MIMO wireless channel emulation

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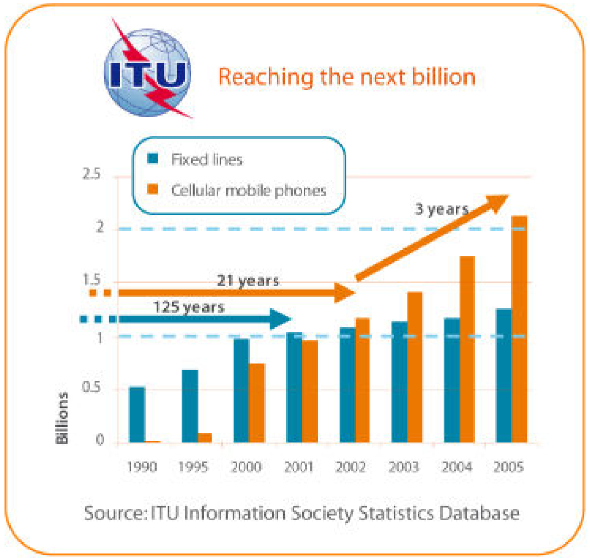
MIMO wireless channel emulation

- Overview:
  - Wireless systems
  - Mobile channel
  - OFDM
  - MIMO
  - IEEE 802.11n
  - Channel models
  - Simulation/Emulation
  - Wireless channel emulation
  - Future work

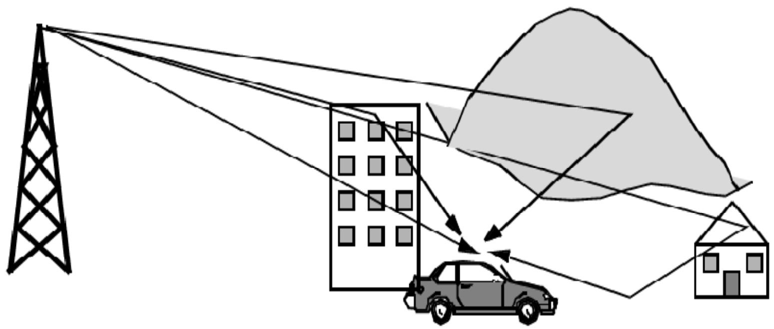
Wireless systems

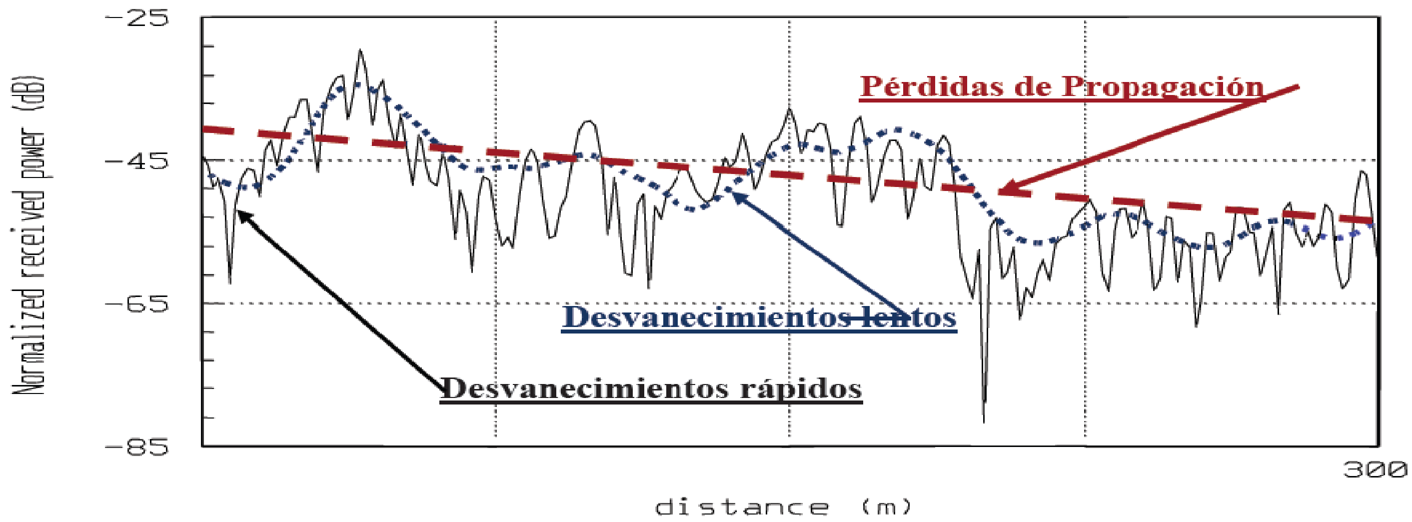
- Why wireless systems?



Mobile channel

- The mobile channel is a complex channel:
  - Multipath, scattering
  - Doppler spectrum
  - Shadowing





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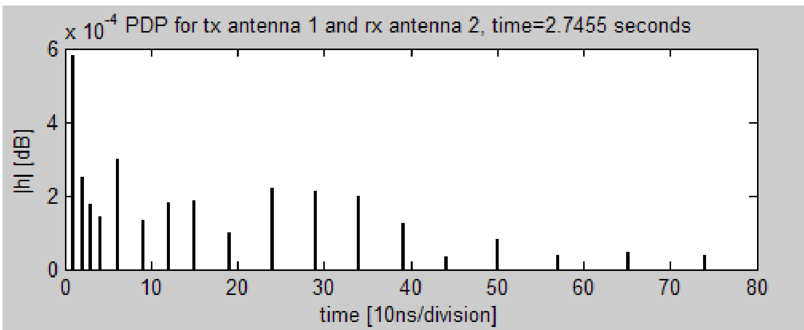
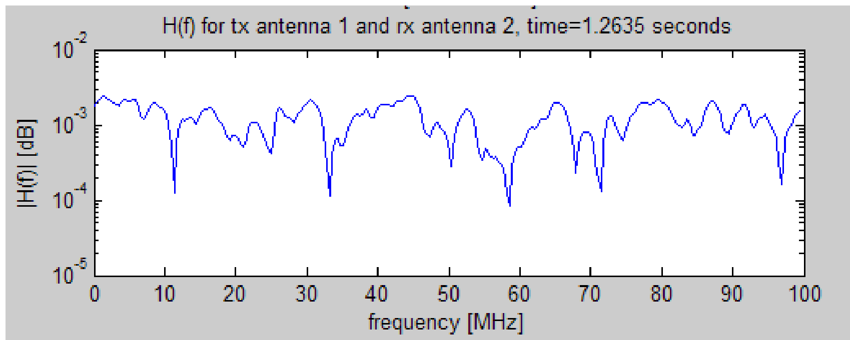
Mobile channel

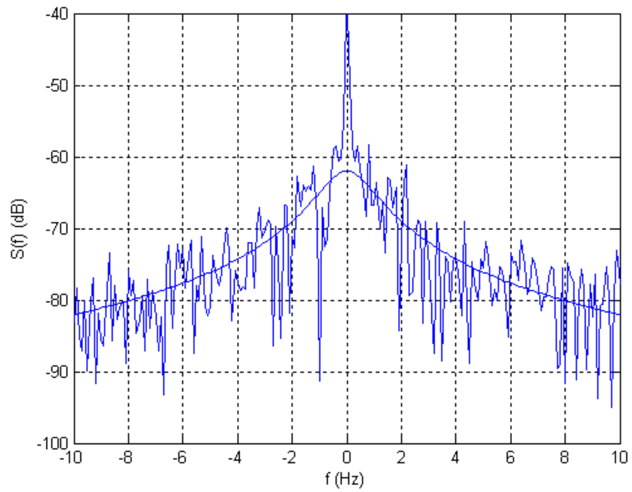
- Multipath →Frequency selective channel
  - Time domain response of the channel consists on various rays having a complex Gaussian distribution
  - Channel frequency response is not flat
  - Coherence bandwidth





Mobile channel

- Doppler spectrum/fading → Time varying channel
  - Change in the carrier frequency due to relative movement between the mobile and the BS
  - $f_D max = v/\lambda$ → Coherence time ≈ $1/f_D max$
  - Fading channel → severe changes in the recieved signal power every coherence time



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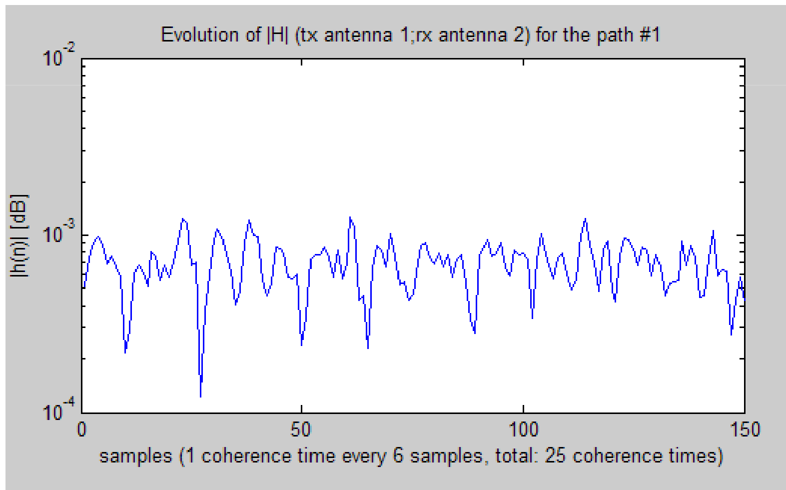


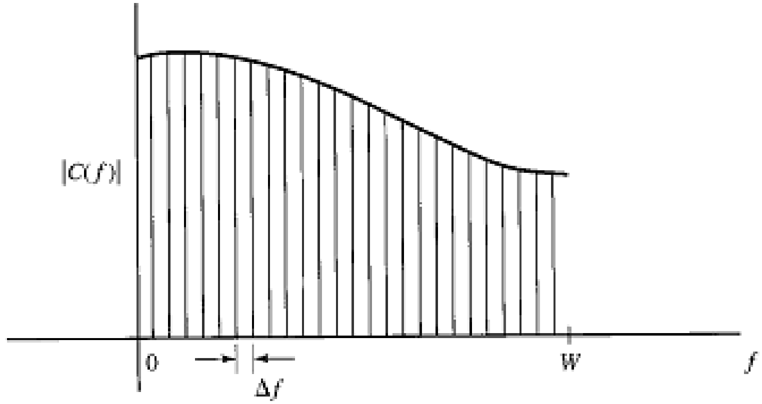
How can we overcome or mitigate the negative effects of the mobile channel?

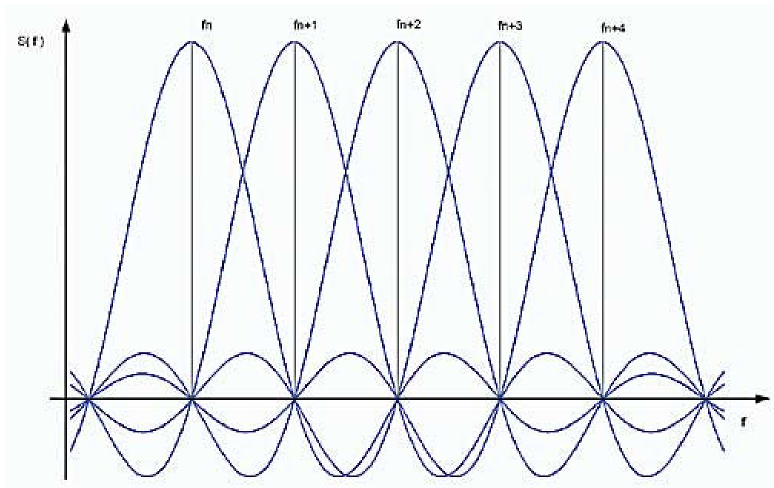
Mobile channel

- New techniques to handle frequency selectivity and fading channels, such as...
  - OFDM
  - MIMO

Orthogonal Frequency-Division Multiplexing (OFDM)

- OFDM converts a wideband signal into multiple narrowband signals placed side by side in the frequency domain.
  - Part of the signal is modulated in each subchannel and transmitted through an almost flat fading channel.
  - If one of the subchannels is affected by a severe fading, simply nothing is transmitted in that subchannel
- This results in a strong resiliency against frequency selective channels





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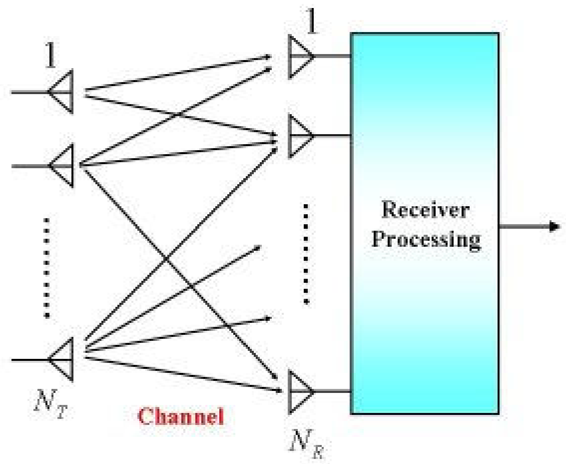
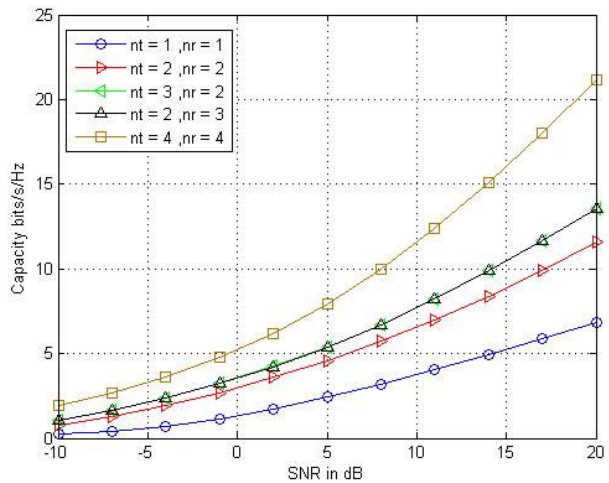
Multiple Input-Multiple Output (MIMO)

- Traditionally multiple antennas placed at the receiver to apply diversity
  - Spatial diversity (each antenna will see a different and independent channel)
  - Significant immunity to fading
  - Results improve as the number of antennas increase

- Even better results are achieved when multiple antennas placed also at the transmitter
  - Total available transmit power is split uniformly across transmit antennas
  - Finite optimum number of tx antennas



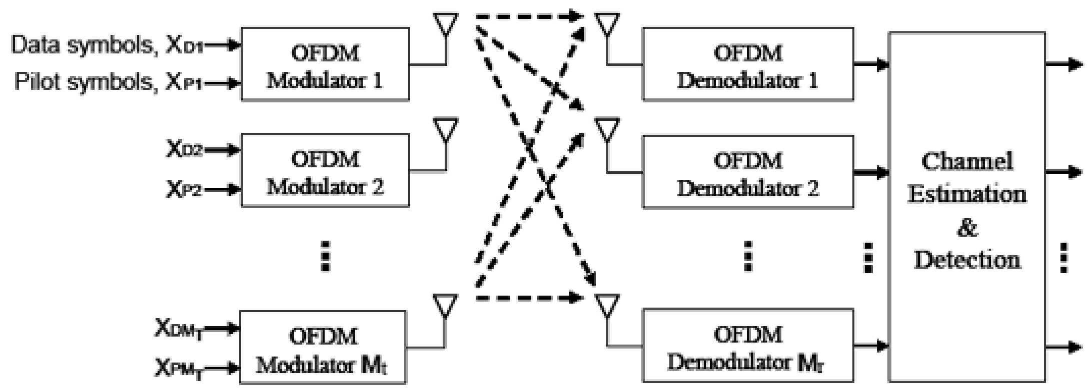


IEEE 802.11n

- OFDM → Resiliency aganist frequency selective channels
- MIMO → Resiliency against fading channels
- Mobile channel is a fading and frequency selective channel

MIMO+OFDM is a good solution for mobile communications

- IEEE 802.11n standard



IEEE 802.11n

- IEEE 802.11n standard
  - WLAN standard improving the Physical Layer and MAC Layer of the traditional WLAN's
  - Indoor MIMO/OFDM system
  - Range ~ 100 meters
  - Maximum bit rate: 600Mbps (3x3 antennas) (typical bit rate 74 Mbps)
  - Carrier frequency: 2.4 or 5 GHz
  - Full compatibilitywith current WLANs

Wireless LAN Throughput by IEEE Standard

IEEE WLAN Standard	Over-the-Air (OTA) Estimates	Media Access Control Layer, Service Access Point (MAC SAP) Estimates
802.11b	11 Mbps	5 Mbps
802.11g	54 Mbps	25 Mbps (when .11b is not present)
802.11a	54 Mbps	25 Mbps
802.11n	**200+ Mbps**	**100 Mbps**

Table 1. Comparison of different 802.11 transfer rates. (Source: Intel Labs)

- Project to develope IEEE 802.11n began in 2003
- Just starting to be in a commercial stage
- Intel has started to add 802.11n in some of its products
- For future commercialization, many tests have to be done

→ Wireless channel on OFDM-MIMO systems simulation

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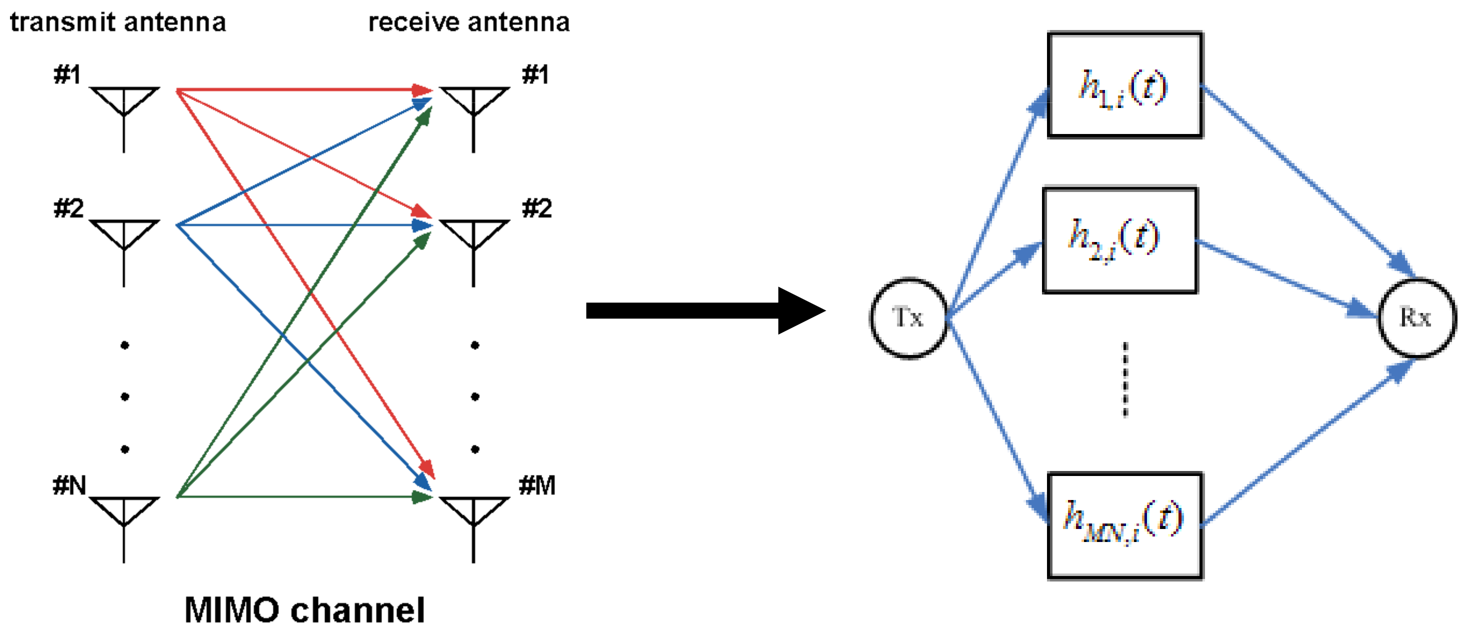
Channel models

- MxN MIMO channel is equivalent to MN impulse responses, each representing a subchannel
- Model a SISO channel, then extend to MIMO (repeat MN times plus adding other artifacts, such as spatial correaltion between antenna elements...)



Channel models

- Statistical Model for Indoor Multipath Propagation (A. Saleh, R. Valenzuela)
  - Channel measurement

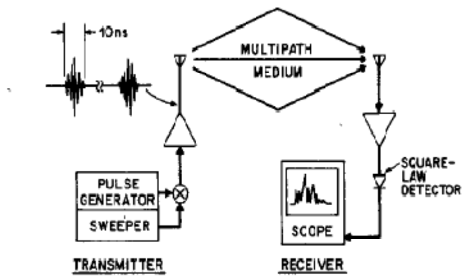
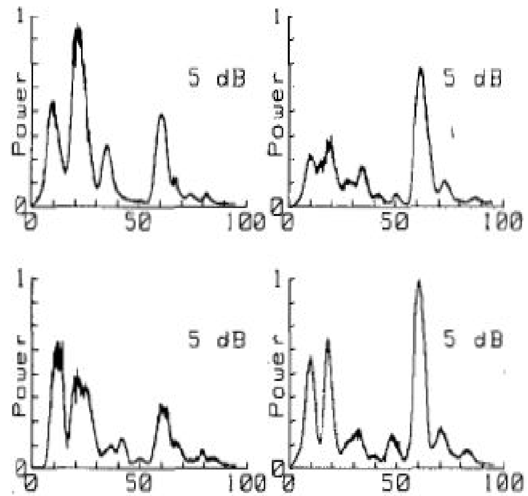


Fig. 2. A schematic representation of the measurements setup.

  - Results (Power Delay Profile)

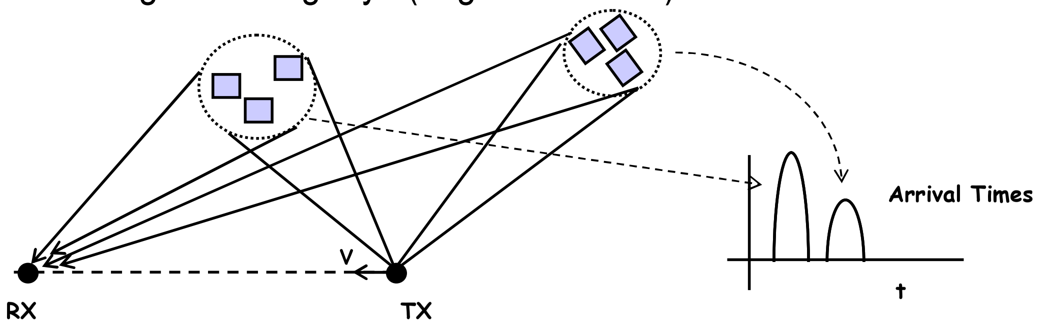


Channel models

- Wireless indoor channel modeling
  - Channel modeled as an FIR

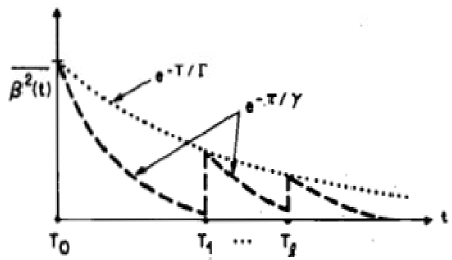
$$h(t) = \sum_{l=0}^{\infty} \sum_{k=0}^{\infty} \beta_{kl} e^{j\theta_{kl}} \delta(t - T_l - \tau_{kl}).$$

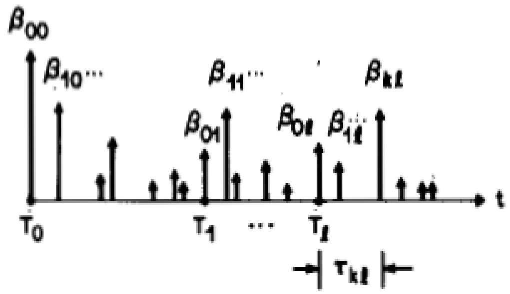
  - Multipath: clustering of arriving rays (angular clusters)



  - Double exponential decay of the impulses (clusters and rays within a cluster)

$$\overline{\beta_{kl}^2} \equiv \overline{\beta^2(T_l, \tau_{kl})} = \overline{\beta^2(0,0)}\, e^{-T_l/\Gamma} e^{-\tau_{kl}/\gamma},$$





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Channel models

- Clustering of rays
- Doppler spectrum/Fading
- Shadow fading
- Path loss model
  - Free space loss (L_{FS}) up to a breakpoint distance (d_{BP})
  - Slope of 3.5 after d_{BP}

$$L(d) = L_{FS}(d) \qquad d <= d_{BP}$$

$$L(d) = L_{FS}(d_{BP}) + 35 \log_{10}(d / d_{BP}) \qquad d > d_{BP}$$

- Adding these elements together → SISO channel model

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Channel models

- Set of channel models applicable to indoor WLAN systems

Model	Environment	LOS/NLOS	RMS delay spread (ns)	# of clusters
A (optional)	Flat fading	NLOS	0	1 tap
B	Residential	LOS	15	2
C	Residential/ Small Office	LOS/NLOS	30	2
D	Typical Office	NLOS	50	3
E	Large Office	NLOS	100	4
F	Large Space/ (Indoors and Outdoors)	NLOS	150	6

- Channel model is a FIR → Extend to MIMO (matrix of MxN FIRs)
- Other MIMO channel artifacts should be added

Channel models (MIMO)

- MIMO matrix formulation (for each tap)

$$H = \sqrt{P}\left(\sqrt{\frac{K}{K+1}}H_F + \sqrt{\frac{1}{K+1}}H_v\right)$$

$$= \sqrt{P}\left(\sqrt{\frac{K}{K+1}}\begin{bmatrix} e^{j\phi_{11}} & e^{j\phi_{12}} & e^{j\phi_{13}} & e^{j\phi_{14}} \\ e^{j\phi_{21}} & e^{j\phi_{22}} & e^{j\phi_{23}} & e^{j\phi_{24}} \\ e^{j\phi_{31}} & e^{j\phi_{32}} & e^{j\phi_{33}} & e^{j\phi_{34}} \\ e^{j\phi_{41}} & e^{j\phi_{42}} & e^{j\phi_{43}} & e^{j\phi_{44}} \end{bmatrix} + \sqrt{\frac{1}{K+1}}\begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} \\ X_{21} & X_{22} & X_{23} & X_{24} \\ X_{31} & X_{32} & X_{33} & X_{34} \\ X_{41} & X_{42} & X_{43} & X_{44} \end{bmatrix}\right)$$

Power of each tap

Ricean K-factor (0 for NLOS taps)

LOS
[S] (**constant** Rice Steering matrix)

NLOS
[X] (**time varying Rayleigh** and **Correlation** matrix)

Channel models (MIMO)

- LOS → Rice Steering matrix
  - Difference in phase between the rays arriving/leaving the tx and rx antenna elements
  - Constant matrix
  - Only first tap (LOS)

$$[S] = \underbrace{\begin{bmatrix} 1 \\ \exp\{2j\pi \frac{d_{Rx}}{\lambda} \sin(AoA_{Rx})\} \\ \cdots \\ \exp\{2j\pi \frac{d_{Rx}}{\lambda} \sin[(n_{Rx}-1)AoA_{Rx}]\} \end{bmatrix}}_{\text{Rx antenna elements}} \cdot \underbrace{\begin{bmatrix} 1 \\ \exp\{2j\pi \frac{d_{Tx}}{\lambda} \sin(AoD_{Tx})\} \\ \cdots \\ \exp\{2j\pi \frac{d_{Tx}}{\lambda} \sin[(n_{Tx}-1)AoD_{Tx}]\} \end{bmatrix}^T}_{\text{Tx antenna elements}}$$

MxN matrix

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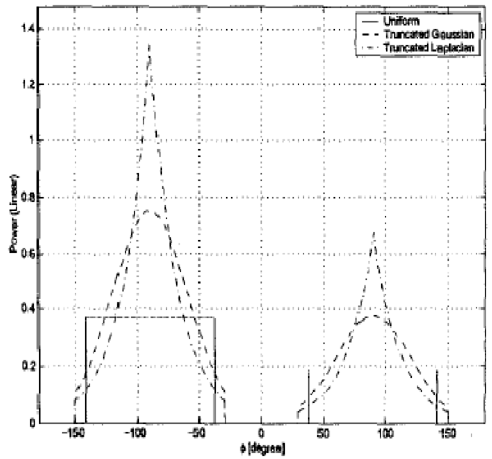
Channel models (MIMO)

- NLOS → Rayleigh and Correlation matrix (I)
  - Correlation between tx antennas and rx antennas ([Rtx] and [Rrx] matrixes)
    - From antenna spacings to theoretical capacities (L. Schumacher, K. Pedersen, P. Morgensen)
    - Power Angular Spectrum (PAS): Uniform, Gaussian or Laplacian



    - Uniform linear antenna array → correlation of rx/tx signals between antenna elements

$$\rho_{ij} = \int_{-\pi}^{\pi} e^{j\frac{2\pi}{\lambda}kd\cdot\sin(\theta)} \cdot PAS(\theta)\cdot \underbrace{A_i(\theta)\cdot A_j(\theta)}d\theta$$

Spacing between antennas

Element electromagnetic pattern

Channel models (MIMO)

- NLOS → Rayleigh and Correlation matrix (II)
  - Correlation between tx antennas and rx antennas ([Rtx] and [Rrx] matrixes)
    - Generation of the correlation matrixes

$$[R_{tx}] = [\rho_{txij}]$$

$$[R_{rx}] = [\rho_{rxij}]$$

→

$$R_{tx} = \begin{bmatrix} 1 & \rho_{tx12}^* & \rho_{tx13}^* & \rho_{tx14}^* \\ \rho_{tx21} & 1 & \rho_{tx23}^* & \rho_{tx24}^* \\ \rho_{tx31} & \rho_{tx32} & 1 & \rho_{tx34}^* \\ \rho_{tx41} & \rho_{tx42} & \rho_{tx43} & 1 \end{bmatrix}$$

$$R_{rx} = \begin{bmatrix} 1 & \rho_{rx12}^* & \rho_{rx13}^* & \rho_{rx14}^* \\ \rho_{rx21} & 1 & \rho_{rx23}^* & \rho_{rx24}^* \\ \rho_{rx31} & \rho_{rx32} & 1 & \rho_{rx34}^* \\ \rho_{rx41} & \rho_{rx42} & \rho_{rx43} & 1 \end{bmatrix}$$

Example: 4x4 MIMO channel

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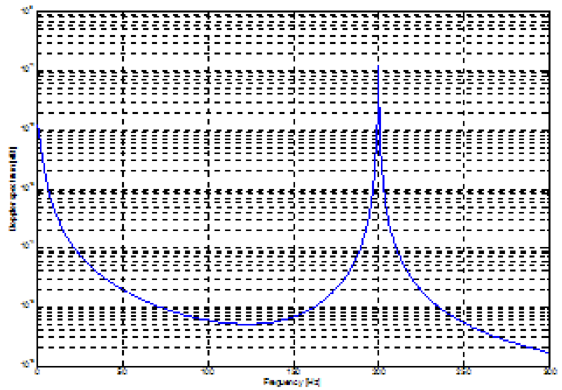
Channel models (MIMO)

- NLOS → Rayleigh and Correlation matrix (III)
  - Rayleigh fading
    - Generation of a Rayleigh vector
    - Shaping of the vector with a FIR (order=7) to generate the adequate Doppler spectrum
  - Combination of the Correlation and the Rayleigh fading

$$[X] = \{[R_{tx}] \otimes [R_{rx}]\}^{1/2} [H_{iid}]$$

Kronecker product ($\otimes$) — Rayleigh vector ($[H_{iid}]$)

  - Adding other artifacts
    - Shadow fading
    - Doppler component due to a moving vehicle (optional)
    - Doppler components due to fluorescent lights (optional)



Bell shape doppler spectrum with a 200Hz Doppler component

Simulation/Emulation

- IEEE 802.11n still in testing stage (already being implemented by Intel)
- Performance of advanced wireless techniques such as MIMO is highly dependant on the channel
  - Necessity of realising credible tests and validations under realistic conditions
  - Inefficiency of real measurements (moving the rx along a specific indoor location)

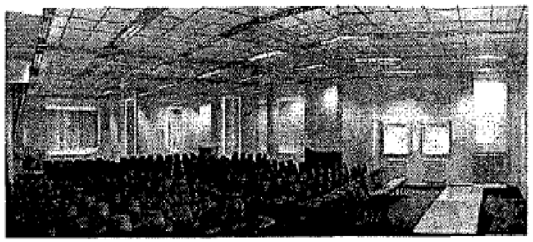


Figure 4: Location used for Empty Room measurements

D.P. McNamara, M.A. Beach, P.N. Fletcher, P. Karlsson, Initial Investigation of MIMO Channels in Indoor Enviroments

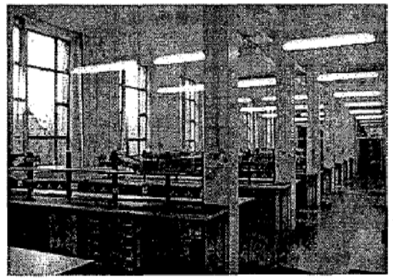


Figure 2: Laboratory measurement environment

Necessity of replicating the wireless channel in the laboratory

Simulation/Emulation

- Wireless channel replication in the laboratory
  - Traditional option → Simulation
  - "Easy" solution, but...

$$H = \sqrt{P}\left(\sqrt{\frac{K}{K+1}}H_F + \sqrt{\frac{1}{K+1}}H_v\right)$$

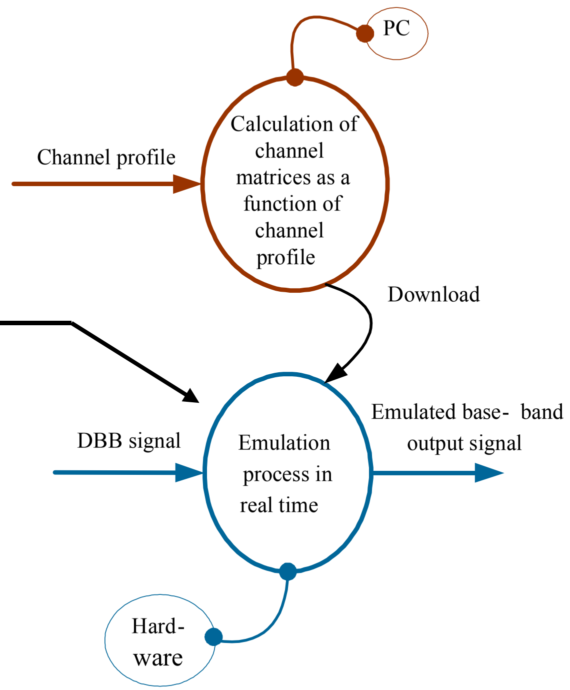
$$= \sqrt{P}\left(\sqrt{\frac{K}{K+1}}\begin{bmatrix} e^{j\phi_{11}} & e^{j\phi_{12}} & e^{j\phi_{13}} & e^{j\phi_{14}} \\ e^{j\phi_{21}} & e^{j\phi_{22}} & e^{j\phi_{23}} & e^{j\phi_{24}} \\ e^{j\phi_{31}} & e^{j\phi_{32}} & e^{j\phi_{33}} & e^{j\phi_{34}} \\ e^{j\phi_{41}} & e^{j\phi_{42}} & e^{j\phi_{43}} & e^{j\phi_{44}} \end{bmatrix} + \sqrt{\frac{1}{K+1}}\begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} \\ X_{21} & X_{22} & X_{23} & X_{24} \\ X_{31} & X_{32} & X_{33} & X_{34} \\ X_{41} & X_{42} & X_{43} & X_{44} \end{bmatrix}\right)$$

  - MIMO systems → The channel matrix [H] has to be generated at least every coherence time!
  - A more realistic simulation will require many samples per coherence time
  - **Huge computational complexity** (that even **grows quadratically** with the number of tx and rx antennas)

Simulation is not enough → Real time emulation

Wireless channel emulation

- Channel emulator
  - A platform that replicates an actual wireless channel and all its artifacts in the lab enviroment
  - Due to the large amount of real-time operations demanded, usually implemented as high speed dedicated hardware platforms
- Traditional approach
  - Represent the channel as a FIR filter compliant to the PDP
  - Emulation core performs convolution in time over the incoming data and the channel response
  - Replicate for the number of subchannels (MxN)
  - Computations are a funtion of the channel response length and increase quadratically with M and N



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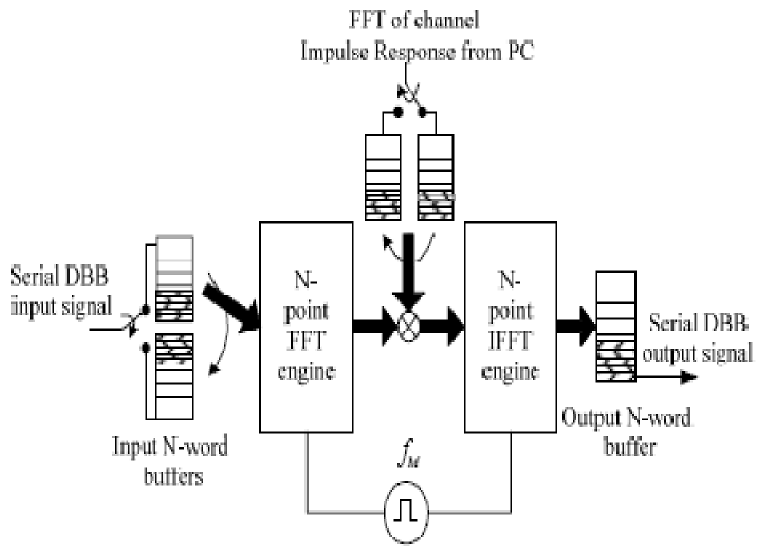
Wireless channel emulation

- New scalable solutions → **Frequency domain channel emulation**
- A real-time wireless channel emulator for MIMO systems (H. Eslami, A. Eltawil)
  - Generate the frequency response for each subchannel ($H_{ij}(f)$)
    - One sample of the channel state every coherence time
    - For accurate emulations, multiple samples can be generated every coherence time
  - 1 FFT/IFFT per each tx/rx element (M FFT, N IFFT) as opose to one FIR per each subchannel
  - Emulator core is a single multiplier for each subchannel

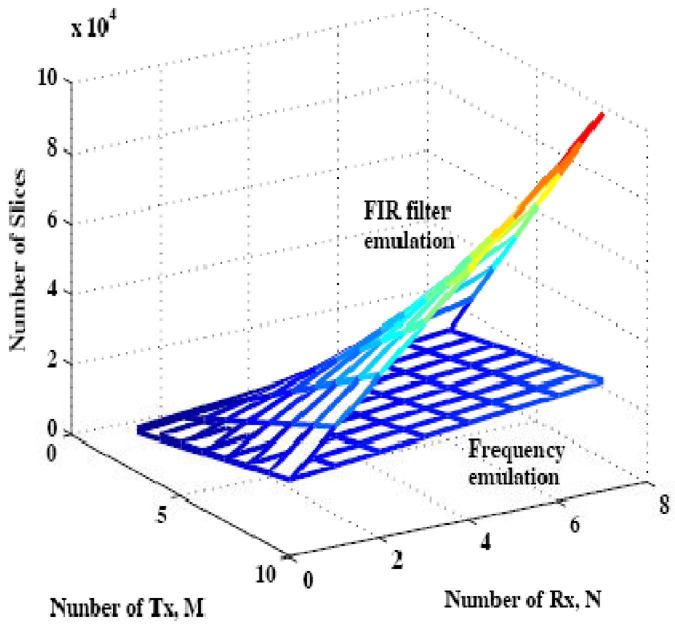


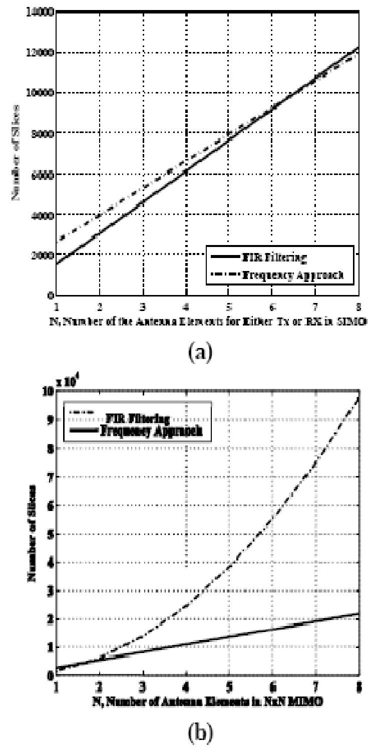
Wireless channel emulation

- Improvements
  - Each extra sub-channel is only an additional multiplier
  - Less computational complexity
  - Scalable (no changes needed if the length of the channel FIR varies)
- For example, for a 4x4 MIMO system
  - 4 FFT engines at the input of the emulator
  - 16 multipliers (1 per each subchannel)
  - 4 IFFT engines at the output of the emulator

Wireless channel emulation

- Some results...
  - FPGA implementation of the time domain emulator vs the frequency domain emulator





Future work

- Optimize and reduce computational complexity
  - Hybrid time/frequency channel emulator
- ...