SNR increases as the case for SISO channels for which the capacity is only equal to $C = \log_2 [1 + \rho]$b/s/Hz.

The corresponding ergodic capacity expressions are given in paper 17 as the expected value, since the capacity is a random variable. For these the channel capacity expressions are:

$$C = E \left\{ \log_2 \left[\det \left(I_m + \frac{\rho}{n} HH^{tc} \right) \right] \right\} \text{b/s/Hz} \qquad (4.a)$$

where ρ is the average receive SNR at each branch.

When the product of the channel matrix and its transpose conjugate is equal to the identity matrix, (this could happen when n is very large), the capacity becomes

$$C = E\{ n. \log_2 (1 + \rho) \} \text{b/s/Hz} \qquad (4.b)$$

which increases linearly with n.

The corresponding capacities in terms of the eigenvalues or singular values are:

$$C = E \left\{ \sum_{i=1}^{k} \log_2 \left(1 + \frac{\rho}{n} \lambda_i \right) \right\} \text{b/s/Hz or} \qquad (4.c)$$