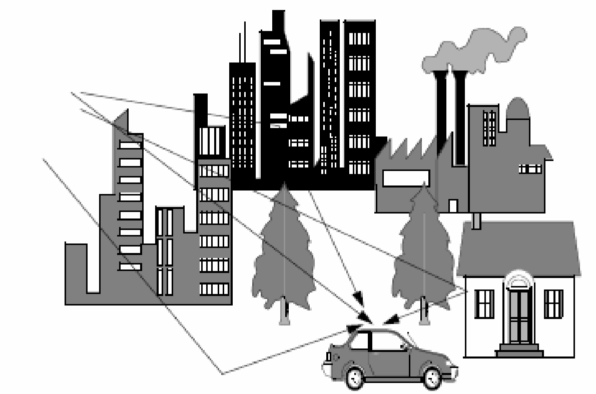
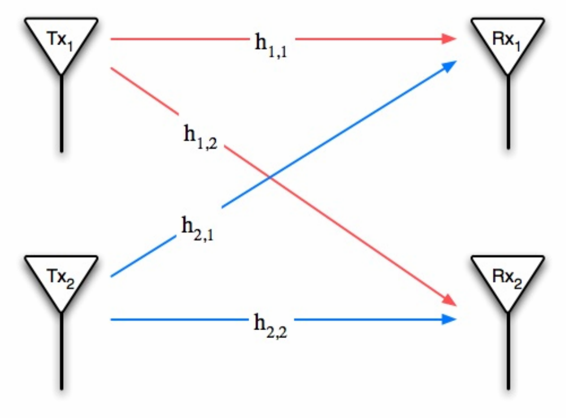
Introduction to Wireless MIMO – Theory and Applications



Multipath is not enemy but ally



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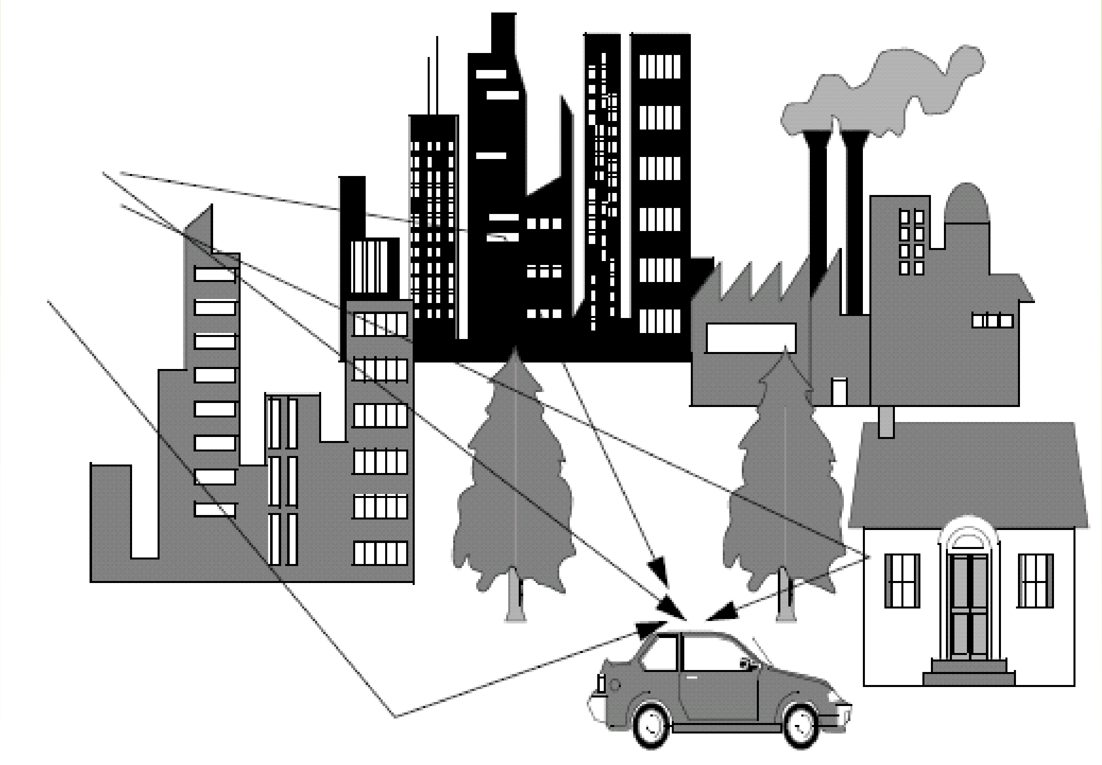
Why MIMO

- Motivation: current wireless systems
  - Capacity constrained networks
  - Issues related to quality and coverage
- MIMO exploits the *space* dimension to improve wireless systems capacity, range and reliability
- MIMO-OFDM – the corner stone of future broadband wireless access
  - WiFi – 802.11n
  - WiMAX – 802.16e (a.k.a 802.16-2005)
  - 3G / 4G

Transmission on a multipath channel

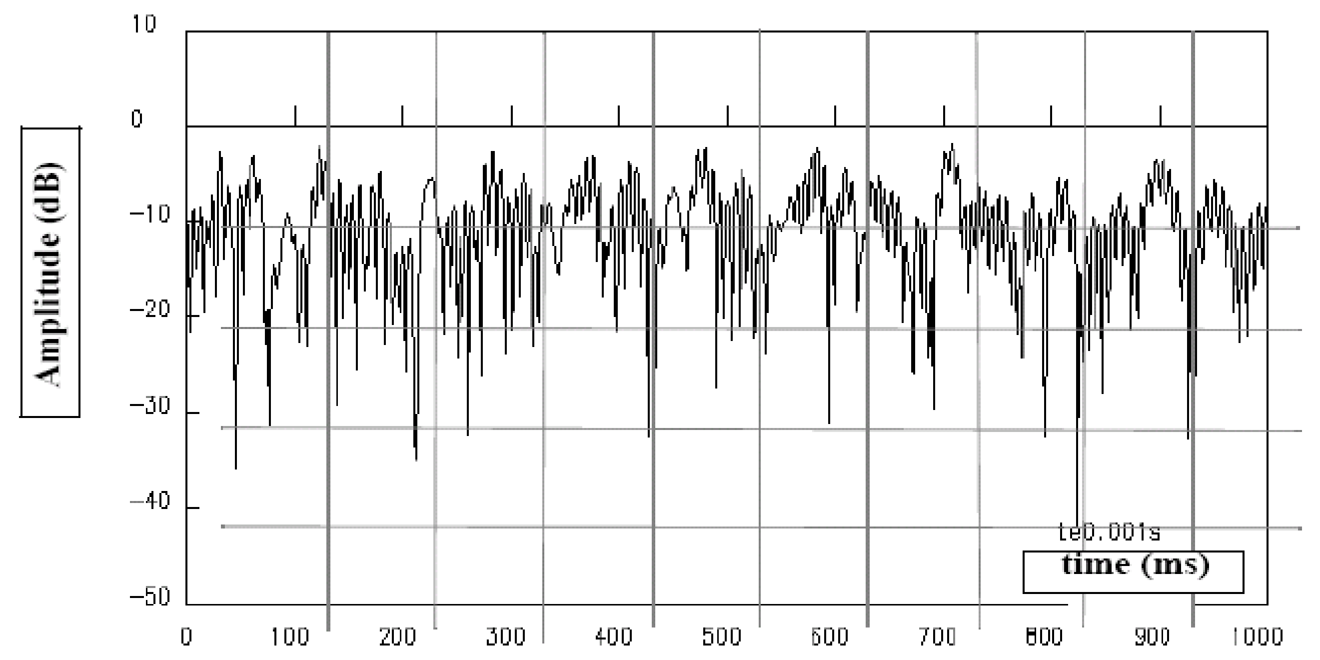
In wireless communication the propagation channel is characterized by multipath propagation due to scattering on different obstacles



- Time variations: Fading => SNR variations
- Time spread => frequency selectivity

Transmission on a multipath channel

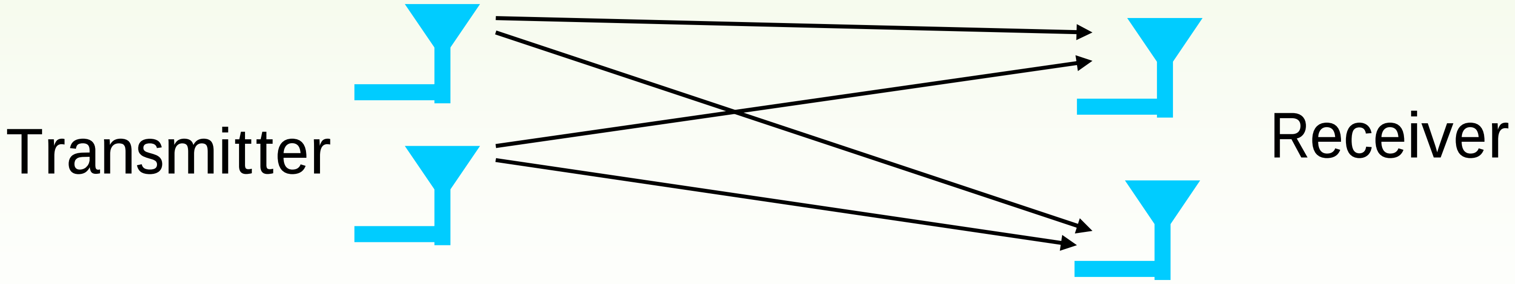
Fading:



- The received level variations result in SNR variations
- The received level is sensitive to the transmitter and receiver locations

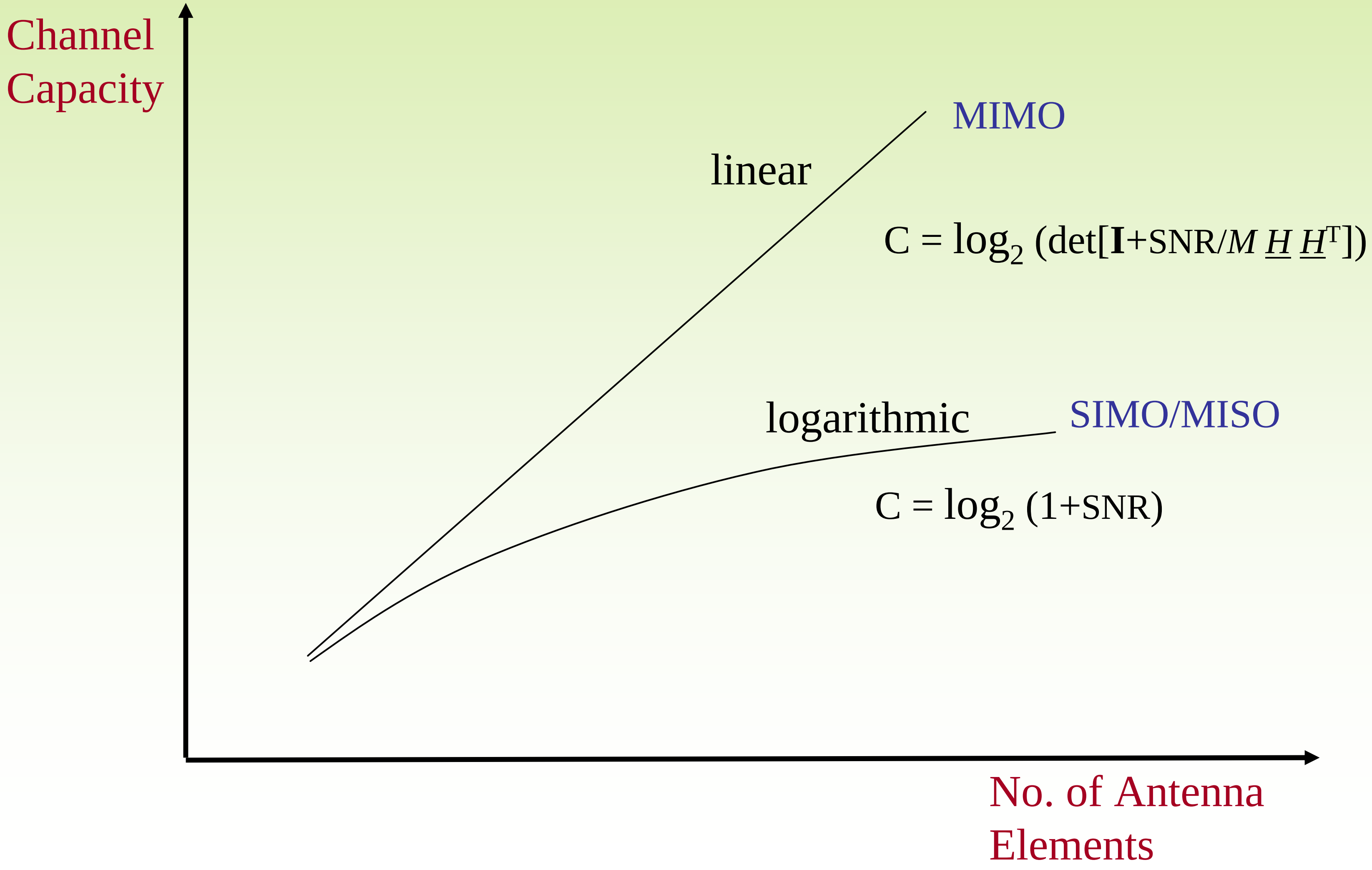
MIMO Defined

- MIMO is an acronym that stands for **M**ultiple **I**nput **M**ultiple **O**utput.
- It is an antenna technology that is used both in transmission and receiver equipment for wireless radio communication.
- There can be various MIMO configurations. For example, a 2x2 MIMO configuration is 2 antennas to transmit signals (from base station) and 2 antennas to receive signals (mobile terminal).



MIMO vs. SIMO/MISO

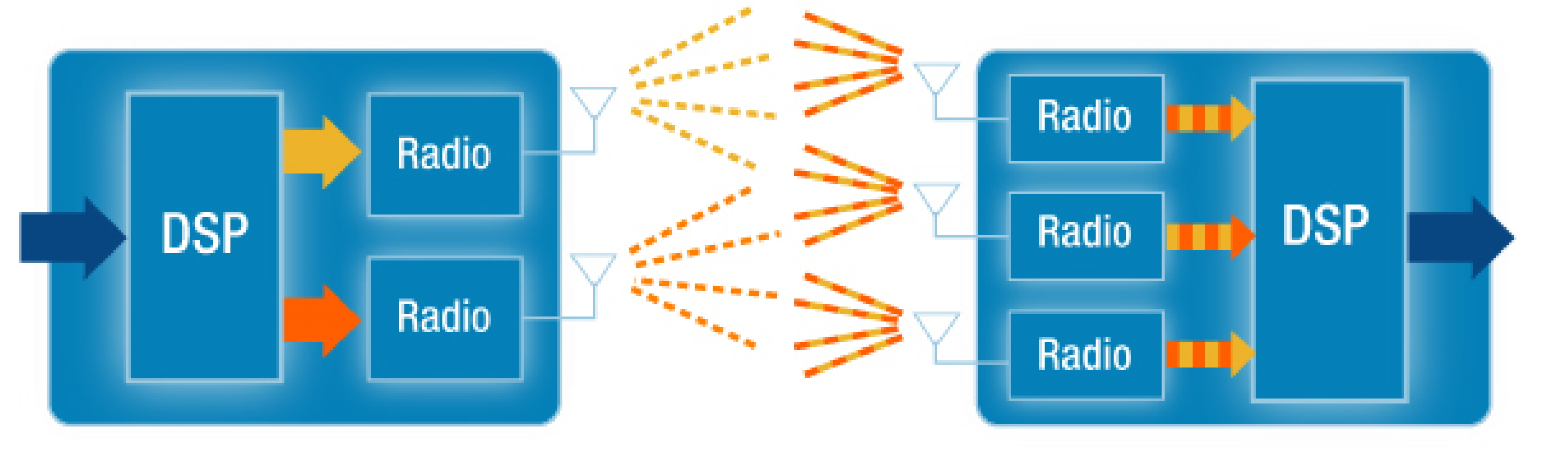
(Linear vs. Logarithmic Improvement)



How MIMO Works

- MIMO takes advantage of multi-path.
- MIMO uses multiple antennas to send multiple parallel signals (from transmitter).
- In an urban environment, these signals will bounce off trees, buildings, etc. and continue on their way to their destination (the receiver) but in different directions.
- “Multi-path” occurs when the different signals arrive at the receiver at various times.
- With MIMO, the receiving end uses an algorithm or special signal processing to sort out the multiple signals to produce one signal that has the originally transmitted data.

How MIMO Works (cont.)



Multiple data streams transmitted in a single channel at the same time

Multiple radios collect multipath signals

Delivers simultaneous speed, coverage, and reliability improvements

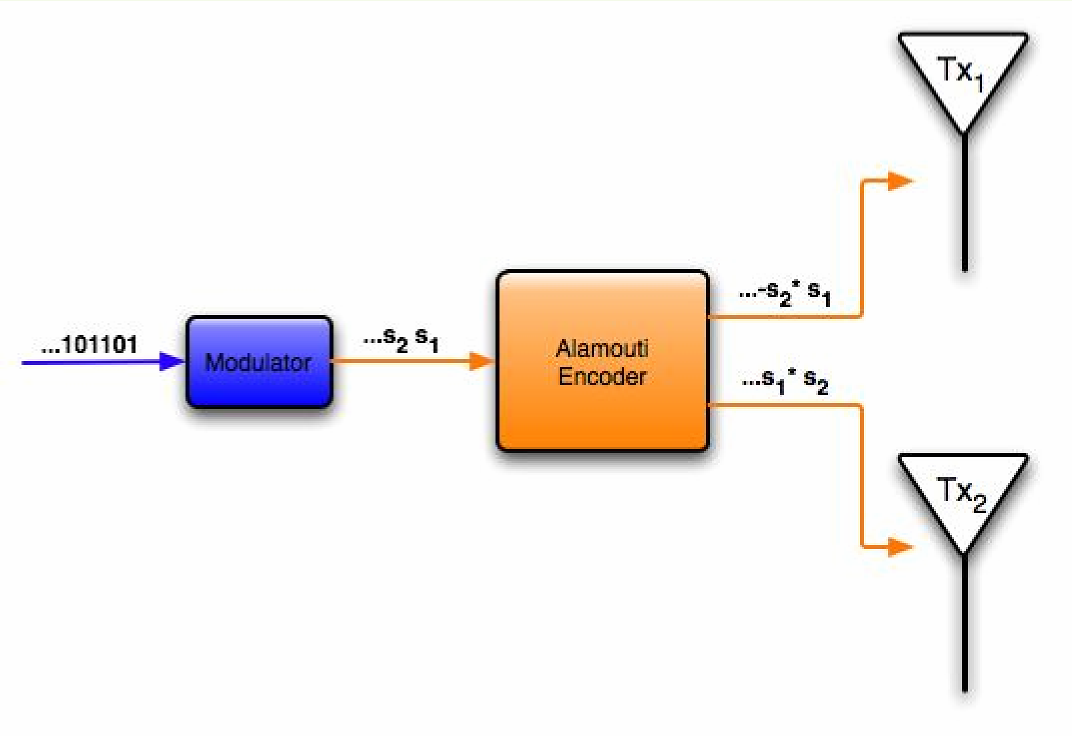
Types of MIMO

- MIMO involves Space Time Transmit Diversity (STTD), Spatial Multiplexing (SM) and Uplink Collaborative MIMO.
- ***Space Time Transmit Diversity (STTD)*** - The same data is coded and transmitted through different antennas, which effectively doubles the power in the channel. This improves Signal Noise Ratio (SNR) for cell edge performance.
- ***Spatial Multiplexing (SM)*** - the “Secret Sauce” of MIMO. SM delivers parallel streams of data to CPE by exploiting multi-path. It can double (2x2 MIMO) or quadruple (4x4) capacity and throughput. SM gives higher capacity when RF conditions are favorable and users are closer to the BTS.
- ***Uplink Collaborative MIMO Link*** - Leverages conventional single Power Amplifier (PA) at device. Two devices can collaboratively transmit on the same sub-channel which can also double uplink capacity.

Space-Time Transmit Diversity

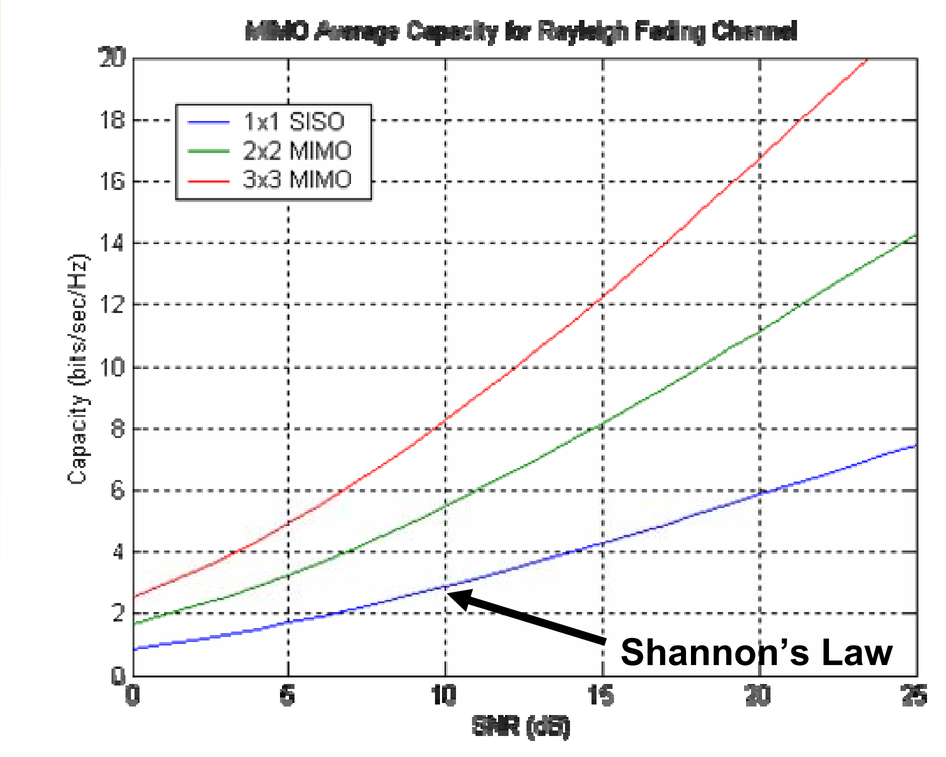
Alamouti Code

$$X = \begin{array}{cc} \text{time} & \\ \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix} & \text{space} \end{array}$$



MIMO Increases Throughput

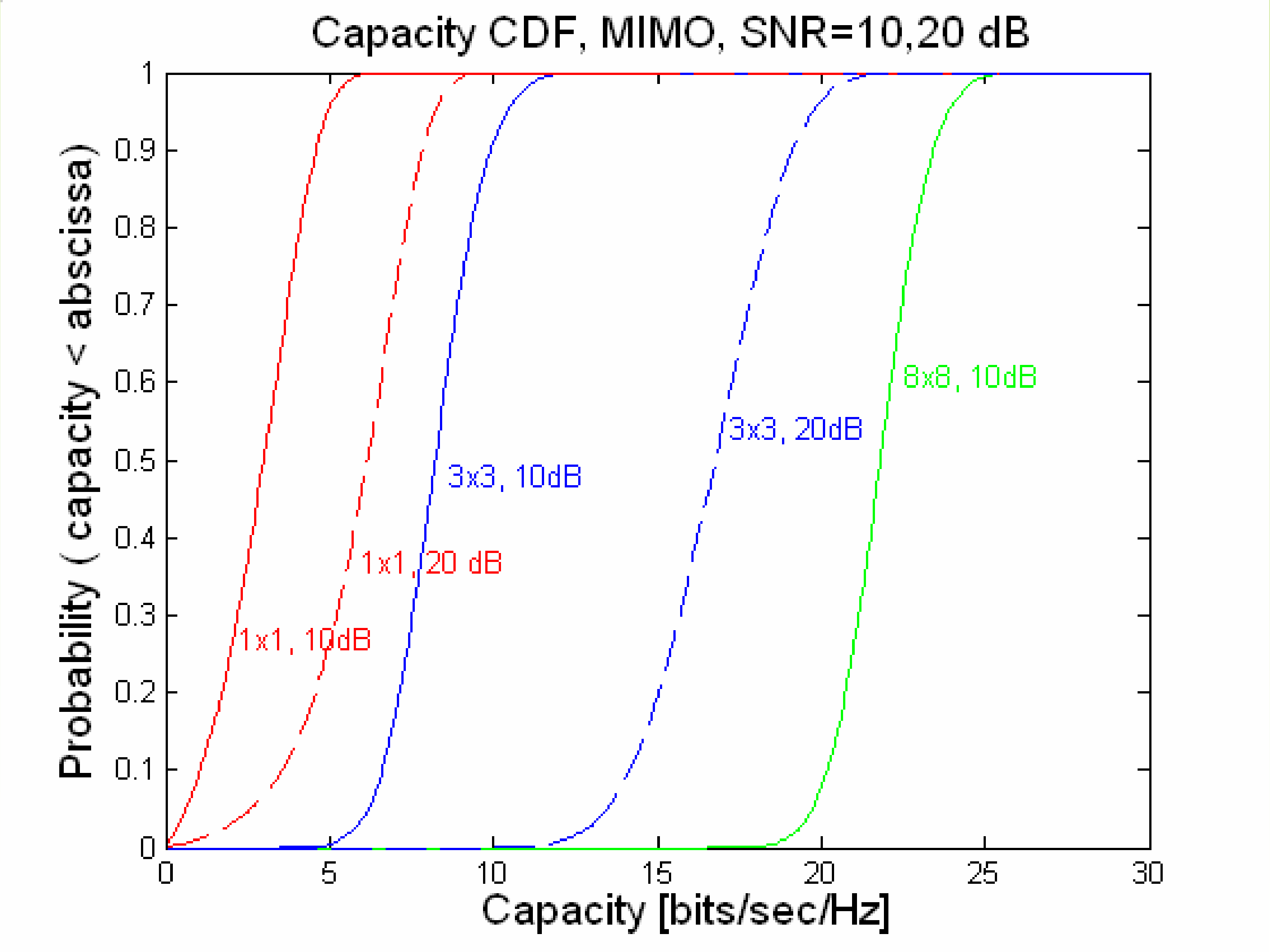
Spatial Multiplexing



Wireless throughput scales as more radio transmissions are added onto the same channel

Only baseband complexity, die size/cost, and power consumption limits the number of simultaneous transmissions (assuming good channel conditions)

MIMO Channel Capacity

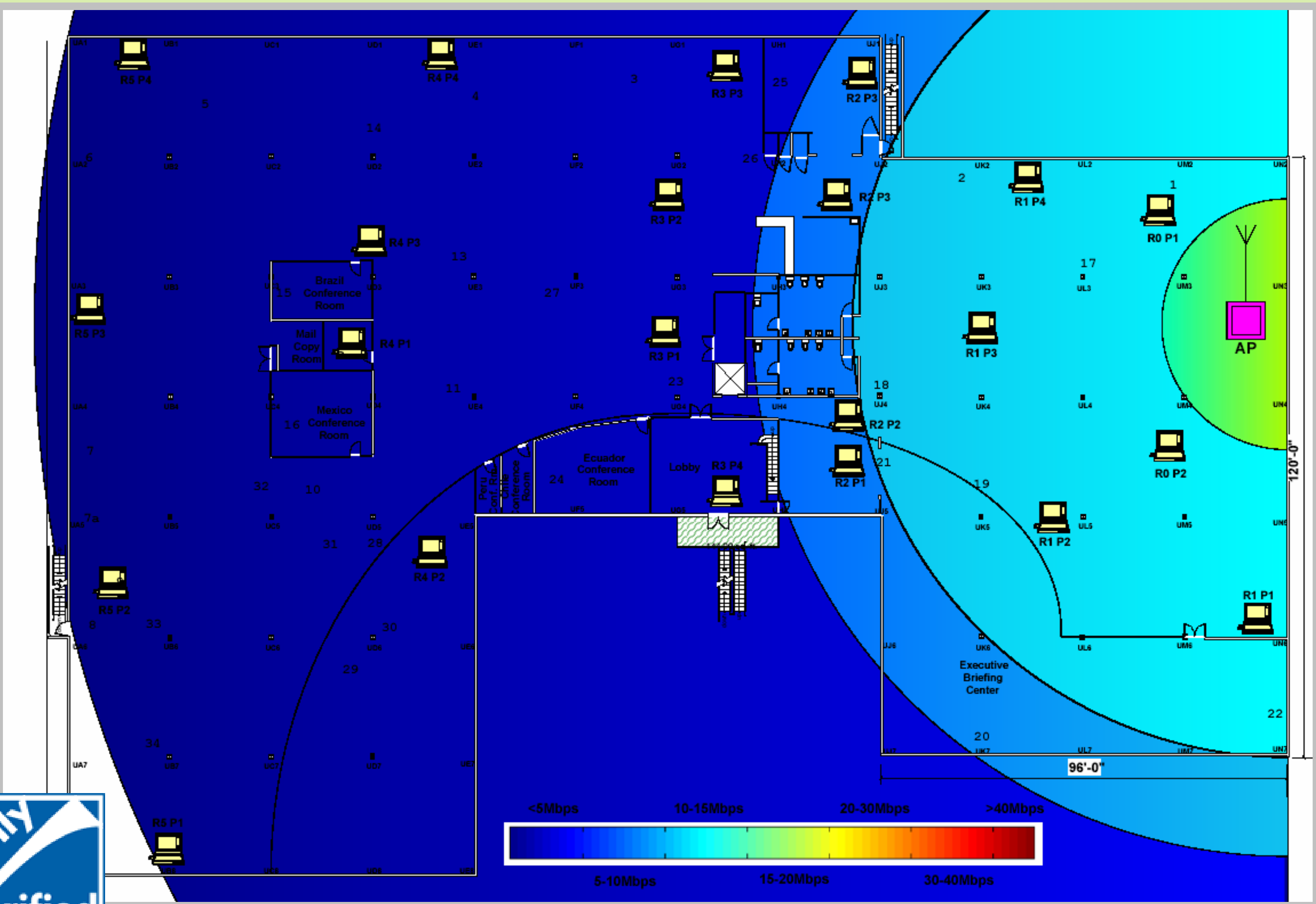


MIMO Increases Range

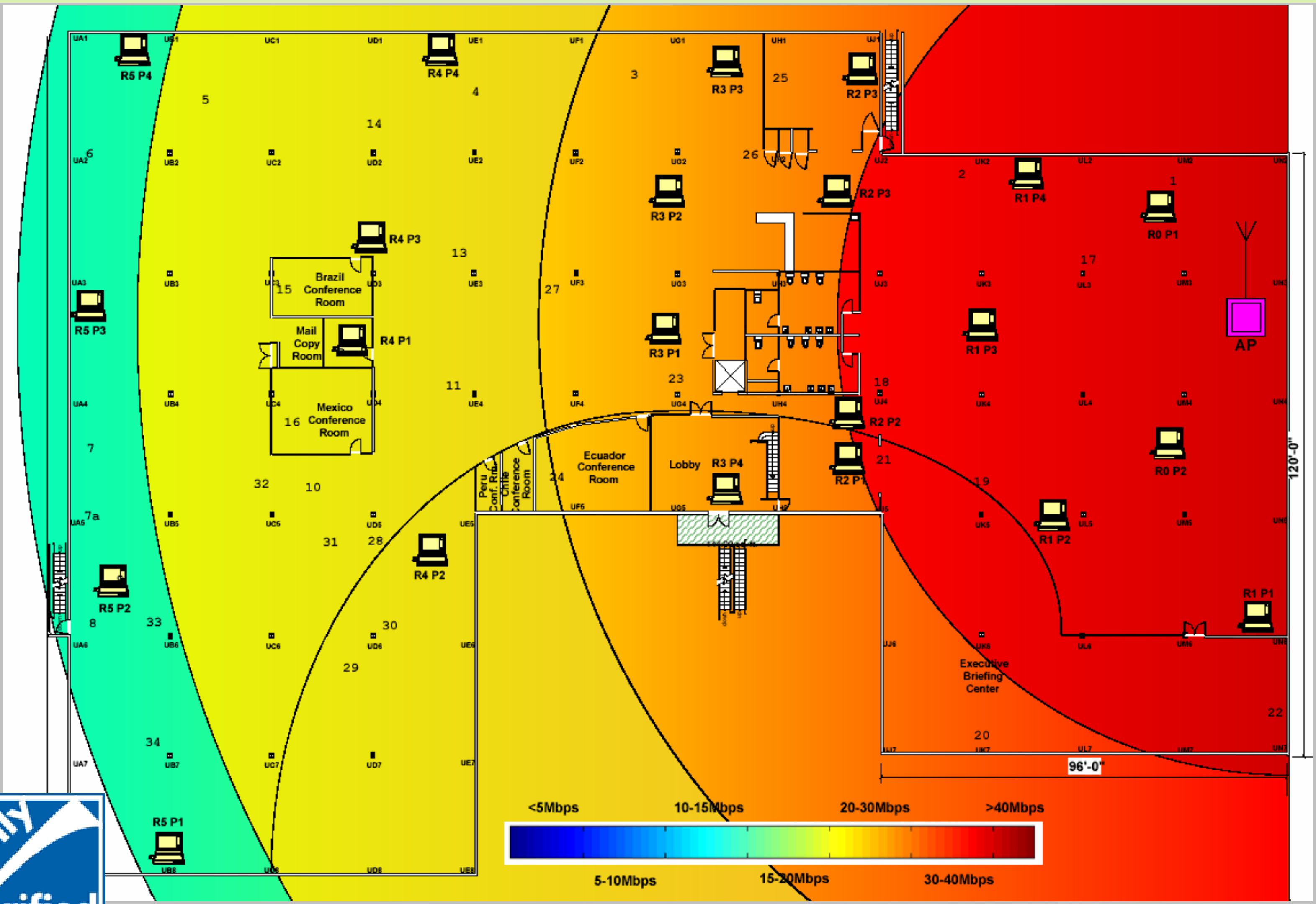
Each multipath route is treated as a separate channel, creating many “virtual wires” over which to transmit signals

Traditional radios are confused by this multipath, while MIMO takes advantage of these “echoes” to increase range and throughput

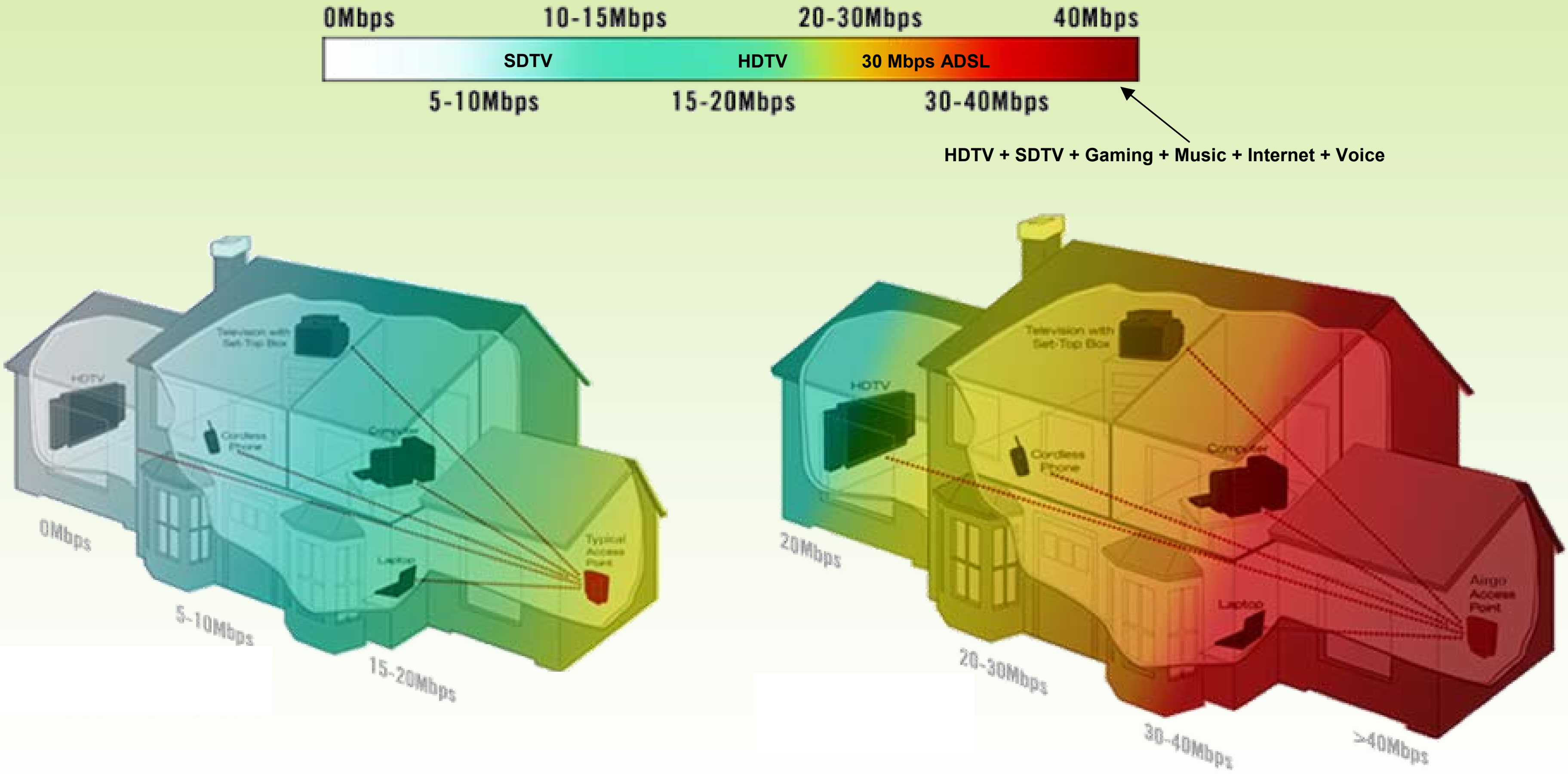
Single Radio Performance (Office)



MIMO Performance (Office)



Single Radio vs. MIMO Performance



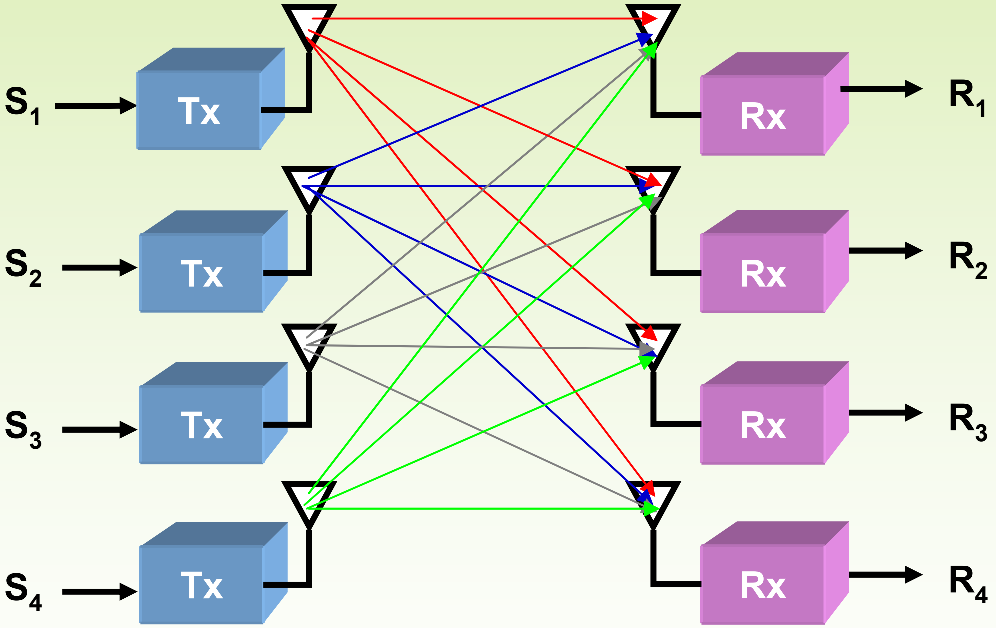
HDTV + SDTV + Gaming + Music + Internet + Voice

Different from Traditional Multiple Access Techniques

- It is not FDMA – multiple users using the same frequency
- It is not TDMA – multiple users communicate simultaneously
- It is not CDMA/Spread Spectrum – frequency band occupied is similar to that of conventional QAM system
- It is not SDMA – there are no directed steered/switched beams in space (e.g., smart antennas)
- *It is ECDMA (Environmental CDMA): like CDMA without having to spread the signal through space-time coding; here the code is the imprint of the environment on the signal and it comes free…*

Exploiting Multipath Rather than Mitigating It

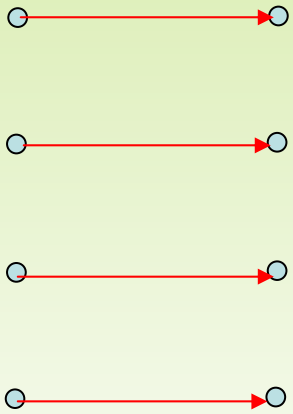
MIMO Channel



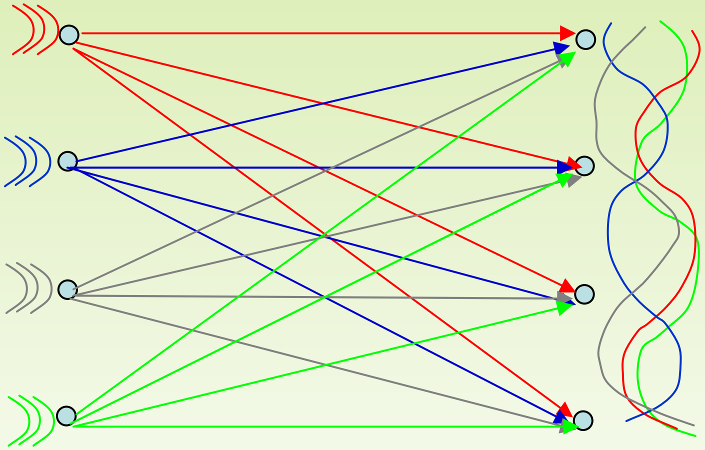
$H(4x4)$

The "Magic":

Separating the self-coded signals

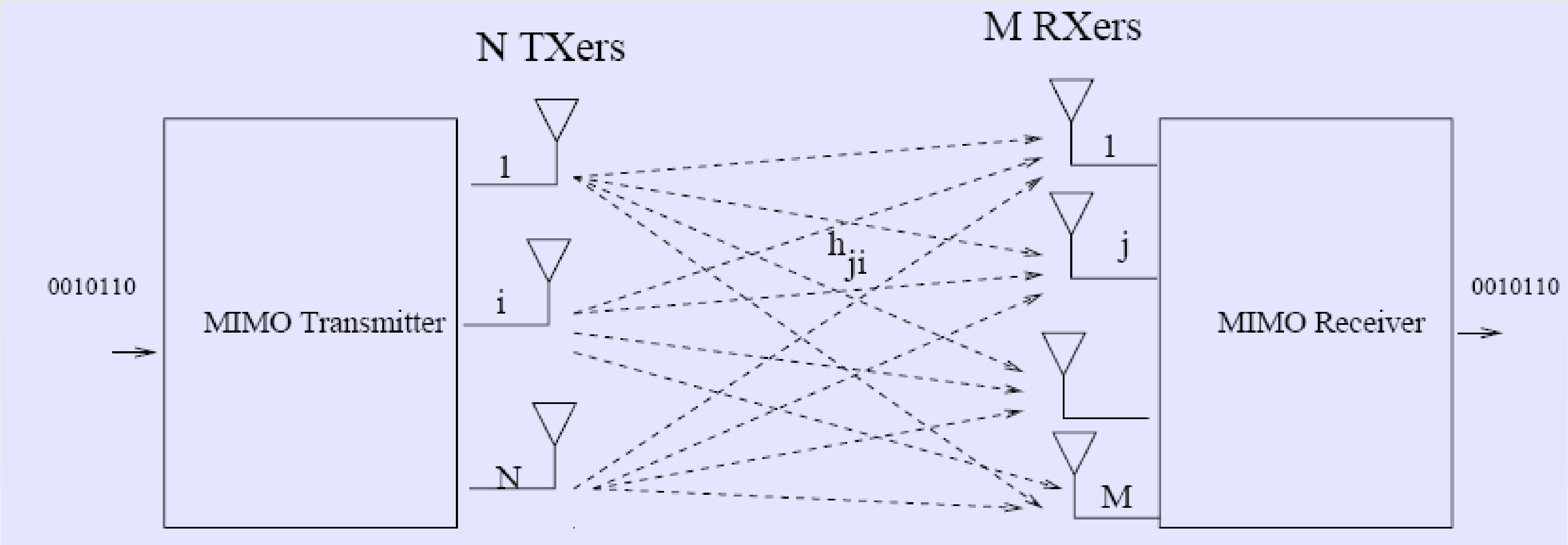


using laser diodes



using radio frequency

MIMO Channel Matrix

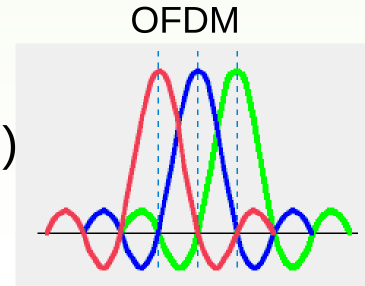


Example for 3 X 4 system:

Number of spatial streams equals rank(H) ≤ min(M, N)

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \\ h_{41} & h_{42} & h_{43} \end{bmatrix}$$

h_{ij} are complex numbers: a+jb (amplitude&phase) and frequency selective



How It Works

Example for 3 X 3 system:

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \underbrace{\begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix}}_{\mathbf{H}} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} + \textbf{Noise}$$

$$\begin{bmatrix} \hat{b}_1 \\ \hat{b}_2 \\ \hat{b}_3 \end{bmatrix} = \mathbf{H}^{-1} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

Impact of Channel Model

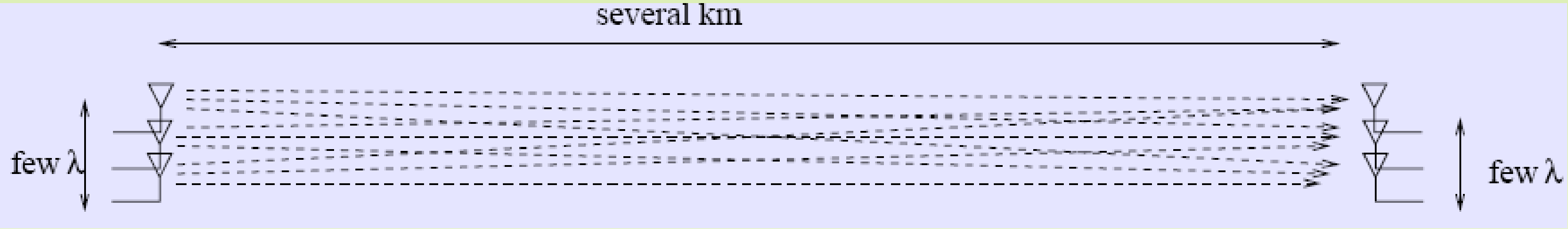
MIMO performance is very sensitive to channel matrix *invertibility*

The following degrades the conditioning of the channel matrix:
- Antenna correlation caused by:

- small antenna spacing, or
- small angle spread

Line of sight component compared with multipath fading component:
- multipath fading component, close to i.i.d. random, is well conditioned
- Line of sight component is very poorly conditioned.

MIMO-SM in Line-of-Site



$$\mathbf{H} \approx \alpha \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

The system is near rank one (non invertible)!

Spatial multiplexing requires multipath to work!!!

Zero-Forcing Receiver

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & .. \\ h_{21} & h_{22} & .. \\ \vdots & \vdots & \vdots \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ \vdots \end{bmatrix} + \mathbf{n}$$

Zero Forcing implements matrix (pseudo)-inverse (ignores noise enhancement problems):

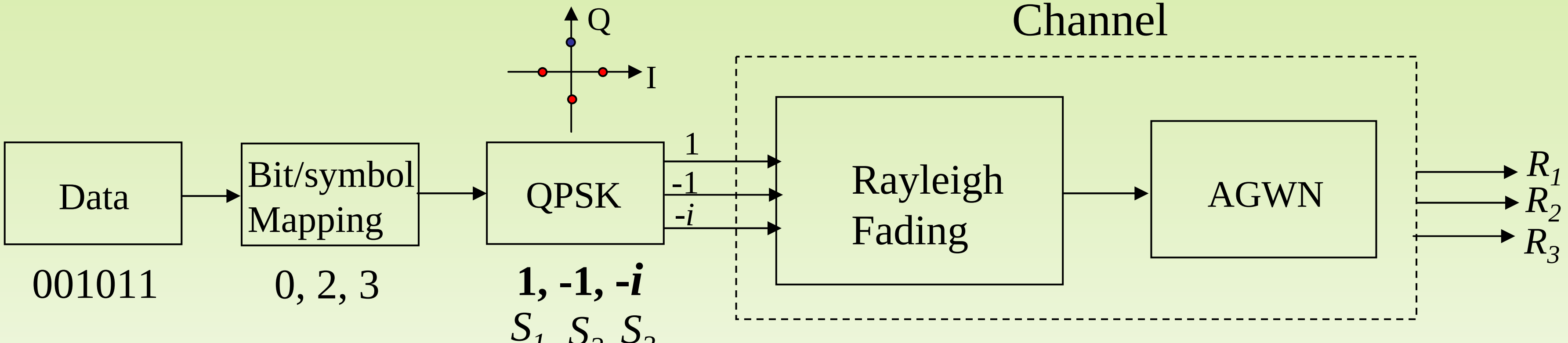
$$\hat{\mathbf{s}} = \mathbf{H}^{\#}\mathbf{x}$$

Where,

$$\mathbf{H}^{\#} = (\mathbf{H}^{*}\mathbf{H})^{-1}\mathbf{H}^{*}$$

Example

Simultaneous Transmission of 3 Different Bit-Streams



Q

I

Channel

Data

Bit/symbol Mapping

QPSK

1

-1

-*i*

Rayleigh Fading

AGWN

R_1

R_2

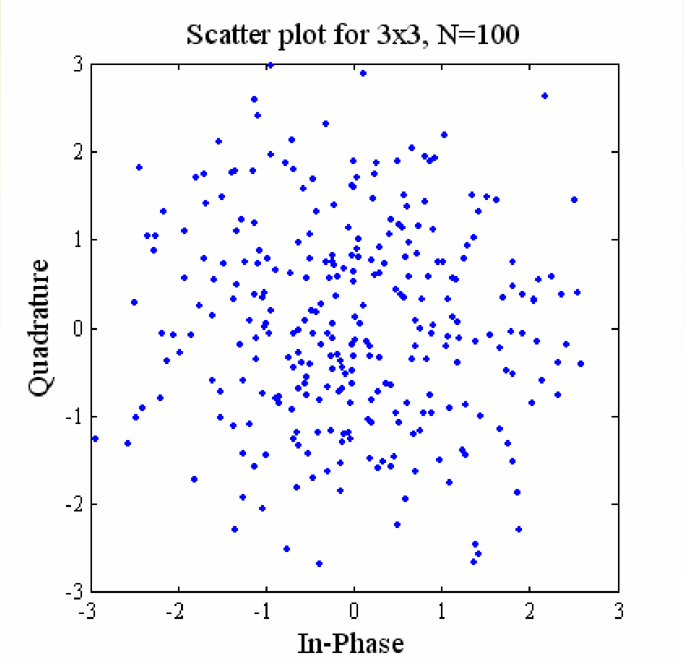
R_3

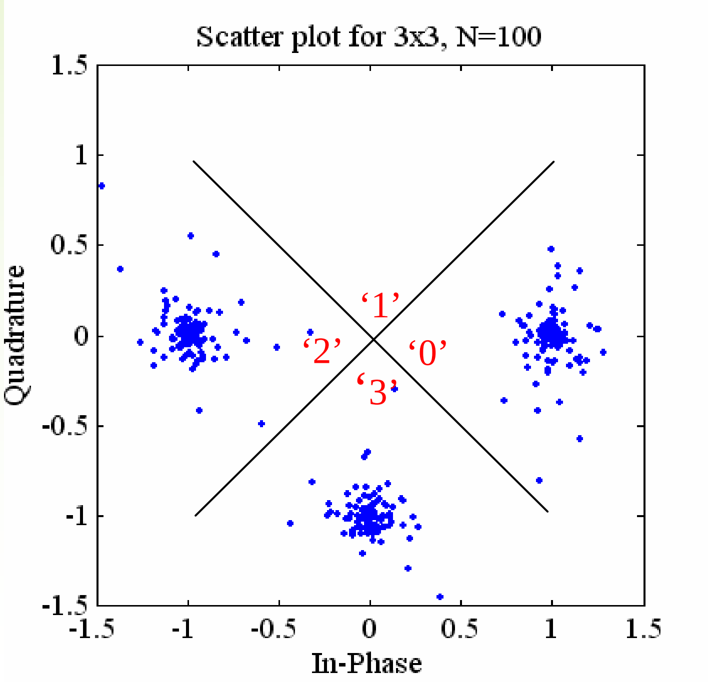
001011

0, 2, 3

1, -1, -*i*

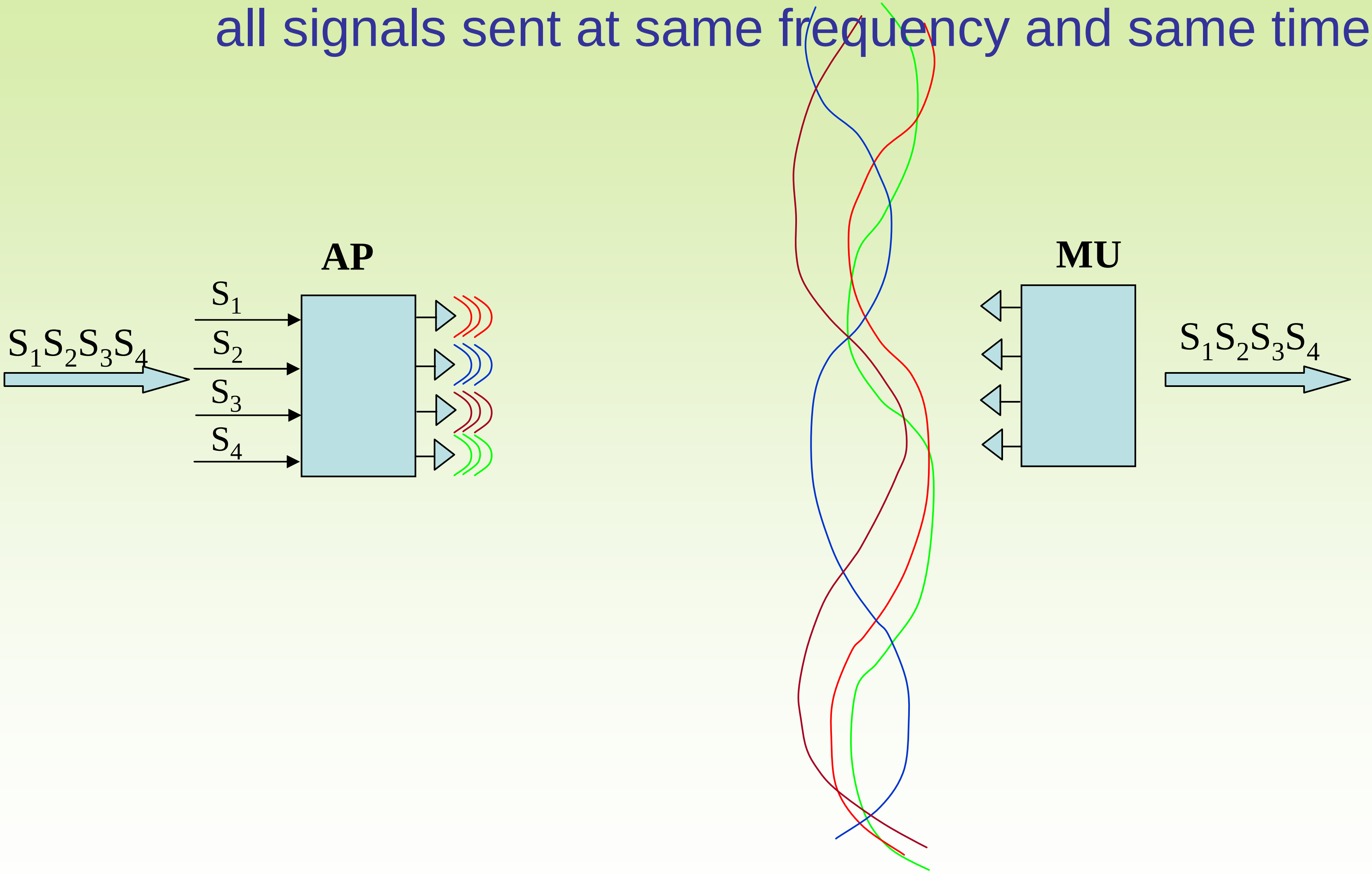
S_1 S_2 S_3





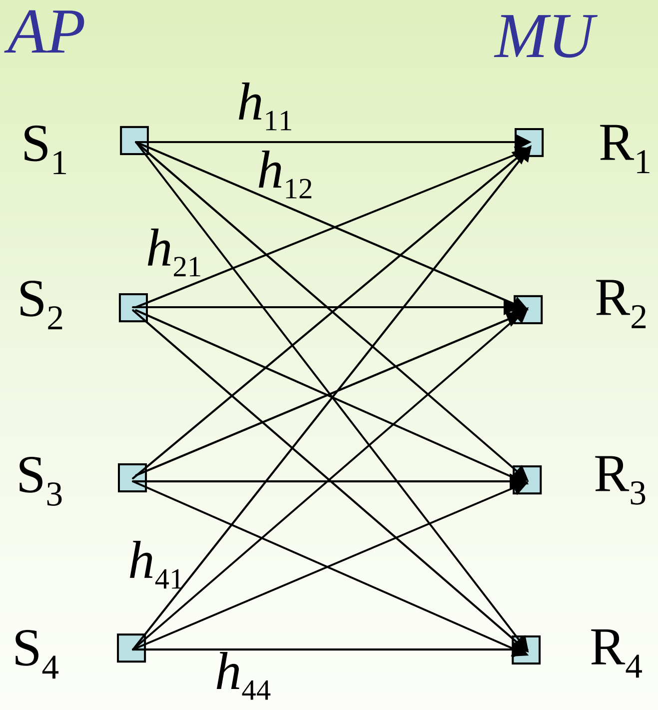
Downstream Signals

all signals sent at same frequency and same time



Mixed Signals

Downstream



channel mixing matrix

noise

$$\boxed{\underline{R} = \underline{H} \cdot \underline{S} + \underline{n}}$$

e.g., $R_1 = h_{11}S_1 + h_{12}S_2 + h_{13}S_3 + h_{14}S_4 + n_1$

The Received Signals

$$
\begin{aligned}
R_1 &= h_{11}S_1 + h_{12}S_2 + h_{13}S_3 + h_{14}S_4 + n \\
R_2 &= h_{21}S_1 + h_{22}S_2 + h_{23}S_3 + h_{24}S_4 + n \\
R_3 &= h_{31}S_1 + h_{32}S_2 + h_{33}S_3 + h_{34}S_4 + n \\
R_4 &= h_{41}S_1 + h_{42}S_2 + h_{43}S_3 + h_{44}S_4 + n
\end{aligned}
$$

$$\underline{R} = \underline{H} \cdot \underline{S} + \underline{n}$$

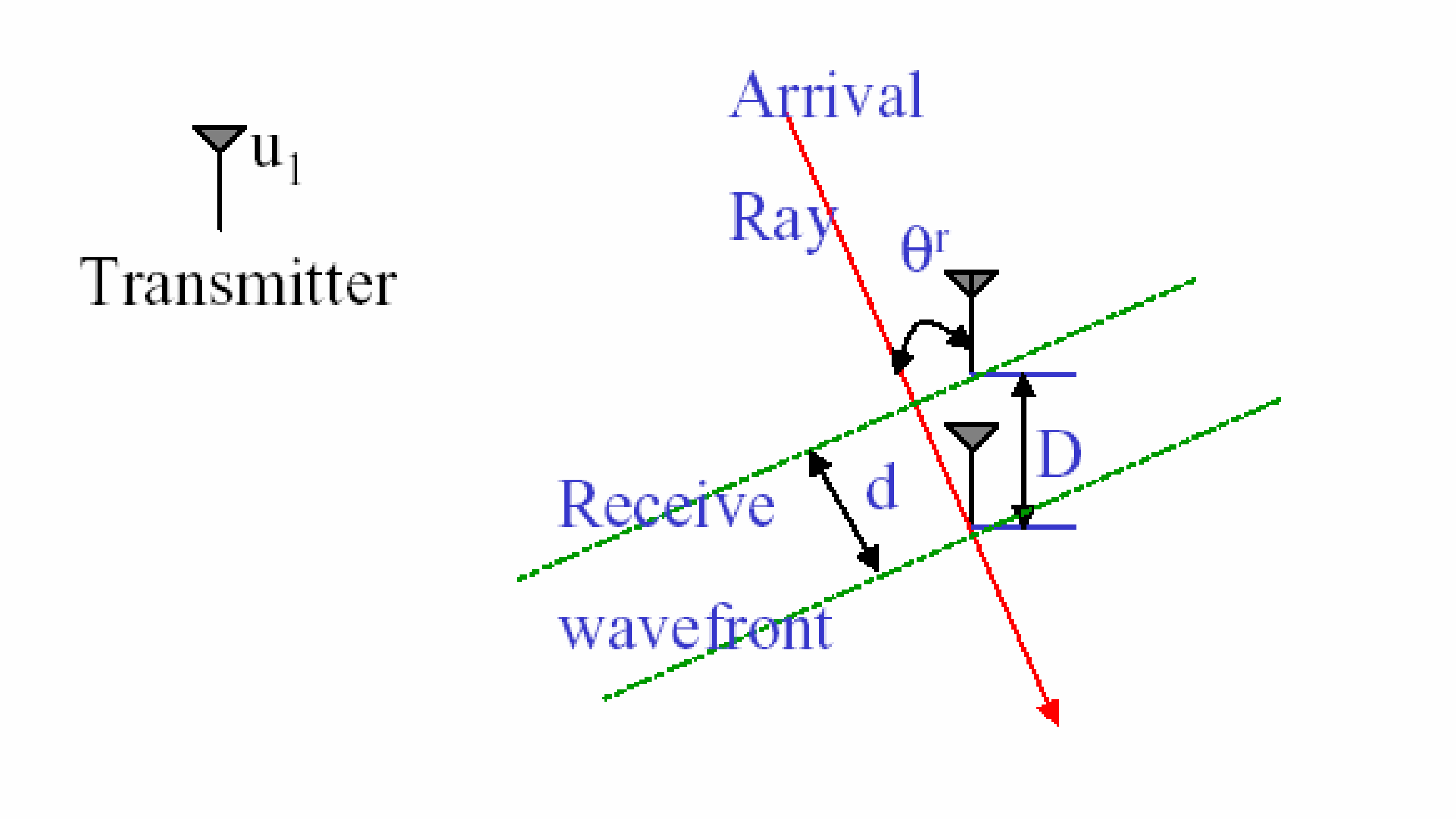
$$\underline{H} = \begin{pmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{pmatrix}$$

$$\underline{\hat{S}} \Leftarrow \underline{H^{-1}} \cdot \underline{R} \approx \underbrace{\underline{H^{-1}} \cdot \underline{H}}_{\underline{Y}} \cdot \underline{S}$$

If H is ill-conditioned (close to singular)
Y will be far from the identity matrix
Resulting in co-channel interference

Spatial Correlation

or how well the matrix H is conditioned



Spatial Correlation (cont.)

Correlation

$$\rho = \frac{\mathrm{E}\left[(v_1 - E(v_1))(v_2 - E(v_2))\right]}{\mathrm{E}\left[(v_1 - E(v_1))^2\right]\mathrm{E}\left[(v_2 - E(v_2))^2\right]}$$

Receive *Antenna* 1

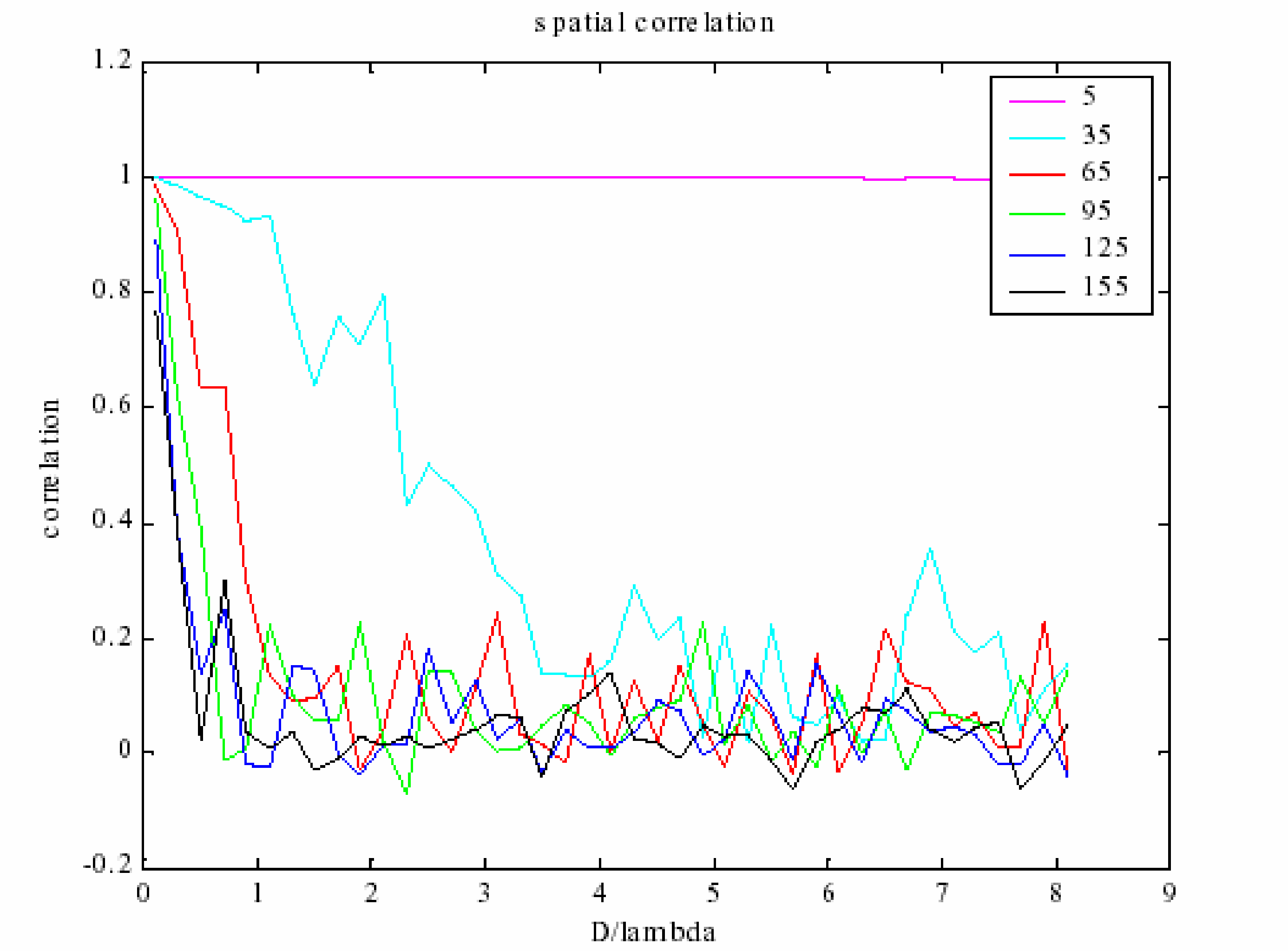
$$v_1 = \left(\sum_{j=1}^{L} \alpha_j \quad e^{i\phi_j}\right) \quad u_1$$

Receive *Antenna* 2

$$v_2 = \left(\sum_{j=1}^{L} \alpha_j \quad e^{i\phi_j} e^{i\beta d_j}\right) \quad u_1; \quad \beta = \omega / c; \quad d_j = D\cos\theta_j^{r}$$

Spatial Correlation (cont.)

Correlation Drops Significantly for D>λ When Angle Spread >65°



Co-Channel Interference

$$\underline{Y} = \underline{H_{est}^{\;-1}} \cdot \underline{H_{true}} \neq \underline{I}$$

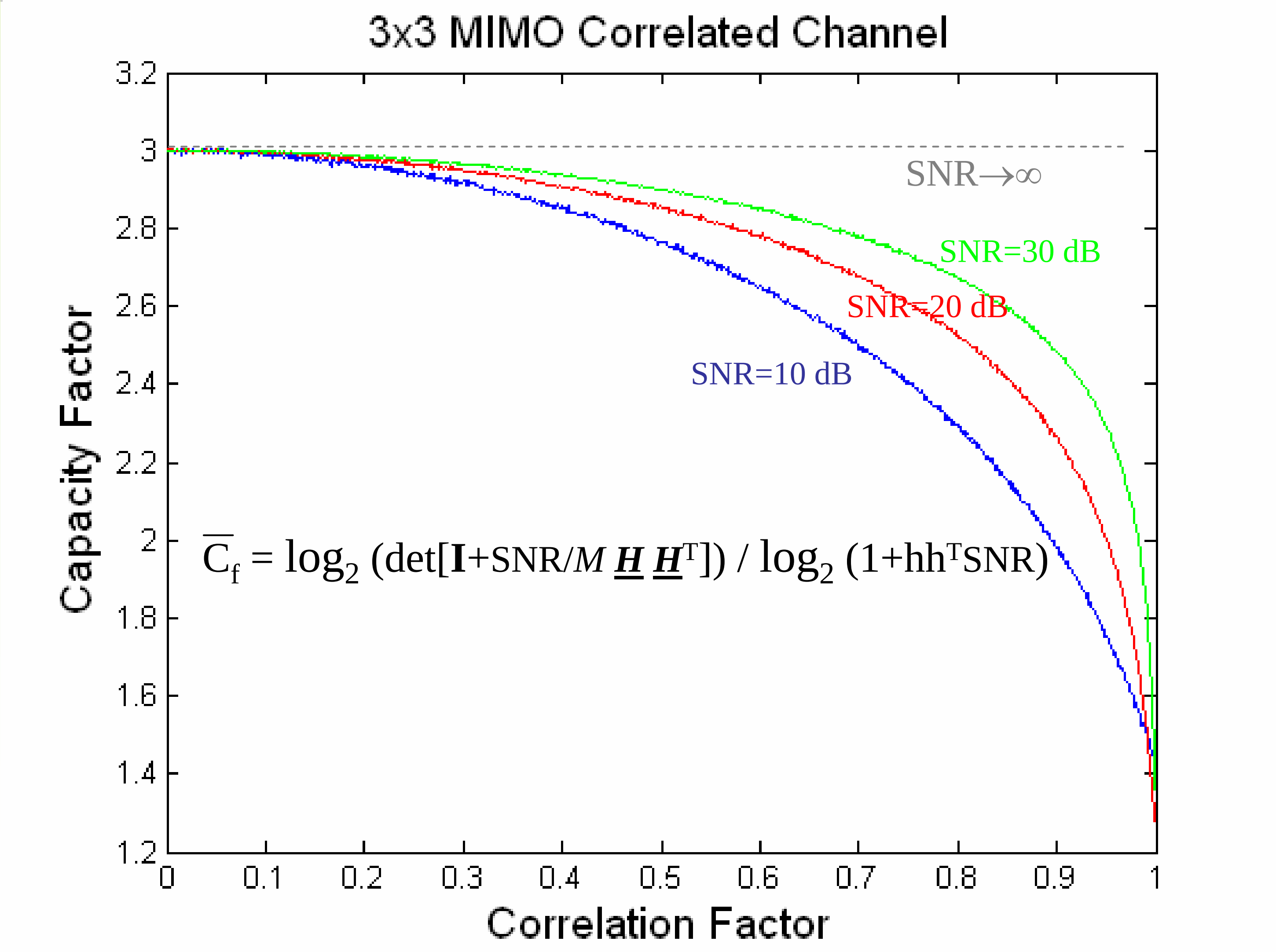
$$\underline{\hat{S}} \Leftarrow \underline{Y} \cdot \underline{S}$$

$$SINR_{S_k} = 20\log\frac{\left|y_{kk}\right|}{\left|\sum_{j\neq k} y_{kj}\right|}$$

$$\underline{Y} = \begin{pmatrix} y_{11} & y_{12} & y_{13} & y_{14} \\ y_{21} & y_{22} & y_{23} & y_{24} \\ y_{31} & y_{32} & y_{33} & y_{34} \\ y_{41} & y_{42} & y_{43} & y_{44} \end{pmatrix}$$

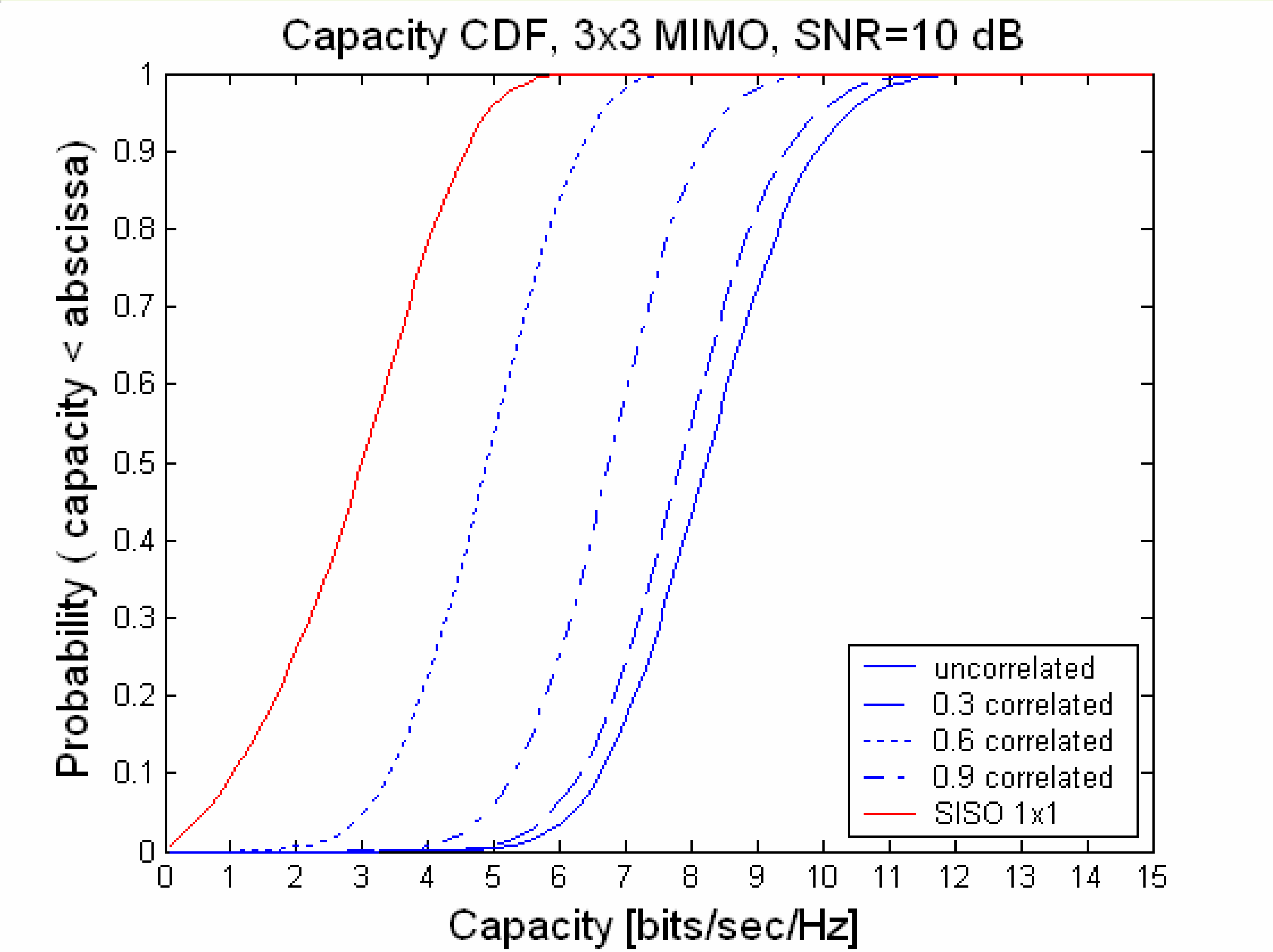
Graceful Capacity Degradation in Partially Correlated Channels

Multi-path components do not need to be fully independent



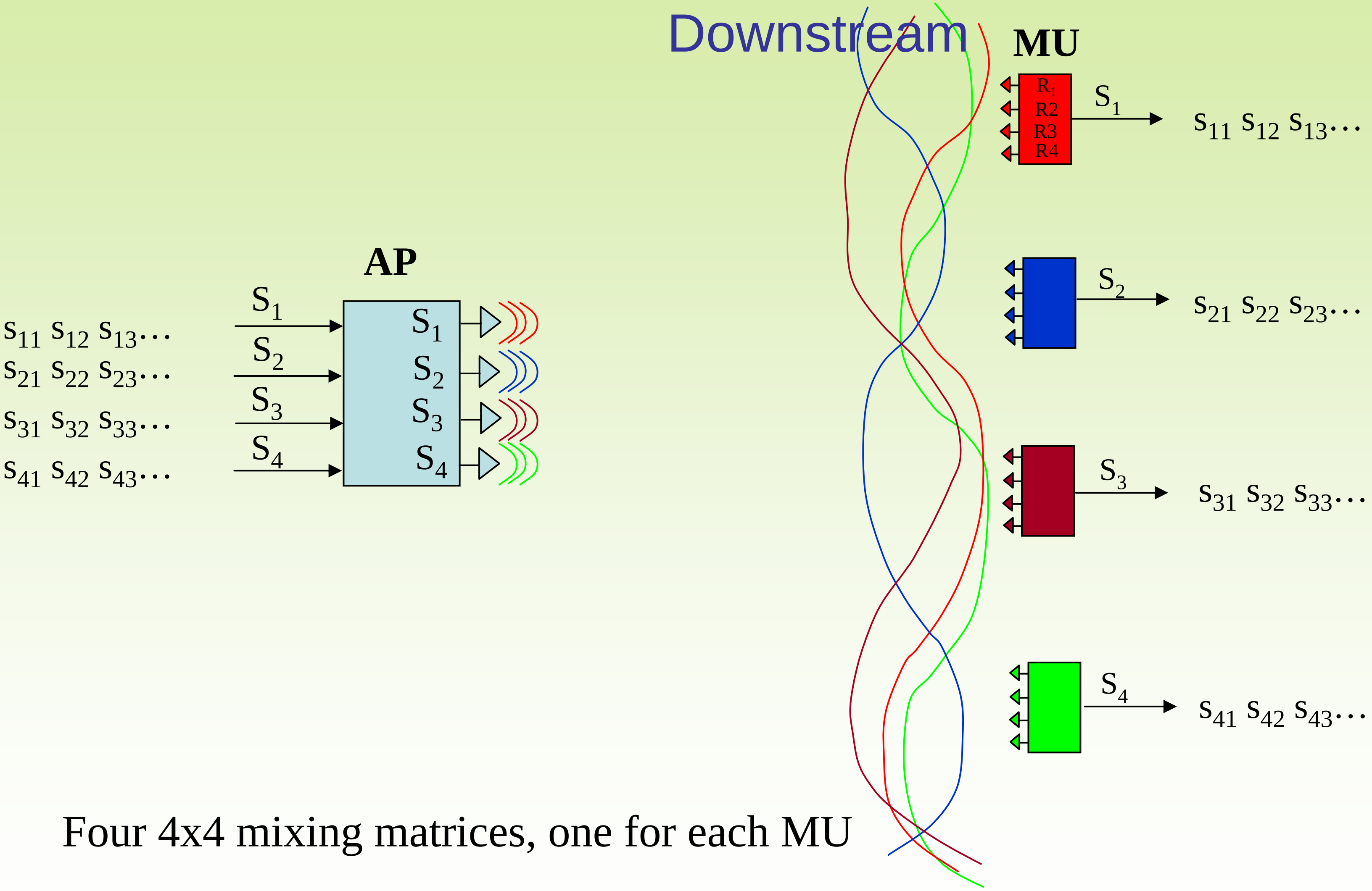
Random Capacity in MIMO Channels

Correlation Effect



Collaborative MIMO

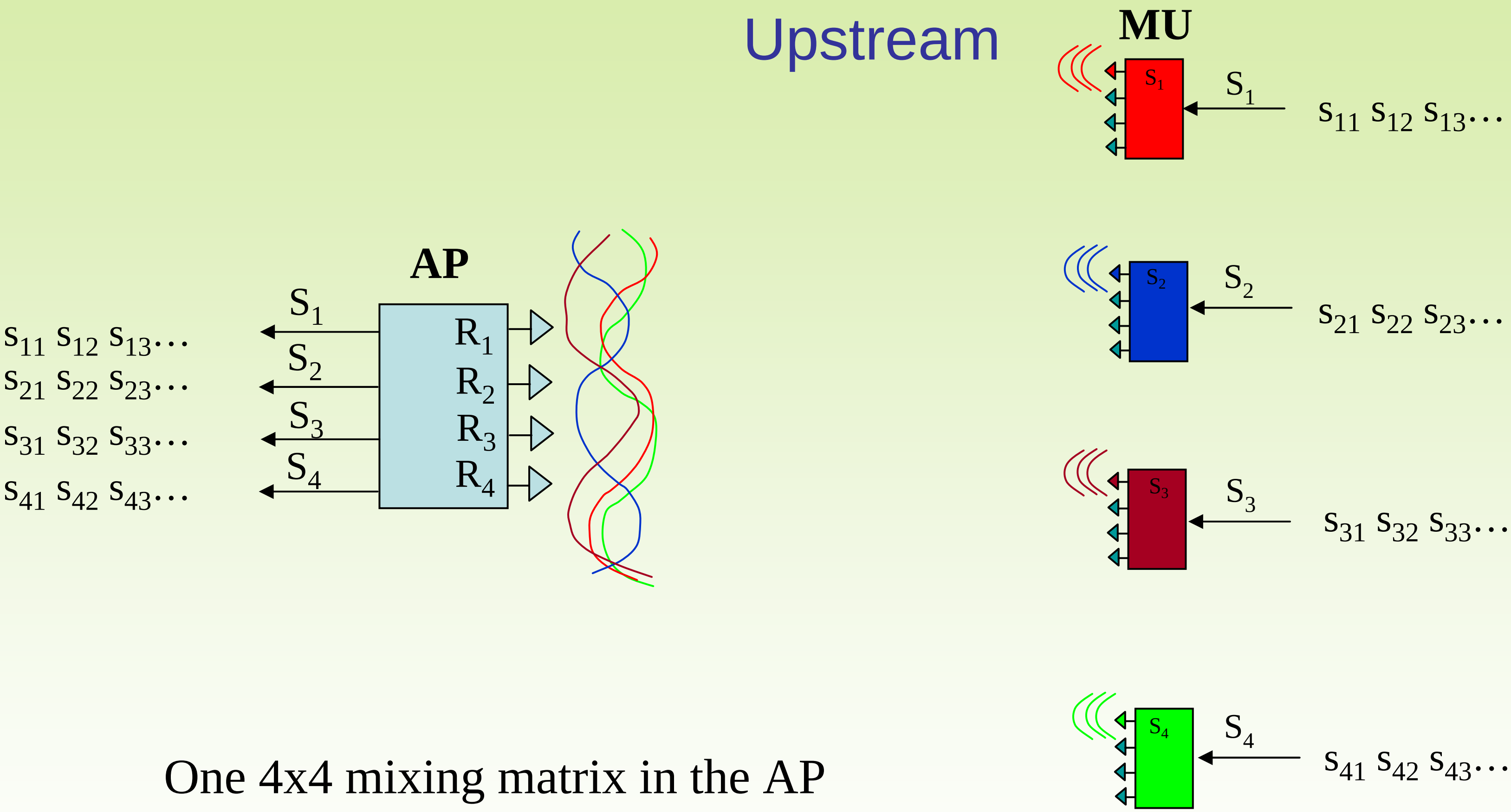
Downstream



Four 4x4 mixing matrices, one for each MU

Collaborative MIMO

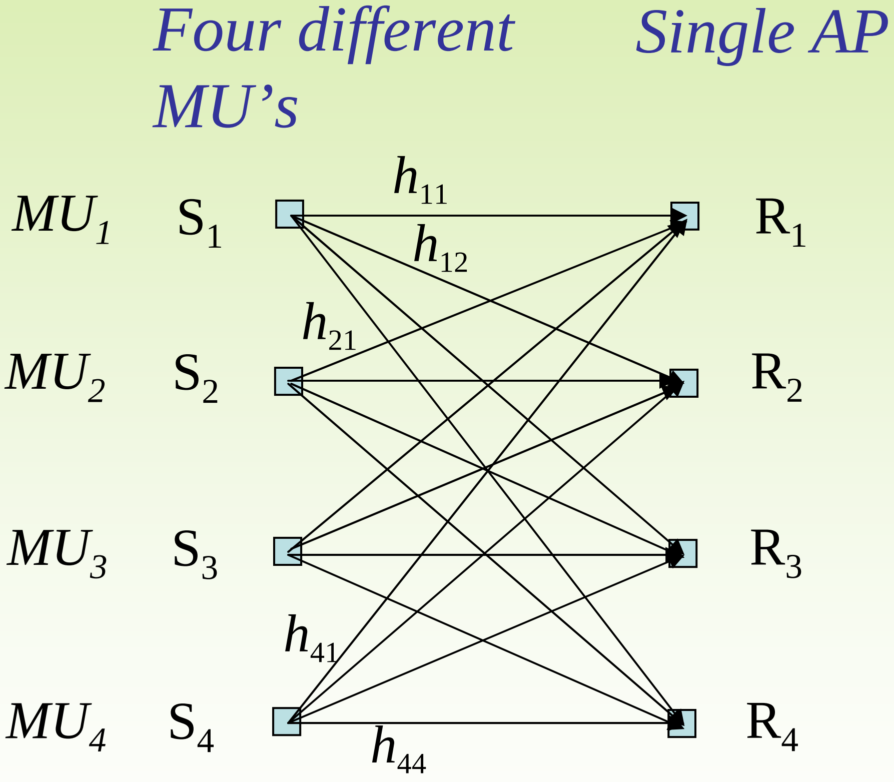
Upstream



One 4x4 mixing matrix in the AP

Mixed Channels

Upstream



channel mixing matrix

noise

$$\boxed{\underline{R} = \underline{H} \cdot \underline{S} + \underline{n}}$$

e.g., $R_1 = h_{11}S_1 + h_{12}S_2 + h_{13}S_3 + h_{14}S_4 + n_1$

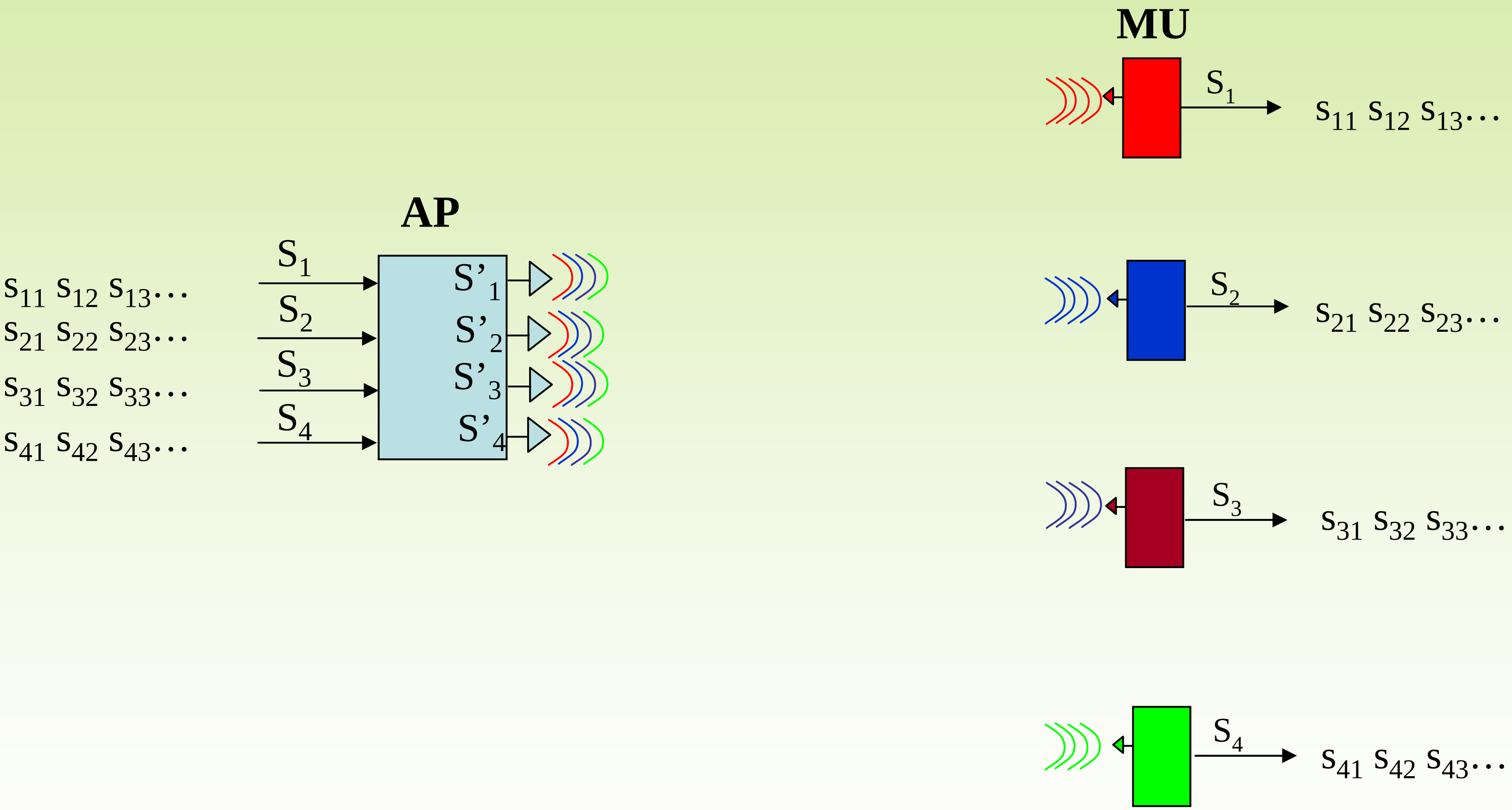
MIMO Pre-Processing at the Transmitter

A single antenna at the mobile

- AP pre-processes the signals based on channel knowledge (CSI Tx)
- No MIMO processing in the mobile
- AP sends linear combination of all signals from each antenna such that when they all arrive at the mobile all undesired signals cancel out
- Effectively AP solves the equation to each mobile
- Benefits:
  - Mobile: lower cost, power and size
  - Scalability: more MIMO channels possible resulting in higher aggregate capacity
  - Strong physical-layer security, hard to break

MIMO Pre-Processing at the Transmitter

A single antenna at the mobile



MU

AP

$s_{11}\ s_{12}\ s_{13}\ldots$

$s_{21}\ s_{22}\ s_{23}\ldots$

$s_{31}\ s_{32}\ s_{33}\ldots$

$s_{41}\ s_{42}\ s_{43}\ldots$

S_1 S_2 S_3 S_4

S'_1 S'_2 S'_3 S'_4

S_1 → $s_{11}\ s_{12}\ s_{13}\ldots$

S_2 → $s_{21}\ s_{22}\ s_{23}\ldots$

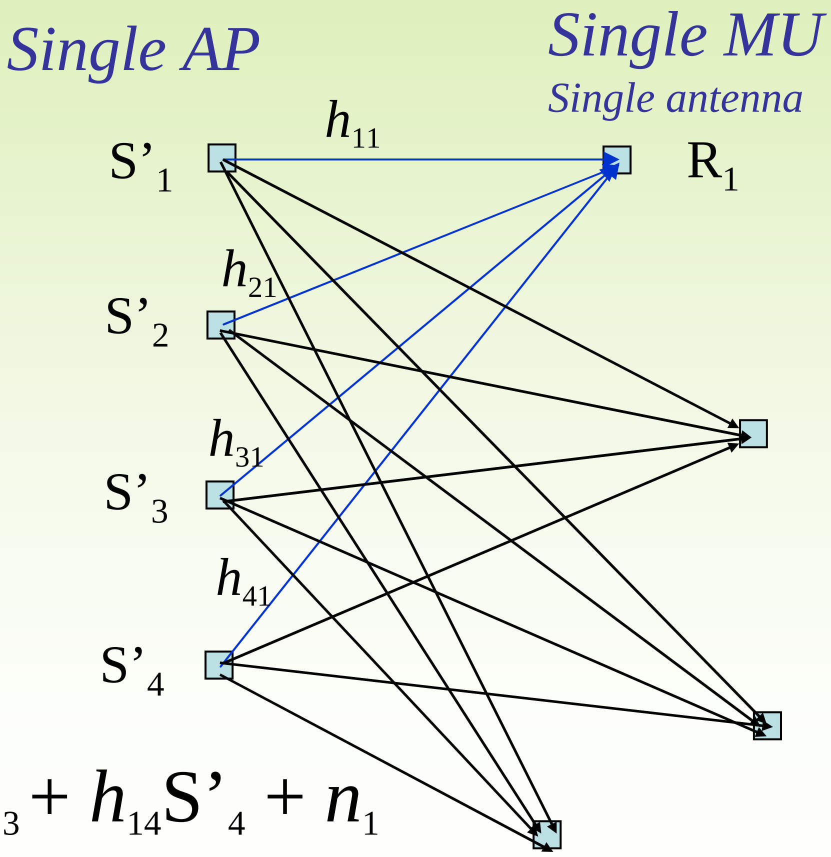
S_3 → $s_{31}\ s_{32}\ s_{33}\ldots$

S_4 → $s_{41}\ s_{42}\ s_{43}\ldots$

All undesired signals cancel out at the mobile

Mixed Channels

Downstream



channel mixing matrix

noise

$$\boxed{\underline{R}=\underline{H}\cdot\underline{S'}+\underline{n}}$$

e.g., $R_1 = h_{11}S'_1 + h_{12}S'_2 + h_{13}S'_3 + h_{14}S'_4 + n_1$

MIMO Pre-Processing at the Transmitter

Downlink

$$\underline{R} = \underline{H} \cdot \underline{S} + \underline{n}$$

$$\underline{S}' = \underline{W} \cdot \underline{S}$$

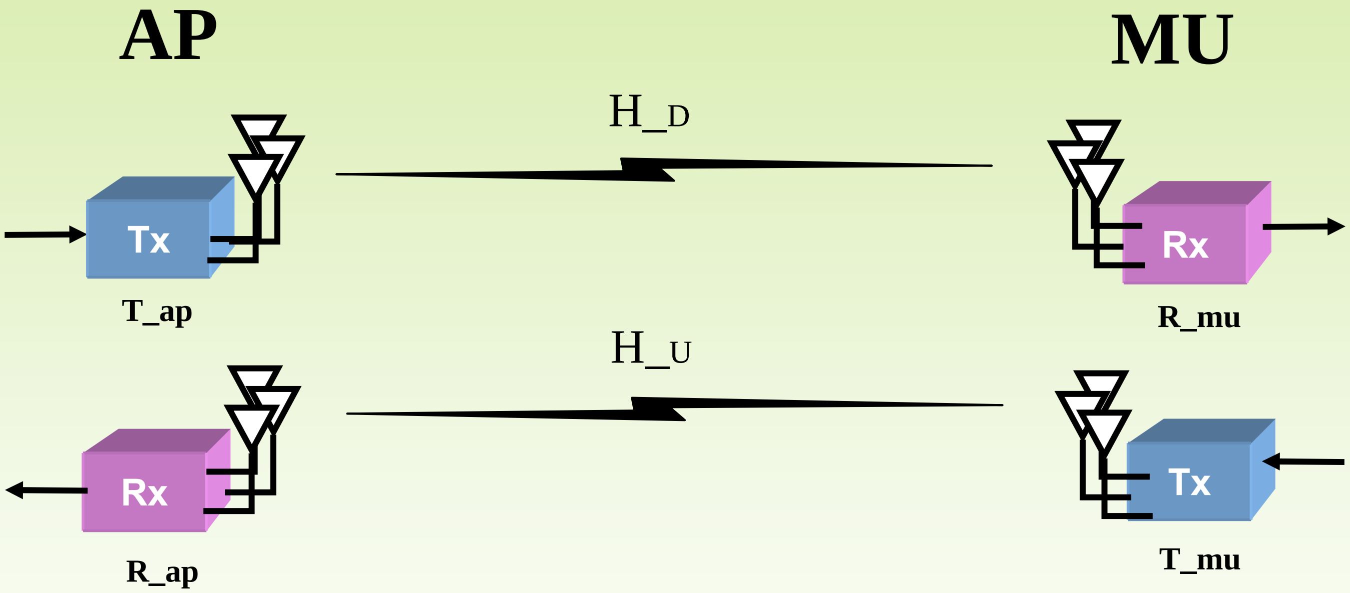
$$\underline{R}' = \underline{H} \cdot \underline{S}' + \underline{n} = \underbrace{\underline{H} \cdot \underline{W}}_{\underline{Y}} \cdot \underline{S} + \underline{n}$$

$$\underline{W} = \underline{H^{-1}}$$

$$\underline{Y} = \underline{H_{true}} \cdot \underline{H_{est}{}^{-1}} \neq \underline{I}$$

$$\underline{\hat{S}} \Leftarrow \underline{Y} \cdot \underline{S}$$

End-to-End Reciprocity



- Practically, downstream and upstream channel matrices are not reciprocal
- AP Tx/Rx chain mismatch could result in significant performance degradation

End-to-End Reciprocity (cont.)

$H'_{D}=R_{mu} H_{D} T_{AP}$ end-to-end downstream

$H'_{U}=R_{AP} H_{U} T_{mu}$ end-to-end upstream, estimated using training sequence

Note that R_{mu}, T_{mu}, R_{AP} and T_{AP} are diagonal matrices

H_{D} and H_{U} are the channel matrices (antenna-to-antenna) for downstream and upstream, respectively

$H_{D}= R^{-1}_{mu} H'_{D} T^{-1}_{AP}$ antenna-to-antenna downstream

$H_{U}= R^{-1}_{AP} H'_{U} T^{-1}_{mu}$ antenna-to-antenna upstream

$H_{D}= H^{T}_{U}$ reciprocity from EM theory

$R^{-1}_{mu} H'_{D} T^{-1}_{AP} = (R^{-1}_{AP} H'_{U} T^{-1}_{mu})^{T}$

$R^{-1}_{mu} H'_{D} T^{-1}_{AP} = T^{-1}_{mu} H'^{T}_{U} R^{-1}_{AP}$

$$\boxed{H'_{D}= R_{mu} T^{-1}_{mu} H'^{T}_{U} R^{-1}_{AP} T_{AP}}$$

Note that R_{mu} and T_{mu} are unknown

H'_{U}, T_{AP} and R_{AP} are known

Calibration at the AP

$P'_{D}=H'^{T}_{U} R^{-1}_{AP} T_{AP}$ matrix used for pre-processing

$$Y=R_{mu} H_{D} T_{AP} P'^{-1}_{D} = R_{mu} H_{D} T_{AP} (H'^{T}_{U} R^{-1}_{AP} T_{AP})^{-1}$$
$$Y= R_{mu} H_{D} T_{AP}((R_{AP} H_{U} T_{mu})^{T} R^{-1}_{AP} T_{AP})^{-1}$$
$$Y= R_{mu} H_{D} T_{AP}(T_{mu} H^{T}_{U} R_{AP} R^{-1}_{AP} T_{AP})^{-1}$$
$$Y= R_{mu} H_{D} T_{AP}(T_{mu} H_{D} R_{AP} R^{-1}_{AP} T_{AP})^{-1}$$
$$Y= R_{mu} H_{D} T_{AP}(T_{mu} H_{D} T_{AP})^{-1}$$
$$Y= R_{mu} H_{D} T_{AP} T^{-1}_{AP} H^{-1}_{D} T^{-1}_{mu}$$

$\boxed{Y= R_{mu} H_{D} H^{-1}_{D} T^{-1}_{mu}}$ highly diagonal (low interference)

No Calibration at the AP

$P'_{D}=H'^{T}_{U}$ matrix used for pre-processing

$$Y=R_{mu}\,H_{D}\,T_{AP}\,P'^{-1}_{D} = R_{mu}\,H_{D}\,T_{AP}\,(H'^{T}_{U})^{-1}$$
$$Y= R_{mu}\,H_{D}\,T_{AP}((R_{AP}\,H_{U}\,T_{mu})^{T})^{-1}$$
$$Y= R_{mu}\,H_{D}\,T_{AP}(T_{mu}\,H^{T}_{U}\,R_{AP})^{-1}$$
$$Y= R_{mu}\,H_{D}\,T_{AP}(T_{mu}\,H_{D}\,R_{AP})^{-1}$$

$$\boxed{Y= R_{mu}\,H_{D}\,\underbrace{T_{AP}\,R^{-1}_{AP}}\,H^{-1}_{D}\,T^{-1}_{mu}}$$

diagonality could
be spoiled resulting
in interference

End-to-End Reciprocity

Conclusions

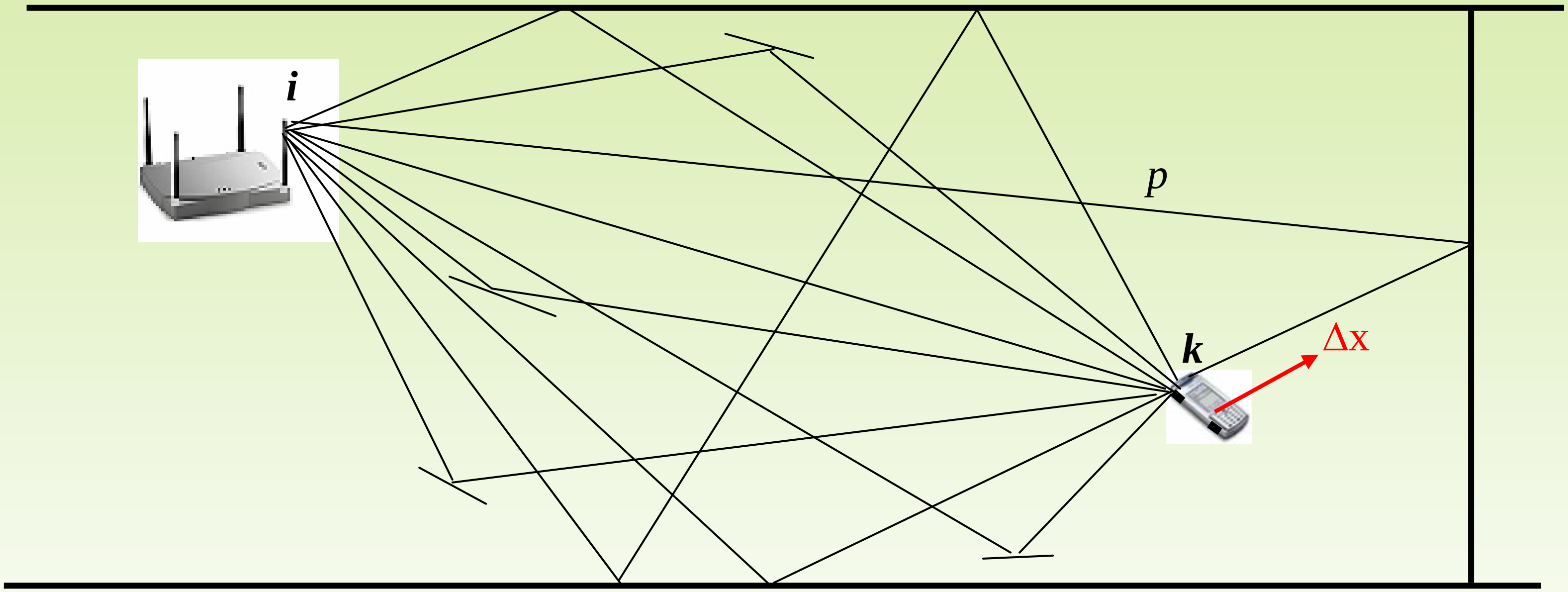
- AP Tx/Rx mismatch could result in significant performance degradation
- MU Tx/Rx mismatch has relatively small effect on performance
- Calibration in the AP is *necessary* and *sufficient*

Mobility Effects

- Motions of mobiles change the channel matrix
- Since the packet length is very short, the change of channel matrix is supposed to be negligible. Estimation of channel matrix using header (preamble) only is considered as the channel responses for decoding the entire packet.
- The SINR results are much worse than what were expected originally. The reason is: when the condition number of H is very high, H^{-1} is very sensitive to small changes of H.
- SINR for some multiplexing channels may be less than 10dB even when the displacement of a Tx or Rx is less than 2% of the wavelength
- Better estimation of channel matrix is required.

Effect of Mobilty

Statistical Model

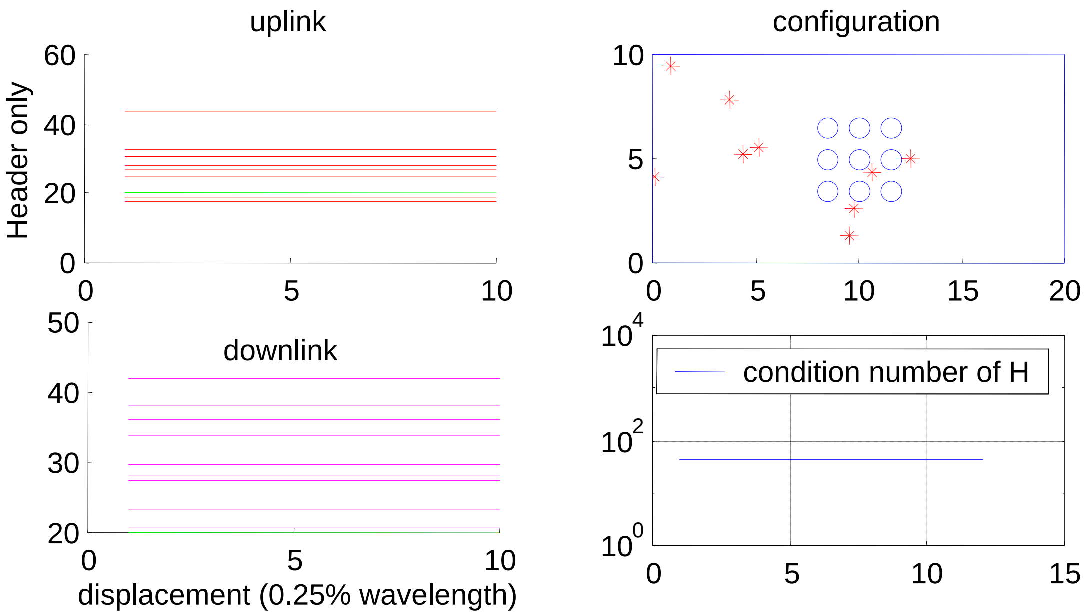


$$h_{ik} = \sum_p a_p e^{-j\theta_p} \longrightarrow \tilde{h}_{ik} = \sum_p a_p e^{-j(\theta_p + (2\pi/\lambda)\Delta x \cos\varphi_p)}$$

θ_p, φ_p iid uniformly $[0,2\pi]$

9 Mobiles; None Move

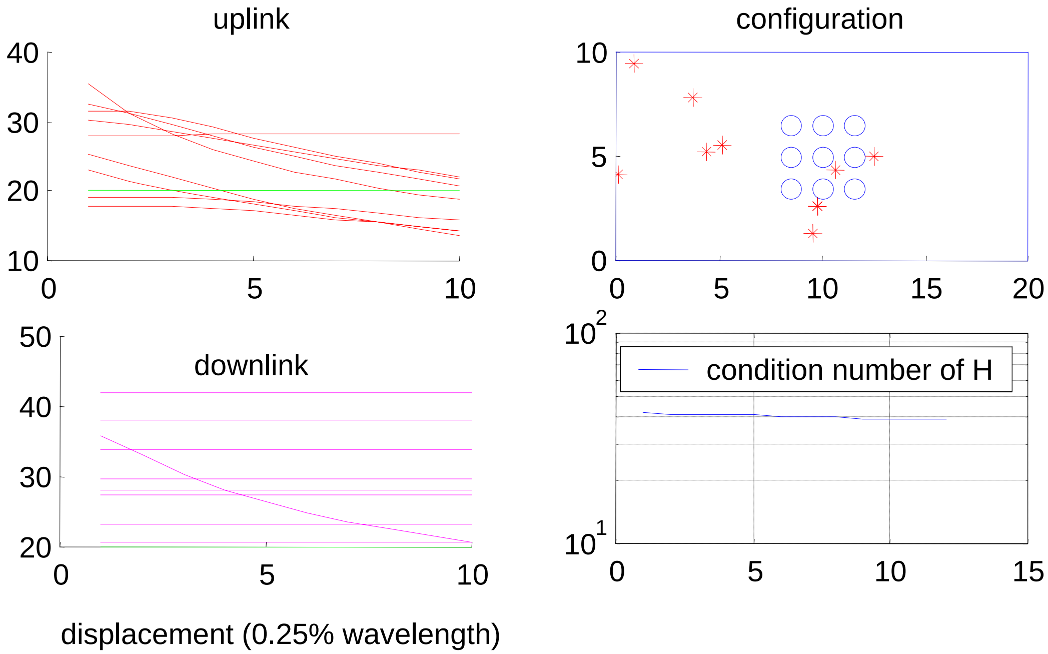
Input SNR=20dB



SINR’s constants and finite (imperfect channel estimation due to noise)

9 Mobiles; 1 Moves

Input SNR=20dB



-Uplink: ALL SINR's are deteriorating as the displacement increases except that for the moving mobile

-Downlink: ALL SINR's remain unchanged except that for the moving mobile

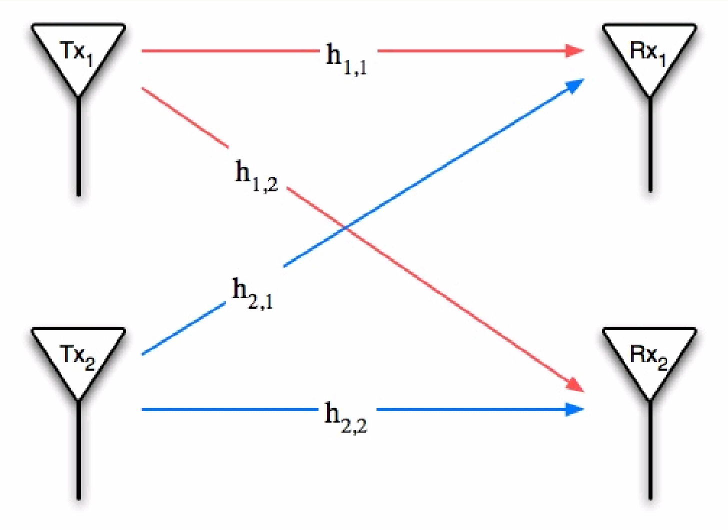
Applications

- WLAN – WiFi 802.11n
- Mesh Networks (e.g., MuniWireless)
- WMAN – WiMAX 802.16e
- 4G
- RFID
- Digital Home

High Throughput WiFi - 802.11n

General

- Using the *space* dimension (MIMO) to boost data rates up to 600 Mbps through multiple antennas and signal processing
- Target applications include: large files backup, HD streams, online interactive gaming, home entertainment, etc.
- Backwards compatible with 802.11a/b/g



High Throughput WiFi - 802.11n

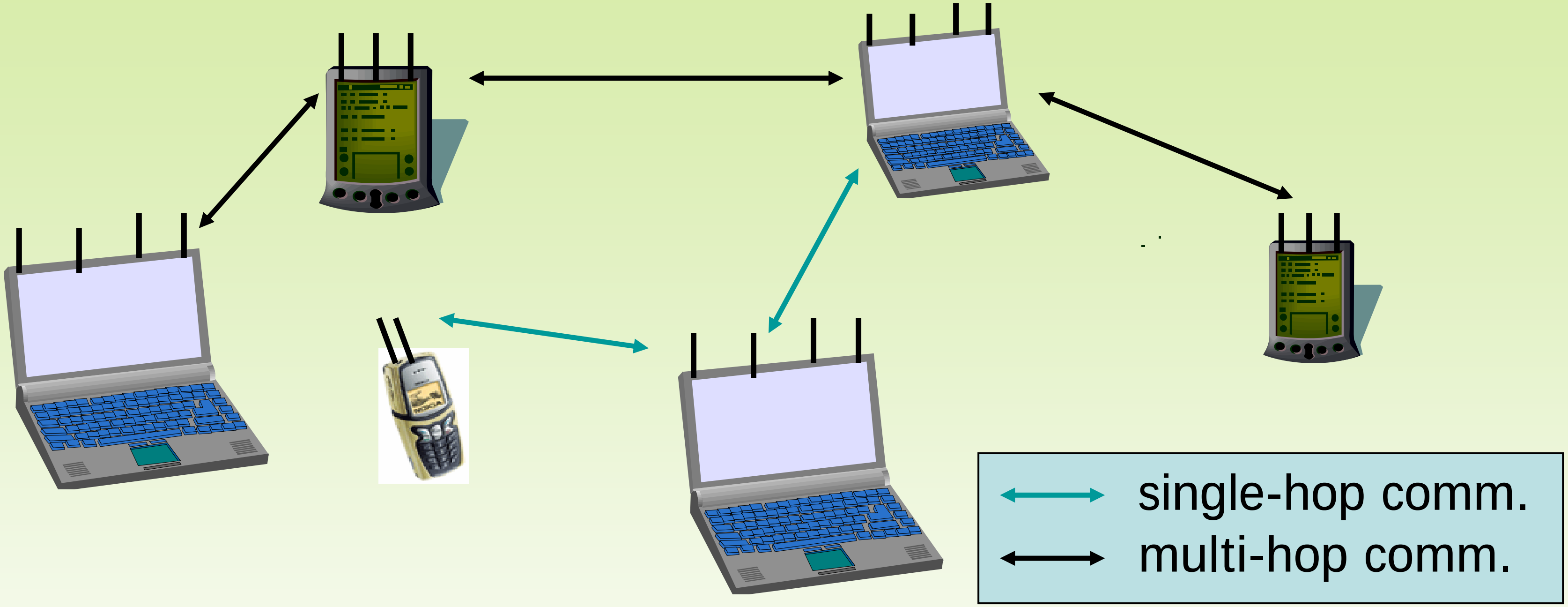
Technology Overview

- 2.4 GHz and 5.8 GHz unlicensed bands
- Channel bandwidth of 20 MHz and 40 MHz
- Up to 4 spatial streams (e.g., 4x4)
- Current product offerings (pre-N) use only 2 spatial streams with 3Tx / 3Rx in the AP and 2Tx / 3Rx in the mobile supporting up to 300 Mbps
- Spatial diversity, spatial multiplexing, beamforming
- Enhancements in both PHY and MAC (e.g., frame aggregation, block-ACK, space-time coding, power save, green field mode, etc.)

MIMO in MuniWireless

- High capacity (MIMO) cross-links
- WiFi access

MIMO in Ad-Hoc Network



⟷ single-hop comm.

⟷ multi-hop comm.

- A collection of wireless mobile nodes that self-configure to form a network (data rate + range)
- No fixed infrastructure is required
- Any two nodes can communicate with each other
- High capacity link are useful for scalability and multimedia services

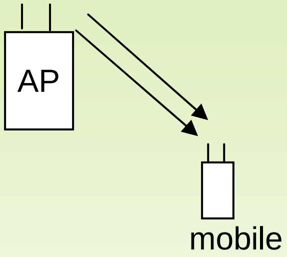
Mobile-WiMAX 802.16e

Technology Overview

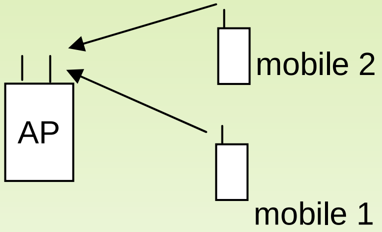
- Non line of site, up to 4-6 mbps per user for a few km
- 2.5 GHz (US) and 3.5 GHz licensed bands
- Channel bandwidth from 1.25 to 20 MHz
- QPSK, 16 QAM and 64 QAM modulation
- OFDMA access (orthogonal uplink)
- TDD for asymmetric traffic and flexible BW allocation
- Advanced Antenna Systems (AAS): Beamforming, spatial diversity, spatial multiplexing using MIMO (2x2)

MIMO in WiMAX

A 2x2 MIMO Configuration in 802.16e



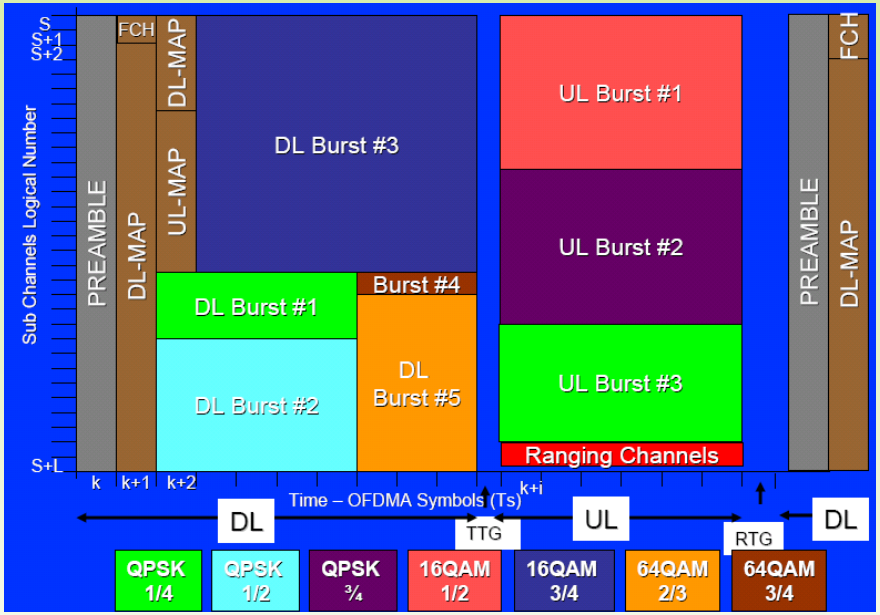
Downlink



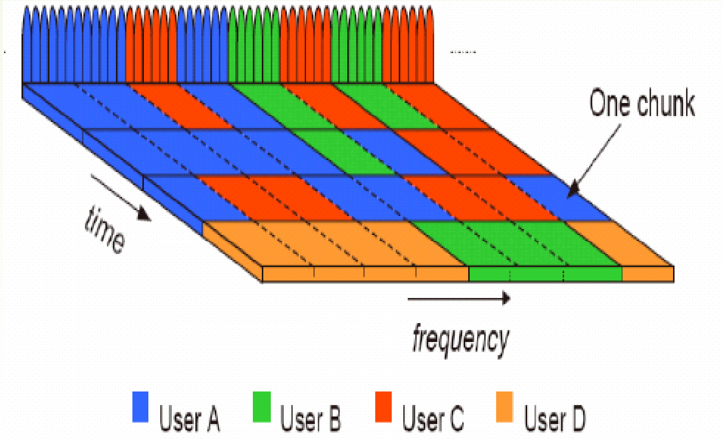
Uplink (collaborative)

- Increasing spectral efficiency (bps/Hz)
- Downlink – higher capacity and user peak rates
- Uplink – higher capacity only

MIMO in WiMAX (cont.)



OFDMA TDD Frame Structure



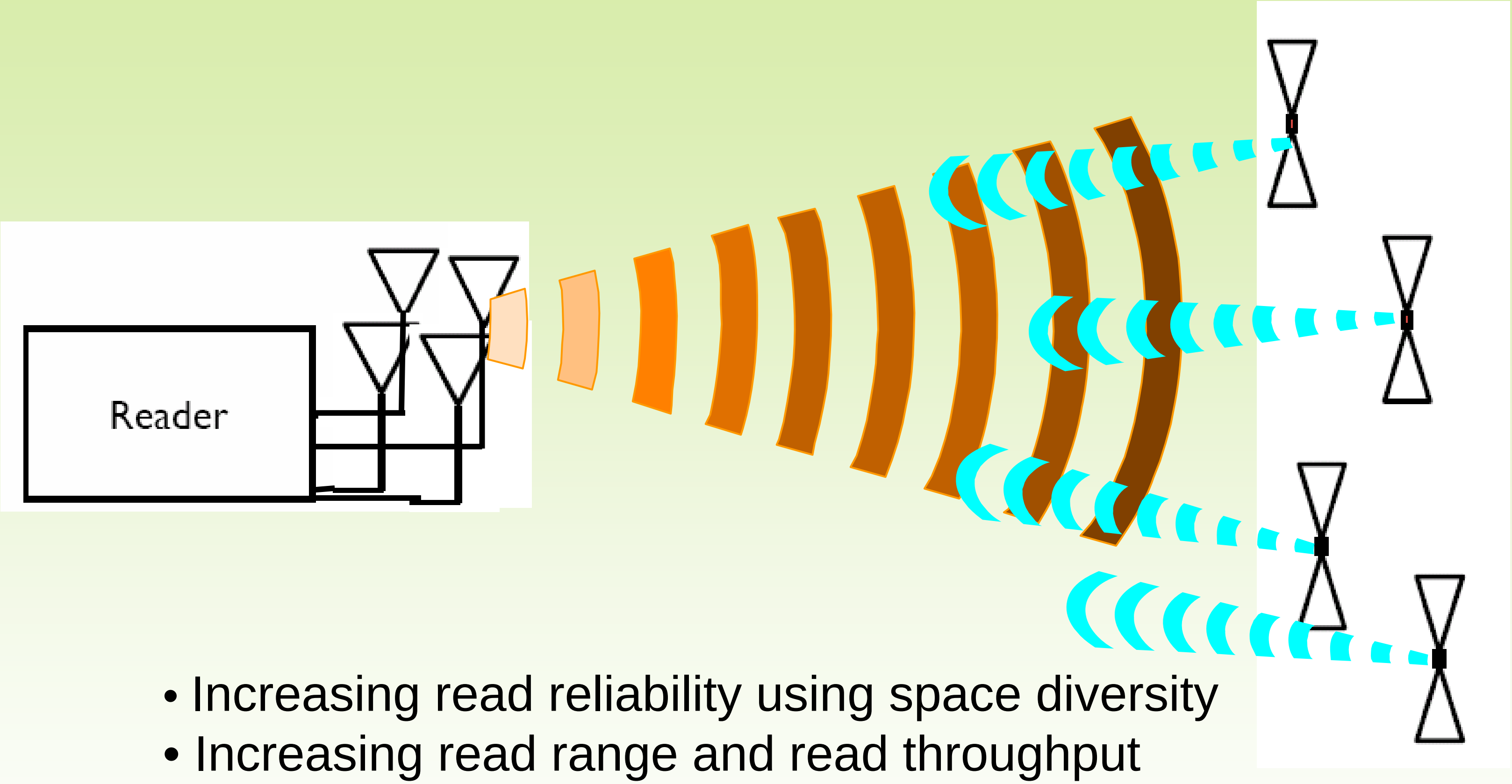
Time/Frequency Multi-User Diversity

MIMO in WiMAX (cont.)

Layer 3 Throughput Comparison

technology	***throughput per sector/per channel***		
	downlink		uplink
	1 Rx	2 Rx	2 Rx
1XEVDO rev A 2.5 MHz	0.9 Mbps	1.3 Mbps	0.5 Mbps
HSPA 10 MHz	2.4 Mbps	3.6 Mbps	1.5 Mbps
Mobile WiMax 2:1 DL/UL 2x2 -10 MHz	NA	14 Mbps	5.3 Mbps

MIMO in RFID



- Increasing read reliability using space diversity
- Increasing read range and read throughput
- Full channel information at the reader comes for free (tag backscatter)

.

MIMO Enables the Digital Home

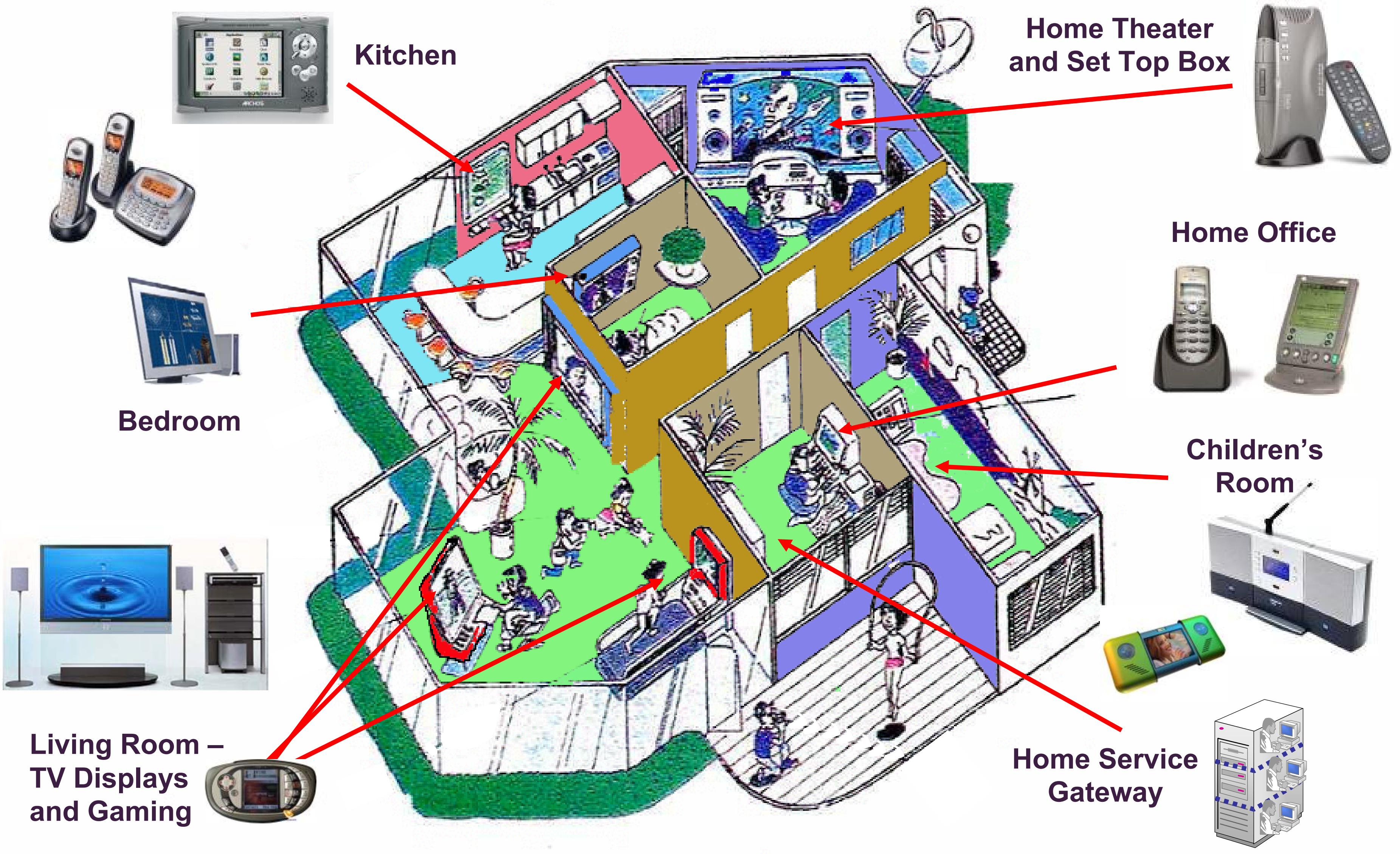
MIMO delivers whole home coverage with the speed and reliability to stream multimedia applications

MIMO can reliably connect cabled video devices, computer networking devices, broadband connections, phone lines, music, storage devices, etc.

MIMO is interoperable and can leverage the installed based of 802.11 wireless that is already deployed: computers, PDAs, handheld gaming devices, cameras, VoIP Phones, etc.

The Ultimate Digital Home

WiFi 802.11n



Kitchen

Home Theater and Set Top Box

Bedroom

Home Office

Children's Room

Living Room – TV Displays and Gaming

Home Service Gateway

Questions ?

Contact Information:

jacob.sharony@stonybrook.edu

Thank You!

Introduction to MIMO

Application Note

Products:

- R&S®SMU200A
- R&S®AMU200A
- R&S®SMATE200A
- R&S®TS8980
- R&S®TS8970
- R&S®TS8975
- R&S®CMW270
- R&S®CMW500
- R&S®FSQ
- R&S®FSG
- R&S®FSV

Modern radio communication systems have to provide higher and higher data rates. As conventional methods like using more bandwidth or higher order modulation types are limited, new methods of using the transmission channel have to be used. Multiple antenna systems (Multiple Input, Multiple Output – MIMO) gives a significant enhancement to data rate and channel capacity.

This application note gives an introduction to basic MIMO concepts and terminology and explains how MIMO is implemented in different radio communications standards.

Application Note

Schindler, Schulz

07.2009-1MA142_0e

Table of Contents

1 Introduction

All radiocommunications systems, regardless of whether mobile radio networks like 3GPP UMTS or wireless radio networks like WLAN, must continually provide higher data rates. In addition to conventional methods, such as introducing higher modulation types or providing larger bandwidths, this is also being achieved by using multiple antenna systems (Multiple Input, Multiple Output – MIMO).
This application note gives an introduction to basic MIMO concepts and terminology and explains how MIMO is implemented in the different radiocommunications standards. The solutions offered by Rohde & Schwarz are presented in the conclusion. The MIMO terminology refers to the channel, thus the transmitter is the channel input and the receiver the channel output.

2 MIMO

Several different diversity modes are used to make radiocommunications more robust, even with varying channels. These include time diversity (different timeslots and channel coding), frequency diversity (different channels, spread spectrum, and OFDM), and also spatial diversity. Spatial diversity requires the use of multiple antennas at the transmitter or the receiver end. Multiple antenna systems are typically known as Multiple Input, Multiple Output systems (MIMO). Multiple antenna technology can also be used to increase the data rate (spatial multiplexing) instead of improving robustness.
In practice, both methods are used separately or in combination, depending on the channel condition.

2.1 Conventional Radio System (SISO)

Conventional systems use one transmit and one receive antenna. In MIMO terminology, this is called Single Input, Single Output (SISO) (Figure 1).

Figure 1: SISO antenna configuration

Shannon-Hartley theorem

According to Shannon, the capacity C of a radio channel is dependent on bandwidth B and the signal-to-noise ratio S/N. The following applies to a SISO system:

$$C = B \log_2 \left(1 + \frac{S}{N} \right)$$

Formula 1: Shannon-Hartley theorem for SISO

2.2 Multiple Antenna Systems

A MIMO system typically consists of *m* transmit and *n* receive antennas (Figure 2). By using the same channel, every antenna receives not only the direct components intended for it, but also the indirect components intended for the other antennas. A time-independent, narrowband channel is assumed. The direct connection from antenna 1 to 1 is specified with h_{11}, etc., while the indirect connection from antenna 1 to 2 is identified as cross component h_{21}, etc. From this is obtained transmission matrix **H** with the dimensions ***n x m***.

$$H = \begin{bmatrix} h_{11} & h_{12} & h_{..} & h_{1m} \\ h_{21} & h_{22} & h_{..} & h_{2m} \\ h_{..} & h_{..} & h_{..} & h_{.m} \\ h_{n1} & h_{n2} & h_{n.} & h_{nm} \end{bmatrix}$$

Formula2: Matrix H

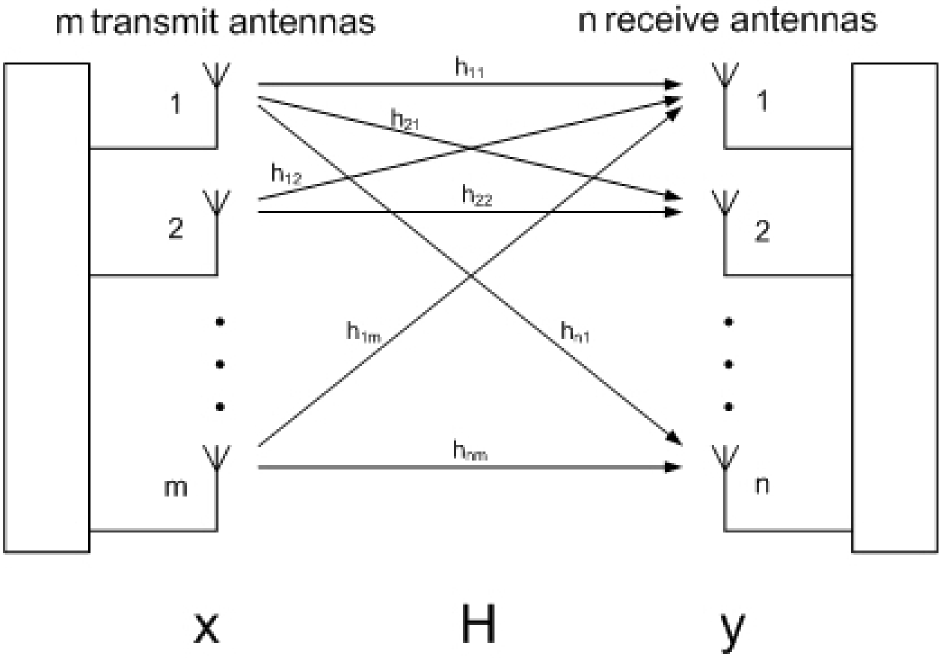


Figure 2: General MIMO

The following transmission formula results from receive vector **y**, transmit vector **x**, and noise **n**:

$$y = \mathbf{H}x + n\ .$$

Formula 3: MIMO transmission

Data to be transmitted is divided into independent data streams. The number of streams M is always less than or equal to the number of antennas; in the case of asymmetrical (m ≠ n) antenna constellations, it is always smaller or equal the minimum number of antennas. For example, a 4x4 system could be used to transmit four or fewer streams, while a 3x2 system could transmit two or fewer streams. Theoretically, the capacity C increases linearly with the number of streams M.

$$C = M\,B\,\log_2\left(1 + \frac{S}{N}\right)$$

Formula 4: Shannon-Hartley theorem for MIMO

Single User MIMO (SU-MIMO)

When the data rate is to be increased for a single UE, this is called Single User MIMO (SU-MIMO)

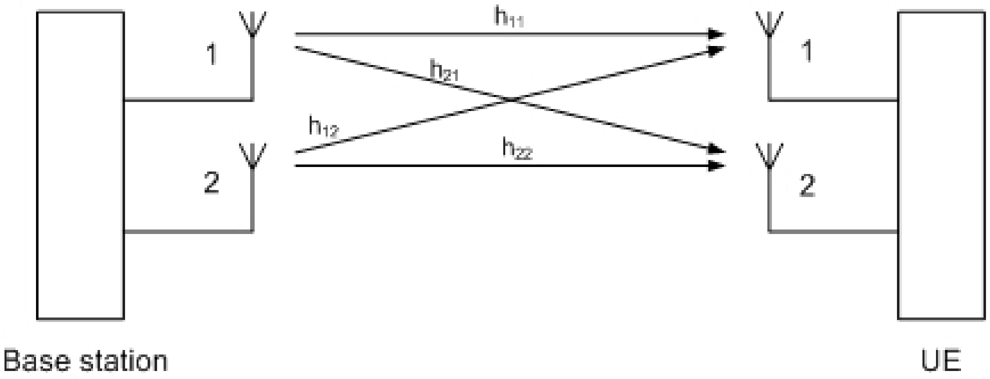


Figure 3: SU-MIMO

Multi User MIMO (MU-MIMO)

When the individual streams are assigned to various users, this is called Multi User MIMO (MU-MIMO). This mode is particularly useful in the uplink because the complexity on the UE side can be kept at a minimum by using only one transmit antenna. This is also called 'collaborative MIMO'.

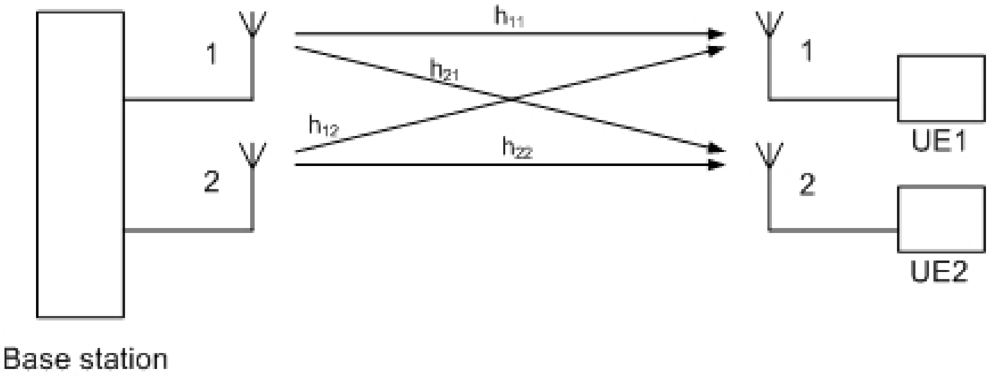


Figure 4: MU-MIMO

Cyclic delay diversity (CDD)

CDD introduces virtual echoes into OFDM-based systems. This increases the frequency selectivity at the receiver. In the case of CDD, the signals are transmitted by the individual antennas with a time delay. Because CDD introduces additional diversity components, it is particularly useful as an addition to spatial multiplexing.

2.2.1 Spatial Diversity

The purpose of spatial diversity is to make the transmission more robust. There is no increase in the data rate. This mode uses redundant data on different paths.

2.2.1.1 RX Diversity

RX diversity uses more antennas on the receiver side than on the transmitter side. The simplest scenario consists of two RX and one TX antenna (SIMO, 1x2).

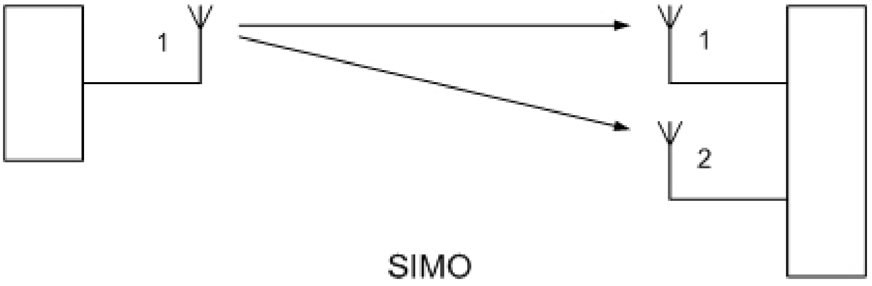


Figure 5: SIMO antenna configuration

Because special coding methods are not needed, this scenario is very easy to implement. Only two RF paths are needed for the receiver.

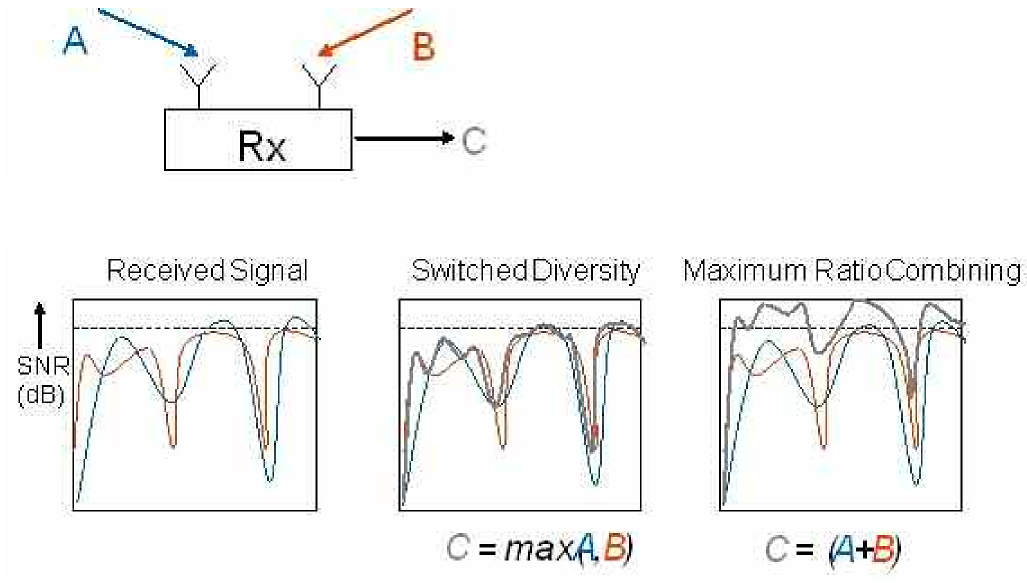


Figure 6: RX diversity

Because of the different transmission paths, the receiver sees two differently faded signals. By using the appropriate method in the receiver, the signal-to-noise ratio can now be increased. Switched diversity always uses the stronger signal, while maximum ratio combining uses the sum signal from the two signals (see Figure 6).

2.2.1.2 TX Diversity

When there are more TX than RX antennas, this is called TX diversity. The simplest scenario uses two TX and one RX antenna (MISO, 2x1).

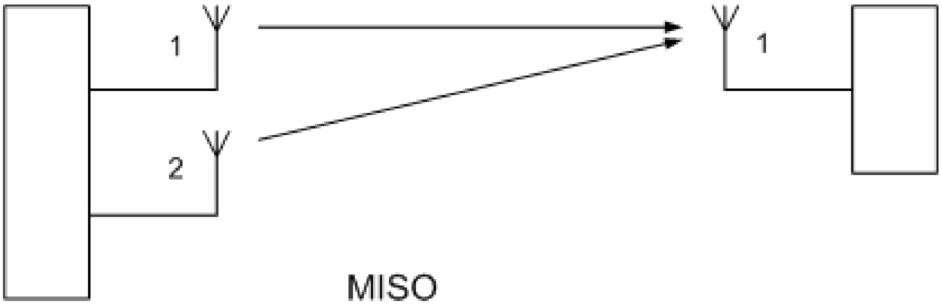


Figure 7: MISO antenna configuration

In this case, the same data is transmitted redundantly over two antennas. This method has the advantage that the multiple antennas and redundancy coding is moved from the mobile UE to the base station, where these technologies are simpler and cheaper to implement.

To generate a redundant signal, space-time codes are used. Alamouti developed the first codes for two antennas.

Space-time codes additionally improve the performance and make spatial diversity usable. The signal copy is transmitted not only from a different antenna but also at a different time. This delayed transmission is called delayed diversity. Space-time codes combine spatial and temporal signal copies as illustrated in Figure 8. The signals s_1 and s_2 are multiplexed in two data chains. After that, a signal replication is added to create the Alamouti space-time block code.

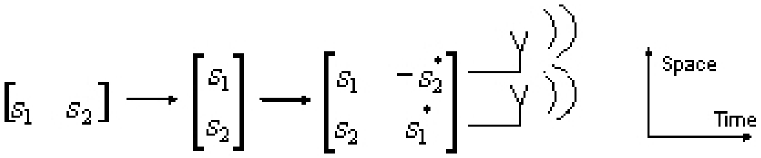


Figure 8: Alamouti coding

Additional pseudo-Alamouti codes were developed for multiple antennas [14][15].

The coding can also be handled in the frequency domain. This is called Space-frequency coding.

2.2.2 Spatial Multiplexing

Spatial multiplexing is not intended to make the transmission more robust; rather it increases the data rate. To do this, data is divided into separate streams; the streams are transmitted independently via separate antennas.

Because MIMO transmits via the same channel, transmissions using cross components not equal to 0 will mutually influence one another.

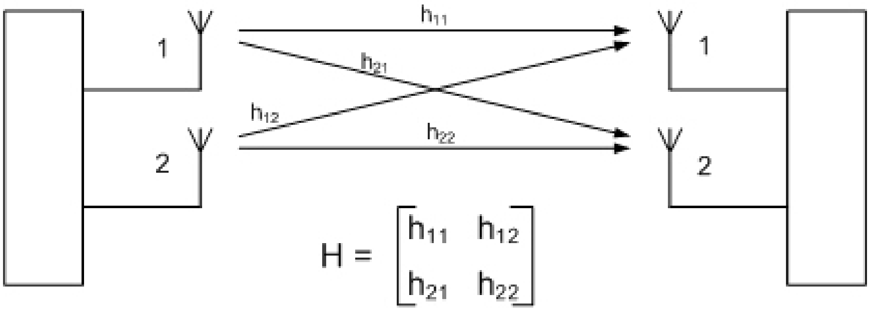


Figure 9: MIMO 2x2 antenna configuration

If transmission matrix H is known, the cross components can be calculated on the receiver.

In the open-loop method, the transmission includes special sections that are also known to the receiver. The receiver can perform a channel estimation.
In the closed-loop method, the receiver reports the channel status to the transmitter via a special feedback channel. This makes it possible to respond to changing circumstances.

2.2.3 Beamforming

Antenna technologies are the key in increasing network capacity. It started with sectorized antennas. These antennas illuminate 60 or 120 degrees and operate as one cell. In GSM, the capacity can be tripled, by 120 degree antennas. Adaptive antenna arrays intensify spatial multiplexing using narrow beams. Smart antennas belong to adaptive antenna arrays but differ in their smart direction of arrival (DoA) estimation. Smart antennas can form a user-specific beam. Optional feedback can reduce complexity of the array system.
Beamforming is the method used to create the radiation pattern of an antenna array. It can be applied in all antenna array systems as well as MIMO systems.
Smart antennas are divided into two groups:

- Phased array systems (switched beamforming) with a finite number of fixed predefined patterns
- Adaptive array systems (AAS) (adaptive beamforming) with an infinite number of patterns adjusted to the scenario in realtime

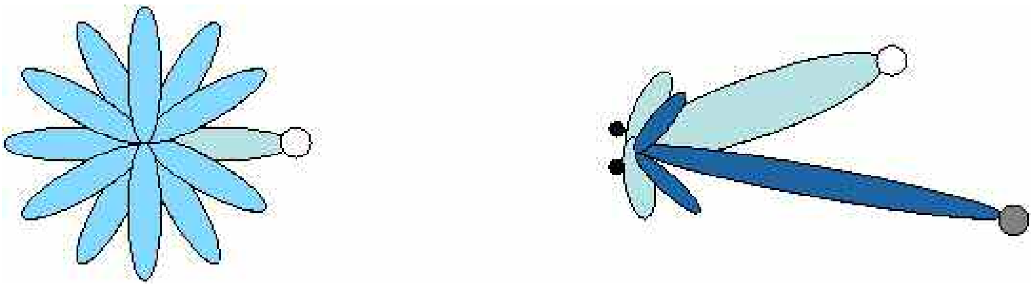


Figure 10: Switched beamformer and adaptive beamformer

Switched beamformers electrically calculate the DoA and switch on the fixed beam. The user only has the optimum signal strength along the center of the beam. The adaptive beamformer deals with that problem and adjusts the beam in realtime to the moving UE. The complexity and the cost of such a system is higher than the first type.

3 MIMO in Radio Communications Systems

Various mobile radio and network standards use MIMO. This section provides a brief overview of the various implementations. In principle, all standards use TX diversity and spatial multiplexing.
More detailed explanations for the individual standards are provided in the dedicated sections.

3.1 3GPP UMTS

The 3GPP mobile radio standard (UMTS) has undergone numerous phases of development. Starting with WCDMA, various data acceleration methods have been introduced, including HSDPA and HSUPA. The newest releases cover HSPA+ and Long Term Evolution (LTE).

3.1.1 HSPA+ (3GPP Release 7/8)

A transmit diversity mode had already been introduced in Release 99 (WCDMA). Release 7 of the 3GPP specification (HSPA+) expanded this approach to MIMO and again increased the data rate with respect to Release 6 (HSDPA). The introduction of 64QAM modulation and MIMO in the downlink makes a peak data rate of 28 Mbps (Rel. 7) possible. In Rel. 7 MIMO and 64QAM can not be used simultaneously. Since Rel. 8 the simultaneous use is possible which leads to peak data rates up to 42 Mbps. Uplink MIMO is not provided.

MIMO was introduced in the form of a double transmit antenna array (D-TxAA) for the high speed downlink shared channel (HS-DSCH).

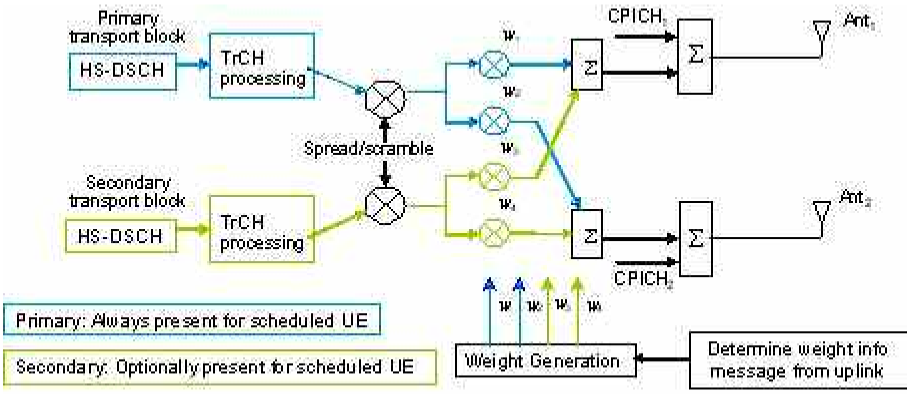


Figure 11: HSPA+ MIMO

With D-TxAA, two independent data streams can be transmitted simultaneously over the radio channel using the same WCDMA channelization codes. The two data streams are indicated with blue and green color in Figure 11. After spreading and scrambling, precoding based on weight factors is applied to optimize the signal for transmission over the mobile radio channel. Four precoding weights w1 to w4 are available. The first stream is multiplied with w_1 and w_2, the second stream is multiplied with w_3 and w_4. The weights can take the following values:

$$w_3 = w_1 = 1/\sqrt{2}$$

$$w_4 = -w_2$$

$$w_2 \in \left\{ \frac{1+j}{2},\ \frac{1-j}{2},\ \frac{-1+j}{2},\ \frac{-1-j}{2} \right\}$$

Formula 5

Note that w_1 is always fixed, and only w_2 can be selected by the base station. Weights w_3 and w_4 are automatically derived from w_1 and w_2, because they have to be orthogonal. The base station selects the optimum weight factors based on proposals reported by the UE in the uplink.
In addition to the use of MIMO in HS-DSCH, the weight information must be transmitted to the UE via the HS-SCCH control channel. Although MIMO is not provided in the uplink, MIMO-relevant information still does have to be transmitted in the uplink. The UE sends a precoding control indication (PCI) and a channel quality indication (CQI) in the HS-DPCCH, which allows the base station to adapt the modulation, coding scheme, and precoding weight to the channel conditions.

For more information on HSPA+, refer to [7].

3.1.2 LTE (3GPP Release 8)

UMTS Long Term Evolution (LTE) was introduced in 3GPP Release 8. The objective is a high data rate, low latency and packet optimized radio access technology. LTE is also referred to as E-UTRA (Evolved UMTS Terrestrial Radio Access) or E-UTRAN (Evolved UMTS Terrestrial Radio Access Network).

The basic concept for LTE in downlink is OFDMA (Uplink: SC-FDMA), while MIMO technologies are an integral part of LTE. Modulation modes are QPSK, 16QAM, and 64QAM. Peak data rates of up to 300 Mbps (4x4 MIMO) and up to 150 Mbps (2x2 MIMO) in the downlink and up to 75 Mbps in the uplink are specified.

For an introduction to LTE, refer to [2] [3] [4]. For more information on MIMO in LTE, refer to [6].

Downlink

The following transmission modes are possible in LTE:

- Single antenna transmission, no MIMO
- Transmit diversity
- Open-loop spatial multiplexing, no UE feedback required
- Closed-loop spatial multiplexing, UE feedback required
- Multi-user MIMO (more than one UE is assigned to the same resource block)
- Closed-loop precoding for rank=1 (i.e., no spatial multiplexing, but precoding is used)
- Beamforming

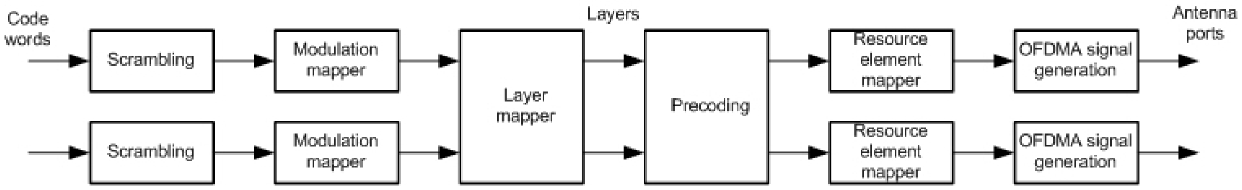


Figure 12: LTE downlink

In LTE, one or two code words are mapped to one to four layers ("layer mapper" block). To achieve multiplexing, a precoding is carried out ("precoding" block). In this process, the layers are multiplied by a precoding matrix **W** from a defined code book and distributed to the various antennas. This precoding is known to both the transmitter and the receiver. In the specification, code books are defined for one, two, and four antennas, as well as for spatial multiplexing (with and without CDD) and transmit diversity. Table 1 shows the code book for spatial multiplexing with two antennas as an example. Code books for four antennas are also defined.

Spatial multiplexing LTE		
Code book index	**Number of layers** υ	
	1	**2**
0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$
1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 1\\j & -j\end{bmatrix}$
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	-

Table 1: LTE precoding matrix for a maximum of two layers

Uplink

In order to keep the complexity low at the UE end, MU-MIMO is used in the uplink. To do this, multiple UEs, each with only one Tx antenna, use the same channel.

3.2 WiMAX^{TM} (802.16e-2005)

WiMAX^{TM} promises a peak data rate of 74 Mbps at a bandwidth of up to 20 MHz. Modulation types are QPSK, 16QAM, and 64QAM.

Downlink

The WiMAX^{TM} 802.16e-2005 standard specifies MIMO in WirelessMAN-OFDMA mode. This standard defines a large number of different matrices for coding and distributing to antennas. In principle, two, three or four TX antennas are possible. For all modes, the matrices A, B, and C are available. In the "STC encoder" block, the streams are multiplied by the selected matrix and mapped to the antennas (Figure 13).

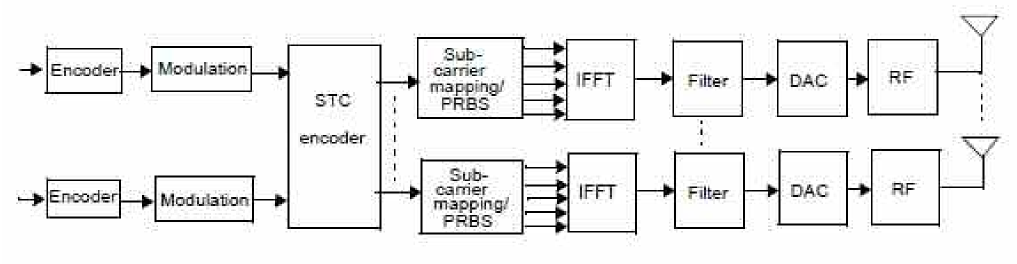


Figure 13: WiMAX^{TM} downlink

In actual systems typically only matrices A and B are implemented:

$$A = \begin{bmatrix} S_1 & -S^*_2 \\ S_2 & S^*_1 \end{bmatrix} \qquad B = \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}$$

Formula 6: WiMAX^{TM} matrices A and B for two antennas

Matrix A corresponds to TX diversity, while matrix B corresponds to spatial multiplexing (known in the literature as "True MIMO").

Corresponding matrices also exist for three and four antennas.

Uplink

In Uplink-MIMO only different pilot patterns are used. Coding and mapping is the same like in non-MIMO case. In addition to single user MIMO (SU-MIMO) two different user can use the same channel (collaborative MIMO, MU-MIMO).

For more information on WiMAX^{TM}, refer to [10] [11].

3.3 WLAN (802.11n)

WLAN as defined by the 802.11n standard promises a peak data rate of up to 600 Mbps at a bandwidth of 40 MHz. Modulation types are BPSK,QPSK,16QAM, and 64QAM. It is backward compatible with the previous standards 802.11 a/b/g.
With up to four streams, it supports up to a maximum of four antennas.

For more information on WLAN, refer to [12] [13].

WLAN differentiates between spatial streams (SS) and space-time streams (STS). If $N_{SS} < N_{STS}$, then a space-time block encoder ("STBC") distributes the SS to the STS and adds transmit diversity by means of coding (Downlink block diagram Figure 14).

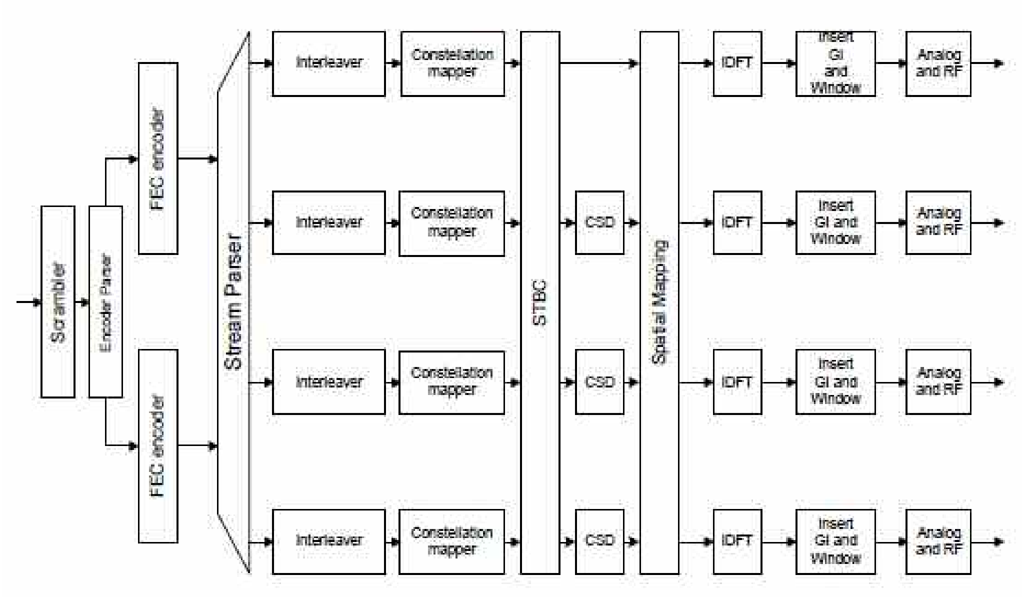


Figure 14: WLAN downlink

Figure 15 shows the matrix for $N_{SS} = 1$ and $N_{STS} = 2$ as an example.

$$\begin{bmatrix} d_i & d_{i+1} \\ -d^*_{i+1} & d^*_i \end{bmatrix}$$

Figure 15: Coding for SS -> STS ($N_{SS} = 1$, $N_{STS} = 2$)

In the "spatial Mapping" block, the STS is mapped to the transmit chains (N_{TX}). Three different methods are provided:

- Direct mapping
  - 1-to-1 mapping from STS to TC.
- Spatial expansion
  - Additional multiplication with a matrix. Figure 16 gives an example of two STS and three TX antennas.

$$\sqrt{\frac{2}{3}}\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \end{bmatrix}$$

Figure 16: Example matrix for two STS and three TX

- Beamforming
  - Additional multiplication with a steering vector

3.4 Outlook

Future standards will continue to use MIMO technology. At present, the following standards with MIMO are being worked on:

- LTE Advanced

The goal is to provide 1 Gbps at 100 MHz bandwidth in downlink direction.

- 1xEV-DO Rev. C

The goal is to provide 18 Mbps at 1.25 MHz bandwidth in forward link.

- WiMAX^{TM} 802.16m

The goal is to provide 300 Mbps at 20 MHz bandwidth in downlink direction.

4 Rohde & Schwarz Solutions

Rohde & Schwarz offers various instruments and systems for the individual radio communications standards that use MIMO.
Signal generators are able to perform receiver test in MIMO conditions for up- and downlink in non-signaling. Signal analyzers are used to test the transmitter side. Mobile radio testers provide additionally signaling tests for RF testing or protocol testing. RF test systems provide full RF conformance tests.

4.1 Signal Generators

SMU200A vector signal generator
The UE receiver tests can be performed using SMU signal generators from Rohde & Schwarz. The SMU can generate the individual antennas for all MIMO standards (802.11n, 802.16e-2005, and 3GPP Rel. 7 and Rel. 8).

In addition, the SMU performs the channel simulation (MIMO), whereby the individual correlations can be modified. In addition, the SMU realtime fading is available with predefined profiles for all standards. AWGN can be added for both channels.

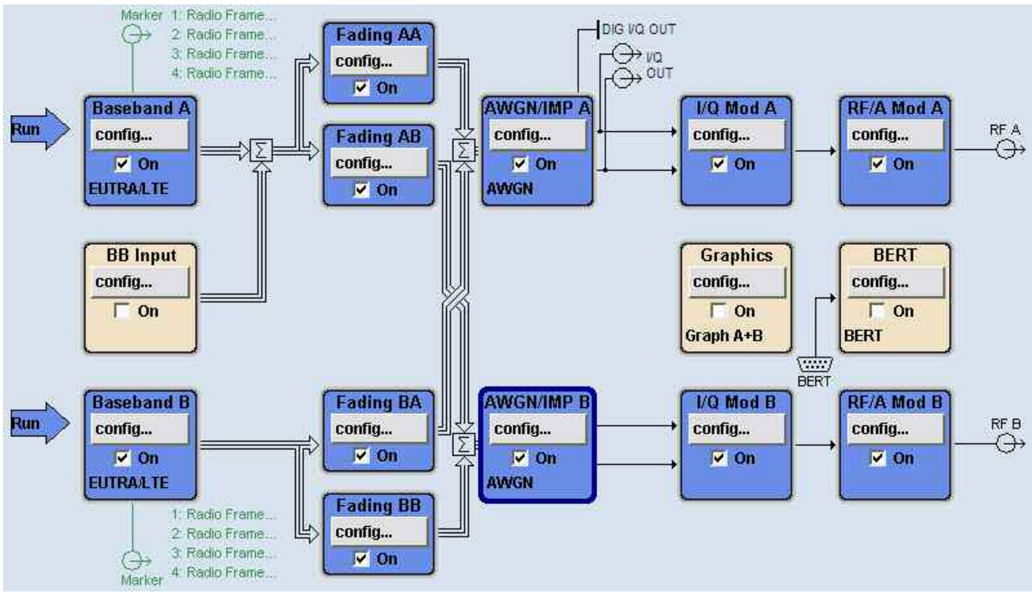


Figure 17: SMU overview

In a single instrument, two antennas can be generated with fading and MIMO for the individual standards. By connecting two instruments together, up to four antennas can be simulated.

By adding the "Phase Coherence" option (SMU-B90), precise phase relationships can be ensured for up to four antennas for beamforming.

AMU200A baseband signal generator and fading simulator

In addition to the baseband generation of various radiocommunications standards, the AMU provides MIMO fading via digital inputs/outputs for the CMW as well as for the SMATE. The combination of AMU and SMATE has the same functionality like a two channel SMU but provides additionally full frequency range up to 6 GHz on both channels.

4.2 Signal Analyzers

For the transmitter test, the FSQ, FSG, and FSV signal/spectrum analyzers are available. They can carry out both the SISO measurements for the individual standards as well as most of the MIMO measurements.

In addition to the SISO measurements, a single FSx can also complete certain MIMO measurements, such as TX diversity and special spatial multiplexing modes. By connecting multiple FSx instruments together (maximum four), up to four antennas can be measured or demodulated simultaneously. A lot of the MIMO measurements anyhow can be performed by a single instrument.

4.3 Mobile Radio Testers

CMW500 wideband radio communication tester

The CMW500 wideband radio communication tester is a scalable tester for all stages of UE testing from R&D up to conformance. As an LTE protocol tester, it allows verification of all protocol layers up to the user plane. Signaling test scenarios can be flexibly created via powerful programming interfaces. CMW500 supports MIMO testing as well.

CMW270 WiMAX™ communication tester

The CMW270 is the first all-in-one test solution for WiMAX™ mobile stations: from realistic mobile station test in full signaling mode to high-speed, low-cost test in non-signaling mode for RF alignment. In addition, the CMW270 supports WiMAX™ MIMO tests, including matrix A and matrix B verification with two antennas.

4.4 Systems

Complex RF test scenarios need to be covered to thoroughly verify MIMO handsets. MIMO also plays an important role in RF conformance testing and UE certification. Rohde & Schwarz provides custom-tailored RF test systems for WiMAX™ and LTE, addressing test applications from R&D up to conformance.

R&S®TS8980 LTE RF test system

The TS8980 supports LTE mobile phone development with fully automatic RF transmitter and receiver tests. It has a modular design and can be configured to support precompliance through conformance tests and is MIMO-ready.

R&S®TS8970 mobile WiMAX™ RCT

The TS8970 RCT was developed in response to a call for proposals from the WiMAX Forum®. The system includes BS and MS radio certification test cases for Mobile WiMAX™, including MIMO tests, adaptive modulation/coding, and beamforming verification. With its scalability and outstanding measurement accuracy, the TS8970 is optimally suited for applications in R&D, quality assurance, precompliance and, of course, for the certification testing of WiMAX™ devices.

R&S®TS8975 WiMAX™ RF preconformance test system

The TS8975 handles most of the tests offered by the TS8970 and is the cost-effective solution for quality assurance and precompliance testing.

5 Appendix

5.1 References

LTE

[1] 3GPP **TS 36.211 V8.4.0**; Physical Channels and Modulation (Release 8)

[2] Rohde & Schwarz: **UMTS Long Term Evolution (LTE) Technology Introduction**, Application Note 1MA111, September 2008

[3] Rohde & Schwarz: **LTE Measurement Guide**, Application Note RSI004, August 2007

[4] Rohde & Schwarz: **RF Chipset Verification for UMTS LTE with SMU200A and FSQ**, Application Note 1MA138, November 2008

[5] Rohde & Schwarz: **E-UTRA Base Station Testing acc. to 3GPP TS 36.141**, Application Note 1MA134, December 2008

[6] Rohde & Schwarz: **LTE Downlink MIMO Verification with R&S®SMU200A and R&S®FSQ**, Application Note 1MA143, June 2009

HSPA+

[7] Rohde & Schwarz: **HSPA+ Technology Introduction**, Application Note 1MA121, March 2008

[8] 3GPP **TS 25.212; Multiplexing and Channel Coding (FDD**), Release 8

WiMAX™

[9] IEEE: **Std 802.16e™-2005 and Std 802.16™-2004/Cor1-2005**, February 2006

[10] Rohde & Schwarz: **WiMAX - General information about the standard 802.16,** Application Note 1MA96, June 2006

[11] Rohde & Schwarz: **WiMAX - Generating and analyzing 802.16-2004 and 802.16e-2005 signals,** Application Note 1MA97, July 2006

WLAN

[12] IEEE: **802.11n™/D8.0: Wireless LAN Medium Access Control** (MAC) and Physical Layer (PHY) specifications, Amendment 5. Enhancements for Higher Throughput, January 2009

[13] Rohde & Schwarz: **WLAN Tests According to Standard 802.11a/b/g,** Application Note 1MA121, July 2004

MIMO

[14] H. Jafarkhani: “Space-Time Coding Theory and Practice”, Cambridge, 2000

[15] M. Jankiraman: “Space-Time Codes and MIMO Systems” Artech House, (2004)

5.2 Additional Information

Please send your comments and suggestions regarding this application note to

TM-Applications@rohde-schwarz.com

Please also visit the technology sites at www.rohde-schwarz.com/technologies/mimo .

6 Ordering Information

Please visit our website www.rohde-schwarz.com and contact your local Rohde & Schwarz sales office for further assistance.

Ordering Information

Vector Signal Generator		
SMU200A	**Vector Signal Generator**	1141.2005.02
SMATE200A	**Vector Signal Generator**	1400.7005.02
AMU100A	**Baseband Signal Generator**	1402.4090.02

Signal Analyzers, Spectrum Analyzers		
FSQ	Up to 3, 8, 26, 31 or 40 GHz	1155.5001.xx
FSG	Up to 8 or 13 GHz	1309.0002.xx
FSV	Up to 3 or 7 GHz	1307.9002.0x

xx stands for the different frequency ranges (e.g. 1155.5001.26 up to 26 GHz)

Radio Communication Tester		
CMW270	**WiMAX^{TM} Communication Tester**	1201.0002K75
CMW500	**Wideband Radio Communication Tester**	1201.0002.50

Systems		
TS8990	**LTE RF Test System**	1510.6002.02
TS8970	**WiMAX^{TM} RCT**	1162.0001.02
TS8975	**WiMAX^{TM} RF Preconformance Test System**	1510.6954.02

Note: Available options are not listed in detail.
Please contact your local Rohde & Schwarz sales office for further assistance.

About Rohde & Schwarz

Rohde & Schwarz is an independent group of companies specializing in electronics. It is a leading supplier of solutions in the fields of test and measurement, broadcasting, radiomonitoring and radiolocation, as well as secure communications. Established 75 years ago, Rohde & Schwarz has a global presence and a dedicated service network in over 70 countries. Company headquarters are in Munich, Germany.

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