Antennas for MIMO systems

Brian Collins
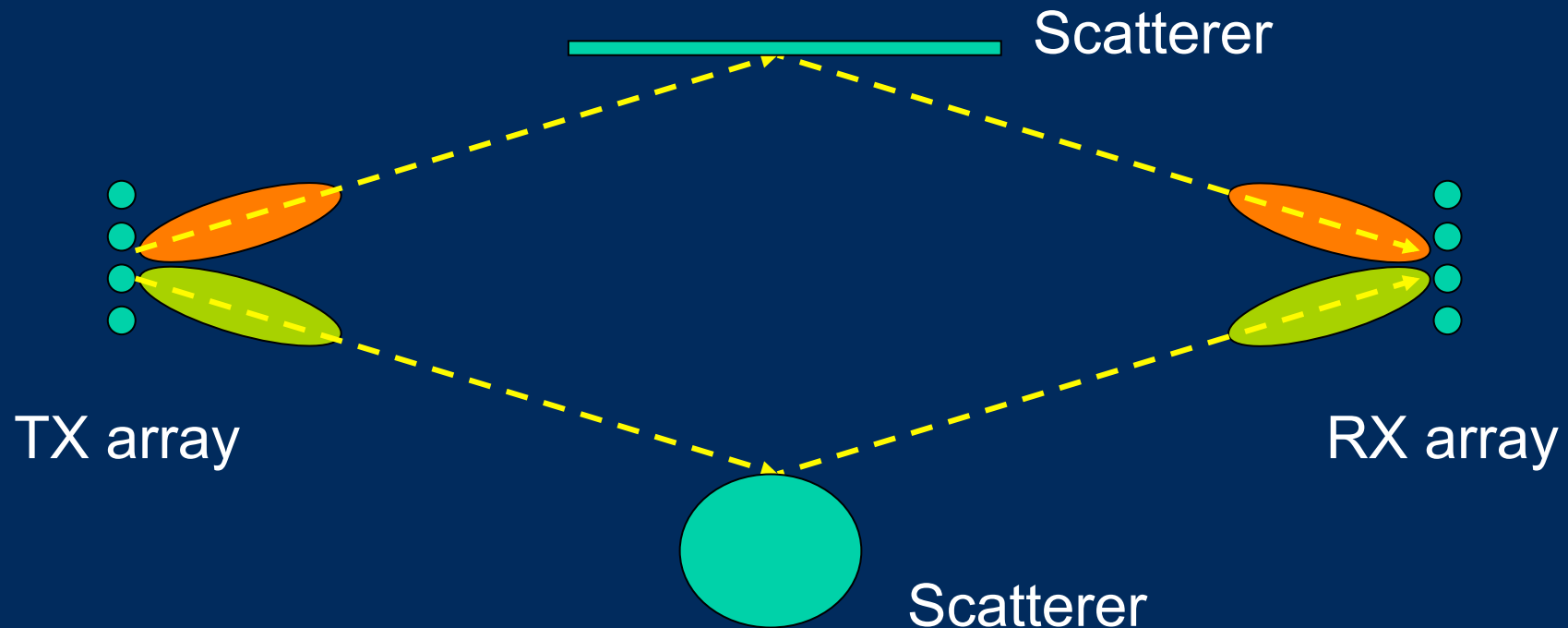
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Something familiar

Receiver 1

Receiver 2

TX array
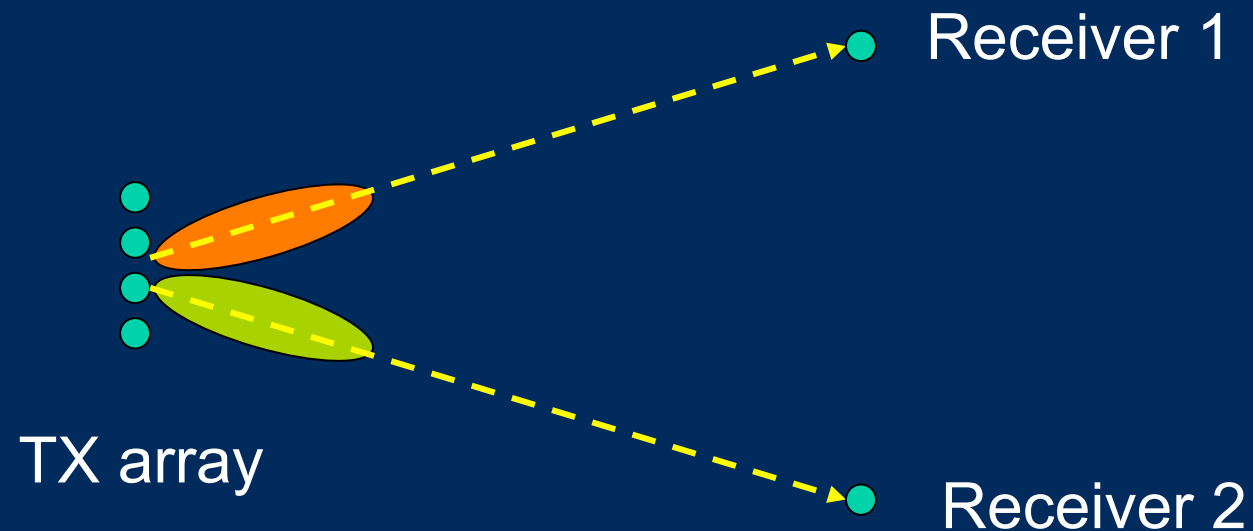
- If the transmit antenna has sufficient resolution, different data streams can be sent to the two receivers using the same carrier frequency

MIMO in a simple environment

Scatterer

TX array

RX array

Scatterer

- Both arrays must be capable of resolving the two paths
- If the paths carry different data streams, increased throughput is achieved without increased bandwidth

Why MIMO?

- In most real-world situations there is more than one signal path between the transmitter and the receiver

MIMO

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- An optimum system can exploit the spatial properties of multipath channels to provide enhanced communication performance

Why MIMO?

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- An optimum system can exploit the spatial properties of multipath channels to provide enhanced communication performance

- MIMO systems are characterised by multiple antenna elements at both the transmitter and receiver

The real world

- Typical wireless channels have many paths, often closely spaced in angle
- With N antennas we can resolve N signal paths
- MIMO implementations rely on advanced signal-processing techniques to exploit the spatial resources of the channel

Key MIMO system parameters

- Coding
- Signal processing
- The propagation channel
- The antennas

Signal constellations
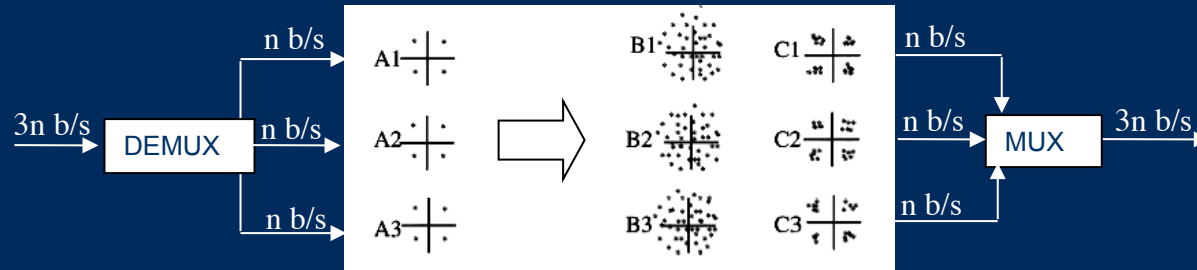
Symbol constellations from a 3 x 3 example

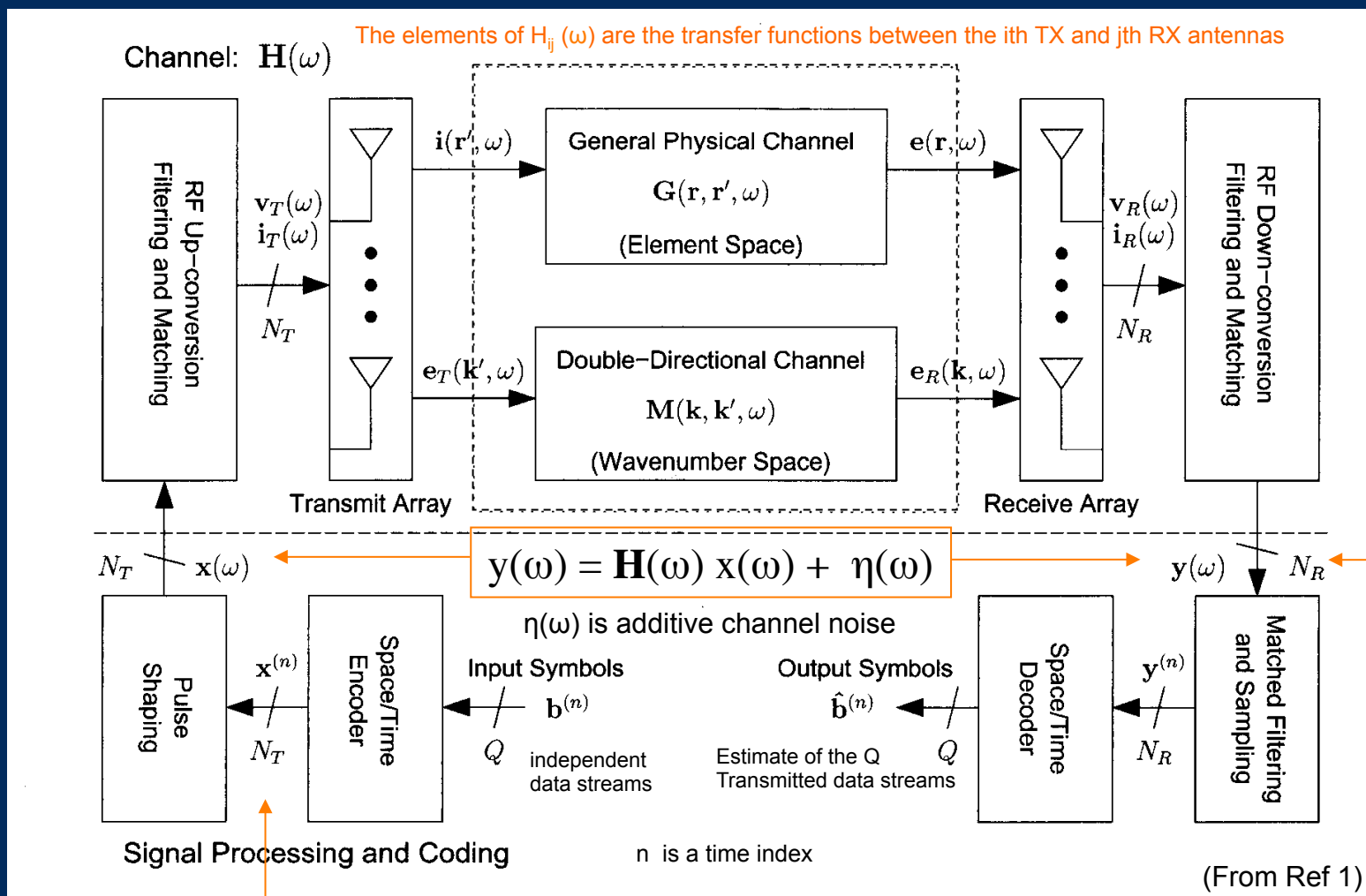A1,2,3 as transmitted by three TX antennas

B1,2,3 as received by three RX antennas

C1,2,3 after processing, at the inputs to three demodulators.

The three parallel symbol streams were derived from a
single stream at 3 times the symbol rate, and are
subsequently reassembled in the original time sequence

(From ref 5)

A generic MIMO system

Note: It is assumed that the channel is invariant with time over the interval of a transmission block

The elements of $H_{ij}(\omega)$ are the transfer functions between the ith TX and jth RX antennas

Channel: $\mathbf{H}(\omega)$

RF Up-conversion Filtering and Matching

$\mathbf{v}_T(\omega)$
$\mathbf{i}_T(\omega)$

N_T

Transmit Array

$\mathbf{i}(\mathbf{r}',\omega)$

General Physical Channel

$\mathbf{G}(\mathbf{r}, \mathbf{r}', \omega)$

(Element Space)

$\mathbf{e}(\mathbf{r},\omega)$

$\mathbf{e}_T(\mathbf{k}',\omega)$

Double−Directional Channel

$\mathbf{M}(\mathbf{k}, \mathbf{k}', \omega)$

(Wavenumber Space)

$\mathbf{e}_R(\mathbf{k},\omega)$

$\mathbf{v}_R(\omega)$
$\mathbf{i}_R(\omega)$

N_R

Receive Array

RF Down-conversion Filtering and Matching

$$y(\omega) = \mathbf{H}(\omega)\, x(\omega) + \eta(\omega)$$

N_T $\mathbf{x}(\omega)$

$\mathbf{y}(\omega)$ N_R

$\eta(\omega)$ is additive channel noise

Pulse Shaping

$\mathbf{x}^{(n)}$

N_T

Space/Time Encoder

Input Symbols

$\mathbf{b}^{(n)}$

Q independent data streams

Output Symbols

$\hat{\mathbf{b}}^{(n)}$

Estimate of the Q Transmitted data streams

Q

Space/Time Decoder

$\mathbf{y}^{(n)}$

N_R

Matched Filtering and Sampling

Signal Processing and Coding

n is a time index

(From Ref 1)

N_T discrete-time complex baseband streams $X^{(n)}$

Continuous baseband waveform $X^{(n)}$

Constraints of the channel

- Since the transmit vector is projected onto the channel matrix $\mathbf{H}(\omega)$, the number of independent data streams that can be supported is limited by the rank of $\mathbf{H}(\omega)$

- The properties of $\mathbf{H}(\omega)$ determine the potential performance for a MIMO system

The channel matrix

The channel matrix $\mathbf{H}(\omega)$ includes the effects of:

- Antenna impedance matching

- Array size

- Antenna configuration

- Element pattern

- Element polarisation

- Element coupling

- Multipath propagation characteristics

The channel matrix

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All of these are characteristics of the transmit and receive antennas

- Multipath propagation characteristics

The channel matrix

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- Element coupling

- Multipath propagation characteristics

… but with no multi-path, there's no MIMO and no performance gain

MIMO v Diversity

- For simple point-to-point transmission (SISO), multipath propagation creates fading and signal loss

- We can restore this degradation using diversity techniques, but the channel is no better than an unobstructed single path

- MIMO offers an enhanced data rate with no increase in bandwidth

Knowledge of the channel

- In a mobile environment we have no *a priori* knowledge of the channel

- By the time we have sounded m x n channels, everything will have changed and we will have no useful result

- In a "portable" application the rate of change could allow effective channel sounding

The prize

- **In a rich multipath environment** a MIMO system with M transmitting and receiving antennas provides M² transmission channels and has a potential throughput up to M times that of a single channel occupying the same bandwidth

- **Every property** of a MIMO system depends on the statistical properties of the environment

MIMO spectral efficiency
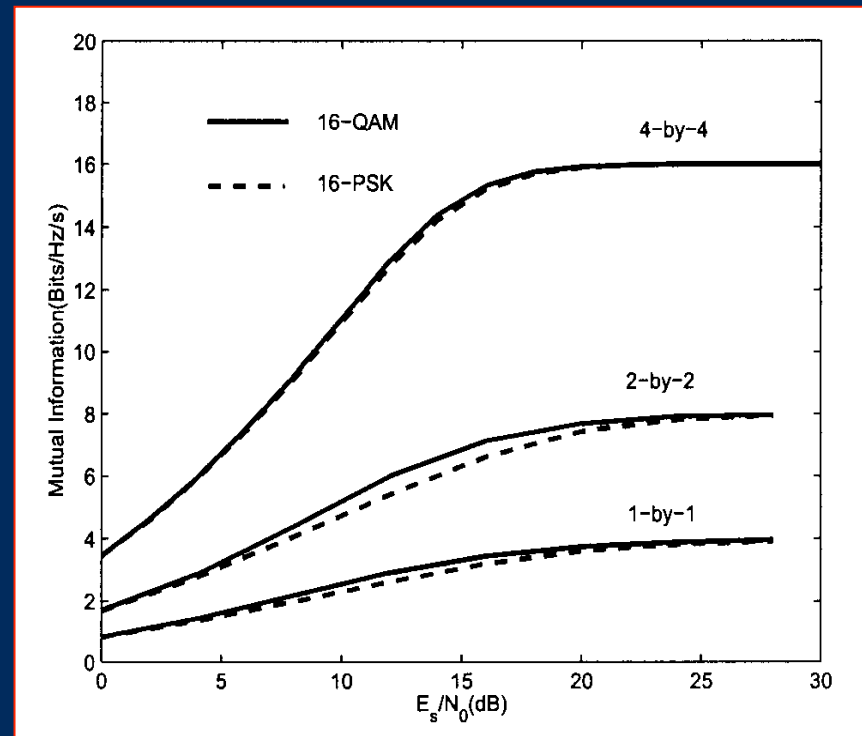
Spectral efficiency (b/s/Hz) for different E_b/N_o, antenna numbers and modulation formats

Diversity and spatial multiplexing

- In traditional antenna diversity, spatial re-sources provide duplicate copies of a single information stream in order to increase the reliability of detection

- In spatial multiplexing, different information streams are sent over the spatial channels to increase throughput and spectral efficiency

- MIMO achieves a mixture of these benefits, trading them against each other, according to the environment and the QoS requirements

Trade-off

MIMO systems provide a trade-off between diversity gain and spatial multiplexing gain. When either is being fully exploited, the other falls to zero.

In severe fading conditions all available resources are used to maintain the channel.

As things improve the resources allow the channel capacity to be increased.
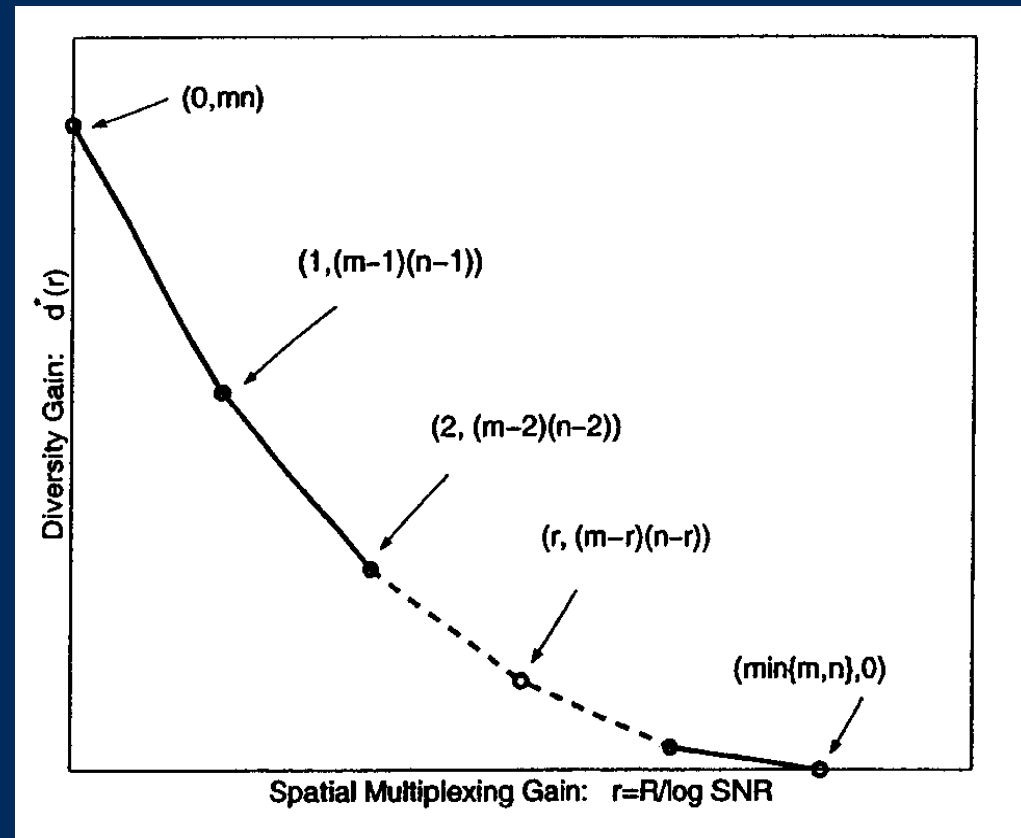
System with M x N antennas   Source: Ref 3

The antenna requirement

- The complex maths of a MIMO system makes it difficult to understand intuitively the impact of individual antenna parameters

- A MIMO system operates in different signal regimes, and must be capable of making the best use of the signals available in any of them

- Antenna system design must take account of this

Characterising the environment

- At a user equipment, signal components:

  — may arrive from any azimuth angle

  — can arrive from any elevation angle (perhaps constrained in some applications)

  — may have any polarisation (generally elliptical)

  — may suffer Doppler shift

  — will experience different time delays

  — will vary in all these respects with time

Low correlation

- Low correlation between antenna outputs is a necessary but not sufficient condition for good MIMO performance

- Low correlation is achieved when each antenna provides a unique weighting to each individual multipath component based on its DOA/DOD

- This weighting can be on phase due to antenna location (spatial diversity), magnitude and phase due to antenna pattern (angle diversity) or polarisation.

…unfortunately…

- Low correlation (good) generally occurs for a large set of multipath components with large angular spread.

- The rich scattering required to achieve this generally also produces low SNR, which in turn decreases channel capacity (bad)

- But some investigators report that good improvements in channel capacity can be realised with correlations as high as 0.5

Angular spread regimes

Typical base station
Angular spread c 30 deg
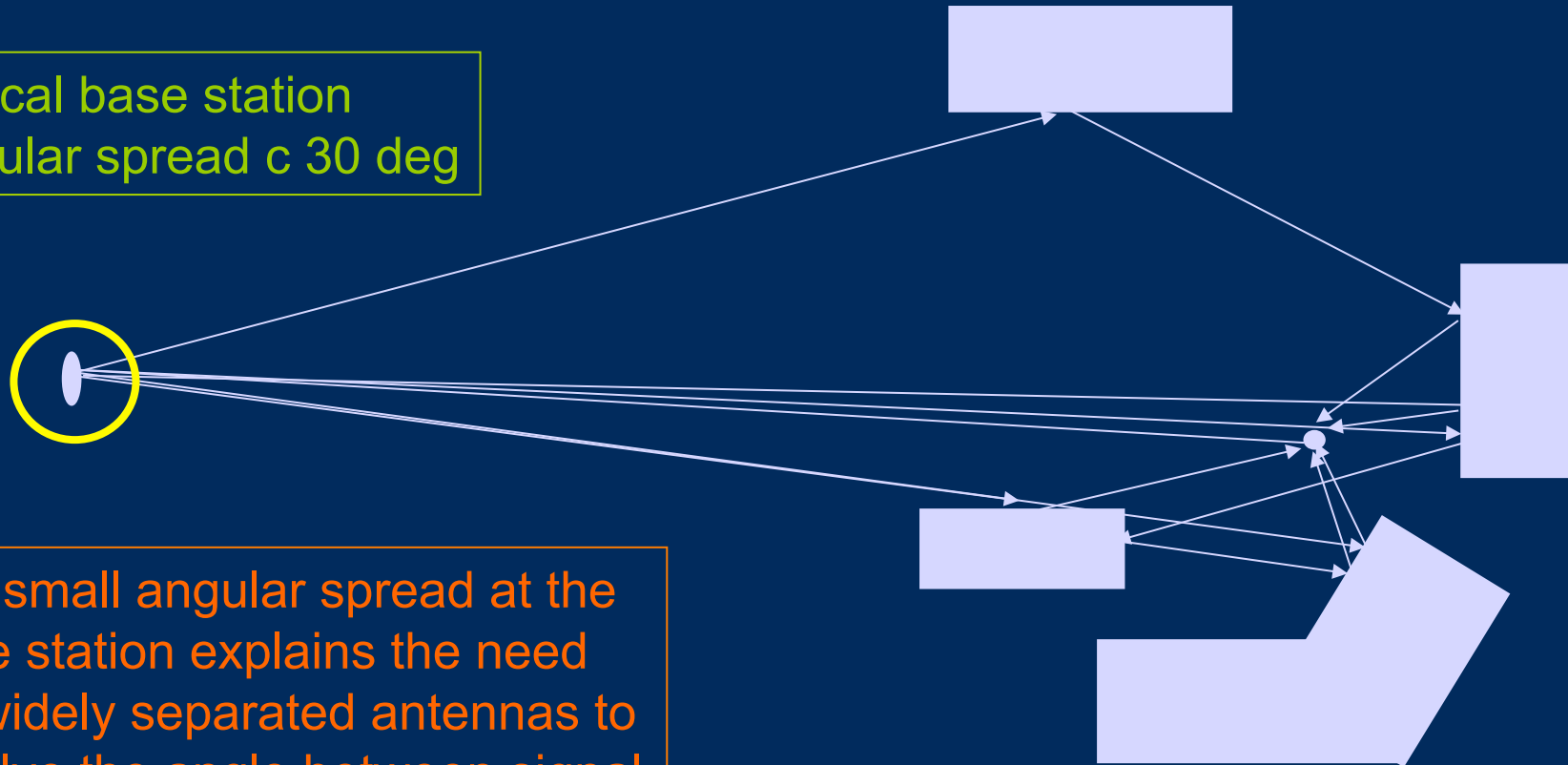
The small angular spread at the base station explains the need for widely separated antennas to resolve the angle between signal paths and get effective space diversity

Angular spread regimes

antenova®

Typical base station
Angular spread c 30 deg
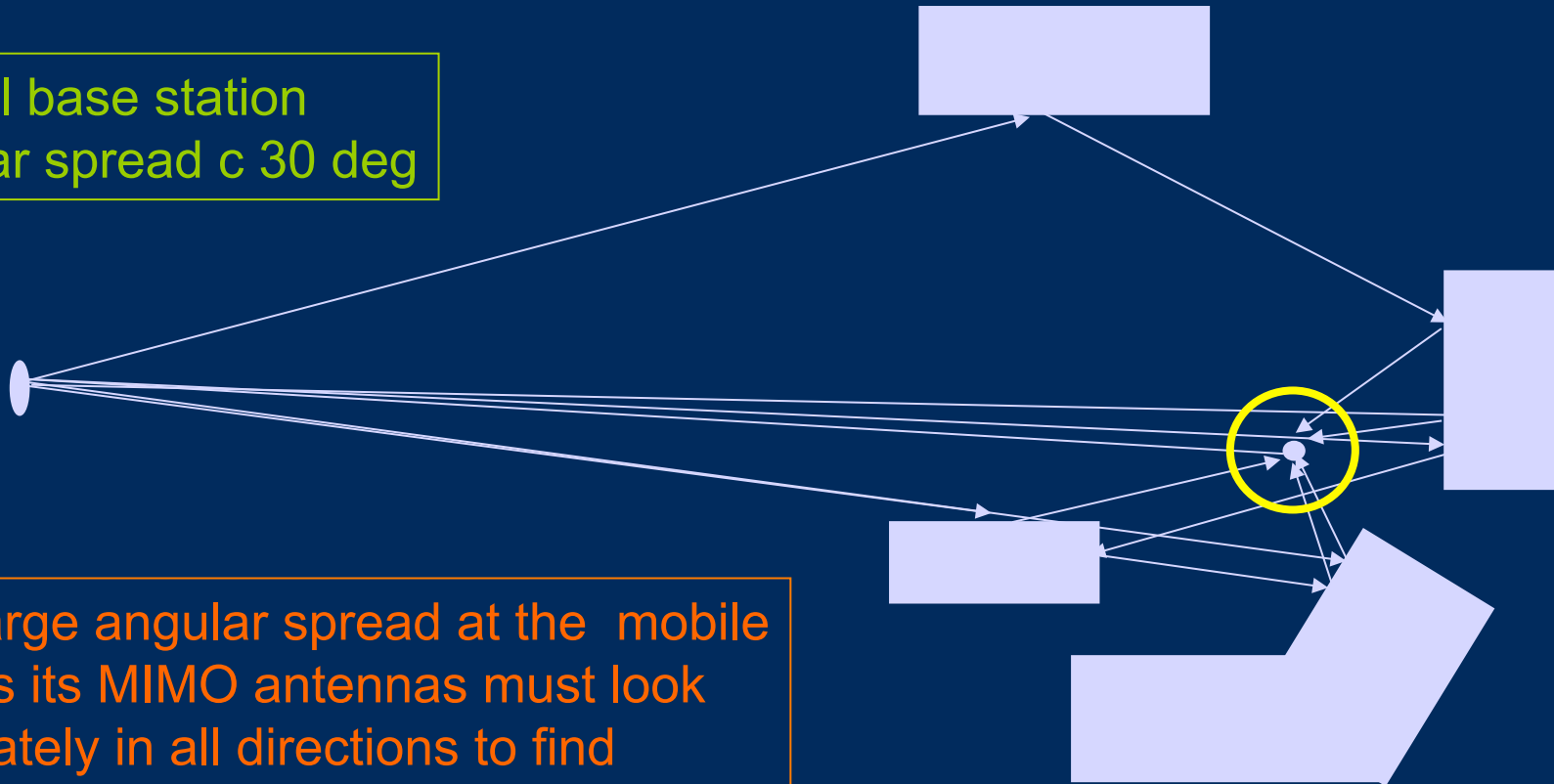
The large angular spread at the mobile means its MIMO antennas must look separately in all directions to find usable signal components.

A single omnidirectional antenna – as currently used - cannot see separate signal paths.

Typical mobile
Angular spread 360 deg

Radiation patterns

At both ends of a link –

- The antennas must be sufficiently spaced to allow resolution of the multipath components

- Taken together, the antenna patterns must cover the whole solid angle over which signal components are likely to arrive

This implies widely spaced antennas at the base station, but allows relatively closely spaced antennas at the UE.

Switched beams v switched antennas

- There are two methods for producing patterns covering different regions of space:

    o   Switching between individual directional antennas

    o   Switching between multiple beams formed from a single multi-element array

In both cases the constraints of an electrically small platform limit the capabilities that can be realised.

Correlation v spacing
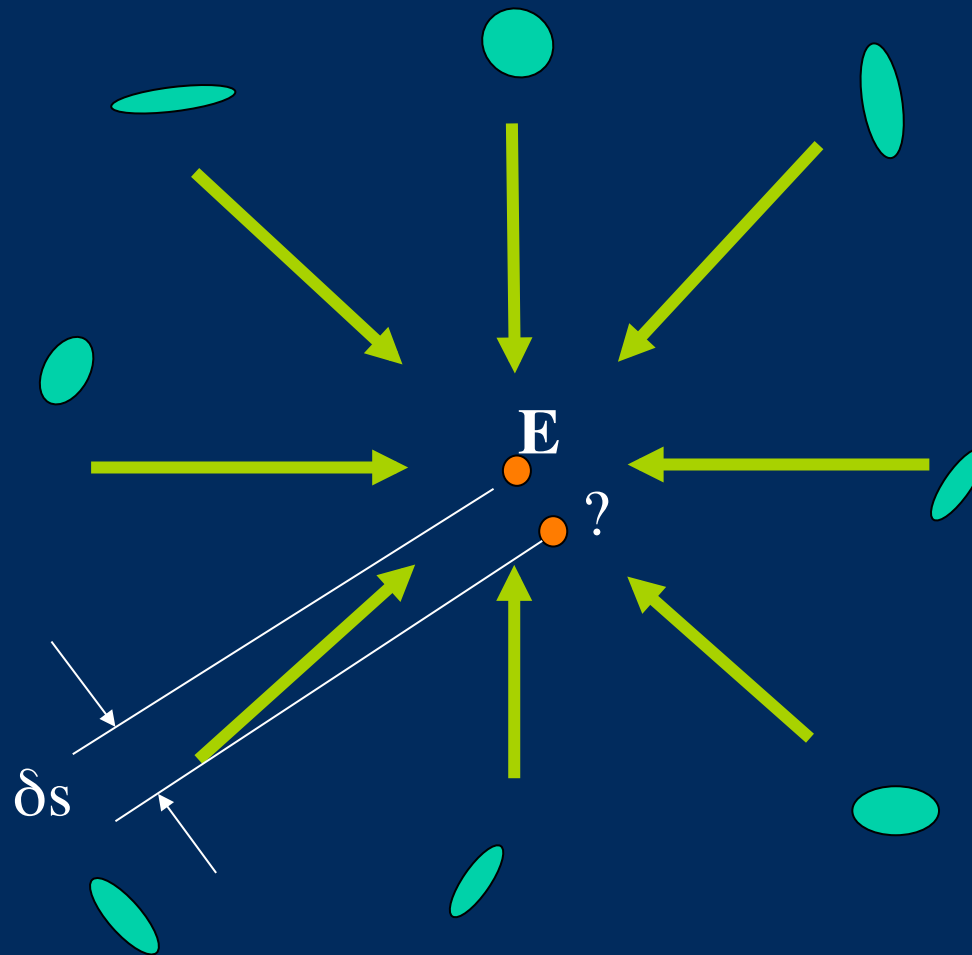
With rich multipath the correlation between signals from even closely spaced antennas is very small, but for very small spacings the outputs of two antennas will be influenced by mutual coupling.

Realisation
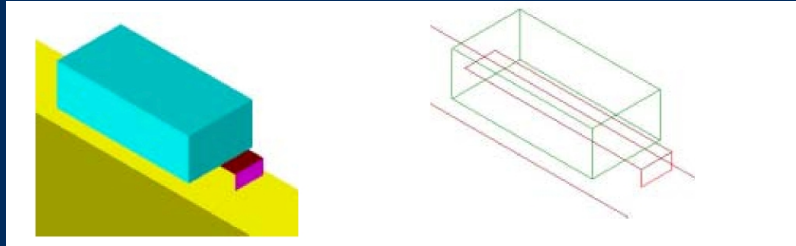
Dielectric antenna technology creates small efficient antennas covering one or more frequency bands. Their contained near-field minimises inter-antenna coupling

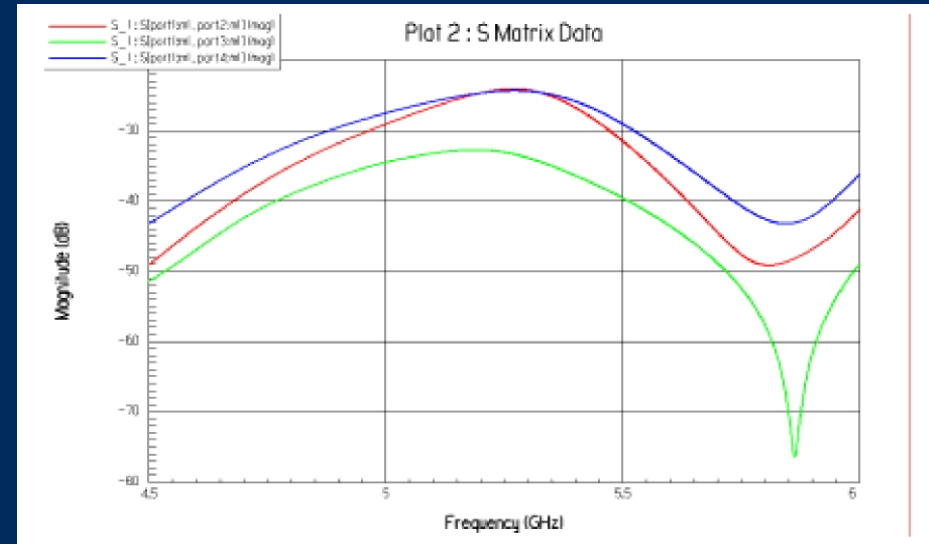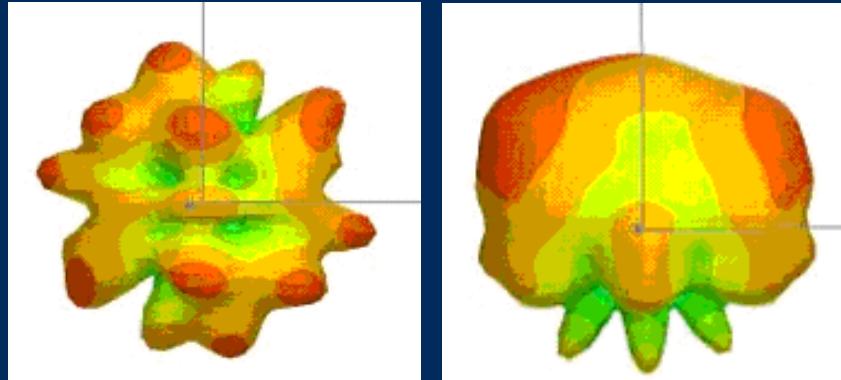**Folded loops demonstrated the advantages of balanced antennas**
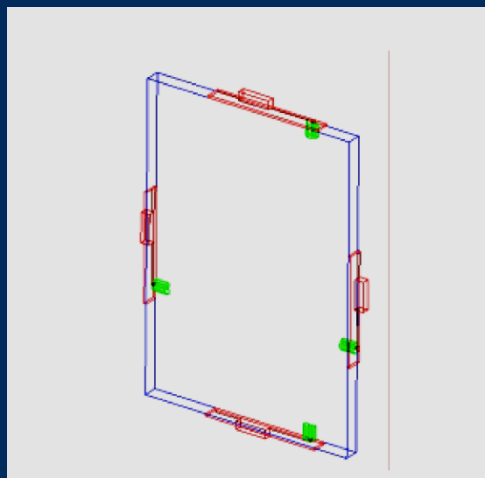
The performance of a group of antennas on a PDA is simulated to optimise positioning

The antennas are mounted on a mock-up user device, ready for pattern and isolation measurements

Results

Measured results show it is possible to achieve functionally useful pattern de-correlation and isolation even on a small groundplane in a hand-held device, but most of the de-correlation relates to signal phase, not pattern shape.

Magnitude of spatial correlation coefficient				
Element	1	2	3	4
1	1	0.0495	0.0087	0.0221
2	0.0495	1	0.0189	0.008
3	0.0087	0.0189	1	0.0385
4	0.0221	0.008	0.0385	1

Caution: These results have been computed from a standard formula, but their physical meaning is not very clear

An ideal mobile MIMO receiving antenna ensemble….

- can form several concurrent overlapping beams in any azimuth direction (or any direction in 3D space)

- responds to signals with any polarisation

- provides isolation between outputs

- provides outputs with low cross-correlation

- has high efficiency

These objectives are not mutually incompatible, but are not easy to achieve on a small platform.
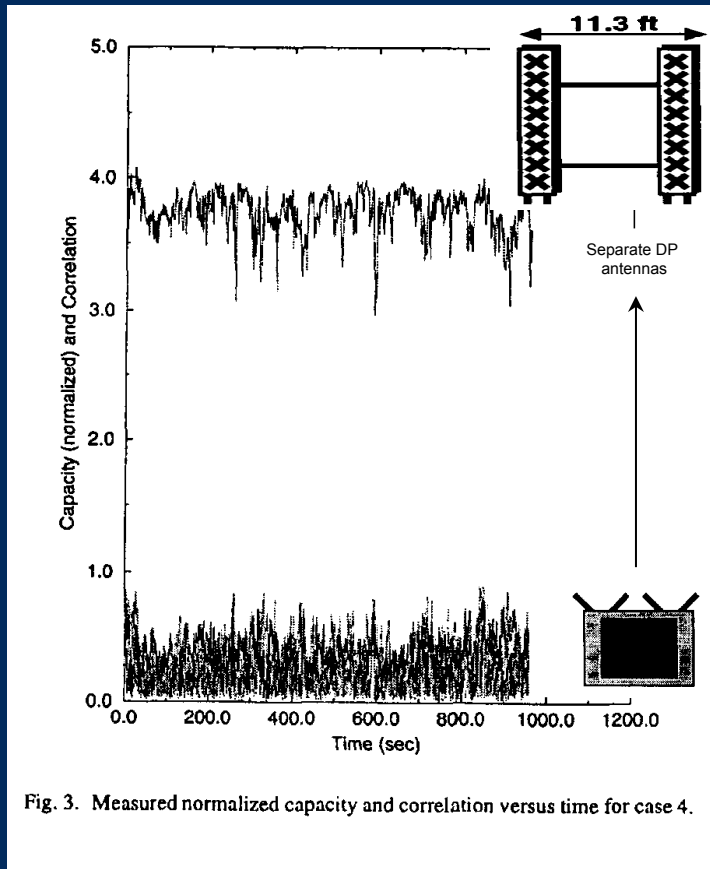
Base station antenna choice

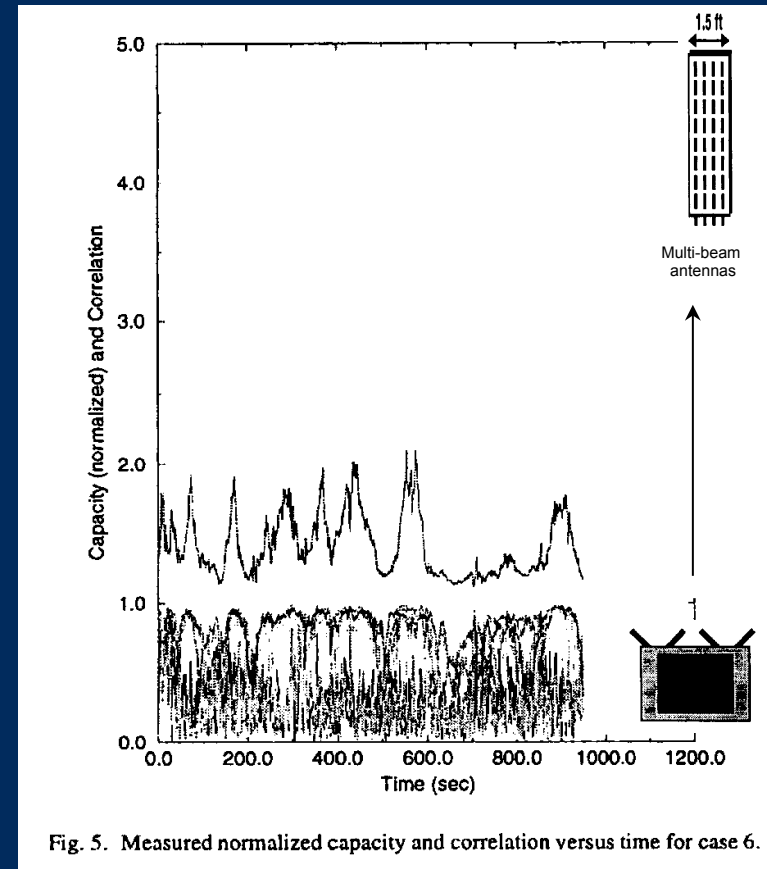Fig. 3. Measured normalized capacity and correlation versus time for case 4.

Fig. 5. Measured normalized capacity and correlation versus time for case 6.
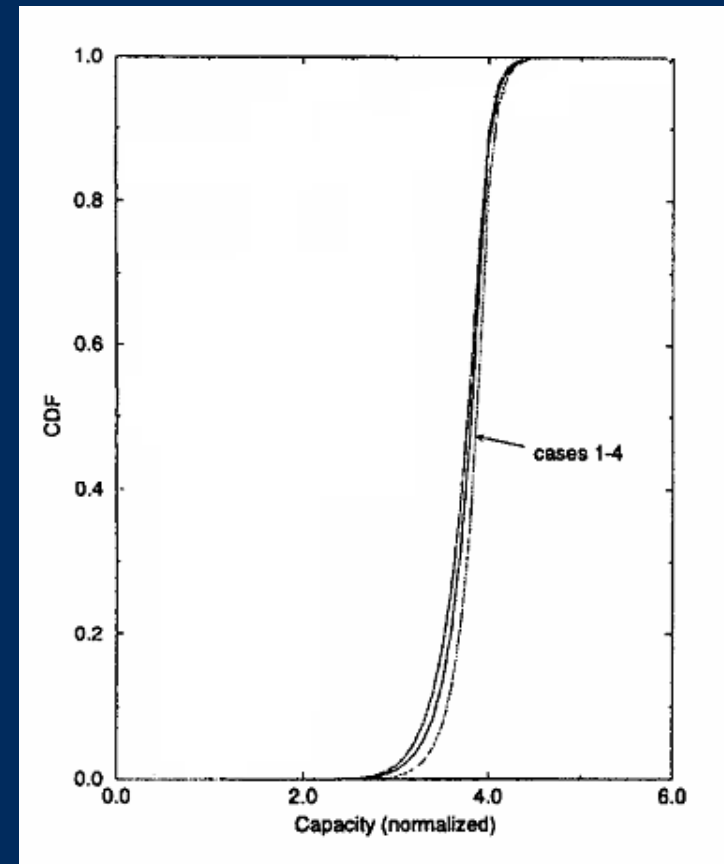
Practical measurement of the increase in capacity relative to a single antenna, using different antenna combinations. Residential area with trees, 1900MHz, ~2 mile range, 30mph. (Ref 4).

UE antenna choice

Surprisingly, the choice of antennas for the user equipment appears to have little effect on system performance
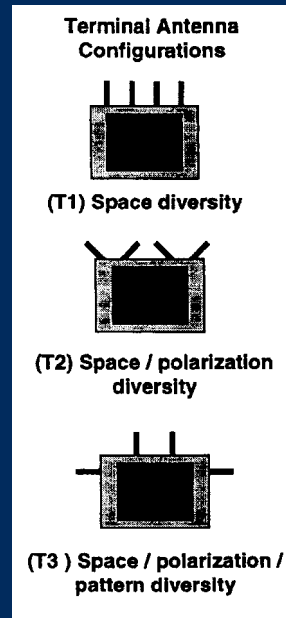
Cases 1 – 4 use the three monopole configurations shown, plus 4 standard handset antennas; the BS antennas were the dual XP arrays.

Terminal Antenna Configurations

(T1) Space diversity

(T2) Space / polarization diversity

(T3) Space / polarization / pattern diversity

Cumulative probability functions for systems with various antennas at the UE

Conclusion

- MIMO is here to stay

- It is being applied to LANs and MANs NOW − not certain whether it will be applied to existing 2G or 3G systems

- Optimum antenna design requires understanding of the propagation characteristics of the target system

References:

1. Jensen M.A & Wallace J.W: A review of antennas and propagation for MIMO wireless communications, *IEEE Trans AP, Nov 2004 (146 refs)*

2. H Zhu, B Farhang-Beroujeny & C Schlegel: An efficient statistical approach for calculation of capacity of MIMO channels, *3rd IASTED Internat Conf on Optical Comms., Banff Canada, Jul 14 – 16, 2003.*

3. Z Zheng & D N C Tse, Diversity and multiplexing: A fundamental trade-off in multiple-antenna channels, *IEEE Trans Inf Theory, May 2003.*

4. C C Martin, J H Winters & N R Sollenberger, MIMO radio channel measurements:Performance comparison of antenna configurations, *Proc. IEEE 54th Veh Tech Conf, Oct 7-11, 2001.*

5. D Gesbert, Shafi M, Shiu D, Smith P J, and Naguib A: From theory to practice: an overview of MIMO space-time coded wireless systems, *IEEE Journal On Selected Areas In Communications, Vol. 21, No. 3, April 2003*