A Brief Overview of MIMO Technology

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Thales, Sydney, 06-Jun-2013

Outline

- What is MIMO?
- Topologies: SISO, SIMO, MISO, MIMO
- Spatial Multiplexing
- Multi-User MIMO (SDMA)
- Information-Theoretic Channel Capacities
- Some Australian Examples
- References
- Questions

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What is MIMO ?

- What? / Why? / When?
- Where?

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What? / Why? / When?

- What?
  - MIMO = Multiple Input Multiple Output
  - Multiple antennas at both input and output
  - Input = transmitter side, Output = receiver side
- Why ?
  - Increased bandwidth efficiency (bit/s/Hz)
  - Increased capacity (bits/s) in the same bandwidth (Hz)
    - Higher datarates for users
    - More users
    - More $$$ for telcos
- When ?
  - Channel has ‘lots of scattering’

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Where ?

Category	Sub-Category	Standard	Year	MIMO	QAM	Max Datarate (Mbit/s)	Bandwidth (Hz)	Bandwidth Efficiency (bit/s/Hz)
SISO	Generic	-	-	1x1	64	-	-	6
"	"	-	-		256	-	-	8
WLAN	-	802.11n	2009	4x4	64	600	40	15
"	-	802.11ac	2013?	8x4	256	6770	160	42 (1)
Cellular	3G	HSPA+	2008	4x4	64	84	5	17
"	3.5G	LTE	2009	4x4	64	300	20	15
"	4G	LTE-A	2014?	8x8	64	3,000	100	30
Wi-Max	4G	802.16m	2011	4x4	64	365	20	18 (2)

NOTES:
(1) Achieved with 2 x Multi-User 4x4 MIMO.
(2) Can aggregate up to 3 x 20 MHz channels to achieve 1,095 Mbit/s in 60MHz.

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Topologies

- SISO
- SIMO
- MISO
- MIMO
- Multi-User MIMO

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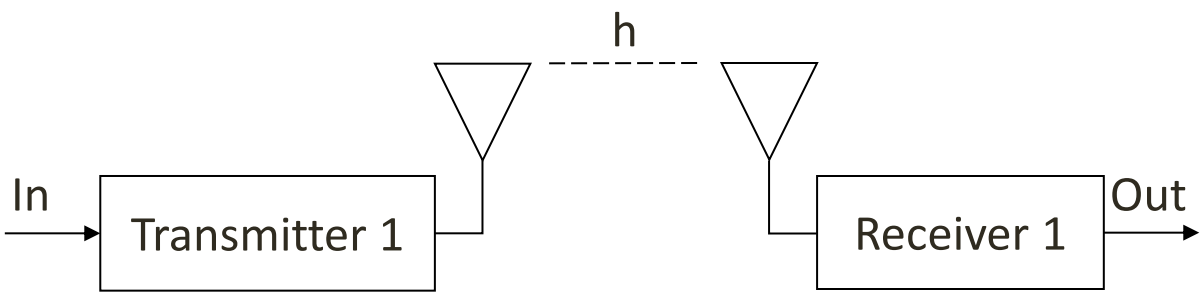
SISO



Channel Gain: h

Guglielmo Marconi
c. 1908

- SISO = Single Input Single Output
- Classical radio link beginning with Marconi (c 1901)
- Single input (transmitter)
- Single output (receiver)
- No receive diversity
  - Fades in propagation path cause outages
  - Countermeasure
    - Increase transmitter power -> Fade Margin
    - Outages can still occur in “deep” fades

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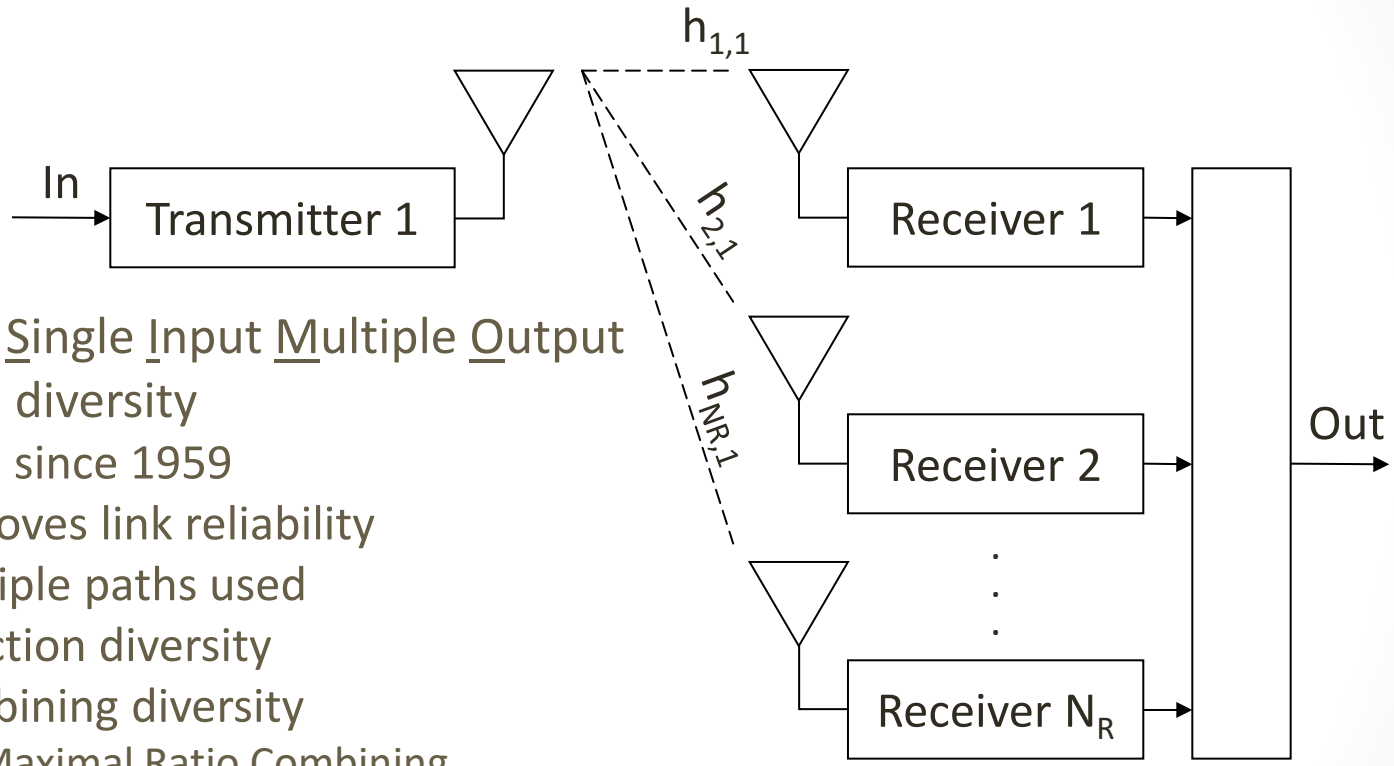
SIMO

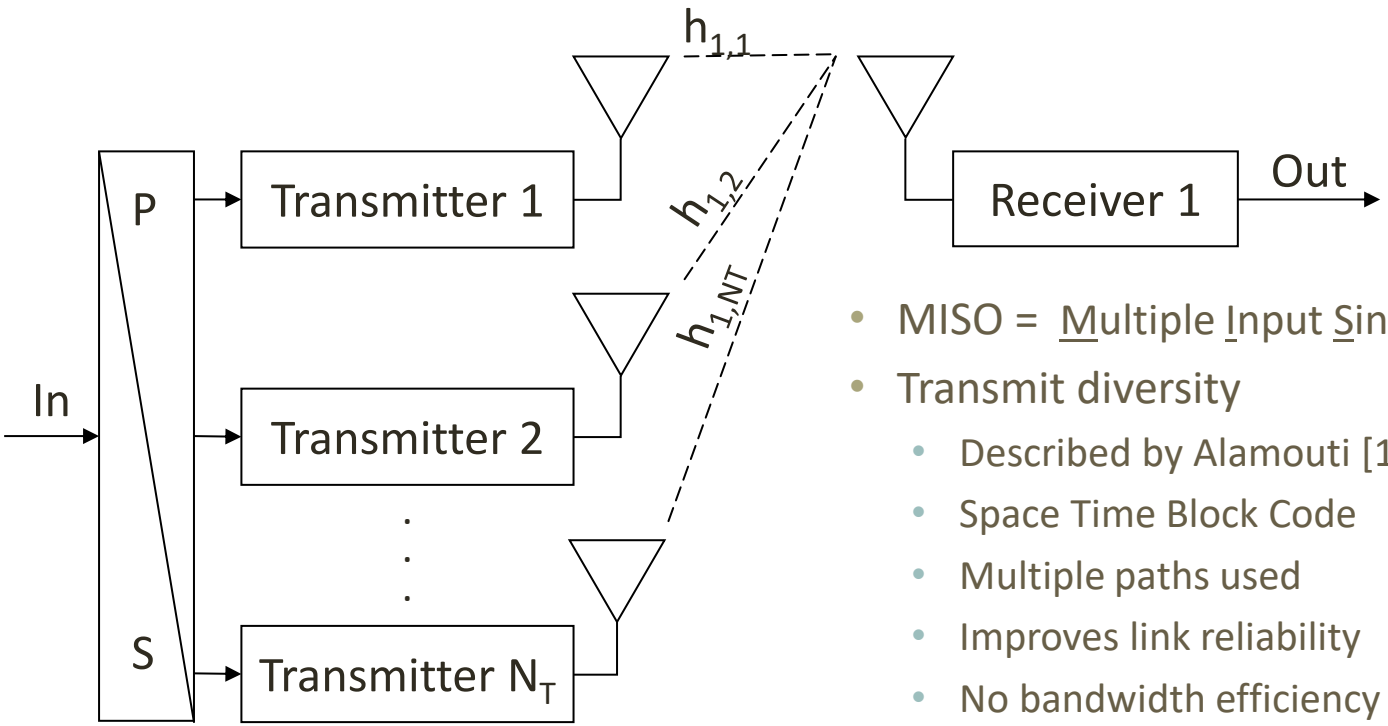


- SIMO = Single Input Multiple Output
- Receive diversity
  - Used since 1959
  - Improves link reliability
  - Multiple paths used
  - Selection diversity
  - Combining diversity
    - Maximal Ratio Combining
    - Optimal Ratio Combining
- Typical usage
  - Microwave point to point
  - Cellular uplink

Channel Vector:

$\mathbf{h} = [h_{1,1}\ h_{2,1}\ \ldots\ h_{NR,1}]^T$

MISO



Channel Vector:

$\mathbf{h} = [h_{1,1}\ h_{1,2}\ \ldots\ h_{1,NT}]^T$

- MISO = Multiple Input Single Output
- Transmit diversity
  - Described by Alamouti [1] 1998
  - Space Time Block Code
  - Multiple paths used
  - Improves link reliability
  - No bandwidth efficiency improvement
  - Good for cellular telephone systems
    - Multiple transmitters at basestation
    - Only 1 receiver at handset
      - Cheaper, less complex, longer battery-life

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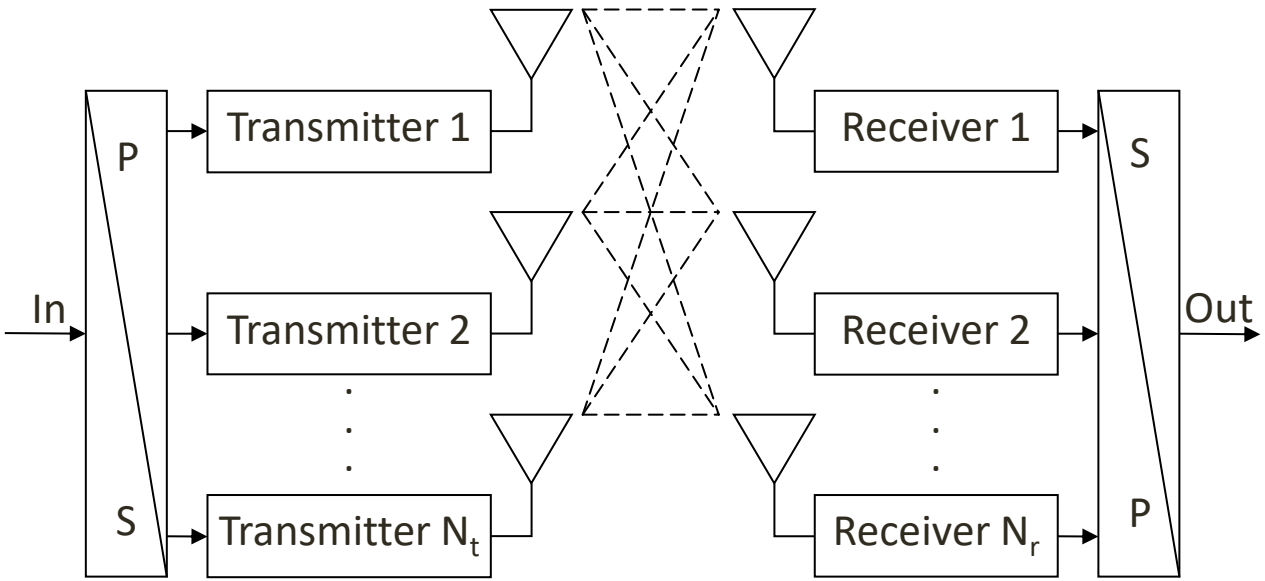
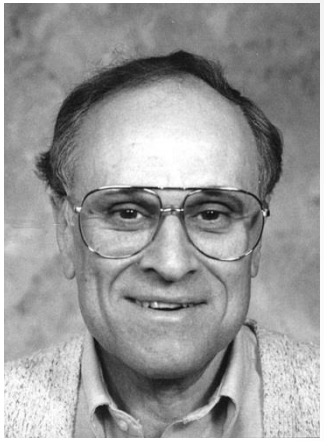
MIMO





Gerard J. Foschini
c. 1998

- MIMO = Multiple Input Multiple Output
- First described circa 1995
  - Foschini & Gans [2]
  - Teletar [4]
- Locations
  - Transmitters co-located
  - Receivers co-located

Channel Matrix:

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & h_{1,2} & \dots & h_{1,Nt} \\ h_{2,1} & h_{2,2} & \dots & h_{2,Nt} \\ \vdots & \vdots & \ddots & \vdots \\ h_{Nr,1} & h_{Nr,2} & \dots & h_{Nr,Nt} \end{bmatrix}$$

- Spatial multiplexing
  - Single User is allocated multiple Tx's & Rx's
  - Users data is split between Tx's
  - Huge increase in bandwidth efficiency
    - Units: bit/s/Hz
- Capacity Comparison
  - SISO, 4QAM:
    - 2 bit/s/Hz
  - MIMO, 16 Tx * 16Rx, 4QAM
    - 32 bit/s/Hz

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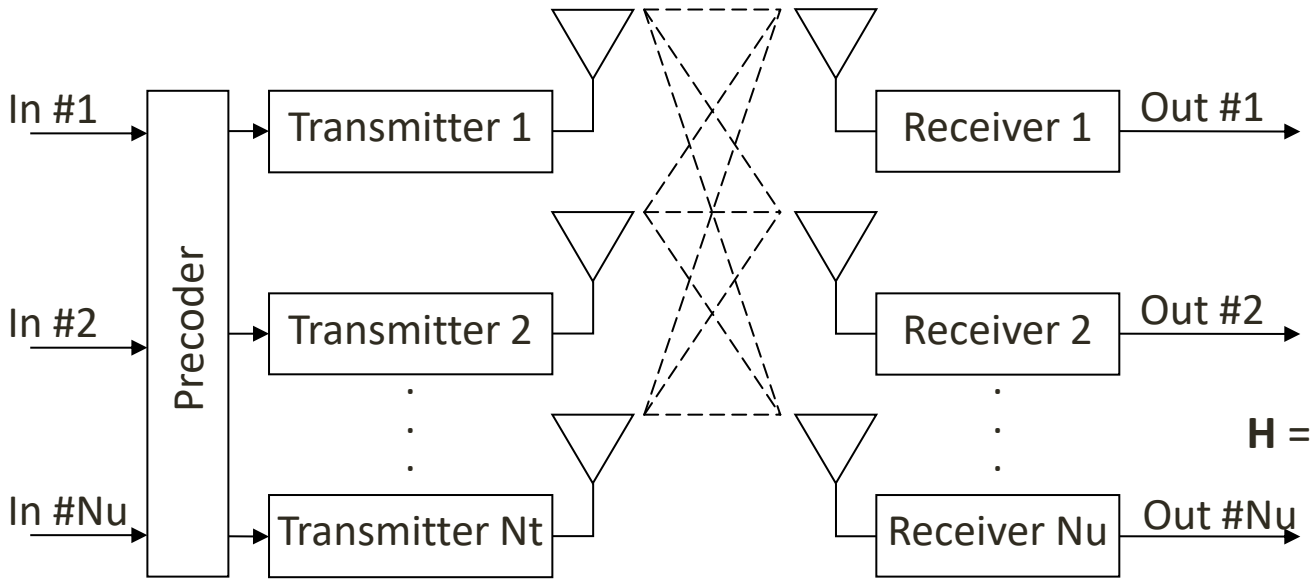
Multi-User MIMO



Channel Matrix:

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,Nt} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,Nt} \\ \vdots & \vdots & \ddots & \vdots \\ h_{Nr,1} & h_{Nr,2} & \cdots & h_{Nr,Nt} \end{bmatrix}$$

- MU-MIMO = Multi-User MIMO
- Locations
  - Transmitters co-located
  - Receivers in <u>different</u> locations
- Each receiver corresponds to a <u>different</u> User
- Each User uses the same spectrum at the same time as all the other Users

- Precoding
  - Focuses AP pattern 'beam' onto required receiver
  - Puts pattern 'nulls' onto all other users
  - 'Spatial filtering'
  - SDMA = Space Division Multiple Access
- Huge increase in bandwidth efficiency
  - Units: aggregate bits/s/Hz

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Spatial Multiplexing

- Model
- Maths

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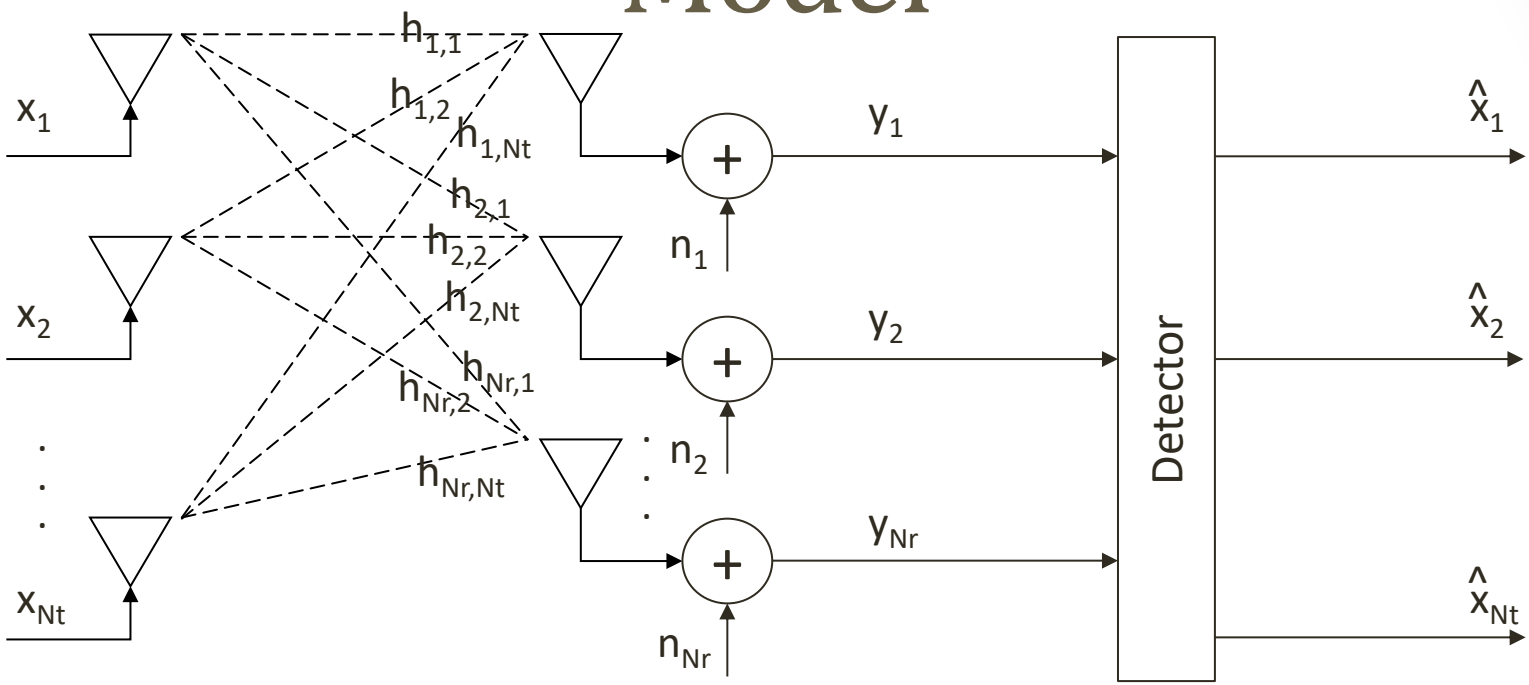
Model



Transmitted Vector	Channel Matrix	Noise Vector	Received Vector	Detector Matrix	Recovered Vector
$\mathbf{x}$	$\mathbf{H}$	$\mathbf{n}$	$\mathbf{y}$	$\mathbf{W}$	$\hat{\mathbf{x}}$
$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{Nt} \end{bmatrix}$	$\begin{bmatrix} h_{1,1} & h_{1,2} & \dots & h_{1,Nt} \\ h_{2,1} & h_{2,2} & \dots & h_{2,Nt} \\ \vdots & \vdots & \ddots & \vdots \\ h_{Nr,1} & h_{Nr,2} & \dots & h_{Nr,Nt} \end{bmatrix}$	$\begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_{Nr} \end{bmatrix}$	$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_{Nr} \end{bmatrix}$	$\begin{bmatrix} w_{1,1} & w_{1,2} & \dots & w_{1,Nr} \\ w_{2,1} & w_{2,2} & \dots & w_{2,Nr} \\ \vdots & \vdots & \ddots & \vdots \\ w_{Nt,1} & w_{Nt,2} & \dots & w_{Nt,Nr} \end{bmatrix}$	$\begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \\ \vdots \\ \hat{x}_{Nt} \end{bmatrix}$

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Maths

- $\mathbf{y} = \mathbf{Hx} + \mathbf{n}$
- $\mathbf{x} = \mathbf{Wy}$

  $= \mathbf{WHx} + \mathbf{Wn}$
- Zero-Forcing Detector
  - $\mathbf{W} = (\mathbf{H}^H\mathbf{H})^{-1}\mathbf{H}^H$
  - $\hat{\mathbf{x}} = (\mathbf{H}^H\mathbf{H})^{-1}(\mathbf{H}^H\mathbf{H})\mathbf{x} + \mathbf{Wn}$

    $= \mathbf{Ix} + \mathbf{Wn}$

    $= \mathbf{x} + \hat{\mathbf{n}}$ ← noise is enhanced by zero-forcing
- Other Detectors
  - MMSE – Minimum Mean Squared Error
    - Optimizes combined enhanced noise and cross-stream interference
  - Maximum Likelihood
  - BLAST

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Multi-User MIMO (SDMA)

- Model
- Maths

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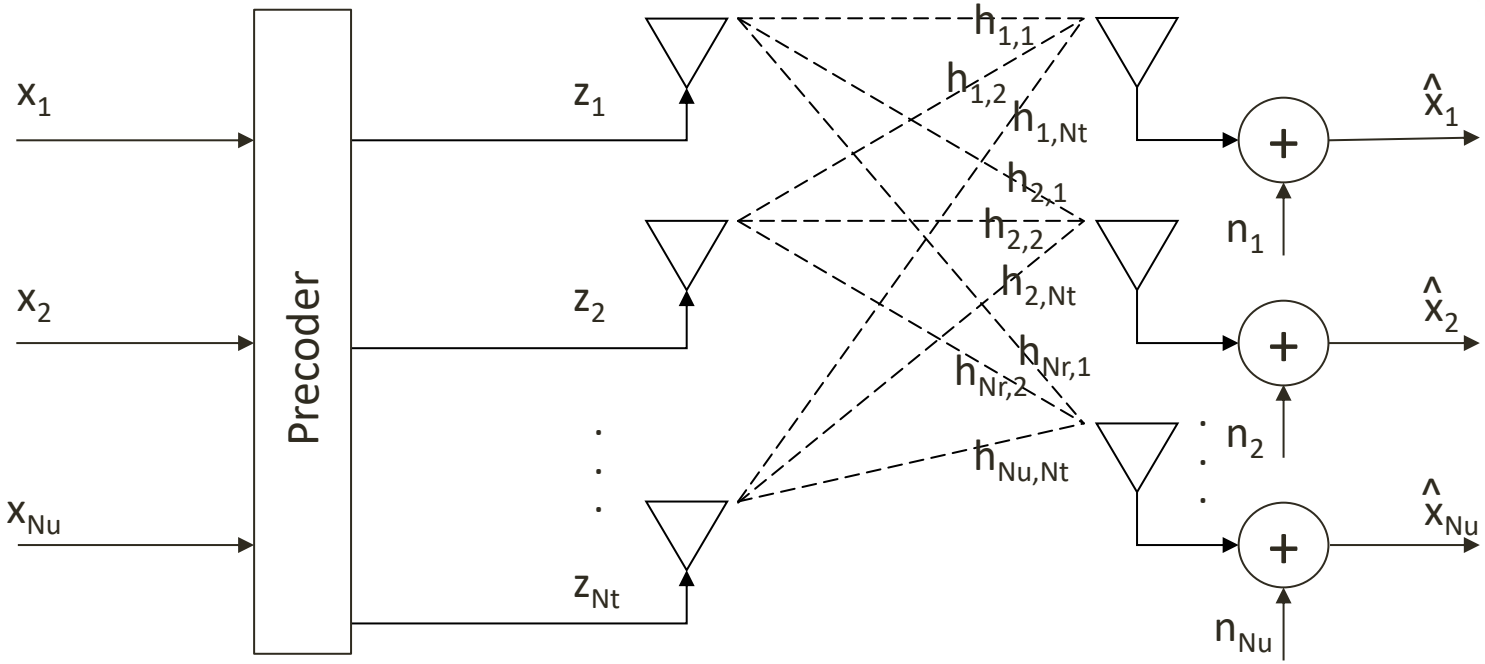
Model



User Vector	Precoder Matrix	Transmitted Vector	Channel Matrix	Noise Vector	Recovered Vector
$\mathbf{x}$	$\mathbf{P}$	$\mathbf{z}$	$\mathbf{H}$	$\mathbf{n}$	$\hat{\mathbf{x}}$
$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{Nt} \end{bmatrix}$	$\begin{bmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,Nr} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,Nr} \\ \vdots & \vdots & \ddots & \vdots \\ p_{Nt,1} & p_{Nt,2} & \cdots & p_{Nt,Nr} \end{bmatrix}$	$\begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_{Nt} \end{bmatrix}$	$\begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,Nt} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,Nt} \\ \vdots & \vdots & \ddots & \vdots \\ h_{Nr,1} & h_{Nr,2} & \cdots & h_{Nr,Nt} \end{bmatrix}$	$\begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_{Nu} \end{bmatrix}$	$\begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \\ \vdots \\ \hat{x}_{Nt} \end{bmatrix}$

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Maths

- $\mathbf{z} = \mathbf{P}\mathbf{x}$
- $\hat{\mathbf{x}} = \mathbf{H}\mathbf{z} + \mathbf{n}$

  $= \mathbf{H}\mathbf{P}\mathbf{x} + \mathbf{n}$
- $\mathbf{P} = \mathbf{H}^{H}(\mathbf{H}^{H}\mathbf{H})^{-1}$
- $\hat{\mathbf{x}} = (\mathbf{H}\mathbf{H}^{H})\,(\mathbf{H}\mathbf{H}^{H})^{-1}\mathbf{x} + \mathbf{n}$

  $= \mathbf{I}\mathbf{x} + \mathbf{n}$

  $= \mathbf{x} + \mathbf{n}$

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Information-Theoretic Channel Capacities

- MIMO
- Multi-User MIMO

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MIMO

- SISO Theoretical Capacity (Shannon)
  - $C/B = \log_2(1 + SNR)$ bit/s/Hz
- MIMO Theoretical Capacity (Foschini [2])
  - Channel Matrix **H** is decomposed into 'Eigen Channels' using matrix singular value decomposition (SVD)
  - The Sum Capacity is the sum of all of the individual Eigen Channel capacities ...

    $C/B = \Sigma_{i=1}^{R} \log_2(1+SNR_i\, \sigma_i^2(\mathbf{H})$ bit/s/Hz,

    where σ_i are the singular values of **H**, & R is the rank of channel **H**
  - Uncorrelated channel **H** (e.g. NLOS)
    - All singular values σ_i are roughly equal
    - C rises linearly with the rank R = min(Nt,Nu)
      - i.e. C rises linearly with number of antennas
  - Correlated Channel H (e.g. near LOS)
    - Some singular values σ_i are near zero
      - For full LOS, only <u>one</u> non-zero singular values σ_i -> SISO capacity
    - Generally, C rises less than linearly with number of antennas

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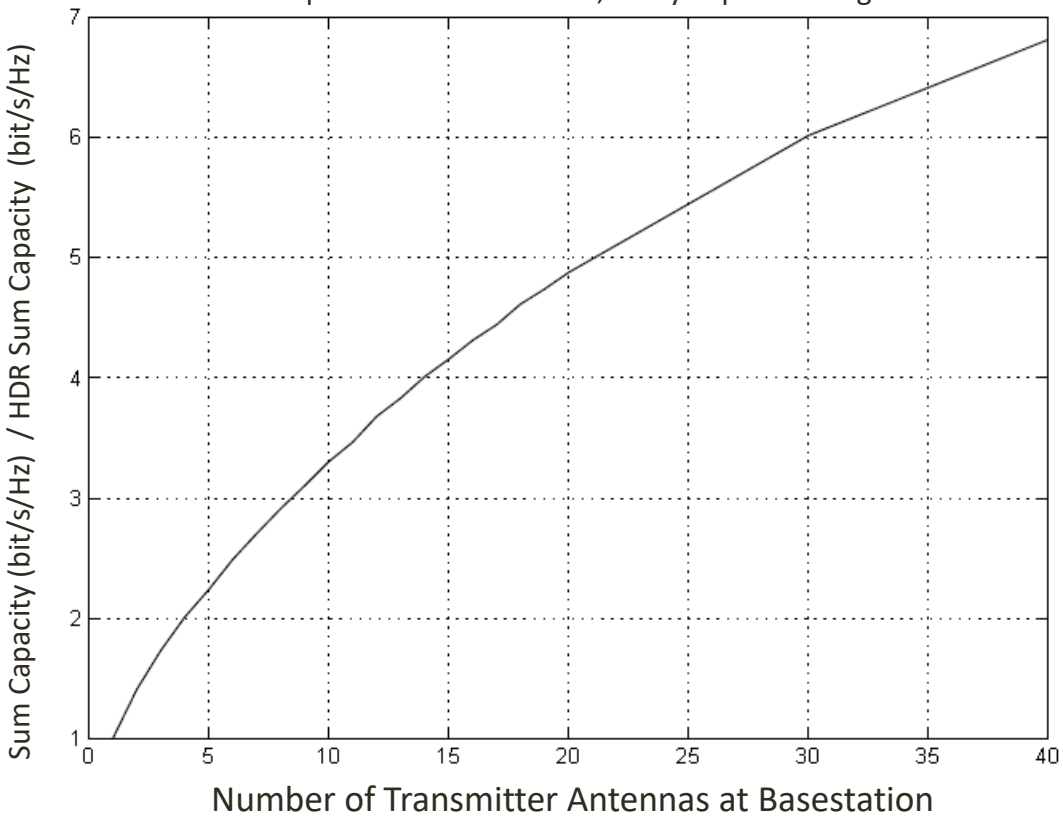
MU-MIMO

Single cell, 20 users, 1 Rx Antenna per User, SNR = 5dB,
Complex Gaussian Channel, 'Dirty Paper' Coding.



Optimal MU-MIMO Sum Capacity Relative to HDR

Source: [9]

Some Australian Examples

- CSIRO Off-Line MIMO Testbed
- CSIRO Real-Time MIMO Demonstrator
- CSIRO Ngara Access Field Trial

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CSIRO Off-Line MIMO Testbed

- CSIRO Wireless Technologies Laboratory Marsfield
- First CSIRO foray into MIMO
  - Instigated by : Dr Boyd Murray
  - Started : 2002
  - Completed : 2004
  - Strategy : Build up CSIRO expertise in MIMO
    - Practical equipment design
    - Academic papers based on real-world experience & measurements
  - Specs
    - Non-real-time
      - Off-line processing in Matlab
    - MIMO: 8x8
    - Bandwidth: 20MHz
    - RF: 2.4GHz
  - Outcomes
    - Near real-time channel measurements
    - MIMO algorithm testing
    - Confidence

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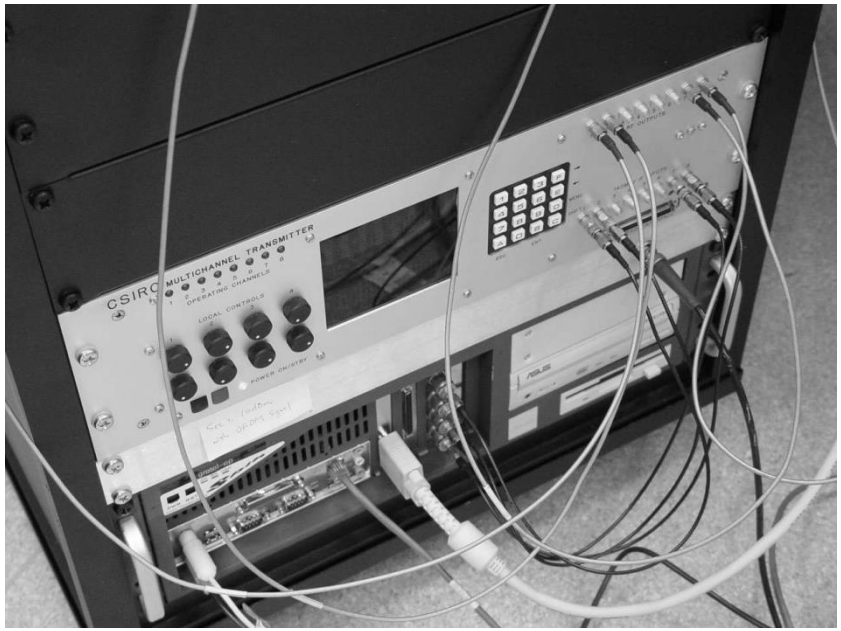
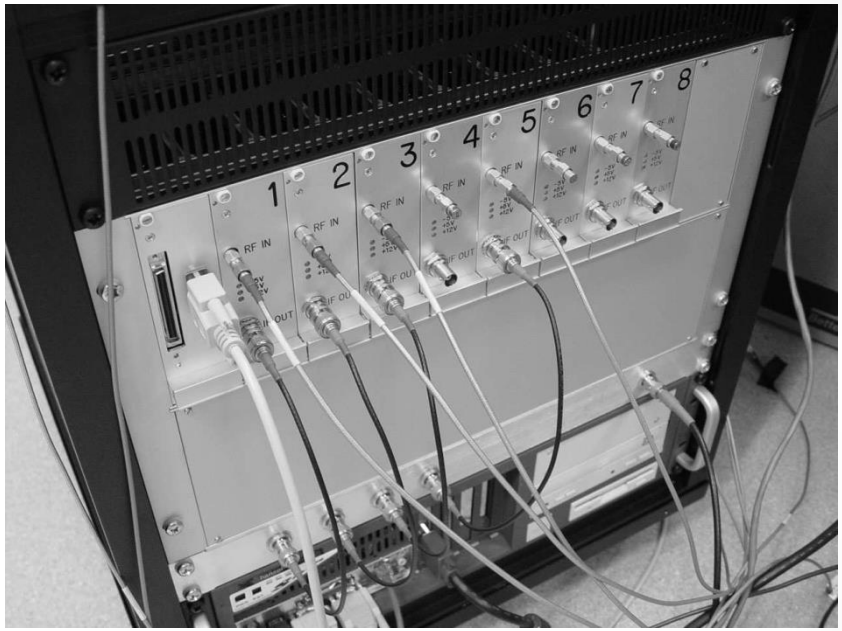
CSIRO Real-Time MIMO Demonstrator (1)



MIMO Transmitter (8 Channels)



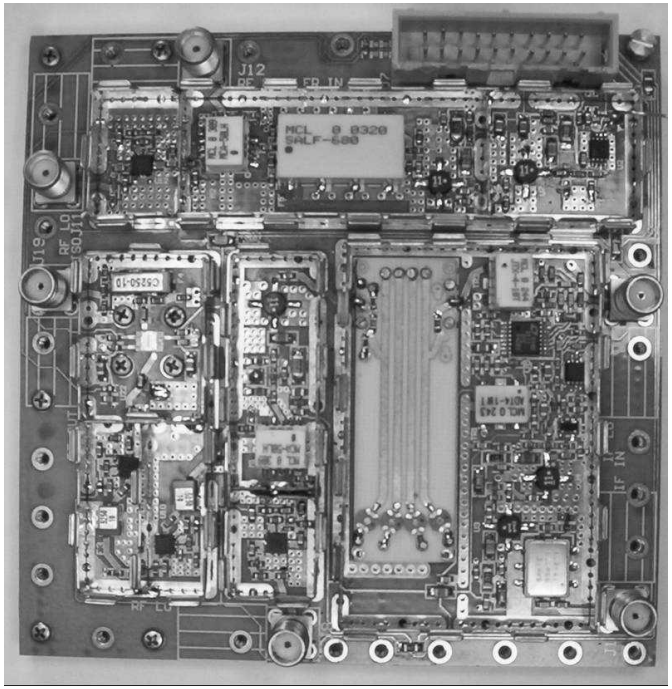
MIMO Receiver (8 Channels)

Source: [7]

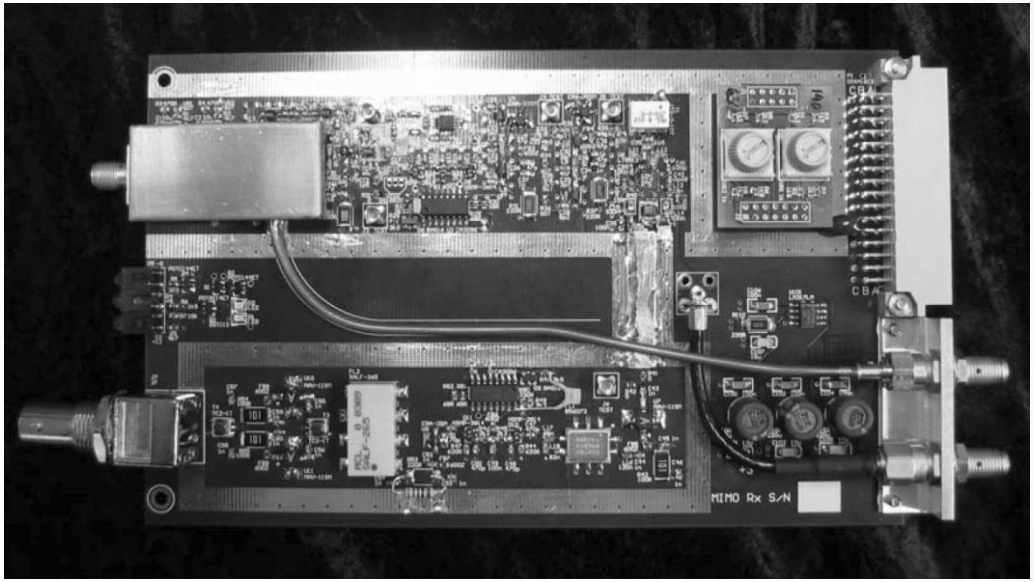
- CSIRO Wireless Technologies Laboratory Marsfield in 2007
- REAL-TIME digital signal processing using FPGAs
- Up to 8x8 MIMO
- Wide Bandwidth: 40MHz
- RF: 5.2GHz
- World's first real-time 4x4 MIMO for WLAN 802.11n
- Several world-record bandwidth efficiencies

- Dr Hajime Suzuki
  - Project Leader
- Dr Boyd Murray
  - RF System Design
  - FPGA DSP Firmware Teamleader
- Project team size: 8

CSIRO Real-Time MIMO Demonstrator (2)



Single Transmitter IF/RF Module



Single Receiver RF/IF Module

Source: [7]

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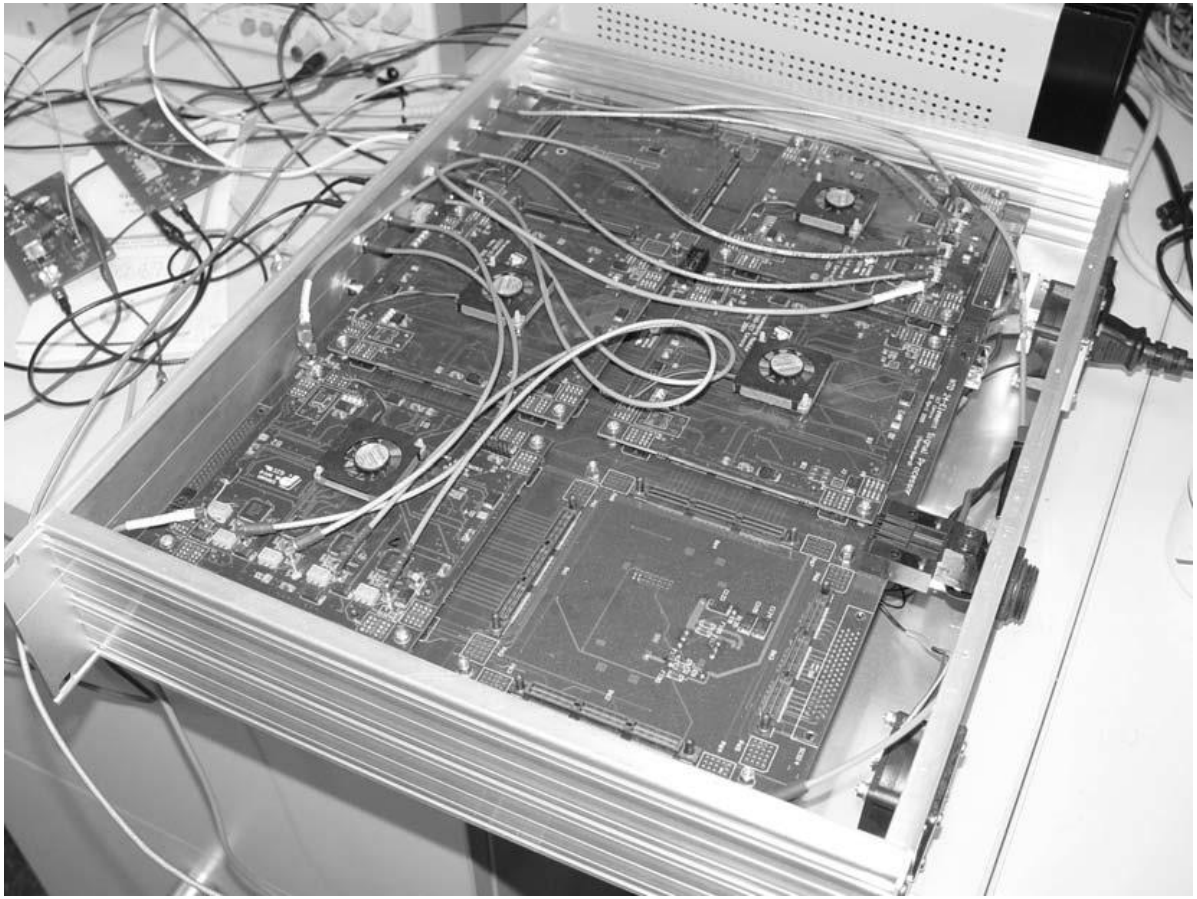
CSIRO Real-Time MIMO Demonstrator (3)



MIMO Digital Module (Uses Xilinx FPGAs)

Source: [7]

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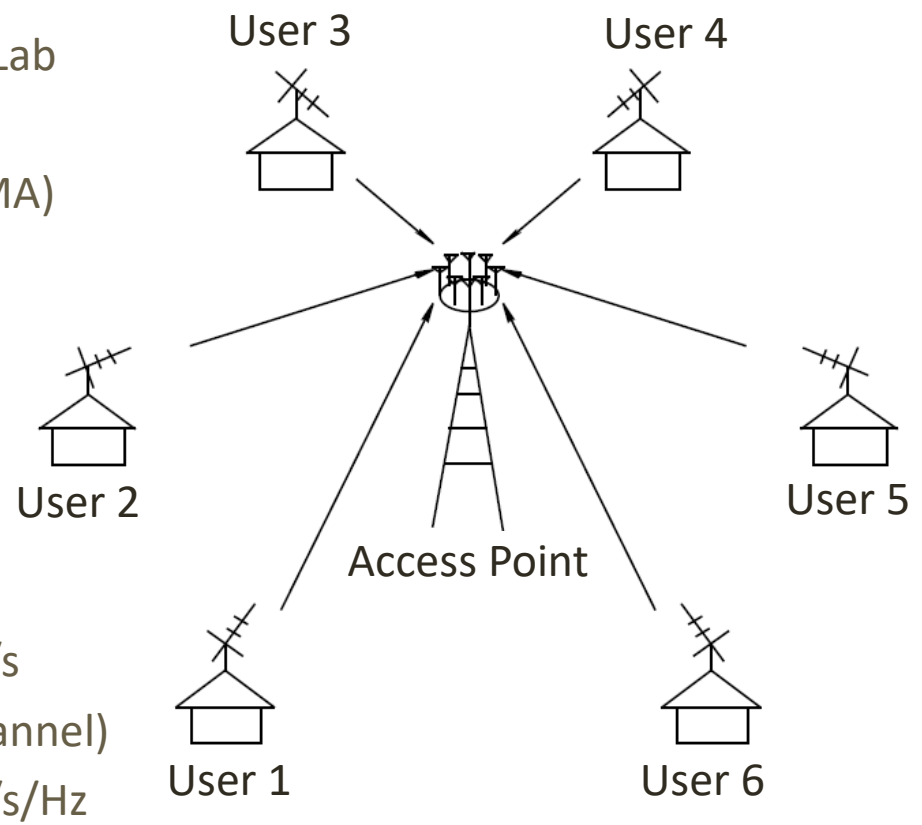
CSIRO Ngara Access (1)

- By: CSIRO Wireless Technologies Lab
- Year: 2011
- Topology: Multi-User MIMO (SDMA)
  - 12 Access Point antennas
  - 6 fixed single-antenna users
- RF: 641.5MHz (UHF TV)
- Modulation: 64-QAM over OFDM
- FEC: ¾ Convolutional Code
- Datarate/User: 23.625Mbit/s
- Aggregate datarate: 141.75Mbit/s
- Bandwidth: 7MHz (cleared TV channel)
- Bandwidth efficiency: 20.25 bits/s/Hz
- Uplink/Downlink: TDD
- Transmitter power: 7W
- Range: 16km



Ngara Access Topology – Multi-User MIMO
Source: [8]

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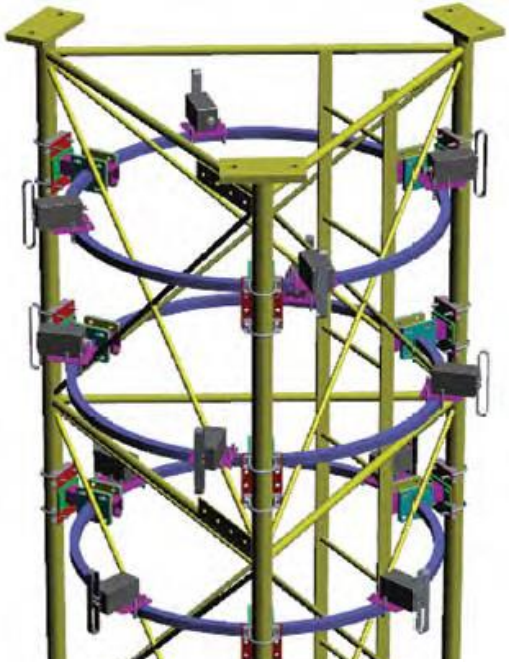
CSIRO Ngara Access (2)

(a) Equipment Rack



(b) Antennas on Tower

Access Point

(c) Tower

Source: [8]

CSIRO Ngara Access (3)

(a) Equipment Rack

(b) Antenna (UHF Yagi)

TBA User Terminal

Source: [8]

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References

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